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THE STABILITY OF SLOPES IN THE ARDENNES REGION[1]

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ABSTRACT

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A number of slope studies in the Ardennes region have revealed that the mode of slope angle frequency distribution for the steep slopes is about 30°. It has been suggested by several authors that this angle corresponds to 'the angle of rest' of the regolith materials on these slopes. Recently, however, new concepts of slope development under mass failure have been elaborated, which show that there may exist more than one critical slope angle value.

Steep straight slope segments were measured and the stability properties of regoliths were determined in a part of the Ardennes region. Stability analysis performed with the obtained strength parameters, revealed that the slopes can develop by mass failure towards two so called ultimate threshold values, one of about 42° in case no pore water pressure develops in the regolith, and one of about 21° in case the regoliths are completely saturated with ground water that runs parallel to the slope. It turns out that the population of the measured steep slope segments is enclosed between these two threshold values.

The mode of the measured slope angle values does not differ between the different lithological units. It is suggested that in periglacial times the slopes became unstable, due to a blockage of the groundwater by the permafrost in the subsurface. At that time the slope population changed from the upper threshold value for dry regoliths to the lower one for completely saturated regoliths via a flattening of the slopes.

INTRODUCTION

Characteristic slope angles are defined by YOUNG (1972) as angles 'which most frequently occur, either on all slopes, under particular conditions of rock or climate or in a local area'.

They are the modes of angle frequency distributions. In the Ardennes region slope measurements made by PISSART (1962), SERET (1963), MACAR (1965) and JUVIGNÉ (1973) have revealed a number of characteristic slope angles. The different characteristic slope angles are attributed to different types of rock and rock structures, stages in the morphological development of the landscape or special types of slope processes. Characteristic slope angles have also been considered as so-called minimum or limiting slope angles for rapid and slow mass movement processes (YOUNG, 1972). In the Ardennes region PISSART (1962), SERET (1963) and JUVIGNÉ (1973) among others found characteristic slope angles from 30-34° for different types of rocks. They postulated that these characteristic slope angles are the lowest angles at which transport by mass movements can occur. However, their hypothesis was never checked by means of stability analysis of the regoliths.

Most denudational processes in the landscape tend to create threshold angles of the slope. At angles above this value rapid denudation occurs which produces a slope of lower angle either by flattening of the existing slope until the threshold angle, or via parallel retreat of the initial slope and emergence of a new slope. CARSON (1969) presented a model for hill slope development under mass failure. He was able to show that on slopes where mass movement is the dominant process, several threshold angles for straight slope segments can be distinguished during the various stages of slope development because of the changes in the strength of the

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regolith material. The aim of the present paper is to apply CARSON's approach to the interpretation of steep characteristic slope angles in the Ardennes.

SLOPE DEVELOPMENT BY MASS FAILURE

In the model of slope development proposed by CARSON (1969), two phases can be distinguished:

- a phase during which the regoliths are in a state of temporary stability. The slope angles have reached a certain threshold value, which depends on the strength characteristics of the regolith and the possibility to build up positive pore-water pressure within it;
- a phase of instability during which the conditions of strength and pore-water pressure in the regolith change. The regolith becomes unstable and mass movement occurs until a lower threshold angle of the slope is achieved.

Phases of stability may alternate with phases of instability due to changes in the strength of the regolith by weathering processes or climatological changes. CARSON's model is thus characterized by a succession of threshold slopes (stable phases) and phases of instability.

The question remains whether the replacement of one limiting angle of slope by a subsequent lower threshold slope is achieved via slope flattening or via retreat of the steeper slope, which leaves gentler slopes as a basal slope. CARSON (1969) and CARSON & PETLEY (1969) argued that if the modes in the slope frequency diagram of a certain area coincide with the calculated threshold values for stable regoliths on these slopes (see e.g. Fig. 1a), the slopes may develop via parallel retreat. In case of parallel retreat a steeper threshold slope leaves a basal slope behind with a lower threshold value. Therefore slope angles in between these threshold slope angles hardly occur in the landscape and the frequency diagram shows gaps at these intermediate values (Fig. 1a).

If slope development occurs via a flattening (wearing down) of the slope the mode of a slope frequency diagram can be found between two calculated threshold values for stable regoliths (Fig. 1b). In that case the slopes are in an instable phase and the whole population is on its way from a steeper threshold slope to a lower one. We will interpret the steep straight characteristic slope angles, which are found in the Ardennes region, in the light of these concepts about slope development under mass failure.

