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Eco-engineering and Conservation of Slopes for Long-term Protection from Erosion, Landslides and Storms

ECO-SLOPES

FIELD PROTOCOL

Version 2

compiled by

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CONTENTS

1. INTRODUCTION

1.1 PREFACE

This field protocol describes the methods that will be employed by the field teams under the core programme of ECO-SLOPES. The field protocol aims to encourage the standardisation that is necessary to enable data from the ECO-SLOPES field sites to be pooled for modelling and final reporting.

The descriptions of the methods are intended as reference and to signal any pitfalls that might impair the quality of the data. In many cases, detailed descriptions of recommended procedures are readily available in other manuals, handbooks or international standards. Those who have difficulty in finding or applying these methods should contact the compilers.

The present document has been finalised after the discussion during the Eco-Slopes meeting in Thessaloniki in December 2001. All methods have been included and a method selection indicator is provided for each method. The objective of this method selection indicator is to identify the essential variables for slope characterisation, given an actual or imminent slope stability problem. It will assist in the selection of appropriate sampling methods and lists the minimum data requirements for a problem of a given complexity.

The field protocol draws upon the experience of many from various disciplines. It is ready to be tested in the field and it has been printed in a handy field format. Notwithstanding, there will be room for improvement once it has been tested in the field and all suggestions are welcome.

The first outline of the field protocol was based on the MEDALUS field manual, produced in 1991-1995 (Cammeraat, 1995) as a baseline document for research on the EU FW III &IV projects Mediterranean Desertification and Land Use (1991-1999). Many field procedures have been kept the same or have been updated, but also new methodology has been included, specifically designed for the Ecoslopes project or adjusted for application in other geo-ecosystems.

Finally, we would like to thank all colleagues who have supplied material included in this field protocol or who have improved its contents with their comments. All contributors are listed on page 2 and next to their contributions.

Amsterdam, December 2001

Eric Cammeraat, Rens van Beek & Luuk Dorren

1.2 LIST OF CONTRIBUTORS

The ECO-SLOPES field manual includes contributions from:

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4. Bruce Nicoll & Barry Gardiner, Forestry Commission, UK
5. Frédéric Danjon & Michael Drexhage INRA – Nancy
6. Joanne Norris & John Greenwood; Nottingham-Trent University

Many useful suggestions and comments on the abiotic part were provided by Vicente Andreu (Centro de Investigaciones sobre Desertificacion).

Some parts of the described methodology have been taken from the MEDALUS field manual (1995), and reference is made to work or contributions of:

7. Simon Clark (School of Biology, Leeds University, UK)
8. Anton Imeson (IBED-Physical Geography)
9. Bas van Wesemael (Dept. of geography, Univ. Louvain la Neuve, Belgium)
10. Jane Brandt (Medalus project office)

1.3 GUIDE TO THE USER

In this manual, many methods are being provided. We hope that they offer help in the determination of the many parameters required within the project.
As the geo-ecosystems and their dominant processes are different for the 7 areas of research, a classification is given with all methods where they should be applied. For instance, on table slopes where only surface soil erosion is active, it is not necessary to look at parameters important for mass movement processes, eg. the Atterberg index or a triaxial test. Below a listing is given of symbols indicated in both the index and in the heading of each described method, whether this method should be applied at a specific site or not.

Symbol	Explanation
@	Compulsory for all (reference) sites.
@@	Strongly recommended for each site.
@1	Only compulsory at the reference site in the UK
@1,2	Only compulsory at the reference site in the UK and Italy.
@…	Etcetera, where the numbers refer to the following sites:

Reference sites:
1. England Motorway Embankment (UK);
2. Molise/Trivento landslide niche (Italy);
3. Vaujany rockfall slope (France);
4. Thessaloniki forest fire (Greece).

Additional sites:
5. Scotland (UK);
6. Valencia (Spain);
7. Almudaina (Spain).

Any comments, suggestions or additions from the users are welcome to improve the working quality of this manual.

2 THE ECO-SLOPES REFERENCE SITES

2.1 The field sites

The Eco-Slopes project encompasses four **reference sites**:

8. England Motorway Embankment (UK);
9. Molise/Trivento landslide niche (Italy);
10. Vaujany rockfall slope (France);
11. Thessaloniki forest fire (Greece).

In addition, the Eco-Slopes project include the following additional sites:

12. Scotland (UK);
13. Valencia (Spain);
14. Almudaina (Spain).

Field sites should encompass the vegetation cover or land use of interest. Preferably, a field site should extend from the foot to the top of the slope. A uniform lithology is essential in order to compare different vegetation covers or land use types at a given site.
A field site should be large enough to accommodate replicated measurements. In addition to the use of methods that ensure consistent and meaningful measurements, replication helps to reduce the uncertainty that accompanies natural variables. Generally, an area of 5 ha will be sufficient but as every landscape has its own scale of uniformity, it may be necessary to adjust the lay-out of the field site to the local situation.

2.2 Measurement areas

Within each field site, at least three replicate **measurement areas** should be marked out. Each measurement area would cover approximately 0.5 ha. Each of the measurement area should have the following characteristics:

- No roads or other disturbances should be present in or above the plot;
- It should be approximately 0.5 ha in size. Preferably it should be a square of 75 x 50 m but if this not possible, it should be made up of 6 contiguous squares each of 25 x 25 m (**sub-areas**; see 2.3);
- It should be situated within an area of uniform lithology, exposition, upstream area and slope (**geomorphological unit**)
- If the size of the geomorphological units of the measurement area is smaller than 0.5 ha, the individual sub-areas should be located in neighbouring, comparable geomorphological units. The sub-areas may then be staggered along the slope transect. The form of the sub-areas is then adjusted to the geomorphological unit form, but its size of 25 x 25 m should be more or less maintained;
- The type of vegetation should be uniform;
- Soil depth and type should be relatively uniform.

2.3 Sub-areas

Each measurement area should be subdivided into 9 contiguous sub-areas, each one being 25 x 25 m. The sub-areas should be used to obtain information on the specified properties. The following standard lay-out is used to prevent disturbance and bias.

Sub-area A & C: vegetation characteristics and patterns (non-destructive);
Sub-area B: semi-continuous soil sampling (non-destructive);
Sub-area D: destructive soil sampling, including destructive soil moisture sampling. Working gradually uphill will help to minimise disturbance and soil moisture flow interruption to the as yet unsampled areas;

Sub-areas F:	vegetation: destructive sampling including tree winching (Section 6.1);
Sub-area E:	extra for (destructive) vegetation or soil sampling if necessary.

Permanent stakes should be placed at all four corners of the measurement areas and at the corners of each sub-area. For ease of operation, it is suggested that the outer boundary and at least the boundaries of the sub-areas are also permanently marked with weather-resistant tape. The tape can be nailed down at regular intervals by smaller pegs.

2.4 Vegetation plots

This section describes both destructive and non-destructive sampling plots. Tree winching experiments can also be performed outside the assigned plots if necessary. However, great care must be taken not to disturb or influence the areas that are designated for non-destructive sampling and monitoring.

The sub-areas A, C and E are reserved for replicate vegetation measurements. The vegetation should be uniform (determined by eye). Within each sub-area a plot is selected to obtain uniformity in vegetation, slope, aspect and soil type.
Within this plot, at least 5 **sampling units** of 5 x 1 m are randomly selected (where the size of the units allows this). One plot is used for determining the biomass at various moments in time (i.e. every season). The other plot can be used for making phenological observations like cover and frequency of dominant plant species. To this end, the sampling units are subdivided into 5 quadrants of 1.0 x 1.0 m.
For the phenological observations, like cover and frequency, continue sampling 25 or more sample quadrants until the running mean (Fig. 1) becomes stable for each vegetation type. Plant frequency can be recorded on a species basis but the criteria for vegetation classification need only be approximate and a classification on functional types suffices (e.g. shrub dominated, annual dominated *et cetera*).

Disturbance of the soil and vegetation in the sub-areas for soil sampling and soil moisture monitoring by destructive vegetation sampling (e.g. biomass) must be avoided. However, data on variables obtained by destructive vegetation sampling may be required for the interpretation of the soil properties and moisture contents. It would appear a reasonable assumption to extrapolate the findings of the adjacent vegetation plots if it can be proven that the vegetation characteristics of plant assemblies and vegetation cover are similar. In order to prove this similarity, the same non-destructive measurements on the vegetation characteristics of interest must be carried out in any quadrant, before it is sampled destructively. Failure to reject the null-hypothesis that the vegetation characteristics are identical would make it plausible that the vegetation properties, which could not be determined, are the same.

The need to demonstrate identical conditions of the vegetation is especially pressing when the measurement areas do not fit the proposed scheme and are dispersed over the slope. In that case, the measurement areas for soil sampling and moisture content monitoring should contain at least 2 randomly placed sampling units of five sample plots (10 sample plots in total) in order to indicate similar vegetation conditions.

