CORRECTION METHODS FOR SOIL INSTABILITY IN NATURAL SLOPES

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Summary

The correction of soil instability in natural slopes is a complex engineering operation requiring several steps:

- Classification of the instability in order to understand the failure mechanism.
- Evaluation of the dimensions and shape of the landslide.
- Selection of the appropriate correction strategy (protective, corrective, evasive).
- Selection and application of the correction method.
- Cheking and monitoring the behaviour of the corrected slope to assess the effectiveness of the correction.

1. INTRODUCTION

In order to choose the most convenient method to correct an instability it is necessary to previously establish the mechanism which causes the observed instability.

The analysis of landslides must begin with the use of some sort of classification. Many authors have proposed different classifications, which usually are based on the morphology of the observed movement, on the class and form of the discontinuity surface which defines the landslides, and/or the form and velocity of movements. Most classifications are geologically oriented.

Appendix I presents some of the best known landslide classifications, all of which can be of help to define the extent and depth of the landslide to be corrected.

However it is also necessary to know the processes which cause the instability, in order to choose a correction method which can prevent successfully the reactivation of the movement. That requires a good understanding of the causal agent in order to neutralise it.

The process of correction must include the following steps:

a) classification of the movement;
b) analysis of morphology and dimensions;
c) proposal of corrective measures;
d) proposal of methods to check the actual correction of the movements.

2. PRACTICAL CLASSIFICATION OF SOIL INSTABILITY IN NATURAL SLOPES

CARSON and KIRKBY (1972) classified the mass movement processes in natural slopes, defining three basic types of movement:

a) flow, with maximum velocity at ground surface and gradual reduction with increasing depth.

b) slide, with constant velocity from the ground surface until a slide plane of separation.

c) heave, with a ciclic stational movement of heave and retract of particles, and with a different summer and winter surface.

Their classification, shown in fig. 2.1., refers to mass processes, excluding individual falls of particles. Two parameters are conditionant: velocity of the movements and water content of the mass. The main characteristics of each basic type of movement are:

a) flow:

- . usually fast, but can be slow at initial and final stages
- . high water content
- . soil behaves like a fluid

b) slide:

- . usually fast with a latent period
- . appreciable water content
- . soils moves like a soil

c) heave:

- . usually slow
- . critical water content depends on the mechanism (high if frost develops; it can be low if gravitational creep).
- . soils deform like a plastic body.

SKEMPTON and HUTCHINSON (1969) presented an extensive classification of landslides and other mass movements in clay slopes. Fig. 2.2. summarises it.

These authors identified the following basic types:

a) Falls at short term in very steep slopes, due for instance to artificial excavations, eroding rivers or sea banks.

