RELATIONSHIP BETWEEN THE APPEARANCE OF A FINISHED LANDSLIDE AND THE MECHANISMS ACTING DURING THE SLIDE

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Summary

In the development of slides in natural slopes there is a close relationship between the degree of strain-softening behaviour of the soil on the one side and the final appearance and disintegration of the soil structure on the other.

In this context the length of the passive zone and the displacement of the soil masses in the direction of the slide are of particular interest. An extensive passive zone and the associated large ground displacements constitute in fact eloquent evidence of the build-up of enormous dynamic and static earth pressures during the failure process.

1. INTRODUCTION

The author has always found it difficult to conceive how landslides in Scandinavia with extensive passive zones (like those in Surte, Rollsbo, Rödbo, Jordbro, Tvåe, Beckelaget, Sem etc.) can be explained by the kinematic behaviour that must result from a plastic failure "slip surface" model. One may e.g. pose the question: "Is there any provable relationship between the actual configuration and appearance of a finished slide and the failure mechanisms which have been active during the slide? Is it e.g. possible to conclude from the topography and the displacements of the soil whether a slide has developed as a result of a progressive (brittle) failure process or as a result of a plastic failure mechanism. It is believed by the author that the answer to this question is - "yes".

2. EARTH PRESSURE DEVELOPMENT DURING A SLIDE IN UNIFORM SLOPES.

Figur 1 shows the action of forces that essentially influence the earth pressure development during a slide.
Fig. 1 Earth pressure development in a uniform slope at failure.

If the laws of equilibrium are applied on the soil element in fig. 1 we get:

\[ N + \Delta N = N + p g \cdot H \cdot \cos \beta \cdot \Delta x - \sin \beta \cdot C_u(y) \Delta x \]  \hspace{1cm} \text{....... 1}

\[ \Delta N = p g \cdot H \cdot \frac{\sin 2\beta}{2} \cdot \Delta x - C_u(y) \Delta x \]  \hspace{1cm} \text{....... 1a}

\[ = \left[ \gamma_0 - C_u(y) \right] \Delta x \]  \hspace{1cm} \text{....... 1b}

where: \( C_u(y) \) = the shear strength of the material as defined by the stress-strain curves P and D.

\( \gamma_0 \) = prevailing stress due to downslope forces (in this case the in-situ stress).

Other notations acc. to fig. 1.

Case a:
It follows from equ. 1 that as long as plastic failure is valid (curve P in fig. 1) then at failure \( F_c = \frac{C_u \Delta N}{\gamma_0} = 1 \) for all values of \( \gamma_0 \). Substituting \( \frac{C_u \Delta N}{\gamma_0} \) for \( C_u \Delta N \) in equ. 1 therefore yields \( \Delta N = 0 \). This means that no build-up (\( \sum \Delta N \)) of the earth pressures in the slope takes place. The sliding masses cannot accelerate or acquire kinetic energy.
Case b: If on the other hand the soil material displays strain-softening properties according to curve D (fig. 1) and $F_t = c_u \gamma_s' / \gamma_o' = 1$ then $\Delta N > 0$ the very moment that $\gamma_s' \ngeq \gamma_P'$. At e.g. $\gamma_s' = \gamma_P'$.

$$\Delta N = (\tau_0 - c_u (\gamma_1)) \cdot \Delta x > 0 \text{ for } c_u^{\max} > \tau_0 \geq c_u (\gamma_1)$$

The earth pressure increment $\Delta N$ now gives rise to a build-up of the static pressure in the slope as well as accelleration of the soil masses. Both of these phenomena originate from the strain-softening properties of the soil.

Conclusion: Build-up of static earth pressures and accumulation of kinetic energy during a slide are conceivable only so far as the failure process diverges from plastic behaviour. (This is true as long the driving forces do not exceed the resistance in plastic failure.)

3. RELATIONSHIP BETWEEN THE TOPOGRAPHY OF A FINISHED SLIDE AND FAILURE MECHANISM.

3.1 Set out - actual observations.
In many finished slides it has been observed that the ground at the foot of a slided slope has been subject to heave in an extensive passive Rankine zone (cf. fig. 2 the Tuve slide). The up slope ground displacements related to this heave are excessive (50-100 m).

3.2 Axiom
In the following reasoning it is regarded as an axiom that this passive zone has been generated by the action of horizontal earth pressures (above the failure zone) in excess of passive Rankine earth pressure. It may also be taken for granted that these large pressures extending over long distances have been built up during the failure process.

![Fig. 2 Section through the Tuve slide.](image)
The length of the passive zone is here $\approx 350$ m.
3.3 Proof

**Step 1:**
The earth pressure build-up is a result of the following agents, separately or in combination.

a) dynamic inertia forces from retarded kinetic energy at the head of the advancing slide.

b) static growth of earth pressures during the progressive failure.

