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THE CONCENTRATION OF STONES INTO A STONE-LINE, AS A RESULT FROM SUBSURFACE MOVEMENTS IN FINE AND LOOSE SOILS IN THE TROPICS

BY

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SUMMARY. – The matrix of soils with a fine texture can undergo internal deformations. Stones, embedded in the matrix undergo greatly these movements. In specific cases, such movements can result in a situation, where stones, which were originally dispersed over the whole thickness of the soil, concentrate at a well-defined depth in the soil profile. In this article it is emphasized how soil creep in Rwanda is maintained by the action of mechanical seepage erosion at two levels. At both levels fine particles are evacuated. Subsequent soil resettlement creep supplies the seepage levels with new soil material, from which the coarse elements are not evacuated but remain in place as underground lag deposits.

RÉSUMÉ. – *La concentration de cailloux dans une nappe de gravats souterraine, à la suite de mouvements internes dans des sols fins et meubles des régions tropicales.* – La matrice des sols fins peut subir des déformations internes. Des cailloux, englobés dans la matrice, subissent en grande partie ces mouvements. Dans certains cas, de tels mouvements peuvent donner lieu à une concentration, à une profondeur bien déterminée du profil du sol, de pierres, dispersées originalement sur toute l'épaisseur du sol. Dans cet article, il est expliqué que la reptation des sols rwandais est maintenue par l'érosion mécanique des eaux de percolation situées à deux niveaux pédologiques. Ces deux niveaux subissent une perte de particules fines qui sont évacuées. Le sol se retasse graduellement, ce qui amène au niveau de percolation des tranchées de sol plus hautes. Les éléments grossiers s'accumulent ainsi à ces niveaux.

SAMENVATTING. – *De concentratie van stenen in een stone-line ten gevolge van ondergrondse bewegingen in fijne losse bodems in de tropen.* – De matrix van bodems met fijne textuur kan interne deformaties ondergaan. Stenen welke in deze matrix aanwezig zijn ondergaan grotendeels deze bewegingen. In bepaalde gevallen kunnen dergelijke bewegingen leiden tot het concentreren, op één welbepaalde diepte in het bodemprofiel, van stenen die oorspronkelijk over gans de dikte van de bodem verspreid zaten. In dit artikel wordt betoogd

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hoe in Rwanda de kruipbewegingen van de bodem op gang worden gehouden door ondergrondse erosie door percolatiewater op twee niveaus. Op beide niveaus worden fijne bodempartikels geëvacueerd. Daardoor zakt de mantel geleidelijk in. Op de percolatieniveaus blijven de grove elementen achter.

Introduction

Some decades ago, it was thought that stones, originally dispersed over the whole depth of the soil profile, were able to sink through the matrix of fines, and would finally concentrate on top of the underlaying bedrock (Delhay 1947, Laporte 1962).

But from soil mechanics it is known that the bearing capacity of a soil generally remains high enough to sustain stones. Even when a normally consolidated soil is subjected to alternating cycles of wetting and drying, stones hardly will penetrate into the soil surface (Moeyersons 1978). Only in the case of high positive porewater pressures, e.g. boiling sands, or in the case of unconsolidated water logged fine sediments, gravity may make stones to sink over an appreciable depth into the soil. But it seems unreal to invoke such conditions as an explanation for the presence of stone-lines in soils on watersheds in tropical areas.

However, there is another way in which buried stones can undergo subsurface movements, even if the soil is "normally" consolidated. Indeed, coarse fragments, embedded within a matrix of fines will be displaced with deformations of the latter. And there is no doubt that such internal deformations frequently occur in tropical soils. In a first part two examples from the literature will be commented. In a second part, attention will be focused on the effects of creep, a type of internal soil deformation recently observed and studied in Rwanda.