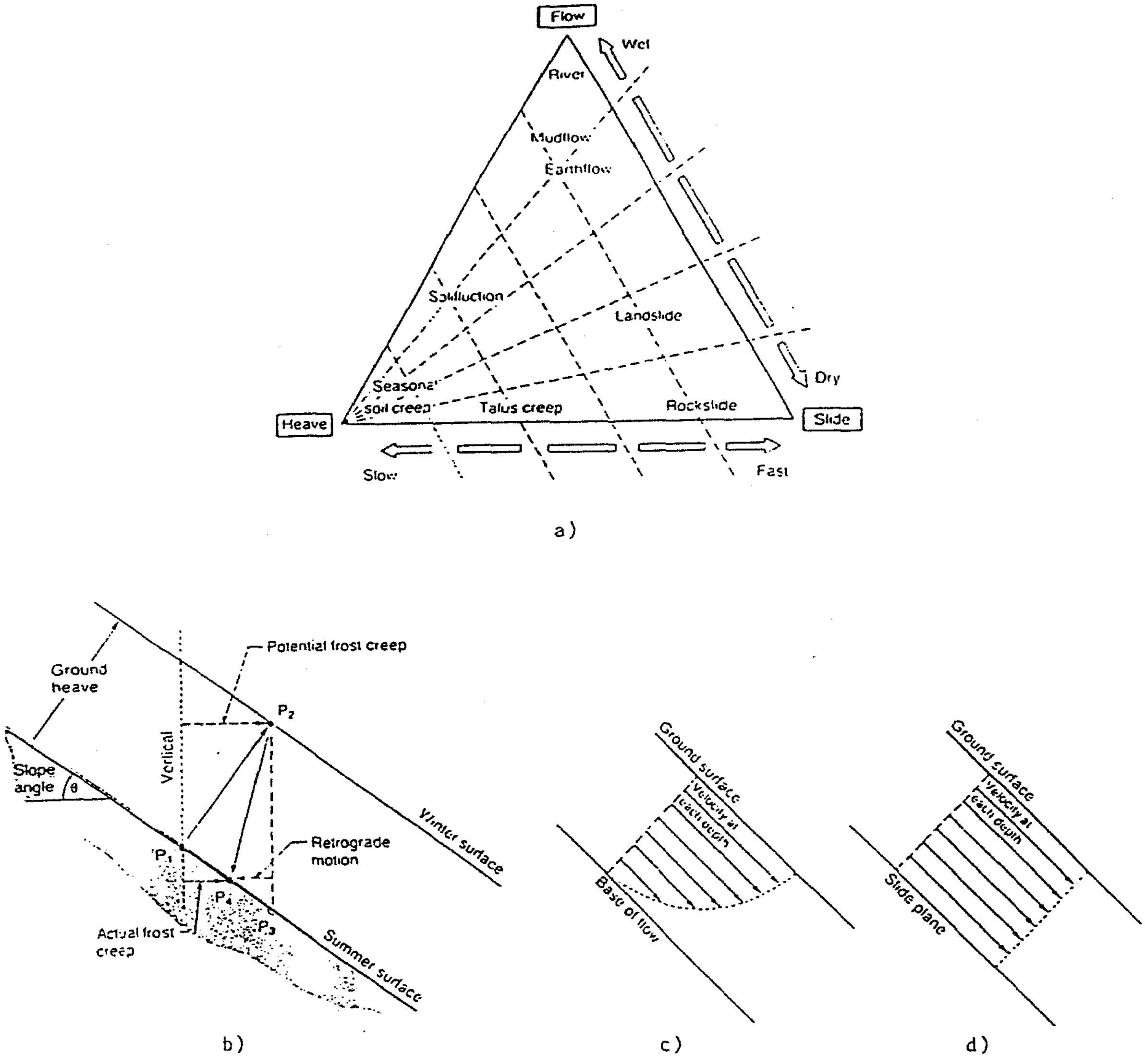


Figure 2.1 Mass movement processes in natural slopes (CARSON, KIRKBY, 1972)

a) general classification
b) creep by seasonal frost heave
c) gravity flow
d) plane slide

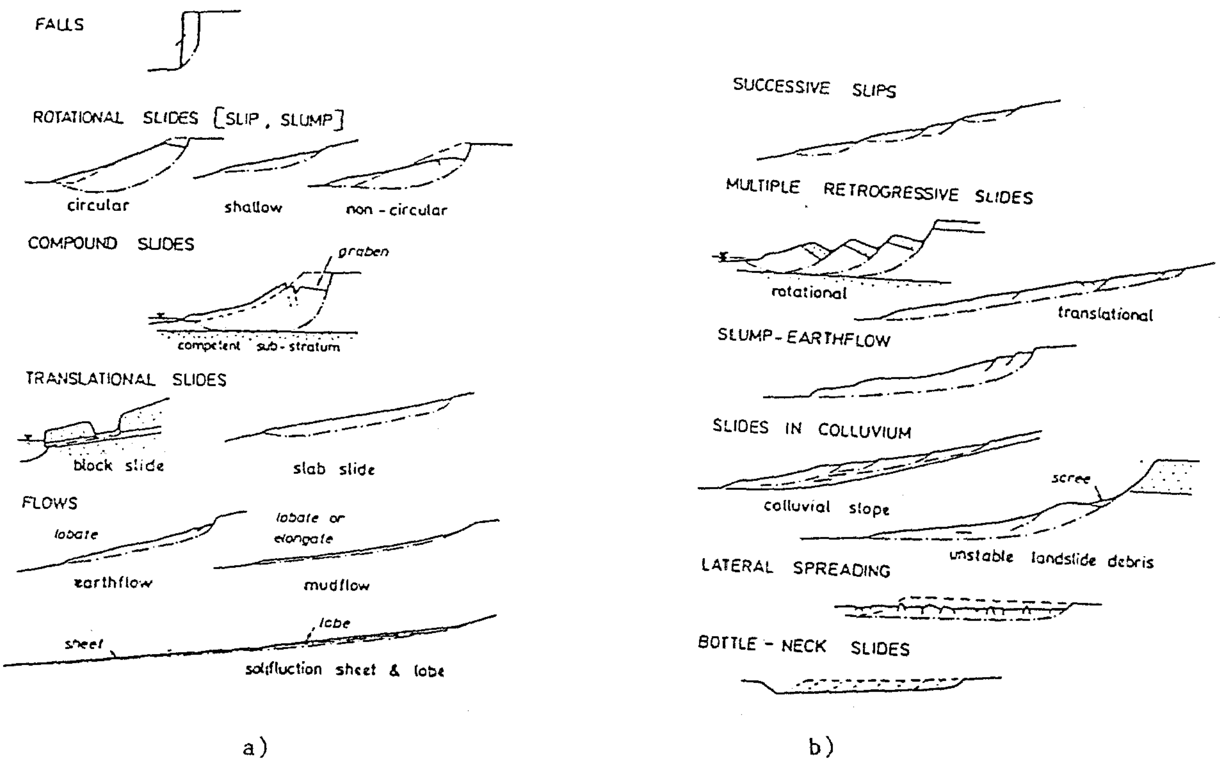


Fig. 2.2 Schematic typology of mass movements in clay slopes (SKEMPTON and HUTCHINSON, 1969)