The following problems will be discussed:

- the relation between characteristic slope angles and the threshold values calculated from stability analysis of the regolith;
- the type of slope development, whether it is by parallel retreat or slope flattening;
- the period in which slope development was most active.

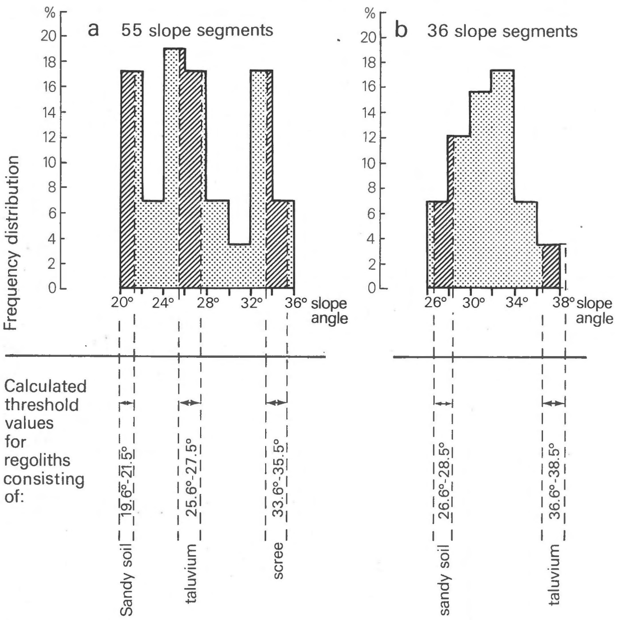

Fig. 1
The frequency distribution of the angles of straight slope segments in relation to calculated threshold values in the Pennines and Exmoor (after Carson, 1969).
a. An example of parallel slope retreat: the modes correspond with the calculated threshold values;
b. An example of slope flattening: the mode lies between the calculated threshold values.

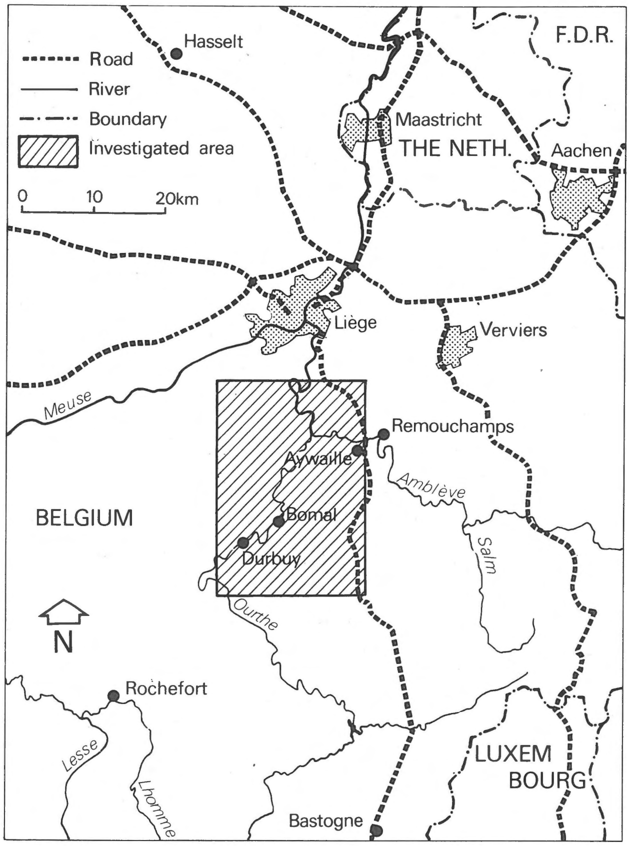

Fig. 2
The study area.