1. Reported cases of internal soil deformation, which lead to the concentration of stones

a. Resettlement of the fine soil skeleton in respons to biogenic upworking of fines

From detailed studies at the famous archeological site of Kalina (Gombe, Kinshasa), it appeared that biogenic upworking of the mantle of reworked Kalahari Sands was very important (Cahen & Moeyersons 1977). The collapse of the different types of voids, cavities and galleries, created by the activity of termites, ants and worms, causes a quasi continuous resettlement and shrinking in thickness of the not upworked part of the soil. Stone artefacts, embedded in this shrinking and reconsolidating soil undergo differential descending movements (MOEYERSONS 1978), but finally concentrate at the base of the clayey sand layer, where the silicified bedrock inhibits deeper faunal activity. Different steps in the formation of the basal stone-line, composed of artefacts of the same age, but originally situated higher in the soil profile, are given in figure 1. It is worth mentioning that it took probably about 5000 years for this biologically induced process of reconsolidation to concentrate most artefacts at the base of the sand layer, about 2,7 m thick, at Gombe.

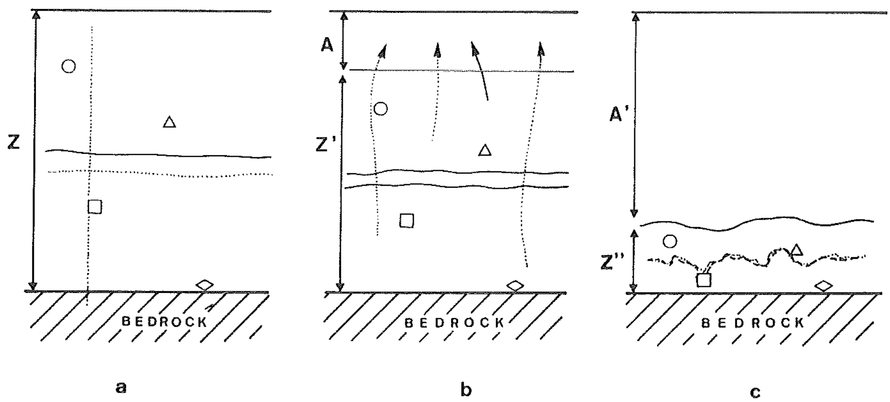

Fig. 1. – Supposed effects of the upworking of fines to the surface by the soil fauna at Gombe. a) original soil, with depth Z. b) the collapse of small cavities and galleries, created by the removal of particles results in a reduction of thickness Z to Z' (resettlement). Layer A consist of fines, brought to the surface. c) final situation with concentration of coarse elements at the base.

b. THE EFFECT OF A VERTICALLY MIGRATING WETTING FRONT IN SOILS WITH SWELLING CLAYS

Another type of internal deformation of the soil matrix of fines, giving rise to displacement of the coarse embedded elements has been described by YAALON and KALMAR (1978) for grumusols. They described the effect of irregular wetting and preferred swelling around the coarser grains which results in considerable upward directional forces. In the case of a descending humectation front, even large stones can be lifted to the surface. The authors consider this mechanism as responsible for the formation of certain desert pavements.

2. Creep as a mechanism of stone-line formation in kaolinitic soils in Rwanda

a. Some considerations about the nature of creep in tropical areas

It is generally accepted that soil creep in the tropics is triggered by the turbating effects of soil fauna and flora, and by changes in temperature and moisture.

In fact, it has never been proved that successive wetting and drying of the soil material can generate creep in non expansive soils. On the contrary, during an experiment whereby reworked clayey Kalahari Sands were subjected to alternating cycles of wetting and drying (Moeyersons 1978), it became clear that the extra-cyclic creep movement stopped as soon as the bulk density of the artificial soil column was stabilised (Fig. 2). Creep accompanied the settlement of the soil because this type of reconsolidation took place on a slope. And as can be seen on Fig. 2, an increase of slope during the experiment only results in a temporary reactivation of creep. Analogous experiments with very simular results have been executed with soil material from Rwanda (Table 1, humic horizon) : creep stopped as soon as the settlement of the soil was in equilibrium with gravity and slope.