a) Basic types b) Multiple and complex landslides

b) Rotational slides which occur in slopes of uniform clays or shale. The shear surface is circular, and relatively deep, in cliffs and slopes of overconsolidated clays. It is non circular in slopes with a degree of anisotropy due to weathering and/or depositional causes. Shallow rotational slides would be common in slopes of moderate inclination in colluvial clays.

c) Compound slides when an heterogeneity appears below the slope, conditioning the form and maximum depth of the shearing surface.

d) Translational slides which develop in plane slopes with heterogeneities placed at shallow depth.

e) Flows occur in saturated slopes of clay debris or interbedded clay and sand water-bearing strata. Solifluctions and seasonal movements are included in this category.

Multiple and complex landslides can include very different types. The classification shows the most common ones according to the SKEMPTON and HUTCHINSON experience.

HUTCHINSON (1988) has recently revised and completed this classification. However, for the purpose of analysis of instabilities in soil natural slopes it seems more appropriate to use the first version of their classification.

3. MORPHOMETRY OF LANDSLIDES

There is an enormous quantity of field data, (gathered by geographers, geologists and geomorphologists), on the shape and dimensions of the various mass transport and erosion processes in natural slopes. In many cases that is also true for data on landslides. Such a detailed study is out of this paper's scope. But we will point out some of the available data on landslides morphometry, in order to help its classification as well as further control and correction. For this purpose we will use some references which include quantitative data, and can directly be applied to geotechnical engineering.

Fig. 3.1., due to BRUNSDEN (1973), shows the morphometric and characteristic dimensions of a landslide. This notation will be used in the following paragraphs.

The non-dimensional characteristic ratios of a landslide are:

D/L	relative depth
L/B	relative width
VI/HE	grade of slope
Ang	angle of slope

The relative depth is a characteristic ratio which can be used to distinguish between rotational and translational landslides.

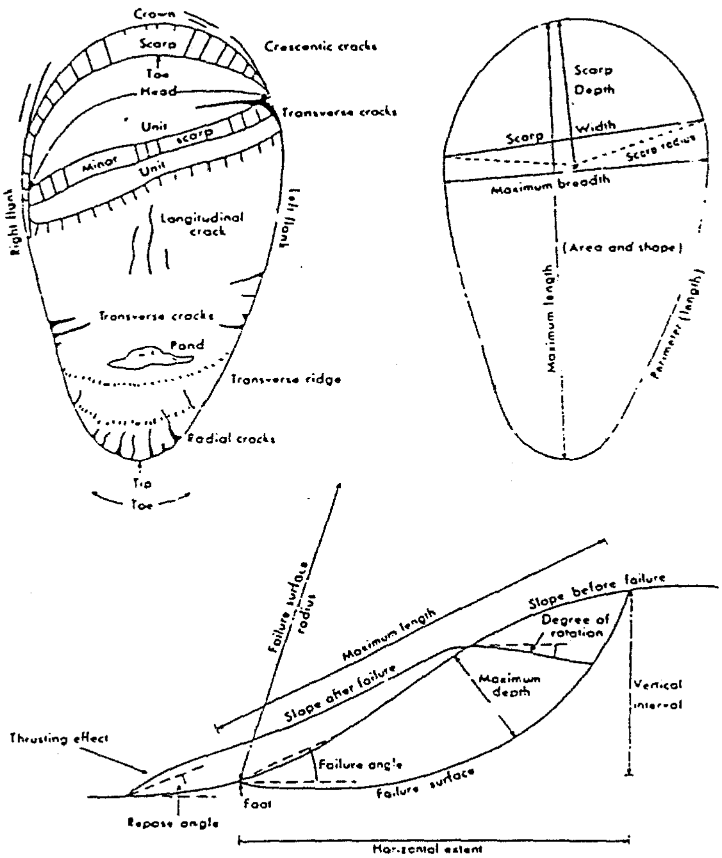


Figure 3.1 Morphometry of mass movement systems used by BRUNSDEN (1973)

Table 3.1. shows data from SKEMPTON (1953), SKEMPTON and HUTCHINSON (1969) and CROZIER (1973) on relative depth of landslides in clays.

TABLE 3.1. RELATIVE DEPTH (D/L) OF LANDSLIDES IN CLAYS

Type of Landslides	S (1953)	S-H (1964)	C (1973)
Rotational	0,15-0,27	0,15-0,33	0,18-0,25
Plane translational	0,03-0,06	< 0,10	0,05-0,08
Flow			0,01-0,025

SKEMPTON notes that rotational landslides have bigger relative depth in steeper slopes.

