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In-situ strength tests of coarse, cohesionless debris on scree slopes

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Abstract

Debris strength is a key factor in the initiation of debris flows. Therefore debris strength must be measured to assess the initiation conditions of debris flows. It is difficult to test the strength of coarse debris in the laboratory, as large quantities of material are needed to eliminate single-particle effects. Therefore in-situ strength tests have been conducted on scree slopes in the southern French Alps to measure the strength of dry, coarse, matrixless debris. The test method consisted of bringing a debris mass into movement parallel to the slope surface on slopes at or near the critical slope angle.

As dry, coarse, matrixless debris is essentially cohesionless, its strength can be characterized by its internal friction angle. Mean kinetic internal friction angles vary from 36.0° to 38.7° for five debris types with mean stone sizes ranging from 33–50 mm. Stone size sorting is the most important cause of variations in kinetic internal friction angle. Stone shape also influences the kinetic internal friction angle, but it is less important. Stone size, stone shape sorting and rock type have no influence. However, rock type may indirectly influence kinetic internal friction angle through stone size sorting and stone shape.

1. Introduction

Debris strength is an important factor in the initiation of debris flows and other types of mass movement. We have investigated debris strength and other factors involved in the initiation of debris flows in a part of the southern French Alps (Fig. 1). The final aims of the research project are:
(a) to quantify the conditions leading to the initiation of debris flows, and
(b) to calculate debris flow frequency by comparing conditions leading to debris flow initiation with the occurrence of meteorological conditions causing these conditions.

In this area debris flows are often triggered by high-intensity rainstorms (Van Asch and Van Steijn, 1991; Van Steijn, 1991; Blijenberg, 1993a,b), which produce large amounts of surface runoff in a short time. When this runoff flows through an accumulation of coarse debris, it changes the force equilibrium of the debris mass and may initiate a debris flow.

Two major mechanisms of debris flow initiation can be distinguished. The first mechanism is the transformation of a landslide into a debris flow. Campbell (1974) and Johnson and Rodine (1984) describe shallow landslides turning into debris flows. The limiting equilibrium conditions are those for the initiation of a landslide on an 'infinite slope':

$$F=\frac{\text{shear resistance}}{\text{shear stress}}=\frac{c'+(\gamma-m\gamma_w)z\cos^2\beta\tan\phi'}{\gamma z\sin\beta\cos\beta} \tag{1}$$

where: c': effective cohesion (Pa); F stability factor (–); m relative groundwater level: from 0 (no

