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LANDSLIDES: THE DEDUCTION OF STRENGTH PARAMETERS OF MATERIALS FROM EQUILIBRIUM ANALYSIS

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SUMMARY

Rotational landslides (slumps) varying in size can develop at different slope angles in the same type of cohesive regolith material. Therefore it is possible to set up independent equilibrium equations for these rotational slides of different size.

In this way, a good estimate of the mean strength parameters of a certain type of material can be obtained on the basis of a number of these independent equilibrium equations. This can be done by means of regression analyses and the correlation coefficients and variances give a good indication of the reliability of the estimate of the strength parameters. In this paper the strength parameters of two regolith materials on schist and claystone are determined in this way and compared with the strength parameters measured in the laboratory.

1. INTRODUCTION

Landslide maps give information about the spatial distribution of landslides in relation to certain controlling environmental characteristics.

On these maps one can make a rough distinction between stable areas and unstable areas. However, the information given in these maps is too limited for them to be used for planning the technical and economic development of a certain area. Maps that are useful for the preliminary planning of for instance certain technical constructions should provide sufficient information to allow one to estimate the degree of stability of certain landscape units and to predict the chances of instability, should there be human interference (COOK & DOORNKAMP 1974).

The information that these maps should contain should relate to the parameters that can be put into a simple stability model which can be used to calculate the degree of stability at a certain site. This means that information should pertain to

a) the soil mechanical characteristics of the material
b) the thickness of the material
c) the maximum rise of the ground-water table
d) slope topography.

The strength parameters are the most important soil mechanical characteristics. These parameters can be determined in the laboratory, but this method is laborious and expensive and should be used only for detailed site investigation at a more advanced stage of planning.

For stability maps in the sense mentioned above, one does not need such accurate local parameters but means and variances of strength parameters of materials are sufficient (see e.g. DRAMIS et al. 1979).

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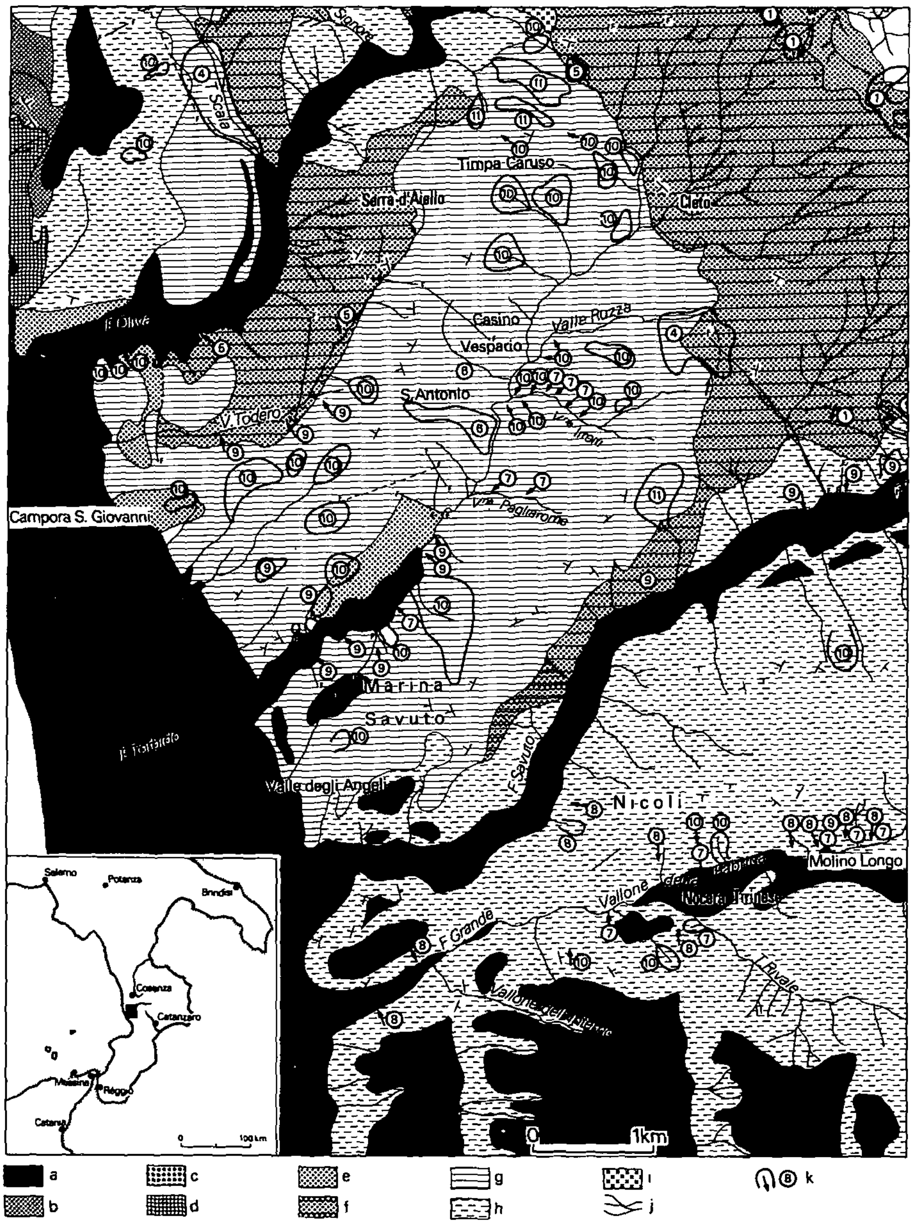