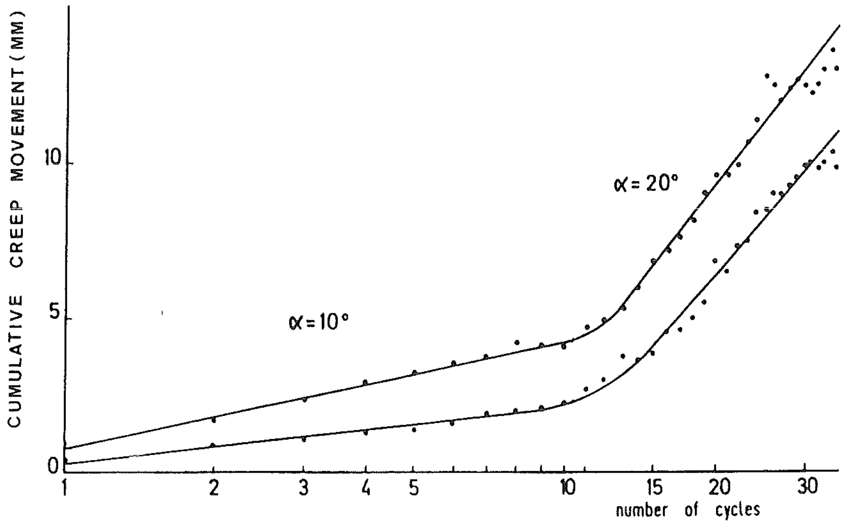

Fig. 2. – Cumulative creep movement as recorded along glass blade tracers at the surface of an artificial soil column of reworked Kalahari Sands. Creep was generated by alternating cycles of wetting and drying. At an inclination of 10°, the extra-cyclic creep movement was dying out (logaritmic scale for number of cycles !) as resettlement of the loosely packed soil ended. Increase of slope inclination resulted in only temporary creep acceleration.

Table 1

Characteristics of the different soil horizons at Rwaza-Rwanda

	Humic horizon	Intermediate horizon	Red subsoil
texture			
clay content (< 2 μm)	12%-19%	mixture	23%-33%
sand and gravel (> 63 μm)	40%-676%	mixture	26%-35%
nature of clay	kaolinite	kaolinite	kaolinite
specific weight	25.8 kNm^{-3}		26.3 kNm^{-3}
plasticity index	3%-15%		5%-15%
unconfined strength			
pocket penetrometer	118 kNm^{-2}-392 kNm^{-2}	29 kNm^{-2}-147 kNm^{-2}	108 kNm^{-2}-392 kNm^{-2}
mean derived dry bulk density			
at 15% water content	13 kNm^{-3}		15 kNm^{-3}
at 30% water content	10 kNm^{-3}		10 kNm^{-3}
apparent cohesion c'			
Thorvane shear device			
at 9% water content	61 kNm^{-2}	54 kNm^{-2}	100 kNm^{-2}
at 16% water content	41 kNm^{-2}	0 kNm^{-2}	36 kNm^{-2}
at 19% water content	32 kNm^{-2}	0 kNm^{-2}	0 kNm^{-2}
apparent angle of internal friction φ'			
portable soil sheargraph			
at 10% water content	40°-43°	38°	53°-58°
at 30% water content	37°-41°	25°	29°-38°

However, from the soil material from Rwanda, it is known that it creeps from the hillsides at surface rates often exceeding a cm/year. This has been confirmed by measurements in more than 25 Young pits, on Rwaza Hill, near Butare. One of these Young pits is shown on Fig. 3.

The different behaviour of the soil material in the experiment and in nature can only be interpreted as that in nature continuous resettlement of the soil is going on. Of course, the biogenetic action, which is not unimportant in the Rwandese soils, might trigger this resettlement. But there is evidence that volume reduction of the soil and consequent resettlement might also be caused by mechanical erosion through percolating waters. In fact, percolation during and after rains is very important, as is shown in Fig. 4 in a road cut. Concentrated throughflow from big and small pipes (1) and diffuse throughflow comes out of the wall. Measurements show that suspension load in pipe flow water sometimes reaches values of 0,1 gram/liter. But also the diffusely percolating waters are not clear. So, underground erosion by percolating waters certainly accounts for some volume reduction of the soil, which leads to resettlement and, on sloping ground, to creep. In some instances, the percolation seems to form a real underground sheet flood with considerable erosive power so that dry ravine like forms originate as a result from erosion from underneath (Fig. 5). In more moderate situations it can be expected that seepage erosion remains quite slow and that subsequently the soil does not fall at once into a suddenly created underground big cavity, but has time to follow the collapse of many macropores by slow resettlement and reconsolidation.