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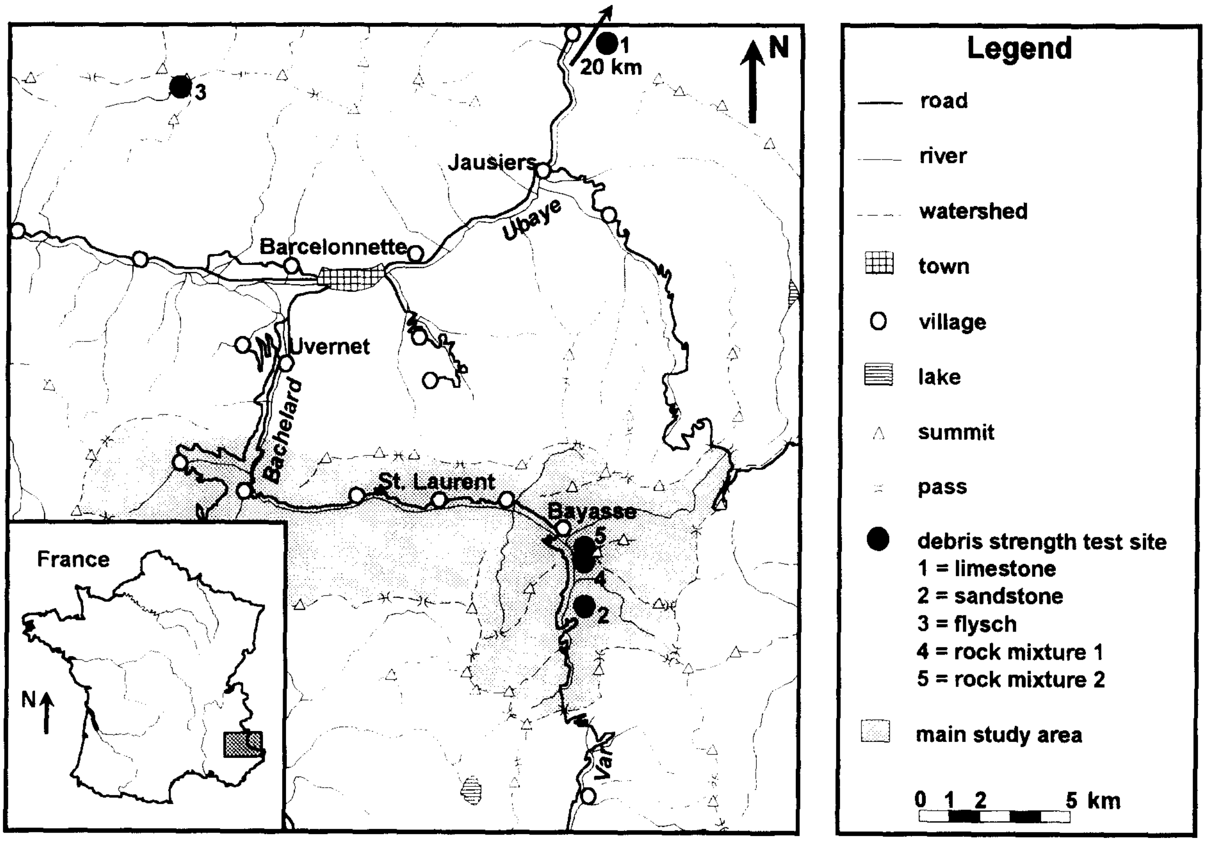

Fig. 1. Location of the study area and the debris strength test sites.

groundwater) to 1 (saturated) (–); z: depth (m); β: slope angle (°); γ: bulk weight of debris (N·m^{-3}); γ_w: unit weight of water (N·m^{-3}); ϕ': effective internal friction angle (°).

If $F=1$, there is a limiting equilibrium; for $F<1$, failure occurs. The second mechanism is the spontaneous initiation of a debris flow from a saturated mass of debris by dilatancy. For fully saturated, cohesionless materials, the following equation is based on Takahashi (1978, 1980, 1981):

$$F=\frac{c_*(\sigma-\rho)}{c_*(\sigma-\rho)+\rho[1+(1/k)]}\cdot\frac{\tan\phi'}{\tan\beta} \qquad (2)$$

where: c_*: volumetric content of solids of static debris (–); k: dimensionless constant, usually $k\approx 1$ (–); ρ: liquid density (kg·m^{-3}); σ: solids density (kg·m^{-3}).

In these equations, strength is represented by the internal friction angle ϕ' and (in Eq. 1) by the cohesion c'. Obviously, strength plays an important role in both equations. Fig. 2 illustrates the importance of strength for stability. This sensitivity analysis plot shows the relative value of F in Eq. 2 as a function of the relative value of the input variables, with original values $F=0.326$ for $\phi=38°$, $\beta=35°$, $c_*=0.7$, $\sigma=2400$ kg·m^{-3} and $\rho=1100$ kg·m^{-3}.