Characteristic intervals of relative depth for each class of landslides can be assessed. The first figures correspond to flatter slopes whereas the second ones refer to steeper ones.

TABLE 3.2. CHARACTERISTIC RELATIVE DEPTH FOR LANDSLIDES IN CLAY (ROMANA, 1990)

Type of landslides	
Rotational	0,15 - 0,35
Plane Translational	0,04 - 0,10
Flow	0,01 - 0,025

The slope angles at which different types of landslides tend to occur are shown in Table 3.3., which has been derived from data by HANSEN (1984) (figure 3.2.), HUTCHINSON (1967) (figure 3.3.), SKEMPTON and HUTCHINSON (1969), ALONSO and LLORET (1988) and from the author's personal experience.

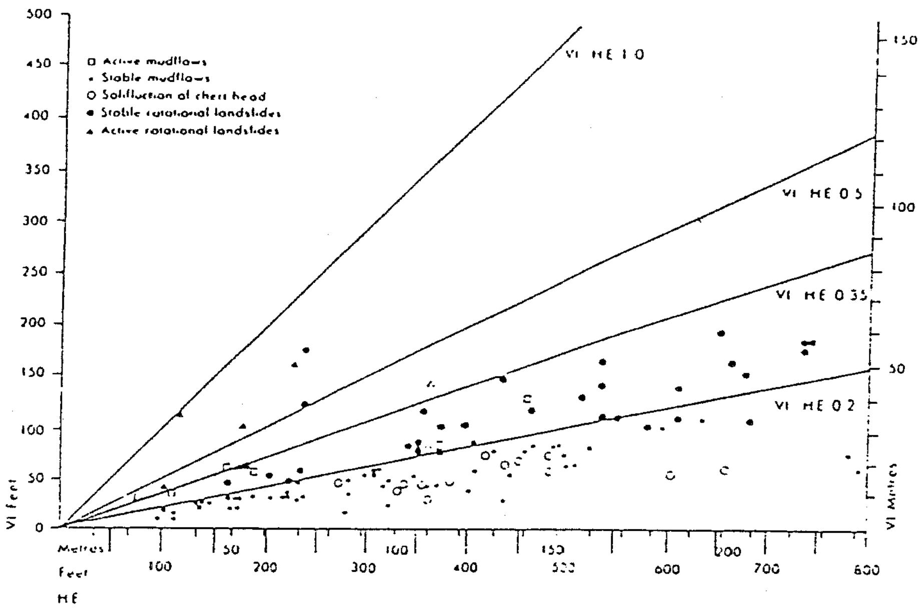


Figure 3.2. Relationships between Vertical Interval (VI) and Horizontal Extent (HE) of some landslides in Charmouth, Dorset, U.K. (HANSEN, 1984)