On Fig. 6 the mean movement of soil particles at different levels is given in the case of seepage erosion in E and consequent resettlement of the soil in this belt. On Fig. 6A, this is done for a situation of a flat surface. The same has been done on Fig. 6B, for a sloping ground. In that case the mean resettling movement vectors have a component parallel to the slope. This component is growing from the bottom of the seepage erosion belt to his top. Above this level, the component roughly remains constant. It is highly suggestive that the evolution of the resettlement component with depth ressembles so closely the creep velocity profile recorded in some deep Young pits on Rwaza Hill in Rwanda (Fig. 3), where it was verified that after heavy rains seepage went on much like in the situation represented on Fig. 6B.

As a first conclusion it can be stated that creep by wetting and drying only can be maintained as long as soil resettlement is going on. This resettlement can be a response, not only to biogenic upworking but also to seepage erosion. This is at least true for the kaolisoils in Rwanda.

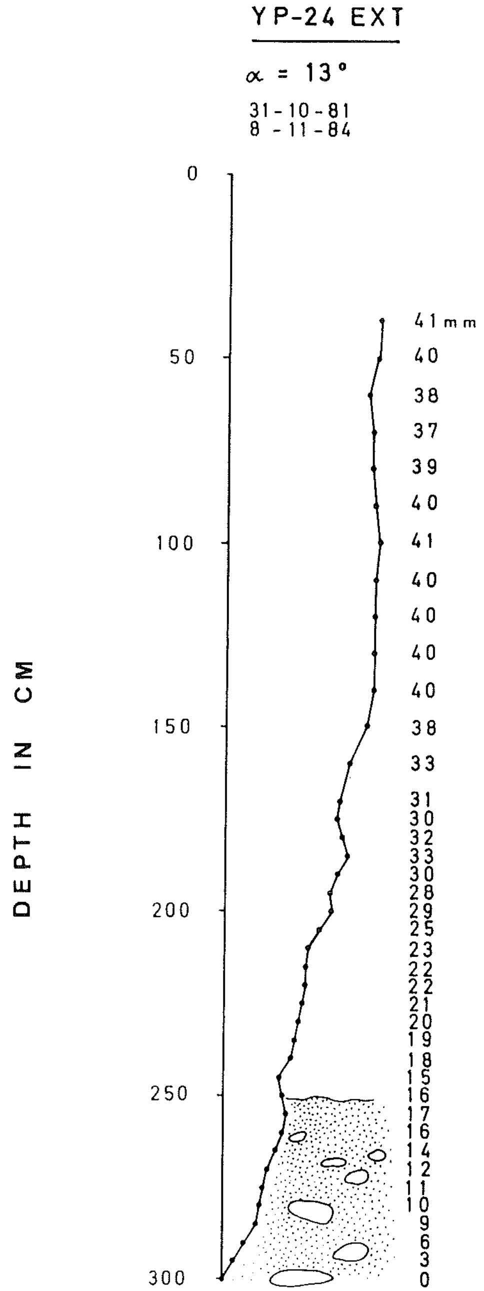

Fig. 3. – Creep velocity profile as recorded in 3 m deep Young pit at Rwaza Hill, Rwanda. The measurement covers a period of three years (31.10.81 to 8.11.84).