In dry, coarse debris with little or no matrix-material, cohesion is negligible. Therefore, the strength of such debris is essentially determined

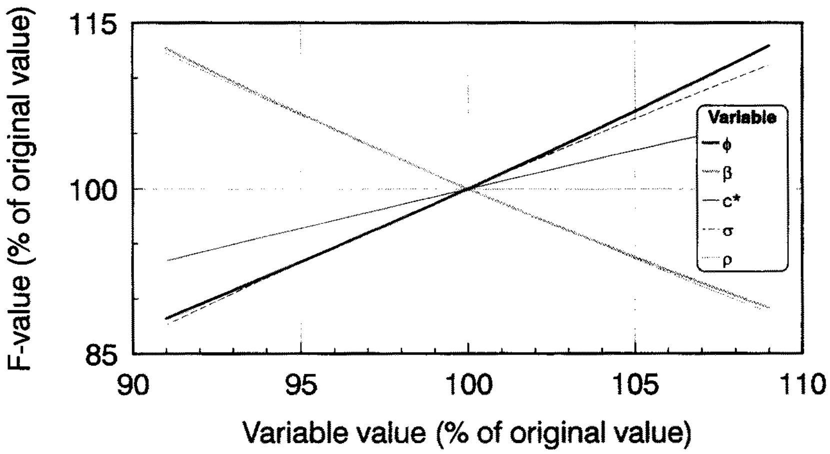

Fig. 2. Sensitivity of Takahashi's debris flow initiation model for its component variables.

by its internal friction angle. This makes limiting equilibrium conditions more simple to model. For cohesionless ($c'=0$), dry ($m=0$) debris, Eq. 1 simplifies to:

$$F=\frac{\tan\phi'}{\tan\beta} \tag{3}$$

This equation shows that dry, coarse, cohesionless debris will fail if the slope angle exceeds the internal friction angle.

Two different types of internal friction angles can be distinguished. The *static internal friction angle* ϕ_s determines the resistance of a static mass against initial movement. ϕ_s is the internal friction angle describing debris flow initiation in Eqs. 1 and 2.

In a sliding mass, the *kinetic internal friction angle* ϕ_k determines the resistance against further movement. This friction angle is sometimes called dynamic internal friction angle or residual friction angle. ϕ_k is usually less than ϕ_s.

2. The test method

The strength test was designed to determine the static and kinetic internal friction angles of coarse, cohesionless material in the field. Suitable locations for this test are locations where coarse, cohesionless debris has accumulated at surface slope angles near the kinetic internal friction angle of the debris, such as the top of scree slopes and steep gullies.

The test starts by digging away debris on a slope. The material upslope of the cut has a steeper local slope and will fail if too much material is dug away (Fig. 3a). The failure plane is steeper than the mean surface slope. Ideally, a straight failure plane starts at downslope point P1 and ends at some point P2 upslope. If the locations of points P1 (depth d) and P2 (distance s) and the mean surface slope angle β are known, the angle of the failure plane can be calculated. The angle of the failure plane equals the static internal friction angle ϕ_s of the debris, provided the mass that starts sliding is large enough. However, if the mass that slides is small, boundary effects caused by

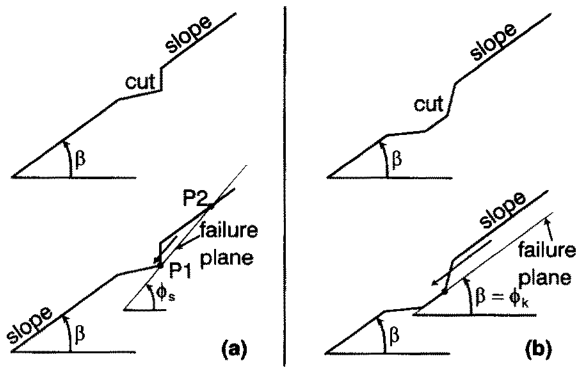

Fig. 3. The test methods for the determination of the static (a), and kinetic (b) internal friction angles of coarse, cohesionless debris.

single particle interactions may play an important role.