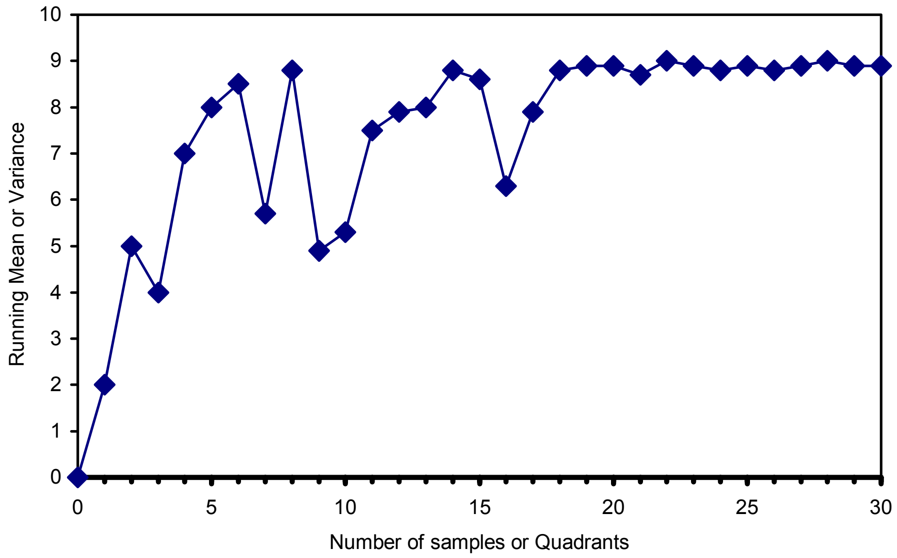


Fig. 1. Suggested relation between sample size and variance for vegetation sampling.

2.5 Sampling routine

The measurement areas should all be inspected and monitored weekly in the same order. Where practical, it is recommended that extra sampling and monitoring is carried out after each significant rainfall event. It will be clear that during dry weather the monitoring will cost less time than after frequent storms.

2.6 Reference system

In order to describe and recover data from different places, a general reference system is needed. It is advised that grid references are made with respect to UTM co-ordinates, which comply fully with GPS measurements. Conversion programs to transpose longitude and latitude into UTM co-ordinates and *vice versa* are available online, e.g. www.dmap.co.uk.

For sample identification, a unique ID should be attributed to each field site. The following site numbers should be used:

1. England Motorway Embankment (UK);
2. Molise/Trivento landslide niche (Italy);
3. Vaujany rockfall slope (France);
4. Thessaloniki forest fire (Greece);
5. Scotland (UK);
6. Valencia (Spain);
7. Almudaina (Spain).

For a field site, sample origins should be indicated by the codes of the measurement area and sub-area. Sample locations can be pinpointed by means of a rectangular grid placed within the measurement area (Cartesian grid with bottom left-hand corner as reference X, Y= 0, 0 m). This local grid can be approximately linked to the UTM and sample locations listed as UTM co-ordinates. To this end, both the UTM co-ordinates of the lower left hand- as the upper right hand corner should at least be known.

Using the Almudaina additional site as an example, the following gives a correct reference for a sample:

Catchment	Río Serpis, Alicante, Spain
Site name	Almudaina
Measurement area	code of each vegetation cover/land use type with replicate number (Roman number)
Sub-area code	A-F
Sub-area reference	X, Y> 0, 0 m
Grid reference (UTM)	30S YH 729.654 4.294.365 (X, Y= 0, 0 m)

e.g. Almudaina-7-F-3-G 10,5: ≈ 30S YH 729.654 4.294.376

2.7 Sample size & number

The size of a sample should be representative at the relevant process scale. The numbers of samples should suffice to reflect the variability and heterogeneity within each measurement unit.
For an unknown population, the number of samples can be calculated using Student's t-distribution for which the standard deviation of the sample population is used to estimate the variance of the population (Ambroise & Viville, 1986):

$$N = \frac{t(\alpha)^2}{\varepsilon^2} CV^2,$$

Where N is the total number of samples, $t(\alpha)$ is the value of Student's t at the two-tailed significance level, α, and ε is the relative precision, which is the relative difference between the found mean and the true population mean. Values of Student's t are listed in Table 1. For a two-tailed test it is hypothetical whether the true mean is under- or overestimated and the relative precision can be specified as a fraction, e.g. 0.05.

Table 1: Student's t for two-tailed significance levels, α, infinite number of degrees of freedom

α [–]	0.01	0.05	0.10	0.25
$t(\alpha)$ [-]	2.58	1.96	1.64	1.15

CV is the coefficient of variation, which is the sample standard deviation over the mean. Thus, it can be estimated if the results of a reasonable number of samples are known or literature values can be used (Table 2).

Table 2: Recommended CV for some common soil properties (after Lee *et al.*, 1982)

Property	CV	Property	CV	Property	CV
Particle density	0.03	Undrained cohesion	0.30	Plasticity index	0.10
Bulk density	0.10	Friction angle		UCS	0.40
Porosity/void ratio	0.25	Sand	0.10	Elasticity	0.30
Permeability	3.00	Clay	Wide variation 0.12 – 0.56		

From the CV, the numbers of required samples can be calculated. It is recommended that during and after sampling, the minimum sample number is updated as more accurate values for the true CV become available. As a guideline, the required minimum number of samples is given for the two-tailed significance level of α= 0.05 at various levels of CV and ε (Table 3).

Table 3: Minimum number of samples at α= 0.05 ($t(\alpha)$= 1.96) for different values for CV and ε

	Relative precision, ε				
CV	0.05	0.1	0.15	0.25	0.5
0.25	97	25	11	4	1
0.50	385	97	43	16	4
0.75	865	217	97	35	9
1.00	1537	385	171	62	16
2.00	6147	1537	683	246	62

Note that still 62 samples are required to establish the mean at a relative precision of only 50% when the variation is large (standard deviation is double the mean). Obviously, this method only provides information on the reliability of the population mean and the standard deviation. For local predictions, spatial interpolation techniques should be used and predictions should be cross-validated with some with-held observations (McBratney & Webster, 1983).

3. GENERAL SITE DESCRIPTION @

Standard fine scale site maps (1:10,000 or 1:25,000) should used as a basis for further investigations. However, all sites should be surveyed specifically for the project. The topographic **site** and **measurement area maps** will be base maps for mapping solid geology, geomorphology, soils, land use vegetation and geomorphological response units.

3.1 Site maps @

After the site has been selected and the measurement areas identified, each site should be surveyed using a theodolite and staff. The datum level should be connected to the local datum level, but if this is not possible, a reference level has to be chosen as close as possible to the local ordnance survey datum-level.
The base map should contain basic physiographic information on a scale 1:1,000:

- contour lines (the equidistance should be chosen adequate to gradient of the surface; 0.5-2.5 m contours);
- (dry) water courses;
- the positions of the measurement areas and sub-areas;
- the positions of paths, roads, the weather station and other human structures;
- delineation of exposed landslide crowns and deposits;
- the positions of vegetation units;
- map and magnetic north and scale.

3.2 Measurement area maps @

Each measurement area should be surveyed in more detail at a scale 1: 250. The measurement area maps should include:

- measurement area boundary
- large trees or shrubs;
- magnetic north and scale;

3.3 Slope profile description @

Comments A simple method is suggested for the measurement of slope profiles on which the measurement areas are situated.

Equipment Abney level, linen tape, ranging poles, compass

Procedure The gradients of the slope where the measurement areas are installed should be measured and presented in the form of slope profile along the steepest gradient, with the measurement area positions indicated. If the measurement areas are staggered across the slope, more profiles are needed.
The slope gradient should be measured at a fixed base-length interval of 5 metres at a maximum. The gradient itself can be measured for each base-length interval with an Abney level, linen tape and ranging poles (Leopold and Dunne, 1971; Goudie, 1981). The slope gradient can then be drawn very quickly. The orientation and the position of the slope profile should be indicated on the site map.

3.4 Soil profile description @

3.4a Soil classification

Comments A soil pit should be dug just outside of each measurement area, adjacent to sub-area D. Each soil horizon should be described using the data-recording sheet (sheet number B).

Equipment Standard soil description equipment.

Procedure The description of the mineral soil profile should be based on the standard F.A.O. (1990)

Soil colours are described by using the Munsell scale handbook.
The classification of the mineral soil profiles may be carried out with the help of the **WORLD REFERENCE BASE for SOIL RESOURCES** manual on soil profile classification (Driessen et al., 2001). This new and soil taxonomy and classification is currently available. It is the modernised version of the formerly used F.A.O. classification (1989/1999) and a revised but complete format from of the well known standard book: "The Major Soils of the World" by the F.A.O.
A third soil classification should also be made using the national soil classification system.