Fig. 1: Landslides and lithology in the vicinity of Amantea (Calabria, S.Italy).
a: Pleistocene and Holocene deposits; b: limestone (Tertiary); c: limestone (Jurassic); d: dolomites (Triassic); e: weakly cemented sandstone (Tertiary); f: cemented sandstone (Tertiary); g: silt- and claystone (Tertiary); h: schists and phyllites (Paleozoic); i: granites; j: hydrographic network; k: landslide and type number. Landslides of type number 8 and 9 (rotational slides) were selected for the purpose of this study.

In this paper it will be shown that in areas where landslides occur, the mean strength parameters of materials, which are needed for stability maps, can be deduced by making an equilibrium analysis of the landslides; these landslides must be investigated in detail in the field. It will be shown that the mean characteristics of a certain type of material can be estimated applying "back analysis" to a number of landslides which have developed in the material under investigation.

2. THE STUDY AREA

Landslides were investigated in a coastal area of Calabria (S. Italy) in the vicinity of Amantea (fig. 1). In the study area paleozoic rocks consisting of phyllites and schists are found which are unconformably overlain by rocks of mainly Miocene age, consisting of weakly consolidated conglomerates, sandstones and siltic claystones. The area has a complex geological structure the main outlines of which were formed during the Tertiary and Quaternary periods (BURTON 1970, DUBOIS 1970). The Tertiary is characterized by a period of large overthrusts (Lower Miocene), folding (Middle Miocene) and intensive faulting that involved an uplift of the Calabrian area up to 1000 M. (BOUSQUET & GUEREMY 1968, BURTON 1970). Faulting occured particularly during the Pleistocene periods, with uplifts ranging from 100 to 300 m.

The turbulent tectonic history has led to the formation of an intense network of discontinuities in the rocks (schistosity, jointing, and faulting). which is one of the main causes of frequent landsliding in Calabria (NOSSIN 1972, VERSTAPPEN 1977, VAN ASCH 1980, CARRARA et al. 1982). Other important factors causing landslides in the area include rock-type and related regoliths, erosion of rivers and gullies, local ponding of ground water, the actions of man and last but not least the dominance of steep slopes, which were caused by the strong upheaval and rapid incision of the rivers. VAN ASCH (1980) found in the area he studied that the incidence of landslides increases with increasing slope angle. However, the total mass of displaced material does not increase with increasing slope angle; this he explained in terms of the equilibrium models of landslides.

Climatically the area has a Mediterranean character with rainfall strongly concentrated in the winter period (November–March) and rather high annual mean precipitation values ranging, for different stations, from 938 to 1161 mm. The mean temperature in the area ranges from 9°C (January) to 25°C (July) (VAN ASCH 1980).