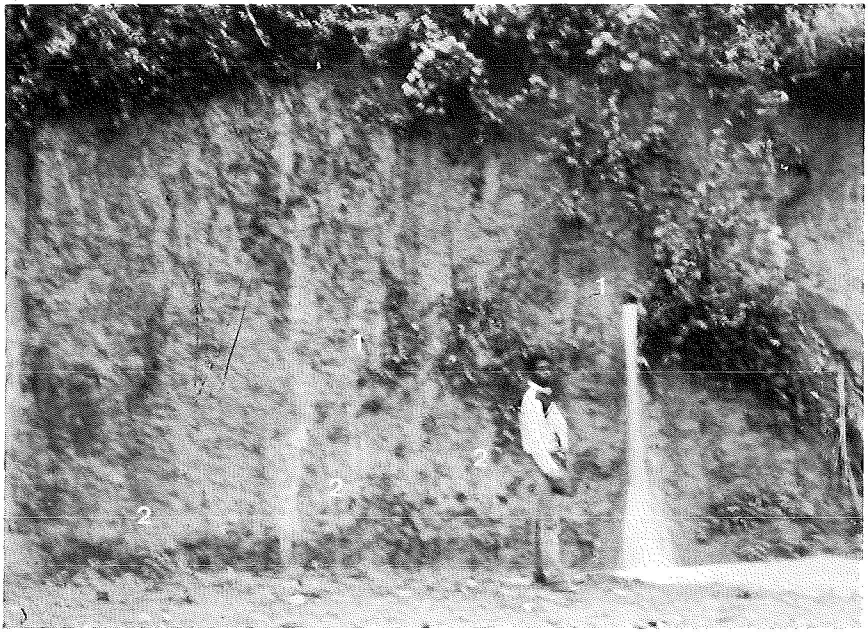

Fig. 4. – Photograph showing subsurface storm flow in road cut in Kivumu (Rwanda) : Concentrated pipe flow (1) ; diffuse seepage (2) above basal stone-line.

Fig. 5. – Ravine-like forms originate as soil sinks down where percolation concentrates to a powerfull underground sheet flow.

b. SLOPE HYDROLOGY AND POSITION OF STONE-LINES IN RWANDA

From Fig. 6 it appears that seepage erosion gradually can consume the overlying soil mantle from beneath. This means that in an intermediate stage a number of stones, originally dispersed in the already consumed part of the soil, can be concentrated in the belt of seepage erosion as a type of underground lag gravels.

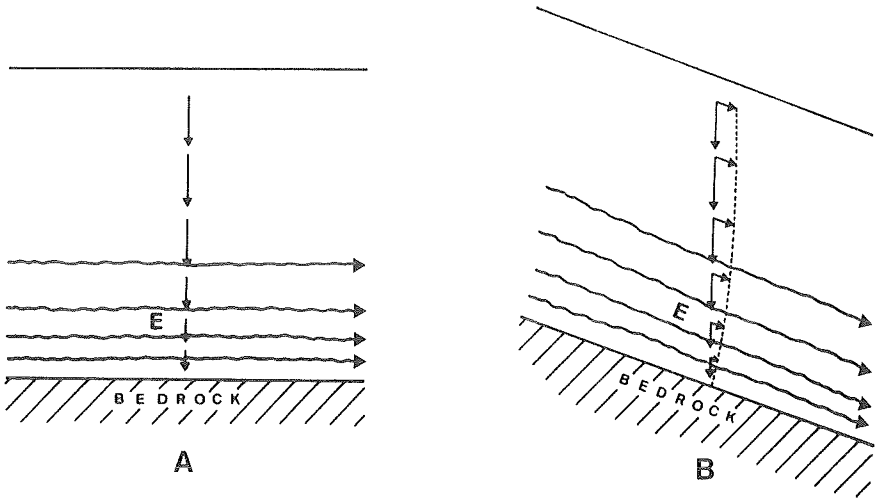

Fig. 6. – Mean movement of soil particles above and in belt of seepage erosion. A. The case of a flat surface. B. When the surface is inclined, this movement can be decomposed in a movement perpendicular to the slope (not indicated) and a movement parallel to the slope.

But the situation in Rwandese soils is most of the time more complex. In many excavations, it has been observed that stones are not only concentrated into the lower part of the soil mantle near to the top of the bedrock. Very often a secund "stone-line", much less developed than the basal one, occurs at a depth of about half a meter, in the belt of gradual transition between the superficial humic horizon and the underlying, more clayey red sub-soil. There is good evidence that this diffuse stone-line results from "resettlement-creep", very much like in the case of the basal gravel floor.