3.4b Organic soil profile classification (cf. Green *et al.*, 1993)

As the F.A.O. classification does not give the organic soil profile the attention it deserves, the ectorganic horizons should be classified using an adapted method of Green *et al.* (|1993) and its revised version (Klinka, 1997). Copies of the latter classification are available on-line: www.forestry.ubc.ca/klinka/sci_sil/sses/sses009.pdf. A short description of the main organic soil horizon is given here.

The main types of organic soil profiles that are *mor*, *moder* and *mull*. These types represent different humus forms that occur on different substrates. Mull humus forms are common on rich soils with a high clay or loam content whereas mor humus forms are characteristic for poor mineral soils. The moder humus type is an intermediate form and occurs on loamy soils that are poor in nutrients under cool and moist climates.

The ectorganic horizon can be subdivided into a succession of layers from the surface downwards: litter, fermentation, and humus. These layers are indicated by the respective codes L, F and H. These layers are further classified into subordinate horizons according to the classification of Green *et al.* (1993). Broadly speaking, the following describes the succession of the organic and mineral horizons with their morphological characteristics:

Litter horizon (L): Relatively fresh plant residues with little to none discoloration or fragmentation. Is void of excrements of soil fauna and contains no roots;
Fermentation horizon (F): Consists of decomposing litter but visible and recognisable plant residues still predominate. Finely divided organic matter (Fz) is nearly always present and stems from the excrements of the soil fauna. However, the quantity of finely divided organic matter is inferior to that of the visible plant residues. The horizon is strongly intertwined with roots and contains possibly fungi (Fm or Fa);
Humus horizon (H): Contains finely divided organic matter (Hh) in quantities that exceed that of visible plant residues (Hr). Mineral soil fragments can be incorporated into the humus layer.
Organic horizon (O): wetland organic horizon of poor decomposition in waterlogged conditions;
Mineral horizon (A): Is the mineral horizon directly under the organic horizons and enriched with organic matter (Ah stand for humic, Ap for tilled soils). Horizon contains less than 17% organic carbon (approx. 30% organic matter by weight) The organic matter has been incorporated into the soil by means of bioturbation This horizon also includes colluvial layers that are enriched in organic matter but that do not classify as a Ah in their own right.

The descriptions of the subordinate horizons (*cf.* Green *et al.* 1993) are:

Ln (new; Babel, 1975 op. cit. Green et al., 1993): an L horizon composed of newly accreted and essentially unfragmented plant residues. These materials have recently accumulated on the ground surface (usually < 1 yr). They are generally loose, show essentially no structural change and may be somewhat discoloured;
Lv (variative; Babel, 1975 op. cit. Green et al., 1993): an L horizon exhibiting initial decay and strong discoloration. These materials are comprised of less recently accreted plant residues in which disintegration and discoloration have occurred but fragmentation and fine substances are lacking;
Fm (mycogenous): an F horizon in which plant residues are aggregated in a matted structure with a tenacious consistence. The matted, tenacious fabric typically features a felty character due to

abundant fungal mycelia. Faunal droppings may be present, but only with low frequency and abundance. Roots may be abundant, contributing to the formation of the matted fabric;

Fz (zoogenous): an F horizon in which plant residues are weakly aggregated with a loose or friable consistency. The friable fabric reflects the presence of active populations of soil meso- and microfauna. Faunal droppings are typically numerous and easily observed under magnification with a hand lens or binocular microscope. Fungal mycelia may be present, but rarely in large amounts. Root residues comprise a moderate proportion of plant residues and are typically less abundant than in Fm horizons;

Fa (amphi): an F horizon in which plant residues are aggregated into a weak to moderate, noncompact matted structure. This is an intergrade between the Fm and Fz horizons, and as such, reflects properties of both. The structure of the material is not strong, therefore aggregates disrupt relatively easily when disturbed. Often, the fabric is variable, featuring clumps of aggregated material with pockets of loose material. Fungal mycelia and faunal droppings may occur; however, neither clearly predominates over the other;

Hh (humic): an H horizon predominated by fine substances with very few if any recognisable plant residues. The organic material has a greasy character when moist, with a massive or blocky structure. The colour is typically black and the material stains the fingers when rubbed;

Hz (zoogenous): an H horizon predominated by fine substances with very few if any recognisable plant residues. Faunal droppings constitute most of the fabric. The organic material is typically black in colour, with a fine granular structure. The abundance of very small cylindrical or spherical faunal droppings gives the appearance of fine black "sawdust" (Hartmann, 1951 *op. cit.* Green *et al.* 1993). Is subdivided in hf and Hg in the classification of Klinka (1997);

Hr (recalcitrant): an H horizon containing macroscopically recognisable plant residues (roots, bark, and/or wood) imposing yellow, brown, or particularly red colours. Fine substances predominate and the material is slightly greasy but does stain fingers when rubbed;]

Of (fibric): a surface O horizon that consists of poorly decomposed plant residues readily identifiable as to their origin;

Om (mesic): an O horizon that consists of partly decomposed plant residues at a stage of decomposition intermediate between Of and Oh horizons;

Oh (humic): an O horizon that consists of well decomposed plant residues which for the most part have been transformed into humic materials.

The descriptions of the horizons can be used to identify the humus forms by using the key of Klinka (1997).

3.4c Engineering soil classification

In addition to the description of the soil profile, it is essential to know at least in descriptive terms the changes in the shear strength and mechanical behaviour of the engineering soil. Such changes could occur within the C-horizon of the profile where no apparent soil formation has taken place. It is proposed to use the **British Code of Practice for Site Investigations** (BS 5930). The classification for field description has been summarised in Tables 4 to 6.

Table 4: Components for engineering soil classification (*cf.* BS 5930)

	Additional	Predominant component (>50%)	Fraction
Over 65% granular material	Slightly sandy	GRAVEL	Up to 5% sand
	Sandy	GRAVEL	5 – 20% sand
	Very sandy	GRAVEL	Over 20 %
		GRAVEL/SAND	Equal proportions
	Very gravely	SAND	Over 20 %
	Gravelly	SAND	5 – 20% gravel
	Slightly gravely	SAND	Up to 5% gravel
	Slightly silty	SAND (or GRAVEL)	Up to 5% silt
	Silty	SAND (or GRAVEL)	5 – 15% silt
	Very silty	SAND (or GRAVEL)	15 – 35% silt
	Slightly clayey	SAND (or GRAVEL)	Up to 5% silt

	Clayey	SAND (or GRAVEL)	5 – 15% silt
	Very clayey	SAND (or GRAVEL)	15 – 35% silt
Over 35% fines	Sandy	SILT (or CLAY)	35 – 65% sand
	Gravelly	SILT (or CLAY)	35 – 65% gravel
Organic soils		PEAT	

The material is described after any cobbles or boulders present are removed. After removal, the fractions of granular material (sand, gravel) and fines (silt, clay) determine the main class of material (Table 4). Composite soils are described with the predominant components written in capitals, e.g. "sandy GRAVEL". Mixes can be described by combining the descriptions of the two components, e.g. "SILT and COBBLES". The description of the components can be elaborated by specifying texture, grading, and particle shape. Also colour and structure can be included (Table 5), which precede the component, e.g.

"reddish-brown fissured sandy CLAY",
"white poorly sorted sub-angular SAND".

Table 5: Structure of engineering soils

Component	
All	Homogeneous/interstratified/heterogeneous
	Weathered
Clays	Fissured/intact
Organic soils	Fibrous/amorphous

The firmness or strength of the in-situ soil can be assessed by simple index tests (Table 6) and is stated at the beginning of the description, e.g.

"Firm, blue-gray fissured CLAY.

Table 6: Index tests for soil firmness

Soil type	Term	Test
Sand and gravels	Loose	Can be excavated with a spade; 50 mm wooden peg can easily be driven into the soil
	Dense	Requires pick for excavation; 50 mm peg is hard to drive into the soil
	Slightly cemented	Soil is excavated with pick in lumps. Lumps can not easily be broken but particles can be abraded
Silt	Loose	Easily moulded or crushed with fingers
	Dense	Strong pressure required to mould material
Clays	Very soft	Extrudes between fingers when squeezed
	Soft	Moulded without pressure
	Firm	Can be moulded with pressure
	Stiff	Can not be moulded but can be indented with thumb
	Very stiff	Can not be indented except with the thumb nail
Organic soils. peats	Firm	Fibres compressed together
	Spongy	Open and compressible structure
	Plastic	Mouldable and smears the hands

Information on the consistency limits of the material can be obtained by means of the Atterberg limits that are determined in the laboratory (Section 4.16) and used to classify the soils with fines according to the *British Classification System for Engineering Purposes* (BS 5930) or to the *Unified Soil Classification System* (Wagner 1957). Simple index tests that provide information on the consistency of fine-grained soils in-situ are listed below. They do not require any special equipment and can be executed in the field and the description added to the ones specified above when appropriate, e.g.

"Firm, blue-gray fissured CLAY of low plasticity".