3. EQUILIBRIUM EQUATIONS FOR ROTATIONAL SLIDES OF DIFFERENT SIZES

A method of applying equilibrium analysis of landslides has been devised to estimate the strength parameters of a certain material. Two types of materials were chosen viz. the thick regoliths on metamorphic rocks and on claystones, in both of which distinct rotational slides (slumps) had developed (fig. 1, photo 1). Equilibrium equations have been developed for this type of landslide (slump) by a number of authors (e.g. FELLENIUS 1927, BISHOP 1955, JANBU 1957). These equilibrium equations describe the balance between driving forces and resisting forces in a slope at the point of failure. The equilibrium model selected for this study has been taken from FELLENIUS and is applicable to rotational slides (slumps) having a more or less circular slip surface. The model, simple and widely used, yields a safety factor whith an accuracy of 9-15% on the safe side (LAMBE & WHITMAN 1969).

a

b

Photo 1a and b: Back scarp of a rotational slide developed in regoliths on a) schist, b) claystone.

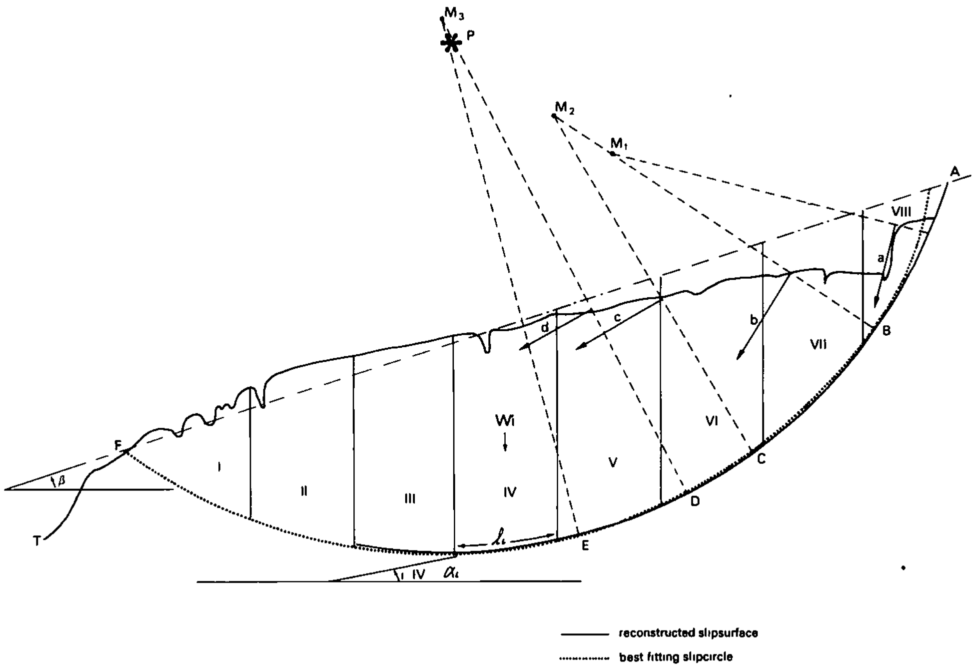

Fig. 2: Reconstruction of a slip surface in a slump developed in Ma-claystone; a, b, c and d: dip of striage lines in side; I-VIII: slices; M1, M2 and M3: centre of circle with respectively arc AB, BC and ED; P: centre of best fitting slip-circle; l_i: length of slip surface of slide i; d_i: mean slope angle of slip surface of slice i.

Fig. 2 shows a rotating block subdivided into a number of slices. It is assumed that at the point of failure the component of the weight of a slice along the slip surface is in equilibrium with the maximum shear strength along the slip surface. In the equilibrium model of FELLENIUS it is further assumed that the forces acting upon the sides of any slice have zero resultants in the direction normal to the failure arc for that slice. When the slope is at the point of failure, one can write for each slice:

$$W_i \sin \alpha_i = c' l_i + (W_i \cos \alpha_i - u_i l_i) \tan \varphi' \qquad (1)$$

where (see fig. 2):
W = weight of slice i (in N)
α = angle of the slip surface of slice i
l = length of the slip surface of slice i (m)
u = pore pressure on the slip surface of slice i (in N/m^2)
φ' = angle of internal friction
c' = cohesion of the material (in N/m^2).

By adding together the terms of the equilibrium equation (1) for the individual slices, one finds the equilibrium conditions for the total block at the point of failure:

$$\sum_{i=1}^{i=n} W_i \sin\alpha_i = c'L + \sum_{i=1}^{i=n} (W_i \cos\alpha_i - u_i l_i) \tan\varphi' \quad (2)$$

where L is the length of the total slip surface and n the number of slices.