When more material is dug away, a larger mass starts to slide. This mass may continue to move downslope over some distance along a failure plane more or less parallel to the slope surface, as shown in Fig. 3b. If it slides with a uniform velocity, the force necessary to overcome friction equals the downslope component of the weight of the mass, so the sliding mass is in dynamic equilibrium: $F \approx 1$. If the dimensions of the sliding mass are large compared to individual stones, single particle effects are negligible, and if the depth of the sliding mass is small compared to its width, friction at the sides is negligible as well. Arching between the stationary boundaries of the sliding mass may be considered a special kind of single particle effect. If these conditions are all met, ϕ_k equals β according to Eq. 3, so the kinetic internal friction angle can be determined by measuring the surface slope angle of the sliding mass.

The surface angle of a sliding mass was measured by placing a 2 m long bar on the surface and measuring its inclination. The maximum error of each measurement was about 2°. In order to avoid a large influence of single particle effects and side friction, the sliding mass must be at least 2 m long and at least 90% of the stones must be smaller than 10 cm. The width of the mass has to be at least ten times mean stone size and the depth of the failure plane must be at least three times mean (estimated) stone size.

Internal friction angle tests were done 50 times at each test location. Besides rock type constituting the debris, at each location 100 stones were randomly picked and the principal axes of the stones measured for a characterization of the debris. From these principal axes other parameters of stone size, stone shape and stone size distribution can be derived and may be related to the kinetic angles of internal friction.

3. Results

In practice it was impossible to determine the static internal friction angle following the test procedure described. The main reason was that it was impossible to find point P2 unequivocally. Often a few stones or small debris masses started to move and the impulse caused by their motion immediately initiated failure of more material upslope. This caused an upslope displacement of point P2 along the slope surface during the test. In these circumstances single particle effects have too much influence to make valid determinations.

Although primary interest was on static internal friction angles, we decided to continue the tests to measure the kinetic internal friction angles, hoping to find a relation from literature between static and kinetic internal friction angles. The rock type constituting the debris determined the choice of the five test locations (Fig. 1). Rock types tested were sandstone, flysch, limestone and two rock mixtures, mix1, consisting of sandstone, limestone and marl debris, and mix2, consisting of sandstone and limestone debris. These rock types are typical for debris on scree slopes in the study area.

All tests were performed on dry debris. Usually the boundary conditions for the tests were amply fulfilled. Typically the sliding mass was 3–6 m long, 50–200 cm wide and 20–50 cm deep. Estimated sliding velocities varied from 1–10 cm/s.

3.1. Kinetic internal friction angle

Kinetic internal friction angles ϕ_k range from 31°–43° for 250 individual tests. The ϕ_k-distributions of the five different location samples are shown in Fig. 4. The five samples all have normal ϕ_k-distributions at a 95% significance level.

Mean ϕ_k values for each of the five samples are given in Table 1. The mean ϕ_k values range from 36.0° for limestone to 38.7° for mix2, a mixture of limestone and sandstone. Standard deviations are about 2°, except for limestone, which has a smaller standard deviation. As all five samples have normally distributed ϕ_k values, the mean ϕ_k values can be compared using a t-test. Table 2 shows which samples have significantly different mean ϕ_k values. As can be seen, most samples show mutually significant differences at the 95% significance level.

The influence of outliers in the data on the ϕ_k-distributions was examined in two different ways. Both methods consisted of rejecting two outliers from each sample data set. In the high–low method