Cohesion in a soil is indicated by the characteristic that it can be moulded into a firm mass at ambient moisture contents. Plasticity is indicated by the malleability of the soil without crumbling or cracking. If cohesion and plasticity are low, a fine-grained soil is poor in clay and clay minerals and may contain a large proportion of silt. Silts usually have a low liquid limit, which can be demonstrated by the toughness and dilatancy test. In the toughness test, a small piece of moist soil is rolled in the hand to form a thread, kneaded and remoulded until the thread breaks in lumps at a diameter of 3 mm. For high plasticity clays, having a high liquid limit, these lumps are firm and are not formed after many attempts. In contrast, short clays and silts of low plasticity are difficult to shape and crumble readily.
The dilatancy test establishes whether stresses lead to a change in void space. This occurs predominantly in fine-grained granular materials (silts and fine sands) that are consequently prone to liquefaction. The dilatancy of a material is tested by putting a pat of soil just dry of the plastic limit in the horizontally extended palm of the hand and tapping it vigorously on the side with the other. The soil is dilatant when a water film appears on the surface on the pat, which disappears when the material is squeezed with the fingers. In that case, the soil becomes dull and dry and crumbles easily. Plastic clays do not show any dilatancy.

3.5 Soil maps @

Soil maps should be constructed after compiling legends based on the soil profile description. The areal extent of the soil units should also be checked. Soil mapping units should also contain important information on depth of the soil to the bedrock interface.

The depth and extent of the engineering soils on site should be delineated by contour lines that represent the thickness of the respective units and the depth to solid bedrock. The geometry of the soil layers can be determined by drilling or augering or appropriate geo-physical techniques.

The soil map should be compiled or checked by an experienced operator.

3.6 Solid geology @

The parent material should be described as adequately as possible in terms of:
- lithostratigraphic unit;
- lithology;
- mineralogical composition;
- rock mass quality (Bienawski, Selby).

3.7 Site History and Climate @

Comments The climate of the site should be described and derived from existing data of nearby comparable stations, preferably based on a 30 year weather record (normal definition of climate). Also the history of the site with respect to changing land use, extreme events (wind, precipitation, flooding, avalanching and rock fall, landsliding, forest fires, major insect plagues), should be described, as this can give important information in changes in vegetation and soil properties

4. DETAILED ABIOTIC SITE DESCRIPTION

4.1 Meteorological measurements @@

Comment The meteorological measurements should ideally be carried out by automated weather stations, with standardized measurement methods. The sensors should regularly be checked on malfunction and be cleaned. All meteorological measurements should be made as hourly averages. These measurements area:

Solar radiation;
Net radiation;
Wind speed;
Rainfall;

And,

Dry bulb temperature;
Wet bulb temperature;

Or,

Temperature;
Relative humidity;
Atmospheric pressure.

All measurements should be made over a typical vegetation cover with equal sampling intervals. For rainfall, the data may be stored at a higher temporal resolution, as this information is needed to characterise the intensity.
When other continuous measurements are carried out it is important to synchronise the different datalogger or mechanical clocks.

4.2 Rainfall @

Comments Rainfall should be measured in two ways. The first method is by continuous registration by means of a tipping bucket. Tips should be stored with a high time resolution (every 5 minutes at least) or upon occurrence during the rainfall event, which gives information on rainfall intensity and duration. The second method is based on the sampling the total rainfall volumes by means of conventional rainfall gauges after each rainfall event. This will help to corroborate the rainfall measurement by the tipping bucket and provide information on the spatial distribution of rainfall totals.

Equipment Standard rain gauge with a tipping-bucket system connected to a datalogger. The rainfall depth resolution should preferably be better than 0.25 mm. The opening of the rain gauge should be at a standard level of 1.5 m height.

The rain gauges for the measurement of the total rainfall depth should all be identical for each field site and mounted at a standard height of 1.5 m.

Method The variability of the rainfall depth is strongly influenced by topographical differences in the terrain and by vegetation structures higher than 1.5 m. Therefore measurements should be carried out at several places (2-3 per measurement area). All rainfall gauges and tipping buckets should be located in the open field and removed by a distance of at least nine times the height of any obstacles.

4.3 Interception @

Comment Rainfall passing through a canopy is intercepted partly by the vegetation and the amount reaching the soil (throughfall) consequently reduced. Moreover, the intercepted rainfall is lost to evaporation, which diminishes the evapotranspiration that can occur. Therefore, the storage capacity of the various vegetation layers should be known as the interception affects the net rainfall that is available for the vegetation and the hydrological processes.

Method *To relate the throughfall to the total rainfall,* rainfall should be measured in the open field and below the canopy. For total rainfall, the measurements below the canopy should be carried out

with at least 15 gauges over a representative area with unifom vegetation (Helvey and Patrick, 1965). To avoid bias in the proportion of throughfall as the result of local conditions, the positions of the rainfall gauges under the canopy should be changed regularly, preferably after every event (Lloyds and Marques, 1988).
Under low canopies, e.g. shrubs, the throughfall can be collected in purpose-built receptacles. If the collected rainfall can not be recorded after every event, the accumulated rainfall should be syphoned into a container from which evaporation is prevented by the presence of an oil film. The rain gauges, however, should be measured, emptied and cleaned regularly as organic material builds up rapidly and affects the functioning of the equipment.
For information on the amount on interception in relation to rainfall duration and intensity, throughfall should be measured by means of a tipping bucket, for which the same considerations apply.

Calculation Throughfall can be related to the gross rainfall through (linear) regressions.

4.4 Gravimetric soil moisture content ($g.g^{-1}$) (destructive method) @

Comment The gravimetric soil moisture determination is based on the loss of water from a sample dried for 24 hours at 105°C.Two methods are described, the core method for soils which are not too dry or stony (Blake and Hartke, 1986), and the excavation method for stony soils (Goudie, 1981; Huntington et al.,1989).
The core method is a general method to determine phase relationships in the soil. In addition to the gravimetric moisture content it can be used to determine the related properties of void ratio, bulk density, specific volume, degree of saturation, *et cetera*.
The gravimetric soil moisture content is synonymous with the water content, w.

Sampling Soil moisture is sampled weekly and after every event. It is evident that sampling frequency during the drying period, after rainfall, should be carried out weekly. When the soil has been dried out, sampling frequency can be reduced to longer time intervals (2-weekly or monthly intervals).

It is recommended to work from the outer side of the plot inwards and upwards (zig-zag) to prevent distortion of possible down-slope flow-paths.
The first samples should be collected from the lower left-hand corner of sub-area D and lower right corner of sub-area F within a square sampling plot of 50 x 50 cm (section 2.2/2.3). In each plot, 4 samples are taken. This should be done carefully as the plots have only a limited surface area. These samples are taken from each soil horizon or when these are absent at 0-2 cm; 5-7 cm; 10-15 cm; 20-25 cm and 35-40 cm depths (20 samples in total).

During the next visit, one week later a sample will be taken in the next 0.5 m square further to the left. In total, there should be sufficient room to collect samples for over 180 weeks.

<u>4.4a Core method</u>

Equipment Field: standard stainless steel rings (50 mm diameter, 100 cm3 volume), a ring driver, hydraulic pressure apparatus for driving cores into the soil (optional), trowel and/or spade, metal saw, plastic ring covers to prevent evaporation and disturbance, tape for sealing the samples.
Laboratory: oven, balance (accurate to 0.01 g), desiccator.

Procedure Drive the ring slowly into the ground, disturbing the soil as little as possible. A hammer should not be used. Inserting the ring with a hydraulic press should be preferred. Remove the soil around the ring with the trowel or knife, without disturbing the soil in the core. Remove the ring with the containing core carefully from the soil, by cutting at least at 2 cm from the core bottom. Soil protruding from the ring should be carefully cut away with a small metal saw, cutting perpendicular to the core edge. Cutting with a knife parallel to the ring edge will smear the sample.
Put the plastic covers on the top and bottom of the ring immediately after sampling.
In the laboratory, weigh the ring with the core (wW; g) as soon as possible, dry it in the oven at 105°C for 24 hours, cool it in a desiccator and reweigh (dW; g). The weight of the clean sampling ring is determined (rW; g) after drying in the oven.

Calculation Gravimetric soil moisture content , w

$$w = \frac{M_w}{M_s},$$

Where Mw is the mass of water and Ms the mass of (dry) solids, i.e.

$$w = \frac{wW - dW}{dW - rW}.$$

The gravimetric soil moisture content is reported in 0.01 $g \cdot g^{-1}$ or in 0.001 if $w < 0.10\ g \cdot g^{-1}$.

4.4b Excavation method (for soils with (porous) stones)

Remarks During the following procedure, the gravimetric soil moisture content of the coarse fraction (> 2 cm) is separately determined. The moisture content of the coarse fragments is important when they have high porosities (Hanson and Blevins; 1979). If the storage of soil water in the stone fragments can be neglected (this must first be determined) then the determination of soil moisture in clods containing the fine fraction will be sufficient (indicated below as $w_{<2mm}$).