In order to set up the equilibrium equation (2) the following characteristics of the landslide have to be examined (see also fig. 1):

a. the topography of the original slope surface (in order to determine W_i)
b. the bulk density (for the determination of W_i)
c. the maximum height of the ground water level (for the determination of u_i)
d. the geometry of the slip surface (for the determination of α_i, l_i and W_i).

If all the above mentioned factors are known, the strength parameters c' and φ' can be solved from equation (2) if at least two slumps of **different size** can be found in the same material. With two slumps one can set up two independent equilibrium equations (2) from which c' and φ' can be solved separately.

The determination of the factors (a) and (b), mentioned above, for different rotational slumps did not present any problems. The difficulty was to determine in the field factors (c) and (d).

With regard to the maximum ground-water level (factor c) the slumps selected were those in which the maximum height of the ground-water table could be estimated by means of reduction/oxidation (gley)zones in the regolith or by measuring ground-water tables during heavy rains in the wet season. For all the slumps selected we had indications that the ground-water could rise almost to the surface of the slope.

The geometry of the slip surface (d) can be determined fairly accurately if the rotating block has moved sufficiently out of the source area. When enough of the slip surface is exposed, it becomes possible to deliniate the slip surface with an arc of a circle. The equilibrium model of FELLENIUS which we shall use here is also based on the assumption that the slip surface has the form of an arc.

In some cases the displacement of the rotating block was very limited, which made it difficult to get an idea of the depth and form of the slip surface. However, especially in the claystone regoliths distinct striation lines in the vertical wall of the sides of the slumps were found. These lines made it possible to reconstruct a part of the slip surface. The direction of the striation lines indicates the direction of movement of the slumped block. Fig. 2 illustrates one of these slumps. The directions of the striation lines found along the side are given in fig. 2 by the arrows a, b, c and d.

By means of this vectors the real slip surface (AE) (continuous line) could be reconstructed. The slip surface begins at the scarp (point A, fig. 2). Assuming that the slip surface has a more or less circular form one can construct the circle arc AB by plotting the centre M_1 found from the point of intersection of the two lines which are drawn normal to vectors (a) and (b). The centre M_2 and the circle arc BC were found in the same way. Since vectors (c) and (d) are nearly parallel, no centre could be found for this part of the slip curve, which means that (CD) is practically a straight line. The circle arc ED has M_3 as its centre.

The best fitted circle arc (dotted line) was constructed through the curve A – E, which is assumed to be the ideal slip surface of the slump. There is a possibility that in reality the slip surface becomes flatter at the toe and may pass through the foot of the slope at T. This, however, could not be detected in the field.

Five slumps were selected, which had developed in claystone regoliths and eight slumps were selected in schist regoliths. For these slumps we were able to assemble the necessary factors mentioned above and related parameters and thus to set up the equilibrium equation of FELLENIUS (2). With regard to the ground-water it was established in the field during wet periods that the ground-water almost reached the surface. Gley zones which were found in the soils in some of these slumps also indicated that the ground-water must have risen almost to the surface during wet periods. In setting up the equilibrium conditions for these slumps we therefore assumed that at the point of failure the regolith was fully saturated with ground-water running parallel to the surface.

The slumps which were investigated had developed at different slope angles and differed in size. These facts are supported by theory: it can be inferred from all types of equilibrium models and from stability charts – which are based upon these models – (see e.g. the stability charts of TAYLOR (1948)) that in cohesive materials slumps can develop at different slope angles. Using the equilibrium models of FELLENIUS (1927) and SKEMPTON & DELORY (1957), VAN ASCH (1980), showed that above a certain minimum critical slope angle, slumps develop with slip circles whose size and depth decrease with increasing slope angle. Above a certain minimum critical slope angle it is the thickness of the regoliths which forms the threshold for failure. The fact that in the two types of regolith material slumps of different sizes are found at different slope angles is thus supported by the theory of the equilibrium models.

We set up independent equilibrium equations for these slumps that differed in size by introducing into equation (2) the values of the parameters found for the different slumps. The equilibrium equations are listed in table 1 (column 3). The c'- and φ'-values in these equations are the unknown parameters.