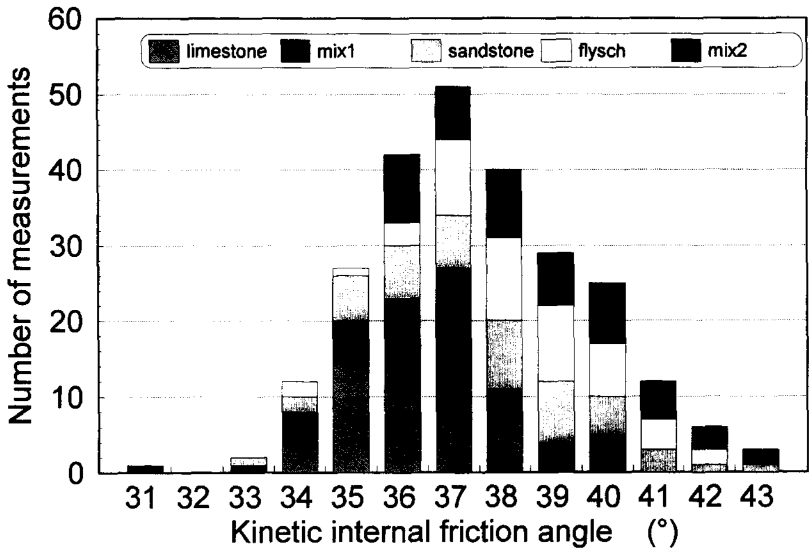

Fig. 4. Kinetic internal friction angle distributions for five debris types.

Table 1
Kinetic internal friction angles of five coarse, cohesionless debris types

Debris type	All data ($N=50$)				Outliers rejected ($N=48$)							
					high–low rejection[a]				stepwise rejection[b]			
	mean[c]	σ	min	max	mean[c]	σ	min	max	mean[c]	σ	min	max
Limestone	36.0 ± 0.4	1.3	34	40	36.0 ± 0.3	1.1	34	38	35.9 ± 0.3	1.1	34	38
Mixture 1	36.6 ± 0.5	1.8	31	40	36.7 ± 0.5	1.6	33	40	36.8 ± 0.5	1.6	34	40
Sandstone	37.7 ± 0.6	2.2	33	43	37.7 ± 0.6	2.0	34	42	37.7 ± 0.6	2.0	34	42
Flysch	38.3 ± 0.5	1.8	34	42	38.4 ± 0.5	1.7	34	42	38.5 ± 0.5	1.6	35	42
Mixture 2	38.7 ± 0.6	2.0	36	43	38.7 ± 0.5	1.9	36	43	38.5 ± 0.5	1.8	36	42

All values are in (°).
[a]Outliers are the highest and the lowest values of the sample.
[b]Outliers are the two values with largest difference from the sample mean, one removed at a time.
[c]Values given are mean and 95% confidence level around the mean (2 × standard error of mean).

outliers were defined as the lowest and the highest ϕ_k values of the sample data. The stepwise method consisted of a stepwise procedure of rejecting the outliers. First the ϕ_k value with the largest difference from the mean was rejected from the data set. Second, the resulting mean ϕ_k was calculated and then the first step was repeated for the second outlier.

The influence of outliers on the means and standard deviations of ϕ_k is also shown in Table 1. It appears that the influence of outliers on mean ϕ_k values is small. The maximum change in mean ϕ_k with 2 outliers rejected is 0.2° (0.5% of the original values). The influence of outliers on the standard deviation is, as might be expected, much larger. With two outliers rejected, standard deviations show a decrease of 0.09–0.24° (5–13%).

As interest is primarily on mean ϕ_k values, and the influence of the outliers on these values is small, the complete sample data sets have been used for further analysis.

Table 2
Significance of differences[a] in mean kinetic friction angles for five debris types

	Mixture 2	Flysch	Sandstone	Mixture 1
Limestone	**0.000**[b]	**0.000**	**0.000**	0.061
Mixture 1	**0.000**	**0.000**	**0.009**	
Sandstone	**0.018**	0.106		
Flysch	0.352			

[a]Values indicate the probability that samples belong to the same population.
[b]Bold values indicate significant difference between samples at the 95% confidence level.

3.2. Factors influencing the kinetic internal friction angle

Even small differences in ϕ have a marked influence on the potential initiation of debris flows, as was shown in Fig. 2. The variation in mean ϕ_k values between the five samples was initially assumed to depend mainly on rock type constituting the debris. However, the two rock mixtures show a large difference in ϕ_k, even though their rock composition does not differ very much. The two mixtures consist mainly of sandstone and limestone, with mix1 also containing some marl.