Equipment Field: spade, transportation material (paper bags, plastic bags, wooden boxes).
Laboratory: balance (accurate to 0.01 g), oven, desiccator, 2mm mesh sieve.

Procedure Excavate three large clods of soil (±500 cm^3) and transport these carefully to the laboratory. Take care water does not evaporate during transport. Before drying, weigh the clods (wW1) (wW2) and (wW3).

1. Dry sample wW1 in the oven at 105 degrees C. and weigh it again (dW1).
2. The fine fraction (<2 mm) is separated from sample wW2 by taking a few small, but relatively homogeneous clods without (estimation by eye) fragments coarser than 2 mm from sample wW2. The clods and the rest of wW2 are weighed (respectively wWCS and wWCR). They are also dried in the oven at 105°C for 24 hours. The clods are cooled in the desiccator and then reweighed on a two decimal reading balance (dWCS and dWCR).
3. The fraction > 2 mm is separated from the sample wW3 by wet sieving. Both fractions ($wW3_{>2mm}$ and $wW3_{<2mm}$) are weighed and dried in the oven for 24 hours at 105°C, and then reweighed.

Calculation The gravimetric soil moisture content is first determined per clod and then recalculated per fraction:

w_{bulk}= (wW1 - dW1) / (dW1) [g/g]
w_{small_clod}= $w_{<2mm}$ = (wWCS - dWCS) / (dWCS) [g/g]
w_{rest_clod} = (wWCR - dWCR) / (dWCR) [g/g]

The fraction <2 mm and >2 mm are expressed as fractions of the total dry weight:
Fraction <2 mm = $p_{<2mm} = (dWW3_{<2mm}) / (dWW3_{<2mm} + dWW3_{>2mm})$
Fraction >2 mm = $p_{>2mm} = (dWW3_{>2mm}) / (dWW3_{<2mm} + dWW3_{>2mm})$

The gravimetric soil moisture content of the coarse fraction can now also be calculated (θg_{bulk} and $\theta g_{<2mm}$ are calculated above):

$w_{>2mm} = (w_{bulk} - (w_{<2mm}) * p_{<2mm}) / p_{>2mm}$ [g/g]

4.5 Volumetric soil moisture content ($cm^{3} \cdot cm^{-3}$) continuous, non-destructive @@

Comment The volumetric moisture content is indicative for the degree of saturation of the soil and the matric suction by which water is bound to the soil skeleton. The volumetric moisture content can be determined from the destructive tests for the gravimetric moisture content when the latter is multiplied by the dry bulk density, i.e. VMC= w·DBD. When using rings of a known volume, the volumetric moisture content is simply the volume of water over the volume of the ring. However, for the continuous measurement of the moisture content under the actual evapotranspiration and rainfall events, destructive sampling is undesirable. First of all, the results are not reproducible as the local conditions on the sample scale vary from measurement to measurement. Secondly, the disturbance of the site, which will be considerable over a long sampling period, will affect the moisture content at other locations in the plot. To overcome these problems, continuous and non-destructive test methods are required.
Non-destructive tests for the volumetric soil moisture content usually use the relationship between the dielectrical constant of the sample volume and the proportion of air and water in the pore space. The measurement of the dielectrical constant is either direct, in the case of time domain reflectrometry and derived methods, or indirect, in which case the resistivity of the material is measured as proxy for the dielectrical constant (e.g. gypsum blocks). These indirect methods are less accurate but still could provide an attractive alternative when relative differences over large areas need to be monitored. Other solutions to monitor the moisture content without disturbance are psychrometers, neutron probes and tensiometers. In comparison to the TDR-method, however, these methods require more maintenance, are less robust and difficult to connect to automatic recording devices for continuous sampling. Therefore, TDR and derived methods are to be preferred. TDR uses probes of various sizes that determine the moisture content for various sample volumes. For detailed process studies on hillslope hydrology, smaller sample volumes in the order of 100 cm3 should be preferred.
The University of Amsterdam has in its possession a TDR-system based on a multiplexed Tektronix 1502b system that is available for short sampling campaigns within the ECO-SLOPES project. This system is ideal for the temporary sampling of soil moisture with a high spatial and temporal resolution. For monitoring the volumetric moisture content over prolonged periods, ready-made equipment is available commercially (TRIME, θ-probes).

Sampling Probes should be installed with due care to avoid any disturbance of the local pathways of soil moisture movement in the soil. Therefore, the probes should be installed via a trial pit of the smallest dimensions possible. The excavated soil horizons should be kept separately and replaced in the right order and with a similar amount of compaction after the probes have been installed. Probes should be installed in the face of the pit parallel to the slope gradient and on the upstream side of the wall. The prongs should be pointing slightly upwards. In this manner, it is the least likely that the sample volume of the probes is affected by the boundary effects of the trial pit. The influence of the anomalous hydrology of the trial pit can be further reduced by sealing the wall face with impermeable substances.
The probes should be placed at different depths along the soil profile. At least one sensor per soil horizon should be installed but more probes may be needed in the topsoil where the fluctuations in the moisture content are the largest. Also sets of probes may be installed at either side of a contact between materials for which different permeabilities can be expected (soil horizons, lithic contact). Thus, they might provide information on the presence of perched ground water levels within the soil profile.

4.6 Dry bulk density (DBD) [$g \cdot cm^{-3}$] @

Comments Dry bulk density (DBD) should be determined for each soil horizon or, when absent, for every 10 cm. The samples can be taken from the soil pits dug at the border of sub-area D when the soils are being described (see: soil profile descriptions 3.4). The number of samples can be determined using the method described in section 2.7.
The dry bulk density can be determined by two methods described here. These methods are the core method for soils which are not too dry or stony (Blake and Hartke, 1986), and the excavation method for stony soils (Goudie, 1981; Huntington et al., 1989). From the dry bulk density, the void ratio can be calculated if the particle density is known. A short description to determine both variables is listed below (section 4.7 and 4.9).

4.6a Core method

Equipment Field: standard, 5 cm diameter stainless steel rings (100 cm^3), a ring driver, hydraulic pressure apparatus for driving cores into the soil (optional), trowel and/or spade, metal saw, plastic ring covers to prevent evaporation and disturbance
Laboratory: oven, balance reading to two decimal places, desiccator.

Procedure Drive the ring slowly into the ground, disturbing the soil as little as possible. Inserting the ring with a hydraulic press is preferred. A hammer should not be used. Remove the soil around the ring with the trowel or knife, without disturbing the soil in the core. Remove the ring and core carefully from the soil, by cutting the soil at least 2 below the core bottom. Soil protruding from the ring should be carefully cut away with a small metal saw, cutting perpendicular to the core edge. Cutting with a knife parallel to the ring edge will smear the sample.
Put the plastic covers on the top and bottom of the ring immediately after sampling.
In the laboratory, weigh the ring with the core (wW; g), dry it in the oven at 105°C for 24 hours, cool it in a desiccator and reweigh (dW; g). The weight of the clean sampling ring is determined (rW; g) after drying in the oven.

Calculation Dry Bulk Density (DBD) = (dry weight core - weight ring) / (sample volume), or,
$DBD = (dW - rW) / 100\ cm^3 [g \cdot cm^3]$.

4.6b-c Excavation method
b: for soils with small stones (2-20 mm)
c: for soils with many and/or large stones (> 20 mm)

Comments Under the following procedures, the bulk density of the coarse fraction (>2 mm) is determined separately.

4.6b Soils with small stones

Equipment Field: spade, transportation material (paper bags, plastic bags, wooden boxes).
Laboratory: liquid paraffin, balance reading to 2 decimal places, oven, desiccator, graduated cylinder.

Procedure Excavate a large soil clod (±500 cm^3) and transport this carefully to the laboratory. Before drying, weigh the clod (wW). Let the clod become air dry (2 weeks drying) weigh it (dW), and attach a thin wire. Dip the clod into the paraffin to make it water repellent. Weigh the clod again (dW_{+par}). Immerse the clod totally under water in a graduated cylinder and measure its volume (Vol) or measure its immersed weight (W_{H2O}). (N.B. If the paraffin seal leaks, discard the sample). Take a sub-sample of the clod as large as possible and weigh it (W_{sub}). Separate the fraction < 2 mm from the rest. Reweigh both fractions ($W_{sub<2mm}$ and $W_{sub>2mm}$) and dry both samples in the oven at 105 °C. and weigh them again ($W_{dsub<2mm}$ and $W_{dsub>2mm}$) (partly after Goudie (1981). The volume of the fraction 2 mm-2 cm can be determined by immersing the fraction in a water filled graduated cylinder (V_{sub2mm}, see also section 4.7).