Tab. 1: EQUILIBRIUM EQUATIONS FOR SLUMPS THAT HAVE DEVELOPED IN REGOLITHS ON CLAYSTONE AND SCHISTS

Regolith on:	slumps	equation
claystone	1	$17.8 = c' + 25.1 \tan \varphi'$
	2	$5.9 = c' + 6.5 \tan \varphi'$
	3	$21.6 = c' + 33.2 \tan \varphi'$
	4	$43.1 = c' + 62.1 \tan \varphi'$
	5	$18.9 = c' + 37.2 \tan \varphi'$
schists	6	$34.8 = c' + 23.7 \tan \varphi'$
	7	$29.5 = c' + 16.7 \tan \varphi'$
	8	$21.2 = c' + 20.7 \tan \varphi'$
	9	$21.1 = c' + 16.3 \tan \varphi'$
	10	$67.8 = c' + 51.8 \tan \varphi'$
	11	$12.6 = c' + 9.4 \tan \varphi'$
	12	$14.9 = c' + 11.3 \tan \varphi'$
	13	$20.4 = c' + 14.6 \tan \varphi'$

4. THE DETERMINATION OF THE MEAN STRENGTH PARAMETERS

From the equations given in table 1 the value of c' and φ' can be found if it is assumed that these values are constant for a certain type of material. Mathematically two independent equilibrium equations set up for two slumps of different sizes are sufficient to solve c' and φ'

separately. However, a more reliable mean estimate of the c' and φ' value is obtained if more than two slumps of different sizes developed in a certain type of material are investigated.

The following procedure is proposed for estimating the mean strength parameters from more than two equilibrium equations:

By subdividing eq. (2) by the total length of the slip surface we get:

$$\frac{\sum_{i=1}^{i=n} W_i \sin\alpha}{L} = c' + \frac{\sum_{i=1}^{i=n} (W_i \cos\alpha_i - u_i l_i) \tan\varphi'}{L} \qquad (3)$$

This equation has the form:

$$y = c' + x \tan\varphi' \quad \text{(see table 1)} \qquad (4)$$

in which:

$$y = \frac{\sum_{i=1}^{i=n} W_i \sin\alpha_i}{L} \qquad (5)$$

$$x = \frac{\sum_{i=1}^{i=n} (W_i \cos\alpha_i - u_i l_i)}{L} \qquad (6)$$

The variation in the x and y values for the individual slumps is caused by the different size of the slumps $\left(\sum_{i=1}^{i=n} u_i l_i\right)$ and the difference in total pore pressure $\left(\sum_{i=1}^{i=n} W_i\right)$ working on the slip surface.

The x and y values found for the two regoliths can be fitted into linear regression equations (eq. 4). These equations are given in table 1 and the regression lines are shown in fig. 3a,b.

The y-intercepts give the mean c'-values, and the slope values of these regression equations give the tan φ'-values.

In order to estimate c' and φ'-values by means of regression analyses it is necessary to keep Δ x small in relation to the x-value. This means that good estimates of the position of the slip surface, the total volume of sliding material and the pore water pressure have to be made in the field.

Further it must be assumed, that the ε_i are identically and independently distributed as a normal distribution with a mean of zero and a variance of σ^2. The confidence limits for c' and $\tan\varphi'$ values are obtained using the unbiased estimate of σ^2 (S^2) which is calculated from the observations.

For the claystone regolith the 95% confidence intervals for c' and tan φ' are 0.13 ± 6.20 (kNm^{-2}) and 0.65 ± 0.17 respectively, while for the schist-regolith these confidence intervals are 1.26 ± 8.90 (kNm^{-2}) and 1.29 ± 0.37. Note, however, that the cohesion (c') of a regolith cannot have a negative value.

The rather large variation in the c' and φ'-values of the two regoliths can be explained by both statistical reasons and the heterogeneity of the regolith material.

The relative small number of samples, the uneven distribution of the sizes of the individual slides (distribution of x_i and y_i-values) and the position of the x_i and y_i-values in relation to $\overline{x}$ and y must have influenced the variation in a negative way. It seems therefore appropriate to take a large number of samples which are more evenly distributed. A better estimate of especially the c'-value can be made when at least a number of small landslides (low x_i and y_i-values) can be investigated in the field.