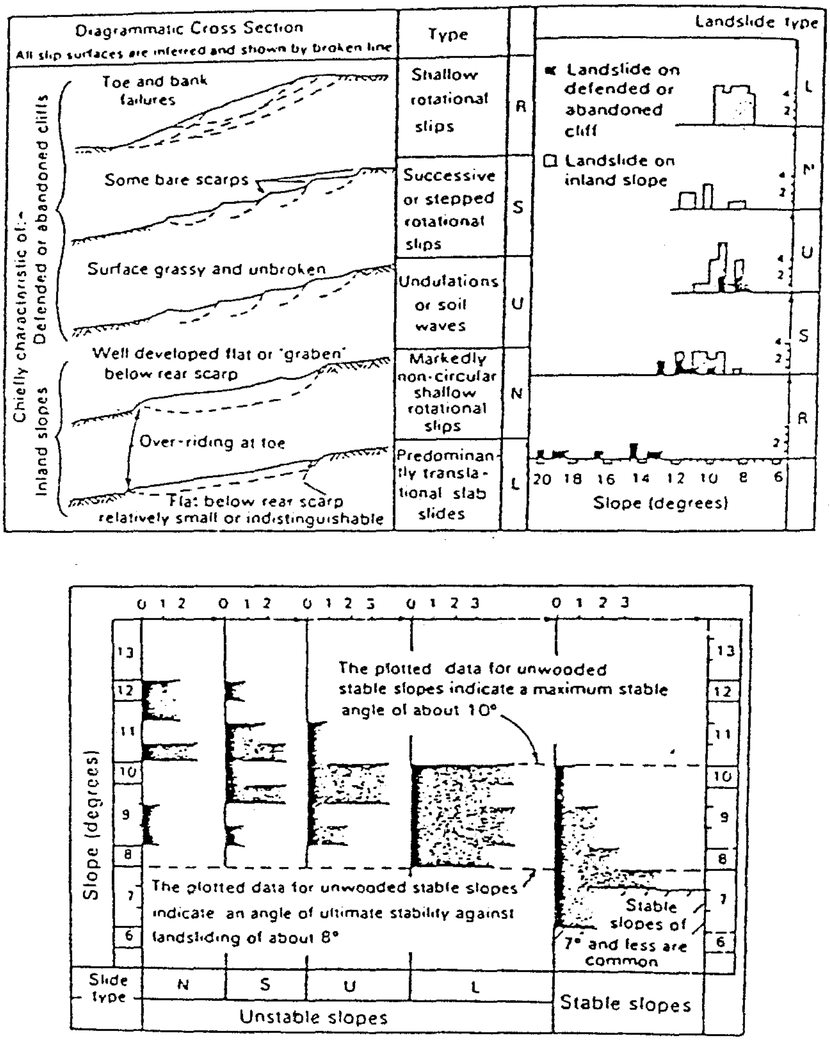


Figure 3.3 Stability of London Clay slopes
(HUTCHINSON, 1967)

TABLE 3.3. SLOPE ANGLES IN CLAYS WHERE THE DIFFERENT TYPES OF LANDSLIDE ARE MORE FREQUENT (ROMANA, 1990)

	Rotational		Translational	
Landslide	**Simple**	**Multiple**	**Plane**	**Flow**
None	< 11°	< 11°	< 8°	5°
Inactive	11°-16°	11°-17°	8°-11°	5°-11°
Active	19°-45°	14°-20°	11°-19°	11°-19°
None	> 45°	> 20°	> 19°	> 19°

The first line of the table above correspond to slopes too flat to reveal instability. The last one correspond to slopes so steep that landsliding fails totally, transporting all the material downslope.

Table 3.3. includes data from homogeneous slopes made of different clays (normally consolidated, overconsolidated, weathered in situ...) and different hydrogeological conditions. The distinction between shallow successive and deep rotational landslides, or between plane landslides and flows may sometimes reveal difficult.

4. SELECTION OF THE CORRECTION STRATEGY AND METHODS

Success in the stabilisation of a slope depends on three factors:

- To have a good appraisal of the instability process:

  . morphometry of the unstable zone
  . main cause of instability
  . relationship of instability with the external factor (climatic, erosive, anthrophication ...).

- To choose the appropriate strategy and select correction measures acting directly against the main cause of instability.

- To have a direct approach to the problem and good luck.

There are three possible general strategies to cope with slope instability:

- To prevent the events avoiding the risk (e.g. not developping a dangerous zone).

- To correct the instability when the process has started (by taking engineering measures).

- To <u>evade the problem</u> (e.g. choosing another pass for a proposed road).

<u>Preventive methods</u> can be applied to slopes with small failures:

- <u>Upper ditches</u> to avoid water infiltration.
- <u>Internal drains</u> to depress water level.
- <u>Toe protection</u> to avoid undercutting.
- <u>Surface protection</u> to stop failures.

In most cases the prevention strategy is based on the knowledge of the stability history of slopes similar to the protected ones.

Success is not assured. A number of protected slopes can fail, specially when the volumes we act upon are smaller than the unstable ones.

<u>Corrective methods</u> can be applied to slopes with important failures and act in one of these basic ways:

- A <u>Decrease of destabilising forces</u>

  . Excavation at head
  . Dewatering of fissures

- AB <u>Decreasing of destabilising forces/Increase of strength</u>

  . Internal drainage

- B <u>Increase of strength</u>

  . Grouting
  . Inclusions
  . Dental concrete
  . Toe walls

- BC <u>Increase of strength/Increase of stabilising forces</u>

  . Anchors

- C <u>Increase of stabilising forces</u>

  . Toe weigth

- CA <u>Decrease of destabilising forces/Increase of stabilising forces</u>

  . Change of geometry

As regards effectiveness, the following can be stated:

- A is always effective and must be considered when studying first measures, but often it is not enough to fully stabilise the slope.

- AB is by far the most cost-effective method, specially in clay slopes, but cannot be applied to slopes suffering big movements. Drainage takes time to act and tends to loose its capacity after several years, requiring conservation and/or substitution.

- B is a massive method, dear to many engineers. The inclusion of piles, concrete ribs, toe walls can be a final solution for the slope. Grouting is effective when introducing new resistent material (e.g. jet grouting), but not when trying to change the nature of soil.

- BC Anchors can be useful in combination with concrete ribs and/or beams on the slope. Anchored toe walls are often effective in urban and semiurban sites. Anchoring requires slope movements to be small and slow.

- C is a simple way to cope with slope instability. Rockfill toe fills add weigth and drain the lower part of the instable zone.