Calculation Calculate the mass of the paraffin coating and the wire. ($dW_{+par}-dW=M_{par}$) Calculate the volume of the paraffin with its specific density (which is dependent on its grade/manufacturer!) ($M_{par}/\rho_{par}=V_{par}$).
Calculate the oven dry mass for all fractions:

$Wdryt= dW * ((W_{dsub<2mm}+W_{dsub>2mm})/(W_{sub<2mm}+W_{sub>2mm}))$(total)
$Wdry<2mm= dW * (W_{dsub<2mm})/(W_{sub<2mm})$ (fraction <2mm)
$Wdry>2mm= dW * (W_{dsub>2mm})/(W_{sub>2mm})$ (fraction >2mm)

The total dry bulk density is calculated by:

$DBD_{tot} = Wdryt / Vol - V_{par}$ or if weight below water is used:
$DBD_{tot} = Wdryt * \rho w /(dW-W_{H2O} + W_{par} -(W_{par}*\rho w/\rho_{par}))$

Where ρw = is the density of water, which is taken as 1 g/cm^3, when using a balance reading to two decimal places.

The dry bulk density of both fractions is equal to:

$DBD_{<2mm}$ = Wdry<2mm / ((Vol - Vpar) - V_{sub2mm}) (fraction <2mm)
$DBD>_{2mm}$ = Wdry>2mm / V_{sub2mm} (fraction >2mm)

4.6c: Soils with large stones (> 2 cm)

Equipment Field: measurement tapes, rectangular frame of 50x50 cm with a 5x5 cm grid, graduated cylinder, field balance, 20 mm and 2 mm mesh sieves.
Laboratory: Oven, 2 decimal balance, paraffin

Procedures In the field an adapted procedure of Huntington et al. (1989) is recommended. A step-wise horizon by horizon, or layer by layer, excavation of a pit of 0.5 - 0.5 m is carried out. The excavation of horizons is preferred when they are present. When horizons are thicker than 10 cm, the sampling of the horizon has to be sub-divided. In the absence of soil horizons, 10 cm thick layers are sampled. Each horizon or layer is subsequently sampled.
A square grid (0.5 x 0.5m with 5 x 5 cm squares) is superimposed on each horizon or layer surface. Each soil horizon is excavated separately and the thickness and surface of the soil horizon is measured at the grid nodes. From these thickness measurements and the surface area of the pit, the volume of the excavated horizon or layer is calculated. All excavated material is weighed (per horizon or layer), passed through a 20 mm sieve and the different fractions subsequently weighed. After air drying the soil is sieved through a 2 mm mesh and weighed.
The volume of rocks present at the sidewall or bottom of the pit is estimated by the use of the grid system and taken into account in the individual soil horizons. The volume of roots, if present, must also be measured and if significant incorporated into the calculations.
In the laboratory the different fractions (the stone fraction also, as soil water in coarse fragments can be considerable (Hanson and Blevins; 1979)) are weighed and oven-dried at 105 degrees C. The volume of the two stone fractions is also determined in order to estimate their bulk density. The volume of the stones is measured by their water replacement in a graduated cylinder. If the stones are porous and water is absorbed by the stones, than the stones have to be immersed in a water repellent paraffin coating of which the volume used is known.
When organic matter (roots etc.) is present in the sample, then the bulk density should be corrected for organic matter.

Calculation The volume of each soil horizon is known, as well as the volumes of the individual fractions (>20 mm, 2-20 mm and roots).
The dry bulk density of the fractions can than be calculated by:

$$DBD_{<2mm} = \frac{M_{<2mm}}{V_{tot} - (V_{>2mm} + V_{roots})},$$

$$DBD_{>2mm} = \frac{M_{>2mm}}{V_{tot} - (V_{<2mm} + V_{roots})},$$

$$DBD_{roots} = \frac{M_{roots}}{V_{tot} - (V_{>2mm} + V_{<2mm})},$$

$$DBD_{tot} = \frac{M_{tot}}{V_{tot}}.$$

The moisture content at the time of sampling can also be calculated for all fractions (see section 4.4).

Reporting Report the dry bulk density to the nearest 0.01 [g·cm^3].

4.7 Particle density (ρ_s, g·cm^{-3}, Mg·m^{-3}) @

Comment The particle density is synonymous with the specific gravity except that the latter is expressed as a dimensionless figure in relation to the density of water (1 g·cm^{-3}). The method described, according to BS 1377, measures the volume of a known mass of soil particles immersed in de-aired water. The method is suitable for granular mineral soils (< 2 mm). Fines can be tested as well, although colloidal substances may pose problems when broken down in small aggregates. If a large amount of organic material is present, it might be preferred to remove all organic material and correct for the content of organic matter of which the density is determined independently (section 4.8). For soils with reasonable fractions of organic material or that contain minerals that dissolve in water, alcohol may be used instead of water.
The density of mineral particles > 2 mm should be determined in a separate test on a larger, representative sample. Alternatively, they may be ground to pass the 2 mm mesh and included directly in the determination.

Equipment 2 pycnometers (density bottles) of 50 ml capacity with stoppers, water bath of constant temperature, vacuum chamber with pump, oven, wash bottle, mixing rod (diameter 3 mm), riffle box and balance (accurate to 0.001 g). De-aired, distilled water or alcohol.

Method Clean and dry the density bottles. Weigh the respective masses of bottles and stoppers to the nearest 0.001 g (m1).
Obtain a representative and homogeneous sample of 100 g by quartering. Remove any particles larger than 2 mm and determine the fraction > 2 mm for a known mass of soil. Determine the particle density of this fraction separately, using the method described below with a graded cylinder or a pycnometer with a larger capacity. Or, grind down this fraction to pass the 2 mm sieve, mix with the original soil and proceed from here.
Riffle the soil to obtain a sample of 20 g, oven dry it at an appropriate temperature (105°C for mineral soils, 60°C for soils with a high organic matter content) and allow it to cool in a desiccator.
Divide the sample in equal parts over the two density bottles. Weigh each bottle with soil and stopper (m2).
Add liquid (de-aired, distilled water or alcohol) until the bottles are half full and the soil covered. Pour the liquid down the side of the pycnometers to avoid the entrapment of air between the soil particles.
Place the bottles without stoppers in the vacuum chamber, evacuate the air and leave overnight. The vacuum pump should be switched on and the vacuum maintained until no further loss of air is observed.
Release the vacuum and remove the pycnometers from the chamber. Stir the sample gently with the rod and wash any adhering particles back into the bottle with a little liquid. Replace in the vacuum chamber and reapply the vacuum until no further loss of air is observed. This process is repeated until no further air is lost from the sample.
Fill the bottle up to the indicated mark with liquid. Close it with the stopper. Place in the warm water bath and leave until the sample has attained the temperature (at least 1 hour),. Remove the bottle from the bath and wipe it dry. Determine the weight of the bottle with stopper, soil and liquid (m3).
Clean out each bottle and fill it entirely with liquid up to the indicated mark. .Place the bottle with liquid and stopper in the water bath as before. After the constant temperature has been attained, wipe the bottle dry and determine the mass of the full bottle with stopper (m4).

Calculation The particle density is readily calculated as the specific gravity, Gs

$$Gs = Gl \frac{(m2 - m1)}{(m4 - m1) - (m3 - m2)}$$

Where Gl is the specific gravity of the liquid used at the constant temperature, m1 is the mass of the empty bottle, m2 is the mass of the bottle with soil, m3 the mass with soil and liquid and m4 the mass of the bottle with liquid alone. The bottle is always weighed with the stopper.
If the individual values of the two tests differ by more than 0.025, the test must be repeated.

Reporting The average value of the two tests is rounded to the nearest 0.01 and reported as the particle density in units of $g \cdot cm^{-3}$ or $Mg \cdot m^{-3}$.

4.8 Organic matter content (O, $g \cdot g^{-1}$) @

Comment The organic matter content is the gravimetric fraction of the soil that consists of living and decomposing organic matter. It is suggested that the roots of living vegetation are excluded as they are covered *in extenso* in the vegetation characterisation. The same applies to burrowing animals that are unlikely to be present in the samples. Consequently, the organic matter content described here represents the decomposing organic matter that is present in the soil and the micro-organisms that subsist on it.
A rapid assessment of the organic matter content is the loss on ignition (LOI). This is the loss in sample weight at elevated temperatures (450°C) that is attributed to the combustion of organic carbon. The method, however, has the disadvantage that the temperature equally affects the crystal water of hydrated minerals (e.g. gypsum, allophane etc.) and organic carbon contents differ for each different type of organic matter and therefore the results may be biased and incomparable between sites. It is recommended that the organic matter content is determined directly as the fraction of organic carbon as part of the soil chemistry (section 4.12).

4.9 Void ratio and porosity (e, $m^3 \cdot m^{-3}$) @

Comment The void ratio (e) and the porosity (n) represent the proportion of pores in relation to, respectively, the total volume and the volume of solids in the soil. The variables can be expressed in terms of each other,

$$e = \frac{n}{1-n} \text{ and } n = \frac{e}{1+e}.$$

Although the porosity is more common in soil science, the void ratio should be preferred from an engineering perspective as it relates the available pore space directly to the volume of solids. Consequently, the change in void ratio is easier to use in constitutive relationships in the case of consolidation or heave.