1. First of all, it has been observed that the intermediate zone between the humic horizon and the red sub-soil consists of a mixture of both types of materials. However, this zone is characterised by a very loose packing when compared with the overlying and underlying material. This appears

from the pocket penetrometer tests, carried out in the pit-wall of Young pit GL-78 (table 1) on Rwaza Hill in Southern Rwanda. The loose packing probably results from the crushing between the humic horizon and the underlying red sub-soil at their interface, as it was established that both horizons display differential swelling and shrinking during wetting and drying.

2. Crushing reduces this intermediate zone to a friable horizon, where the mixed material is mottled and where a lot of macropores are present. Measurements with a ring-infiltrometer showed that the hydraulic conductivity of a typical soil profile close to GL-78 lowers gradually with depth, increases at the level of the intermediate crushed structural horizon and falls abruptly in the top of the underlying red clayey sub-soil, (Table 2). This is an ideal situation to create throughflow, whereby the crushed horizon acts as an aquifer. That this is really the case in the field has been confirmed by the presence of big cavities and galleries in the crushed horizon in GL-78 and elsewhere, manifestly resulting from the erosive power of percolating storm flow along this aquifer. It has also been observed on places where the mottled intermediate horizon comes to the surface, as in ravine walls and slide heads, that water seeps out during and after rains.

Table 2

Hydraulic conductivity, measured by a ring-infiltrometer, close to Young-pit GL-78 at Rwaza (Rwanda)

Position no.	Depth	Horizon	k (cm)
1	10 cm	humic	$9,6 \times 10^{-3}$
2	20 cm	humic	$7,7 \times 10^{-3}$
3	30 cm	humic	$4,1 \times 10^{-3}$
4	40 cm	crushed	$4,8 \times 10^{-3}$
5	50 cm	top red sub-soil	$2,0 \times 10^{-3}$

So, instead of the simple situation in Fig. 6, slope hydrology in Rwanda is characterized by three flow levels. This is illustrated in Fig. 7. The first level (A) is at the surface where runoff originates. In some places lag gravels can be found on the surface. The secund level (B) is formed by the crushed interface between humic horizon and red sub-soil. This level contains a discontinuous stone-line. The third level (C) is situated above the bedrock and contains an important stone-layer. It is now a very characteristic feature in Rwanda that joints and fissures in the soil play an important role in that they are de mean feed-pipes for percolation at levels B and C. This explains why seepage erosion is more important on places where more runoff flows over the surface, so that features of vertical incision, underground collapse of the soil and sliding are occurring together. This explains how a number of ravines can originate by the combined action of incision and sliding.

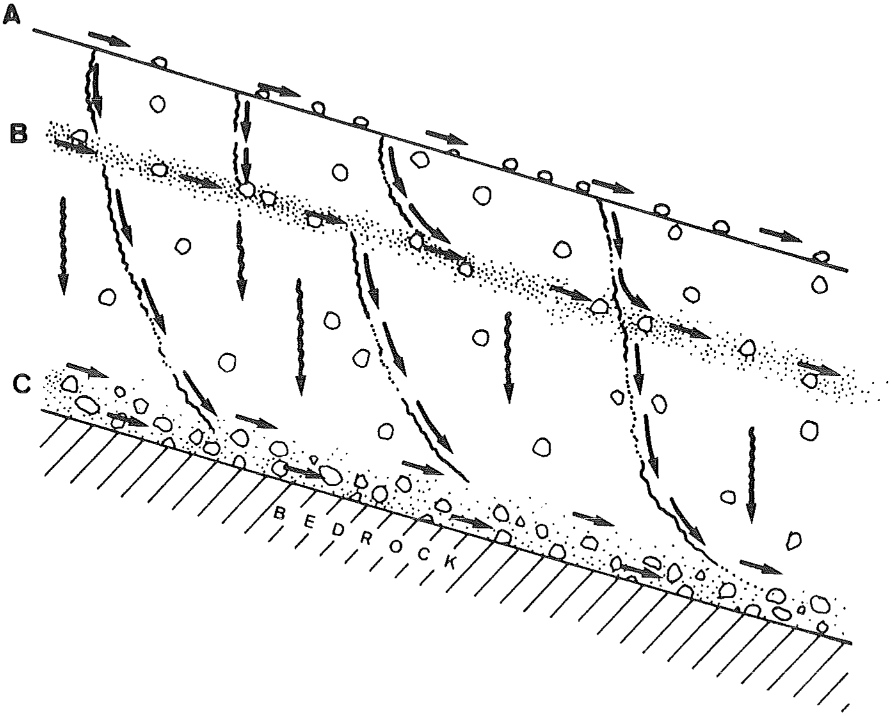

Fig. 7. – Schematic representation of slope hydrology in the koalinitic soils of Southern Rwanda. Runoff water, mainly infiltrating along fissures and joints feeds the crushed belts B and C, which act as aquifers and undergo seepage erosion.