As rock type is not important, mean ϕ_k values were compared to several other parameters of the debris. The parameters are listed in Table 3 in four main groups: mean stone size, mean stone shape, stone size sorting and stone shape sorting (variation in stone shapes). Table 4 gives the values of these parameters.

Comparison of the parameter values with ϕ_k values shows that the stone size sorting parameters have high, positive correlations with ϕ_k (Table 5). This means that the kinetic internal friction angle increases with debris stone size grading. From the stone size sorting parameters, s_V has the best correlation with ϕ_k: it accounts for 71% of the variation in ϕ_k, and the correlation is significant at the 95% significance level. The correlation equation is:

$$\phi_k = 34.50 + 0.993 s_V \quad (4)$$

Although s_a and s_b also explain a large part (63 and 54%) of the variation in ϕ_k, their correlations

Table 3
Definition of debris parameters

Parameter type	Parameter	Description
Mean		
Stone size		
	m_a	major stone axis length: a (mm)
	m_b	intermediate stone axis length: b (mm)
	m_c	minor stone axis length: c (mm)
	m_V	stone volume: $V = a \cdot b \cdot c$ (cm^3)
Stone shape		dimensionless stone size ratios based on:
	$m_{b/a}$	intermediate to major stone axis length: b/a
	$m_{c/a}$	minor to major stone axis length: c/a
	$m_{c/b}$	minor to intermediate stone axis length: c/b
	m_{V/V_c}	stone volume relative to volume of cube with axes a: $b \cdot c/a^2 = V/V_c$
Sorting[a]		
Stone size		variation in stone sizes based on:
	s_a	major stone axis length
	s_b	intermediate stone axis length
	s_c	minor stone axis length
	s_V	stone volume
Stone shape		variation in stone shapes based on:
	$s_{b/a}$	b/a ratio
	$s_{c/a}$	c/a ratio
	$s_{c/b}$	c/b ratio
	s_{V/V_c}	V/V_c ratio

[a]Coefficient of variation = dimensionless ratio of sample standard deviation to sample mean.

with ϕ_k are not statistically significant at the 95% level. These parameters are directly related to s_V. Mean stone volume m_V and mean a-axis length m_a show very weak, positive relations with ϕ_k. These relations are not statistically significant.

Table 5 also seems to suggest, that stone shape and stone shape sorting have no influence on ϕ_k. However, the residual variation in ϕ_k (unexplained by s_V) shows a very high correlation with stone shape, especially with $m_{b/a}$. Together, the parameters s_V and $m_{b/a}$ explain over 99% of the total variation in mean ϕ_k values. This strong correlation is statistically highly significant (at the 99% level).

Table 4
Debris parameter values for five debris types

Debris type	Stone size mean				Stone shape mean				Stone size sorting				Stone shape sorting			
	m_a	m_b	m_c	m_V	$m_{b/a}$	$m_{c/a}$	$m_{c/b}$	$m_{V/Vc}$	s_a	s_b	s_c	s_V	$s_{b/a}$	$s_{c/a}$	$s_{c/b}$	$s_{V/Vc}$
Limestone	51	33	20	71	0.66	0.39	0.61	0.26	0.57	0.60	0.66	1.8	0.24	0.31	0.30	0.46
Mixture 1	79	51	29	307	0.67	0.38	0.57	0.26	0.78	0.70	0.81	2.7	0.23	0.38	0.36	0.51
Sandstone	70	42	27	195	0.62	0.40	0.66	0.26	0.66	0.63	0.61	3.0	0.22	0.25	0.24	0.39
Flysch	95	50	21	347	0.56	0.25	0.45	0.15	0.86	0.78	0.84	2.9	0.30	0.51	0.48	0.68
Mixture 2	65	42	28	351	0.67	0.45	0.68	0.31	0.84	0.80	0.84	4.5	0.20	0.30	0.27	0.42

Table 5
Correlations between kinetic internal friction angle and debris parameters