The void ratio can be derived from the dry bulk density or the gravimetric moisture content and degree of saturation if the particle density is known, i.e.

$$e = \rho_s / \rho_d - 1 \text{ and } e = \frac{w \cdot \rho_s}{Sr \cdot \rho_w},$$

Where ρ_s is the particle density, ρ_d is the dry bulk density, ρ_w is the density of water (1 $g \cdot cm^{-3}$), w is the gravimetric moisture content and Sr is the relative degree of saturation ($m^3 \cdot m^{-3}$), which is the volume of water over the total volume of voids.

The equation based on the dry density is practical to determine the void ratio of coarse soils for which the excavation method has been used (sections 4.6b and c). The equation with the degree of saturation is only practical when it can be assumed that the sample is saturated (Sr= 1). In that case, the void ratio is the product of the particle density with the gravimetric moisture content. If it can be assumed that the soil is non-swelling, saturation is easily achieved for the cores of 4.4a or 4.6a (see 4.9, natural saturation).

Remark As the particle density of mineral soils varies around 2.6 or 2.7 $g \cdot m^{-3}$, it is tempting to assume these values for the calculation of the void ratio. However, soils rich in organic matter or heavy minerals may deviate from this typical particle density. Because of the relationship, the resultant errors in the void ratio that arise from incorrect values of the dry bulk density or the particle density are relatively large. Since the amount of pore space is an essential parameter for the simulation of groundwater levels that reduce the effective shear strength, it is important that biased estimates of the particle density and dry bulk density do not affect the estimated void ratio. Moreover, in the parameterisation, the void ratio must be representative for the slope and location under consideration. Therefore, it is recommended to determine the void ratio by saturation on large volumes and a substantial numbers of samples whenever possible.

4.10 Soil moisture retention curves @

Comment The soil moisture retention curve should be determined for each soil horizon of all reference profiles. Each curve should be determined in duplo. When using the core method the soil should not be too dry. Only the main drying/drainage curve is determined.
From the soil water retention curve the soil pore size distribution can be determined.

Equipment Field: as for dry bulk density (section 4.6)
Laboratory: A balance accurate to two decimal places, sandboxes at different soil water suctions, pressure membrane apparatus for high soil water suction, oven.

Note: This measurement will be done for all sites at Amsterdam University.

<u>4.10a Non-stony soils</u>

Procedure The sampling procedure for collecting the cores, using metal rings, is described under the dry bulk density (**). Small natural clods (a few cm^3) should be collected at the same time as the cores for the determination of the soil moisture retention at higher levels.

In the laboratory the following procedure is followed:
a) Measure the weight of the cores and sample at the field water content.
b) Attach a permeable nylon cover to the bottom of the ring to prevent loss of soil material.
c) Reweigh
d) Completely saturate the core with water to determine the maximum water holding capacity (natural saturation, θ_0, equivalent to porosity *n*). To saturate them, the cores are placed in a vessel and water is poured diligently around them until they are half immersed. The water is absorbed by the soil and saturation usually achieved within several days to weeks. This can be controlled by weighing the samples regularly until a constant weight is achieved.
e) The saturated core should be placed on one of the sand boxes at a specific suction. Again, the samples are weighed regularly to establish whether they have achieved a moisture content that is in equilibrium with the applied pressure. This can take several days or weeks, especially for clayey soils. Starting from saturation, the moisture content is determined for the range of increasing suctions specified below (Table 5). The period that is required to attain equilibrium will increase during the test as the unsaturated hydraulic conductivity decreases drastically with increasing matric suctions (= lower moisture contents).

Table 5: Matric suctions for the determination of the soil moisture retention curve

Suction (head)	Tension (Pa)	pF ($^{10}\log$ |cm| head)	Method	Notation
-1.0 cm	1 hPa	1.0		$\theta0$
-2.5 cm	2.5 hPa	0.4	*	$\theta0.4$
-10 cm	1 kPa	1.0	*	$\theta1.0$
-1.0 m	10 kPa	2.0	**	$\theta2.0$
-3.16 m	31.6 kPa	2.5	**	$\theta2.5$
-10 m	100 kPa	3.0	***	$\theta3.0$
-31.6 m	316 kPa	3.5	***	$\theta3.5$
-160 m	1.6 Mpa	4.2	***	$\theta4.2$
-316 m	3.2 Mpa	4.5	***	$\theta4.5$
-3160 m	31.6 MPa	5.5	Air-dry	$\theta5.5$

*	Sand box-1 filled with dune-sand having very high hydraulic conductivity, and air entry values at 2 kPa
**	Sand box-2 with low hydraulic conductivity and high air entry value (50 kPa)
***	Pressure membrane apparatus

On the sand boxes, the mid of the core is taken as the reference level for the applied suction. For sand box one, the suction is applied as a physical head by means of a water column that is hanging from the sand surface. It is possible to generate suctions up to 0.2 m with this technique (pF< 1.3).

For the second sand box, the higher suction levels are generated by a vacuum pump. This allows suctions in the range from 2 to 5 m (pF 2 to 2.7). For higher suction levels, the pressure membrane apparatus should be used, in which applied by means of the translational technique (Stakman, 1969). This means that over a semi-impermeable membrane, an overpressure is applied and this allows the determination of the equilibrium moisture content at extremely high pF values (pF= 4.5).

Over the trajectory of the sand boxes, the equilibrium moisture content and the corresponding pF-value are noted. After the last determination at pF = 2.5 the ring plus core is weighed and oven dried at 105°C for 24 hours. Then the core is reweighed to determine the dry mass. The weight of the clean metal ring and the plastic retention ring and nylon mesh are also determined in order to calculate the dry bulk density, porosity and void ratio.
If the soil sample contains any particles in excess of 2 mm, these should be washed out and kept apart (see below).

For the determination of the moisture contents for pF > 2.7, the soil clods are tested in the pressure membrane apparatus. The clods should first be moistened and placed upon filter paper on the pF 1 sandbox. When the clod is at equilibrium it should weighed and placed in the pressure box. The pressure should be applied for 3 weeks, after which time the clod should be in equilibrium. This can be checked from the decline in the volume of water that is expelled from the apparatus. The pressure is then released and the clod weighed again. After 24 hours in an oven at 105°C, the dry weight of the clod is determined.

Calculation For each equilibrium soil moisture suction the volumetric soil moisture content is determined.
-For the calculation of the soil cores, for example at $\theta_{2.5}$:

$\theta_{2.5}$= ((Weight ring + core)$_{pF\_2.5}$ - (weight ring + core)$_{oven\ dry}$) / (volume of ring) [g·cm^{-3}]

-For the clods at for instance $\theta_{4.2}$:

Calculate first the gravimetric moisture content, w
$w_{4.2}$= (Weight clod)$_{pF\_4.2}$ - (weight clod)$_{oven\ dry}$) / (weight clod)$_{oven\ dry}$ [g·g^{-1}]

Multiplying the gravimetric soil moisture content with the dry bulk density of the soil gives the volumetric moisture content, θ,

$\theta_{4.2} = w_{4.2}$ x DBD [g·cm^{-3}]

The drying soil moisture retention curve can then be determined from a plot of volumetric soil moisture content against the pF or suction. This procedure is according the methods as described by Stakman (1969). To the plot of the volumetric moisture content against suction, the soil moisture retention curve can be fitted. A closed-form equation for this relationship is the curve presented by Van Genuchten (1980). A soil water retention curve fitting program based on the Van Genuchten parameters is available from the University of Amsterdam, and can be used freely when a reference is made to the author (Freyer; 1990).

4.10b Stony soils

Comments In stony soils, the sample rings can not be used because the rings might deform and the sample volume is not representative for the bulk behaviour of the soil. In those instances, it is better to work with large natural clods, containing the stones. These clods are subjected to the same matric suctions on the sand boxes as the sample rings. At any stage, the equilibrium gravimetric moisture content is determined. From this, the volumetric moisture content is calculated. So, the dry bulk density of the soil should be known as well. This dry bulk density should be determined on a sample for which the initial volume is known.

During the test, it is essential that the sample does not disintegrate and remains in close contact with the surface of the sand box. For the higher pF values (pF> 2.7), smaller parts of the matrix of the clod can be used in the pressure membrane apparatus.
Corrections for the stoniness may be necessary as its influence on the soil moisture content may be considerable (Reinhart, 1961; Klute, 1986). Therefore, the retention characteristics of the stones should be determined, as well as their bulk density and volumetric and gravimetric fractions should be determined (see section 4.6.1).
The retention curve for stones is determined using the sand-boxes and pressure membrane apparatus described above. Care has to be taken that the samples are in close contact with the sand in the sandbox or the pressure membrane!

After the determination of their individual characteristics the combined soil moisture retention curve of the whole soil can be determined.