METHODS OF INVESTIGATION

Slope profiles were measured in a part of the drainage basins of the Ourthe and the Amblève (Fig. 2). The lithology in the basin is made up mainly of limestones, sandstones, and shales of Devonian age. The slope profiles were measured with a slope inclinometer. Measurements within one slope profile were performed with an interval of 10 metres. The measurements were repeated five times. The straight slope segments in the profiles were found according to objective rules, using the so-called best unit analysis of YOUNG (1972). For this purpose a computer program divised by HERWEYER (1979) was used. The slope analysis revealed that 42 slope profiles contained straight slope segments varying in length from 40 to 180 metres. Twelve slopes were selected from which samples were taken, to determine the bulk density, grain-size distribution and the strength parameters. Samples were taken at two depths in the regoliths: in the root zone (10-20 cm) and below the root zone (30-50 cm). The strength characteristics of the samples were measured by using a circular direct shear box with a diameter of 6.35 cm.

THE SLOPE PROFILES AND THE CHARACTERISTIC SLOPE ANGLES

Most of the investigated steeper slope profiles show a concave foot segment, except for some profiles which lie in the outward bend of a river meander, that is still active in undercutting the slope. Most of the slopes have one single straight middle segment and the upper part consists of a relatively small convex segment.

Field investigations showed that in the downstream parts of the valleys (where the stream incision velocity was at its maximum (ALEXANDRE, 1958) the slope profiles contain the longest straight segments (MASSINK, 1978). In the upper part of the valleys the straight slope segments become shorter in relation to the length of the concave and convex elements of the slope profile (MASSINK, 1978).

Fig. 3 gives the frequency distribution of the 42 straight slope segments. The slope segments show a mode in the slope class 27.5°-32.5°. It was not possible to find significant differences between the modes of the different lithological units.

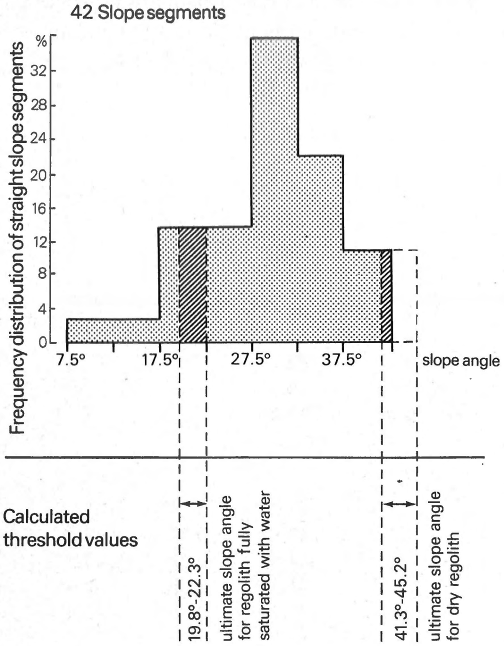

Fig. 3.
The frequency distribution of the angles of straight slope segments in relation to calculated threshold values in a part of the Ardennes region.

THE CALCULATION OF TRESHOLD SLOPE ANGLES

The threshold slope angles were determined by stability analyses of the regolith material. In such stability analyses it is assumed that the regolith material may slide along a common failure plane which runs parallel to the slope surface (LAMBE & WHITMAN, 1969). The stability analysis requires the soil mechanical properties of the regolith to be known. These are given in Table 1. Fig. 4 gives the grain size distribution of the regoliths of the three lithological units. Table 1 shows that two zones with different strength characteristics can be distinguished within the regoliths: the root zone which appeared to have cohesion (c′) is the strongest one, while the layer below the root zone which has no cohesion can be considered as the weakest zone.

In our opinion the cohesion of the upper layer can be ascribed to the binding effect of the roots which gives the material an extra strength compared with the lower zone. The threshold values for these slopes have to be calculated on the basis of the strength characteristics of the weakest zone which is the layer below the root zone. This zone may act as a carrier of the top soil. A critical slope angle on which sliding of cohesionless material can occur is given by the general equation: (after LAMBE & WHITMAN, 1969)

$$\tan i_{crit} = \frac{\gamma_d - \frac{z_o}{z}(\gamma_d - \gamma_s + \gamma_w)\tan\varphi'}{\gamma_d - \frac{z_o}{z}(\gamma_d - \gamma_s)} \qquad (1)$$

In this equation i_{crit} = the critical slope angle for sliding; γ_d = the bulk density of material above the ground water table, γ_s = the bulk density of the water saturated material; γ_w = the water bulk density; φ' = the angle of internal friction; z_o = the vertical height of the ground water above the regolith base; z = the thickness of the regolith. The model assumes a ground water flow parallel to the slope surface.