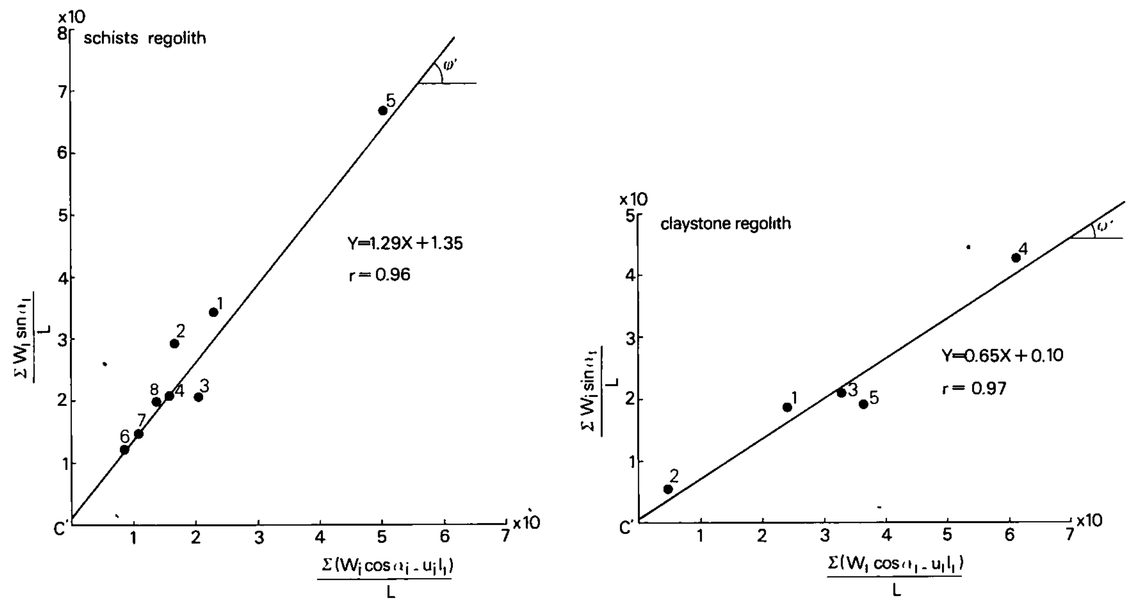

Fig. 3: Regression lines for slumps of different sizes in order to determine the c' and φ'-value of a certain type of regolith material.

The variation of the c' and φ'-values can also be partly attributed to the heterogeneity of the regolith material and it is therefore realistic that the estimated variances of these strength parameters are mentioned in the stability maps.

It is interesting to compare the c' and φ'-values found from the field data with the results of drained direct shear tests which were done in the laboratory. Table 2 shows that the dif-

Tab. 2: A COMPARISON OF STRENGTH PARAMETERS OF TWO TYPES OF MATERIALS DEDUCED FROM DATA IN THE FIELD AND FROM DIRECT SHEAR TESTS

regolith	strength parameters from field investigations		strength parameters from direct shear tests	
	c' (kNm^{-2})	φ'	c' (kNm^{-2})	φ'
claystone	0.1	32.2°	0.1	29°
schists	1.4	52.2°	1.0-1.5	48.2-48.6°

ferences between the estimated mean c' and φ'-values in the field and the laboratory data are rather small. The results obtained in the laboratory are based on a few rather small samples whereas the field data are overall means of strength parameters along slip surfaces of a number of landslides. The variances in c' and φ'-values obtained from a number of these landslides in the field may therefore give a more realistic estimate of the strength characteristics of a certain regolith, which is not always homogeneous.

5. CONCLUSIONS

Stability maps should give information about the mean and variances in strength parameters of soils and rocks. If landslides have developed in these materials the field can be used as a good alternative for the laboratory in order to find good estimates of the strength parameters of these materials. Relevant investigations of these landslides can yield parameters which make it possible to set up equilibrium equations for the individual slides. In cohesive materials individual (rotational) slides of varying size can develop at different slope angles. Therefore it is possible to set up independent equilibrium equations for individual slumps in which the c' and φ' parameters are the unknown. By means of regression analysis a good estimate of the mean and variances of c' and φ'-values of a certain regolith can be obtained on the basis of a number of these independent equations.

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