	Stone size mean				Stone shape mean				Stone size sorting				Stone shape sorting			
	m_a	m_b	m_c	m_V	$m_{b/a}$	$m_{c/a}$	$m_{c/b}$	$m_{V/Vc}$	s_a	s_b	s_c	s_V	$s_{b/a}$	$s_{c/a}$	$s_{c/b}$	$s_{V/Vc}$
Explained[a]	22	13	6	38	18	1	0	2	54	63	20	71	0	2	1	2
t[b]	0.92	0.68	0.44	1.36	0.80	0.17	0.01	0.24	1.87	2.28	0.87	**2.73**[c]	0.06	0.27	0.19	0.25
Relation[d]	+	+		+	−				+	+	+	++				
Residual[e]	41	8	23	0	96	60	36	70	10	9	0	–	55	29	33	39

[a]Variation in ϕ_k explained by variable in %.
[b]t-statistic of correlation. $t_{critical}=2.35$ (one-tailed test; 3 degrees of freedom; 95% confidence level).
[c]Bold value is significant.
[d]−, + and ++ indicate, respectively, weak negative, weak positive and strong positive relations with ϕ_k.
[e]Variation in residual ϕ_k explained by variable in % after regression of ϕ_k on s_V.

The correlation equation is:

$$\phi_k=42.81+1.062s_V-13.4m_{b/a} \quad (5)$$

4. Discussion

The test method seems to have worked well for the determination of the kinetic internal friction angle. The method seems practicable for debris with mean stone sizes of up to 15–20 cm. As the effort needed to test the debris increases strongly with mean stone size, the method seems less practicable for coarser debris.

The test method has several *advantages* over laboratory tests: it is a simple and cheap test to determine ϕ_k on undisturbed, natural debris. The large amount of material needed to avoid single-particle effects is abundantly present on scree slopes and on the floors of some steep gullies and does not have to be transported to a testing facility. Once a suitable location has been found, a large number of tests can be done in a short time. Suitable locations for this type of strength test are locations where large amounts of coarse, cohesionless debris have accumulated at surface slope angles near the kinetic internal friction angle of the debris. Such locations can be found at the top of scree slopes and in some steep gullies, where surface slope angles are 35° or more. Especially the method may be applied when suitable locations are present, but testing equipment facilities, material transport facilities and finances are limited.

Besides these advantages, the test method also has several *disadvantages*. Suitable locations can be difficult to find, as the slope angle must be near the internal friction angle of the material. These locations are often difficult to reach and they can be dangerous, as (single particle) rockfalls often occur. A large number of tests is necessary to eliminate measurement errors from individual tests. Furthermore, debris parameters like mean stone size, stone size sorting or rock type cannot be controlled easily, making it more difficult to single out the influence of such parameters on ϕ_k. The method might be relevant for scree slope development studies.

Justo (1991) mentions the fact, that for coarse material in-situ strength tests are preferred. The tests described by Justo (1991) are usually complicated in the sense of equipment or operation. In difficult terrain like steep scree slopes, such tests seem impossible and the test method used in this study seems preferable.

Most strength tests on coarse, cohesionless materials have been done for sands. For coarser materials only few data have been gathered. This lack of data has also caused a lack of guidelines for testing of coarse materials, as mentioned by Lambe and Whitman (1969). Charles (1991) gives some guidelines for sample sizes to be used in triaxial tests and direct shear tests. To avoid a large influence of single-particle effects, sample height in direct shear tests should be at least ten times maximum grain size, equivalent to a mean depth of the failure plane of at least five times maximum grain size. This condition is more stringent than the condition used in this study, where the failure plane depth had to be at least three times the mean grain size. It seems justified that the condition may be less stringent than in the confined direct shear tests, as single particle effects like arching are much less likely to occur in the unconfined test used in this study.