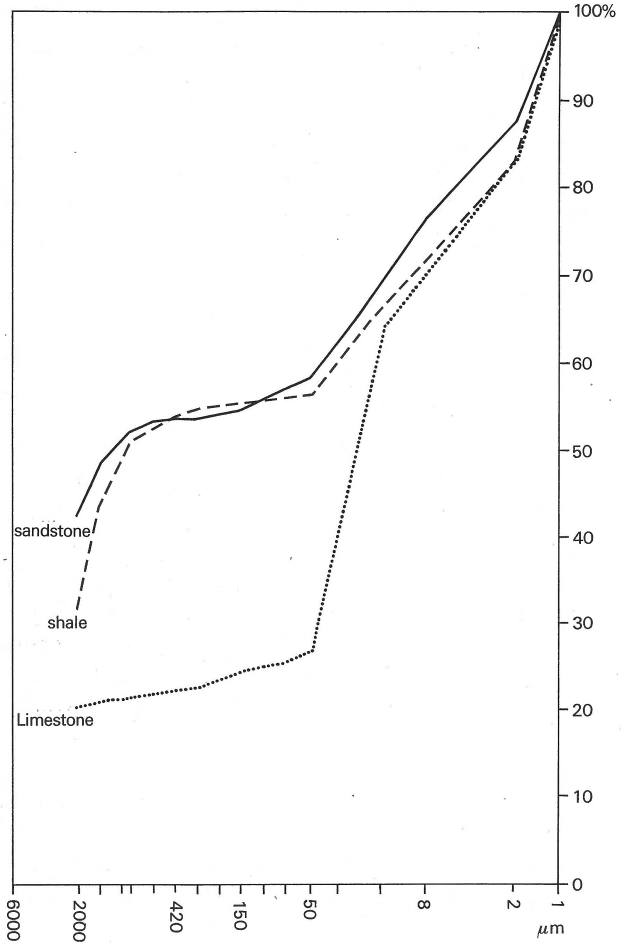

Fig. 4
The grain size distribution of regoliths of three lithological units in the Ardennes region

Under conditions where no ground water table can develop in the regolith ($z_o/z = o$ in equation 1) we can assume that the slopes develop to a higher threshold value. This threshold value for dry regoliths (i_d) calculated according to equation 1, is given in Table 1. It varies between 41°-45° for the different regoliths. We can also imagine circumstances, where the regoliths become fully saturated with water ($z_o/z = 1$ in equation 1). In that case the slopes can develop to a lower threshold value (i_w) which varies between 19° and 22° (see Table 1).

INTERPRETATION OF THE SLOPE FREQUENCY DISTRIBUTION

Fig. 3 shows that the mode of the frequency distribution histogram lies in between the two threshold values (i_d and i_w) and apart from 2 slope segments the whole population is enclosed between these thresholds. Fig. 3 is comparable with Fig. 1b which gives the frequency distribution of the slopes in relation to calculated threshold values in Exmoor (CARSON, 1969). Fig. 3 suggests that the angle values change from the higher threshold angle for dry regoliths to a lower one for fully saturated regoliths. The lowering of the slope angle must occur via the process of slope flattening, because in case of parallel retreat we would have expected modes which correspond with the calculated threshold values (compare Fig. 1a). In case of parallel retreat we would also have expected two slope segments in the slope profiles, a segment corresponding to the higher threshold value and a foot segment corresponding to the lower threshold value (see Fig. 5a). However, as already mentioned, in the area investigated the slope profiles contain only one single straight slope segment and resemble the profile of Fig. 5b given by CARSON (1969).

Table 1
The soil mechanical and stability characteristics of regoliths derived from three lithological units in the Ardennes region.