- CA is the final solution: to flatten the slope. It must be considered from the very beginning and, if geometrically possible, can avoid many costly and nonuseful measures.

In any case and for thoroughness, all corrective measures require prior computation of safety factors with sensibility analysis for every action.

Monitoring of slope (water levels, surface movements, failure slide...) is a prerequisite to control the corrective processes and to know of their successfulness.

Evasive methods are useful when we do not want to act on the slope itself, but change external conditions:

- Stop undermining by rivers...
- Change regional water conditions around the slope.

Normally they can be used only in zones neither populated nor built.

Figure 4.1., due to HUNT (1984), is a good common-sense engineering list of measures which can be taken. It seems to be specially adequate for roads and other transport linear works (railways, pipelines...).

SLOPE FAILURE FORMS: TYPICAL PREVENTIVE AND REMEDIAL MEASURES		
Failure form	**Prevention during construction**	**Remedial measures**
Rock fall	Base erosion protection. Controlled blasting excavation. Rock bolts and straps, or cables. Concrete supports, large masses. Remove loose blocks. Shotcrete weak strata.	Permit fall, clean roadway. Rock bolts and straps. Concrete supports. Remove loose blocks. Impact walls.
Soil fall	Base erosion protection.	Retention.
Planar rock slide	Small volume: remove or bolt. Moderate volume: provide stable inclination or bolt to retain. Large volume: install internal drainage or relocate to avoid.	Permit slide, clean roadway. Remove to stable inclination or bolt. Install internal drainage or relocate to avoid.
Rotational rock slide	Provide stable inclination and surface drainage system. Install internal drainage.	Remove to stable inclination. Provide surface drainage. Install internal drains.
Planar (debris) slides	Provide stable inclination and surface drainage control. Retention for small to moderate volumes. Large volumes: relocate.	Allow failure and clean roadway. Use preventive measures.
Rotational soil slides	Provide stable inclination and surface drainage control, or retain.	Permit failure, clean roadway. Remove to stable inclination, provide surface drainage, or retain. Subhorizontal drains for large volumes.
Failure by lateral spreading	Small scale: retain. Large scale: avoid and relocate, prevention difficult.	Small scale: retain. Large scale: avoid.
Debris avalanche	Prediction and prevention difficult. Treat as debris slide. Avoid high-hazard areas.	Permit failure, clean roadway: eventually self-correcting. Otherwise relocate. Small scale: retain or remove.
Flows	Prediction and prevention difficult. Avoid susceptible areas.	Small scale: remove. Large scale: relocate.

Figure 4.1 Measures against slope instability (HUNT, 1984)