c. CREEP AND THE SETTING OF THE DISCONTINUOUS STONE-LINE AT THE LEVEL OF THE INTERMEDIATE CRUSHED HORIZON

Because seepage erosion is going on two levels in the kaolisoils of Southern Rwanda, it is understandable that consumation of the soil in the two levels will result in a concentration of "lag stones" there.

We had the opportunity to take detailed resettlement creep measurements around the level of the crushed intermediate horizon in Young pit GL-78. On Fig. 8 it is shown how a framework of 8 tracer lines, composed

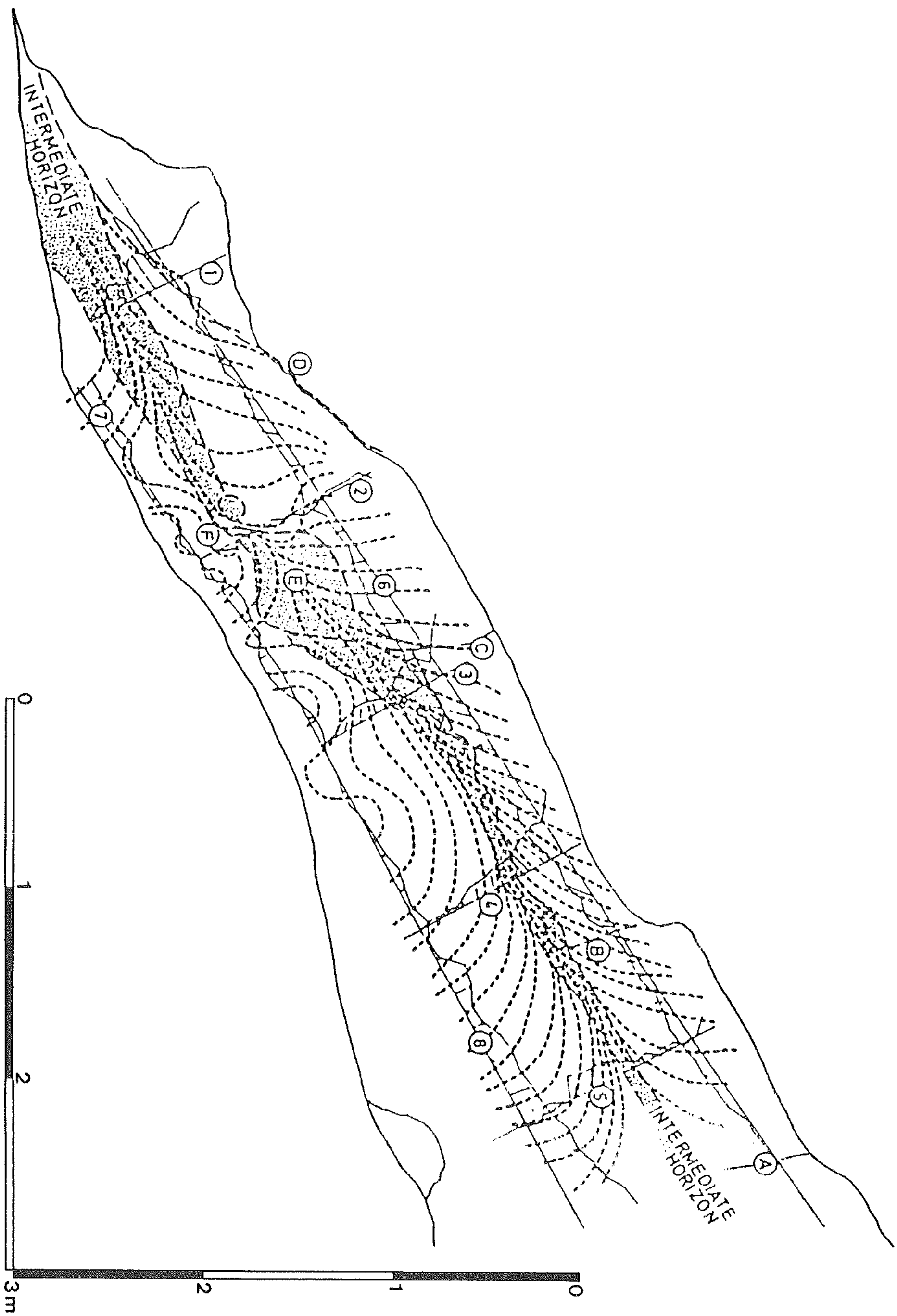

Fig. 8. – Creep-line pattern in the wall of Young-pit GL-78 at Rwaza Hill (Rwanda). Convergence of creep-lines to intermediate, crushed horizon. Period of measurement : three years (1981-1984). The deformation of the tracer lines is exaggerated ten times to the scale of the pit wall.

of metallic blades of 5 × 5 cm, was deformed after a period of three years. The use of a framework of tracer lines instead of the use of one tracer line, as is mostly done in literature, enabled to monitor creep in the two dimensions of the pit wall, instead of in a direction parallel to the surface only. The two-dimensional records are visualised by the interpolated network of creep-lines. Creep-lines can be compared with flow-lines whose orientation and density indicate the direction and velocity of a flow. The most important fact, appearing from the creep-line network is that creep-lines, although indicating a general downslope movement, concentrate near to the intermediate crushed horizon. However, this concentration in volume is not balanced by excessive export of volume out of this belt. It indicates that material there must disappear in another way than by creep. This is happening by seepage erosion which takes place at this level as indicated previously. It is clear that in such conditions, stones, which are originally dispersed over the whole soil profile will be concentrated along and in the crushed and percolated horizon and remain there as underground lag gravels. In fact, the