In section 2 it was demonstrated that irrespective of whether the earth pressure growth is of static or dynamic character its basic source is the strain-softening properties of the soil. Further it was shown that as long as the plastic failure concept is assumed to be valid neither dynamic nor static build-up of the earth pressures is virtually possible - except, may be in a local zone at the foot of the slope. Fig. 3.

**CONCLUSION 1**

The presence of an extensive passive zone in the direction of movement of a finished slide (fig. 1) is a direct indication of strain-softening behaviour in the failure zone. If on the other hand, the failure is of a plastic character, passive Rankine pressure cannot develop over any considerable distance and hence any 'global' collapse or disintegration of the soil mass may be excluded, (fig. 3).

![Fig. 3 Local plastic failure at the foot of a slope.](image)

**Step 2:**
In this context it is necessary to refer to the progressive failure model described by Bernander & Olofsson (1981) [2] where it is demonstrated by means of elementary structural mechanics that there is a stringent relationship between the possibility of progressive failure and strain-softening properties in the soil. (Unfortunately it is here necessary to direct the interested but possibly sceptical reader to reference (2) ICSFME81).
CONCLUSION 2

Extensive passive Rankine failure zones in finished slides cannot be explained unless progressive failure is presumed to be the actual mechanism, which governs the development and final extent of the slide. Conversely it may be established that the plastic failure model can never account for slides with extensive passive zones over horizontal ground of the kind so beautifully exemplified in the Surte and the Tuve slides.

"Quad erat demonstrandum".

It should be pointed out, however, that the 'proof' is not valid in the reverse direction in such a way that strain-softening and progressive failure automatically leads to large passive zones and due disintegration of the soil masses. The slope inclination and the stress-strain properties of the soil may well be such that actual static and dynamic earth pressures are not sufficient to produce a passive Rankine failure at foot of the slope. (Cf. the earth movements at Røvekær described by Löfquist [15] and Björlandavägen).

It must also be stressed that the reasoning above is not necessarily valid for the initiation zone i.e. the portion of the slope where the progressive failure has started. Whether the initial failure is of progressive (brittle) character or not can only be deduced by means of an analysis in which deformations, the stress-strain properties of the soil and the local geometry of the initiation zone are considered. It is e.g. possible to study the critical length \(L_{cr}\) or the influence range \(L_{SR}\) acc. to reference [2].

Moreover it may be appropriate here to point out that any geotechnician, who in his analysis of a slide resorts to dynamic forces in his attempts to explain the - from a conventional outlook - incredibly large passive zones of some slides* has in fact - whether he be aware of it or not - actually presupposed a progressive failure mechanism and a static earth pressure build-up, inevitably associated with the dynamic forces.

5. SUMMARY

In the development of slides in natural slopes there is a close relationship between the degree of strain-softening behaviour of the soil on the one side and the final appearance and disintegration of the soil structure on the other.

*(cf. R Lundström, (1956) [9] and SGI report no 18, (1983) [18])
In this context the length of the passive zone and the displacement of the soil masses in the direction of the slide are of particular interest. An extensive passive zone and the associated large ground displacements constitute in fact eloquent evidence of the build-up of enormous dynamic and static earth pressures during the failure process.

However, the static force increments as well as the kinetic energy of the moving soil masses have their only possible origin in the strain-softening properties of the soil material in the failure zone. As a stringent static relation between strain-softening in the soil and the risk for progressive failure has been demonstrated by Bernander & Olofsson (1981) in [2] it may be established that the presence of an extensive passive zone and associated large ground displacements also constitute indisputable evidence of the fact that progressive failure mechanisms have governed the propagation and final extent of the slide.

Conversely it may be stated that the conventional plastic failure model, where the soil is regarded as an ideally elasto-plastic material, cannot conceivably result in slides where the soil structure disintegrates in passive (and active) Rankine zones over vast areas of horizontal or gently sloping ground as shown in fig. 4a.

As no important build-up of static and dynamic forces can take place in a completely plastic failure there are no pre-requisites for a global collapse of the soil structure in the sliding body or in the soil volume ahead of it. A sliding movement following the laws of plastic failure must therefore result in moderate and slow displacements and a basically integral monolithic structure in the sliding soil volume as shown in fig. 4b.
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Observed and analyzed evidence in many large landslides in Scandinavia demonstrates that these slides cannot be predicted or even phenomenologically understood by means of the conventional plastic failure approach - unless the failure is solely the result of a long term effect. It seems therefore imperative to adopt failure models which consider the true stress-strain relationships of the soil as well as the effect of time on these soil properties. (Cf. the failure model described by Bernander & Olofsson, (1981) in references [2] & [3].


\[ f = \frac{E \text{ (Rankine)}}{E \text{ (current)}} \geq 1 \]

implying that the slope fails primarily due to a global collapse of the soil structure in the passive Rankine zone rather than as a monolithical block of soil sliding down slope according to the laws of the conventional slip surface failure model.

REFERENCES:


[20] SGI - Rapport No. 56