The range of ϕ_k values in this study (36.0–38.7°) is in accordance with data from several other workers. Martins (1991) reports static angles of internal friction $\phi_s = 38$–$41°$ for angular fragments of crushed rock of 30–80 mm. Kinetic angles of internal friction may then be expected to be somewhat smaller, perhaps 0–3°. Farouki and Winterkorn (1964) mention results obtained by Kjellman and Jakobson (1955), who have determined static angles of internal friction for well-sorted, coarse pebbles (38–53 mm). For loose packing they have found $\phi_s = 37.1°$, whereas for dense packing $\phi_s = 44.1°$. The loose packing state friction angle probably compares well with the kinetic internal friction angle. Charles (1991) mentions results from Gallacher (1972, 1988), who has performed field tests on loose gravel at Megget Dam in Scotland giving $\phi_s = 37.5°$. Kenney (1984) reports ϕ_k values of 37° for well-graded crushed, angular sandstone and slate, with mean grain sizes of about 5–40 mm. Finally, Statham (1977) has measured kinetic internal friction angles of 38–42° for angular gravel and talus, i.e., slightly higher than in this study.

The small range of grain sizes tested in this study may have caused the independence of internal friction angles on mean grain size. Mean stone size (intermediate axis length) ranges from 33–50 mm. Still, the results seem to agree with those from other workers. Some workers have found no relation between mean grain size and ϕ (Bishop, 1948), some have found a positive relation (Martins, 1991) and others a negative relation (Lambe and Whitman, 1969; Kenney, 1984). Farouki and Winterkorn (1964) and Statham (1977) have compared results from several workers. From literature surveys and theoretical considerations they have concluded that ϕ is independent of mean grain size. Therefore, it seems acceptable that the ϕ_k values from this study can be applied to coarser debris as well.

Lambe and Whitman (1969), Statham (1977) and Hansen and Lundgren (1960) mention the increase of ϕ when going from a well-sorted to a well-graded material. Their findings agree well with the strong dependence of kinetic internal friction angle on grain size sorting found in this study.

The results of stone shape influence are more difficult to compare. The decrease of ϕ_k with increasing b/a ratio (stone flatness/elongation) seems to agree with the positive relations between ϕ and grain shape mentioned by others (Hansen and Lundgren, 1960; Kézdi, 1974; Statham, 1977; Kenney, 1984; Martins, 1991). However, most workers have used stone shape factors based on stone angularity or stone surface roughness. These factors are usually based on relatively small irregularities on the stone surface. In contrast, this study uses an 'overall stone shape' factor, giving the same values, for example, for spheres and cubes. Kenney (1984) reports that grain angularity influences ϕ_k more than grain size sorting. In this study variation in stone angularity is probably of minor importance, as all tests have been performed on rough, angular material.

The absence of a direct relation between ϕ_k and rock type constituting the debris must be taken with some caution. Even though rock type does not directly influence ϕ_k, stone size sorting and stone shape could depend on rock type.

No clear relation between ϕ_s and ϕ_k has been found in literature yet, making it difficult to use the measured ϕ_k values in the debris flow initiation models. Martins (1991) mentions ϕ_k values 0–3° less than ϕ_s. These differences are as large as the total variation in ϕ_k values caused by debris composition as found in this study. Besides, it is not known whether the difference between ϕ_s and ϕ_k is related to any of the debris parameters from Table 3.

5. Conclusions

The test method seems to have worked well for determination of the kinetic internal friction angle. Therefore, it may be considered an alternative to other strength tests for coarse, cohesionless materials. The method seems preferable in situations where simple and cheap in-situ tests are required, but its practicability depends strongly on the presence and accessibility of suitable test locations.

The independence of ϕ_k on mean stone size justifies the use of ϕ_k values from this test method for coarser debris as well. As far as mean ϕ_k values and the dependence of ϕ_k on stone size sorting are concerned, this study is well in accordance with previous work. The positive relation found between ϕ_k and stone shape cannot be directly compared to positive relations reported by others, because the stone shape factor used in this study differs from those used by other workers.

As no clear relation is known yet between ϕ_s and ϕ_k, the measured ϕ_k values cannot be used in the debris flow initiation models.

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