concentration of creep-lines near to the intermediate horizon results from the fact that tracer line 6 and the line complex 7-8 approached one another during the measurement time of three years over a mean distance of about 3 mm. This is an indication for the order of magnitude of the volume of material seeped out during that period.

Conclusions

1. In the kaolisoils of Rwanda, creep goes on as long as the soil fabric is not in equilibrium with slope and gravity, i.e. as long as soil is (re)settling.
2. Besides biogenic action, seepage erosion is an important factor for underground volume reduction and subsequent resettlement of the Rwandese soils.
3. As a result of this volume reduction, resettlement creep-lines converge towards the seepage belt. There the coarse soil components remain behind as a type of underground lag gravels.
4. This processus is active at the humic horizon – red sub-soil interface and at the red sub-roil – bedrock interface. Both levels contain a stone-line.

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REFERENCES

CAHEN, D. & MOEYERSONS, J. 1977. Subsurface movements of stone artefacts and their implications for the prehistory of Central Africa. – *Nature*, **266** : 812-815.

DELHAYE, F. 1947. Le limon de ruissellement des plateaux et des plaines calcaires du Bas-Congo et du bordure schisto-gréseuse de l'Est. – *In* : La géologie des terrains récents dans l'Ouest de l'Europe (Session extraordinaire des Sociétés belges de Géologie, Bruxelles, 19-26 sept. 1946) : 208-215.

LAPORTE, G. 1962. Reconnaissance pédologique le long de la voie ferrée COMILOG. – Institut des Recherches scientifiques au Congo, Brazzaville, 119 pp.

MOEYERSONS, J. 1978. The behaviour of stones and stone implements, buried in consolidating and creeping Kalahari Sands. – *Earch Surface Processes*, **3** : 115-128.

YAALON, D. H. & KALMAR, D. 1978. Dynamics of cracking and swelling clay soils : displacement of skeletal grains, optimum depth of slickensides and rate of intra-pedonic turbation. – *Earth Surface Processes*, **3** : 31-42.