slope number	parent material	total depth regolith (z) (m)	slope angle of segment (straight)	bulk density dry	wet	c' (kNm^{-2})	φ'value	z_o/z	i_d	i_w
ROOT ZONE (0.1-0.2 m)										
5	sandstone	0.60	30.0°	12.48	16.90	6.61	37.8°	–	–	–
7	schist	0.80	35.2°	12.05	16.65	6.14	38.5°	–	–	–
12	sandstone	0.60	34.2°	9.86	15.72	9.23	42.2°	–	–	–
19	schist	0.65	29.3°	12.33	16.93	8.05	49.0°	–	–	–
28	limestone	0.75	33.8°	10.17	15.42	7.26	51.8°	–	–	–
BELOW ROOT ZONE (0.3-0.5 m)										
5	sandstone	0.60	30.0°	14.43	17.10	–	45.2°	0.69	45.2°	22.3°
7	schist	0.80	35.2°	12.83	16.89	–	43.8°	0.37	43.8°	21.8°
12	sandstone	0.60	34.2°	11.73	16.21	–	44.5°	0.42	45.5°	20.3°
19	schist	0.65	29.3°	13.21	17.23	–	41.3°	0.55	41.3°	22.3°
29	limestone	0.75	33.8°	12.71	15.92	–	42.3°	0.36	42.3°	19.8°

c': drained cohesion; φ': drained angle of internal friction; z_o/z: critical depth of ground water (z_o) in relation to the depth of the regolith (z); i_d: critical threshold slope angle for dry regoliths; i_w: critical threshold slope angle for regoliths fully saturated with ground water running parallel to the slope.

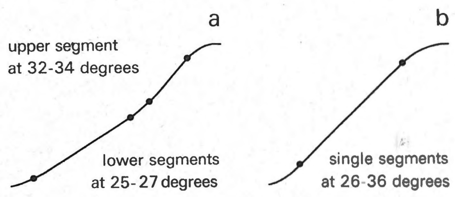

Fig. 5
The development of straight slope segments via mass wasting (after Carson, 1969).
a. A profile which develops via parallel slope retreat;
b. A profile which develops via slope flattening.

A further analysis based on equation 1 enables the following reasoning about the question whether the process of slope flattening by mass movements can occur under present climatological conditions. With equation 1 it is possible to calculate the critical height of the ground water for instability to occur in the regoliths. Table 1 shows that the regoliths become unstable when the groundwater reaches to about half way up the profile depth of the regolith ($z_0/z = 1/2$). The question arises whether this can occur under the present climatological conditions. We may refer to the findings of IMESON & JUNGERIUS (1974) in an area with comparable lithology in the Luxemburg Ardennes. These authors found that the ground water drains rapidly through a very permeable transitory layer of the regolith towards the unweathered rocks.

We observed similar conditions in the studied area of the Belgian Ardennes. Therefore it seems unlikely that under the present climatological conditions the groundwater can rise to a critical height for mass movements. This opinion is supported by the fact that on the investigated slopes we could not find any trace of recent landsliding. It may be suggested that the slopes were unstable during the periglacial periods because the regoliths became impermeable below a certain depth by the development of a permafrost subsurface (see e.g. ROUSE, 1975). In the Ardennes, river incision took place at the beginning and end of the periglacial periods (ALEXANDRE, 1958). Due to the velocity of incision and undercutting of the rivers, straight slopes could be formed. The steepest slope angle on which dry regoliths could be found was about 42°, a value that corresponds to the frictional resistance of the finely weathered cohesionless regolith material. The angles of steeper slopes will have tended, via flattening or retreat, towards this highest threshold value. This condition was fullfilled during interglacial periods, because the ground water could drain freely through the highly permeable transitory layers. During the periglacial periods the steep slopes became unstable because of a blockage of melt water in the regoliths by the permafrost in the subsurface. This led to a flattening of the straight slope segments probably via the process of microslumping (see CARSON, 1969; ROUSE, 1975). During this down wearing of the slopes the angle values ranged from the highest frictional threshold value of about 42° towards the lower value of about 20° for a fully saturated regolith (Fig. 3). Fig. 3 also shows that most slopes in the Ardennes have not yet reached the ultimate stage in the process of flattening. The mass movement processes (microslumping) probably stopped in post-glacial time.

CONCLUSIONS

In the Ardennes region the characteristic angle of straight slope segments was found to be about 30°. This characteristic steep slope angle does not correspond to the threshold value for dry regoliths as was suggested by PISSART (1962), SERET (1963) and JUVIGNÉ (1973), nor to the threshold value for fully saturated regoliths. Our measurements revealed that the population of the angles of straight slope segments falls between these two limiting threshold values. This may suggest that the slopes are changing from one limiting slope angle to a lower one via a flattening of the straight slope segments. This process occured in periglacial times, when the slopes may have become unstable due to a build-up of the groundwater above the permafrost.

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