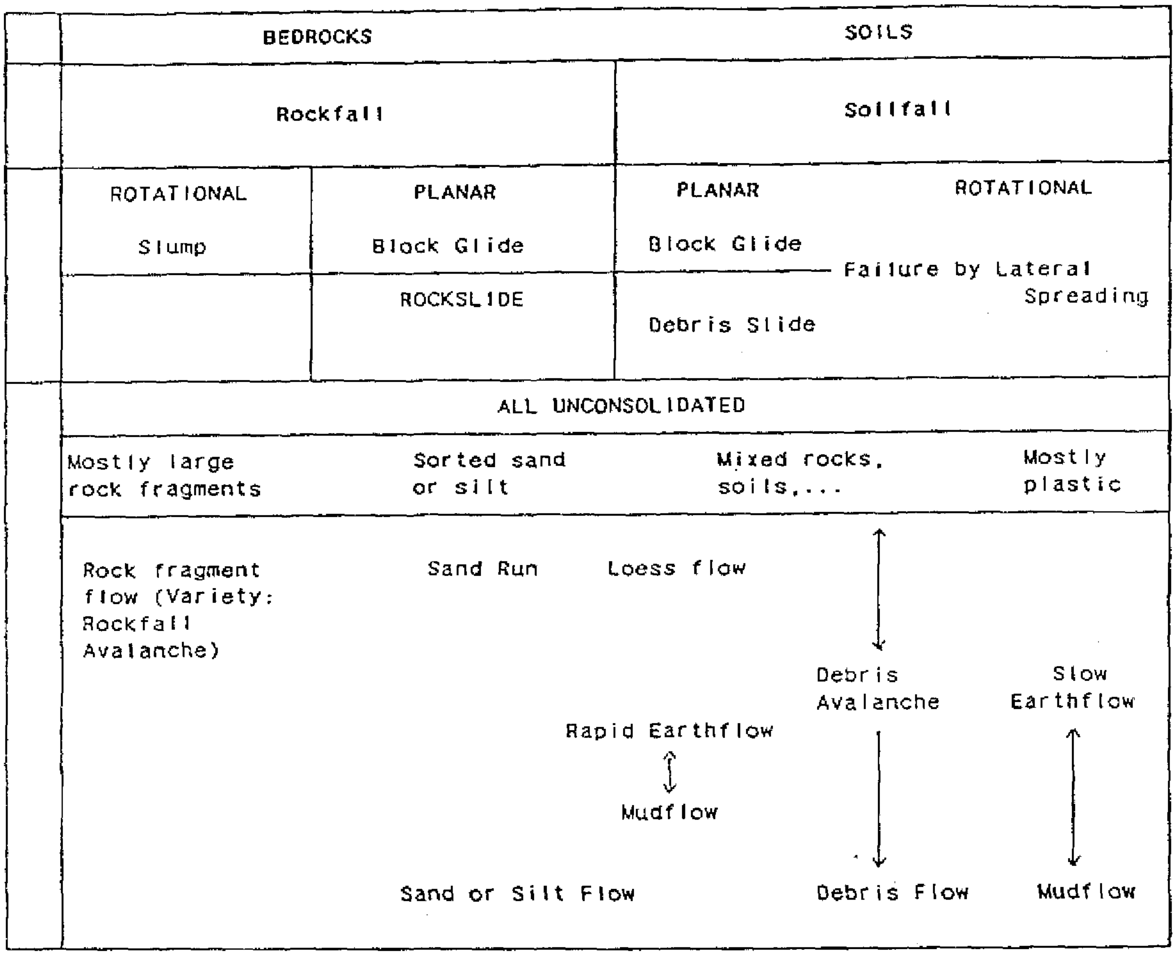
APPENDIX 1

LANDSLIDE CLASSIFICATIONS

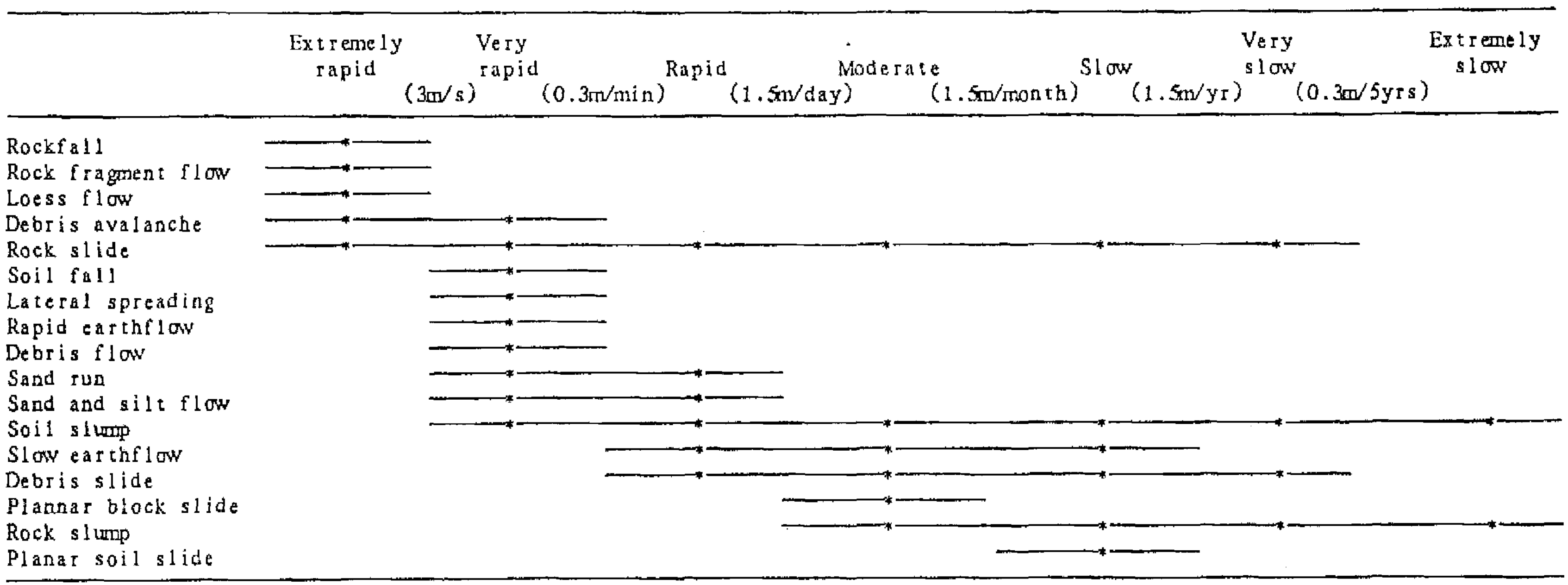
A.1. VARNES (1958)

A.2. VARNES (1978)

A.3. HUNT (1984)



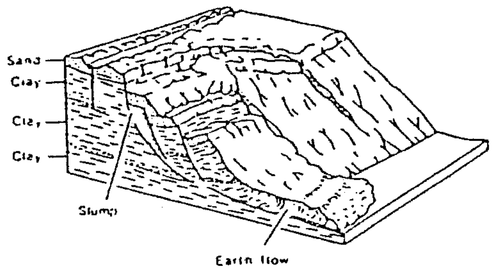
A1 Classification of slope movements (VARNES, 1958)

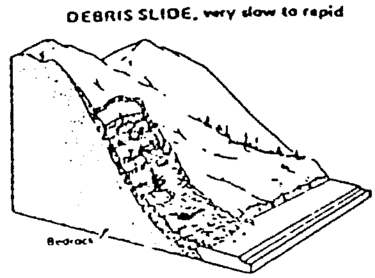


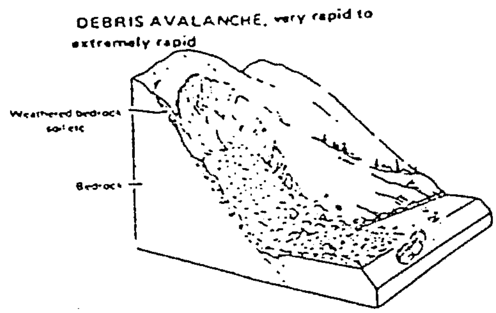
A1 Classification of slope movements (VARNES, 1958)

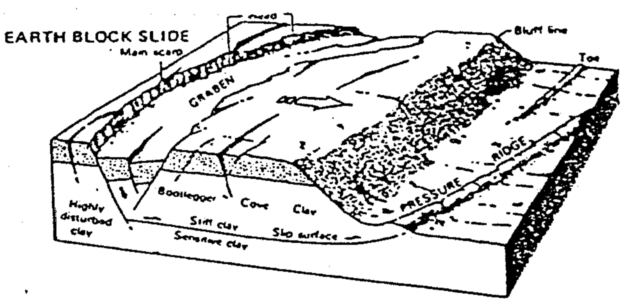
TYPE OF MOVEMENT			TYPE OF MATERIAL: ENGINEERING SOILS — Predominantly fine	ENGINEERING SOILS — Predominantly coarse	BEDROCK
FALLS			Earth fall	Debris fall	Rock fall
TOPPLES			Earth topple	Debris topple	Rock topple
SLIDES	ROTATIONAL	FEW UNITS	Earth slump	Debris slump	Rock slump
SLIDES	TRANSLATIONAL	FEW UNITS	Earth block slide	Debris block slide	Rock block slide
SLIDES	TRANSLATIONAL	MANY UNITS	Earth slide	Debris slide	Rock slide
LATERAL SPREADS			Earth spread	Debris spread	Rock spread
FLOWS			Earth flow	Debris flow	Rock flow
			(soil creep)		(deep creep)
COMPLEX			Combination of two more principal types of movement		

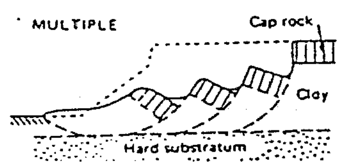
A2 Classification of slope movements (VARNES, 1978)











A2 (cont) Classification of slope movements (VARNES, 1978) with some selected figures.

A CLASSIFICATION OF SLOPE FAILURES		
Type	Form	Definition
Falls	Free fall	Sudden dislodgment of single or multiple blocks of soil or rock which fall in free descent.
	Topple	Overturning of a rock block about a pivot point located below its center of gravity.
Slides	Rotational or slump	Relatively slow movement of an essentially coherent block (or blocks) of soil, rock, or soil-rock mixtures along some well-defined arc-shaped failure surface.
	Planar or translational	Slow to rapid movement of an essentially coherent block (or blocks) of soil or rock along some well-defined planar failure surface.
	Subclasses	
	Block glide	A single block moving along a planar surface.
	Wedges	Block or blocks moving along intersecting planar surfaces.
	Lateral spreading	A number of intact blocks moving as separate units with differing displacements.
	Debris slide	Soil-rock mixtures moving along a planar rock surface.
Avalanches	Rock or debris	Rapid to very rapid movement of an incoherent mass of rock or soil-rock debris wherein the original structure of the formation is no longer discernible, occurring along an ill-defined surface.
Flows	Debris Sand Silt Mud Soil	Soil or soil-rock debris moving as a viscous fluid or slurry, usually terminating at distances far beyond the failure zone; resulting from excessive pore pressures (Subclassed according to material type)
Creep		Slow, imperceptible downslope movement of soil or soil-rock mixtures.
Solifluction		Shallow portions of the regolith moving downslope at moderate to slow rates in Arctic to sub-Arctic climates during periods of thaw over a surface usually consisting of frozen ground.
Complex		Involves combinations of the above, usually occurring as a change from one form to another during failure with one form predominant.

A3 Classification of slope failures (HUNT, 1984)

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