Equipment See section 4.10a

Procedure See section 4.10a

Calculation See section 4.10a

Remark The measurements concerning bulk density and soil moisture suction curves are strictly only valid for rigid soils. For swelling soils, soil properties should be measured as often as possible during the season and additional tests on the shrink and swell behaviour should be carried out. These include the COLE using the SARAN-resin method of Brasher *et al*. (1966) for which the methodology and computer programme are available from the University of Amsterdam. Constitutive equations for the behaviour of swelling soils require that also the volumetric changes and associated stresses are specified (consolidation and swell potential tests).

4.11 Soil texture @

Comments Soil texture should be determined for each soil horizon of each reference profile (see section 3.4)
An automatic particle sizer will be used by the Amsterdam group to obtain soil texture data. For fine-grained soils, the samples will be pre-treated with ultrasound and peptisators. For calcareous soils, the texture will be determined on sub-samples with and without HCl-treatment.
If required, a comparison can be made with the results of the classical particle size analysis (sieves and hydrometer tests).

From the soil texture analysis the following data will be retrieved

- The whole range of particle sizes according to the F.A.O./USDA classification. The size classes are: <2, 2-50, 50-100, 100-250, 250-1000, 1000-2000 microns, 0.2-1 cm, 1-2 cm, 2-7.5 cm, 7.5-25 cm, >25 cm. Remark: This division for individual particle sizes is used for the soil classification.
- The range of aggregate sizes which determines the erodibility for exposed soil, whether at the original surface or on the degraded crown and body of a landslide. This range will be established by performing the above analyses without pre-treatments to break down aggregates or to remove any cementing agents like carbonates, gypsum and organic matter. A more detailed subdivision into finer fractions might be made (Pettijohn, 1975), e.g. <0.1, 0.1-2, 2-4, 4-8, 8-16, 16-32, 32-50, 50-105, 105-210, 210-420 microns, 0.42-1 mm, 1-2 mm, 2-4 mm, 4-8 mm, 8-16 mm, 16-32 mm, 32-64 mm, 64-128 mm, 128-256 mm, >256 mm.

Equipment Spade, geological hammer, knife, saw, pickaxe; 2 mm, 20 mm, 75 mm and 250 mm sieves.

Procedure Disturbed soil samples will be collected for each soil horizon of the soil profile from the trial pits. For soils of which the bulk is smaller than 2 mm, 2 kg of sample is enough. If the fraction larger than 2 mm is substantial, larger samples in the order of 10 kg should be taken. The boulder fraction should be determined in the field by the use of a 20 mm, 75 mm and 250 mm sieves according to the F.A.O.-specifications. For the soil texture analysis, the current ISO-standards will be adhered to.

4.12 Soil chemistry @

Comments The soil chemical analyses should be carried out for each soil horizon of each reference profile (see section 3.4). Most samples can be taken from the material intended for the texture analysis. However, if a higher quality of samples is required, separate, better conserved samples may be taken from the soil profile.

The following values and concentrations will be determined:

- pH, $pH_{(KCl)}$ or $pH_{(CaCl2)}$ according to soil type @
- -$EC_{25;}$ @
- -K^+, Na^+, Ca^{2+}, Mg^{2+}, org C, total N, total P. @

The analysis of the soil chemistry should be carried out according to the standards specified by Page (1982). The soil chemistry should be determined for 1:1 soil-water mixtures that have subjected to vigorous shaking for 10 minutes of shaking, followed by 30 minutes of rest.

Additionally, the following values should be determined for the fraction < 2 mm

- Total Nitrogen (*cf.* Kjeldahl with sulphuric acid - salicylic acid); @
- Organic carbon content (Allison method; oxidation by bichromate); @
- C.E.C (=cat-ion exchange capacity) (if available). @@

Procedure Because of the specialist nature of such tests, it is recommended that all tests tare performed by a single, central (commercial) laboratory.

4.13 Soil Aggregation @

Comments Soil aggregation is spatially and temporally highly variable. It is recommended, therefore, that samples for analyses be collected in relation to surface properties (vegetation, crust etc) at various moments. Samples should be collected from a) open sites and b) sites under shrubs or other plants. It is suggested that a comparison be made between aggregation at the surface, at a depth of 10-15 cm; and in underlying horizons.

Various methods are available to determine soil aggregation and aggregate stability. These methods are listed below and the procedures described afterwards whilst more details can be found in the literature cited. The methods have been used extensively by the Amsterdam group. At the University of Amsterdam, laboratory facilities are available to test material from the field sites. The tests are in principle very simple but for those persons doing the tests for the first time, a small demonstration workshop might be organised.

Common tests for soil aggregation and aggregate stability are

1) Water dispersible silt and clay fractions (WDSC; a modification determination of particle size distribution);
2) Aggregate size distribution (0-1 mm, 1-2 mm 2-5 mm and 5-10 mm);
3) Aggregate stability (wet-sieving or water drop test method);
4) The HEM test (based on water retention of slow and rapidly moistened samples);
5) A crusting or permeability test;
6) A dispersion test;
7) The C5-C10 index obtained from liquid limit;
8) Turbidity measurements of suspensions;
9) Ultrasound.

General Procedures

1) WDSC. The recommended procedure can be found in Imeson and Verstraten (1985). The reported procedure is made more or less aggressive by varying the time of shaking or the ratio of soil to water;
2) Aggregate size distribution. Many procedures are described but gently sieving aggregates is the most simple. The stone content should be subtracted from the aggregate content afterwards;
3) There are very many procedures with very little between them. The drop test procedure is most simple (see below). For compatibility, it is important that both the height as the drop size are standardised (usually 1 m and 0.1 g). Aggregates in the range from 4 to 5 mm in size should be used. A comparison of pre-wetted and dry aggregates is useful. A standard soil moisture content is pF 1;
4) The HEM test is described in detail in Collis-George and Figueroa (1984);
5) The crust test described by Farres (1987) is recommended;
6) Dispersion can be measured by following Loveday and Pyle (1973), or, if a chemical laboratory is available, the method of Ramathan *et al*. (??);
7) The C5-C10 index suitable for loamy soils and can be determined from the liquid limit (De Ploey, 1979);
8) Turbidity methods offer a rapid assessment of aggregate stability in relative terms. Thus, it is applicable when for the same soil changes in aggregate stability are followed over time or under different conditions. Methods of this type, however, should be discouraged when different soils are compared.
9) The ultrasound method is suitable for soils relatively resistant to erosion (forest soils for example; Imeson and Vis 1984).

Recommended procedures:
The following procedures describe the aggregate size distribution test and the WDSC-method. These methods are easy to perform and recommended for preliminary tests on soil aggregation.

<u>4.13a Aggregate size distribution:</u>

<u>Macro-aggregation</u>

Equipment Balance, sieving set (25mm, 16mm, 8mm, 4mm, 2mm, 1mm, 0.5mm, 0.25mm, 0.106mm and 0.63mm mesh and the 5mm mesh sieve when the aggregate stability test of Lowe is applied), plastic tubes to store 4-5mm aggregates, and small boxes to store the aggregate's < 106 microns, cooling box to store samples in the field during sampling.

Procedure a)Take the samples in the field when the soil is dry!. This prevents disturbance of the aggregates during transport. Transport the samples preferably in a cool and dark environment and analyse the samples as soon as possible after taking them from the field, or store them cool (approx.2-5 °C), dry and dark.
b) When starting the work in the lab: Split the sample into two parts after carefully homogenising the sample.
One half is used for the determination of the soil aggregation, the other half for the texture.
c) Gently sieve the dried non disturbed aggregates taken from the first half of the sample for one minute by hand, using the mesh sieves the mesh sieves. Measure the weight of each fraction, and determine after that also the rock fragment content of each fraction, either by picking them manually out, or by wet sieving. Keep approximately 60 aggregates of the fraction 4-5mm apart if one is to apply the drop test of Low to determine the aggregate stability. Calculate the weight percentages of each aggregate fraction. In fact this is the size distribution of the soil aggregates and primary particles together.
The fraction < 106 microns should also be kept separate for further analyses, when an automated particle sizer is available (e.g. Microsan etc.; see below). Otherwise the particle size of the silt and clay particles can be analysed using the pipette method and the finer micro-aggregation can be obtained following the WDSC method of Imeson and Verstraten (1985). Both procedures are described below.

d) The next step is to determine the primary particle distribution. The other half of the sample is put in water and treated with ultrasound and dispersion chemicals (see below type of dispersive chemical, depending on material properties). This is done to break down all aggregates into primary particles. After full sonification (North, 1976, Imeson and Vis, 1984) the sample is sieved over the same sieving mesh-set as the dry aggregates. Then the weight fractions are determined per size class.
e) By subtracting the primary particle distribution (obtained under d) from the aggregate+primary particle distribution (obtained under c) the real aggregate distribution can be obtained.

Micro-aggregation

Comments Two methods can be used, finding the water stable aggregate distribution in combination with the determination of the primary particles (WDSC method; Imeson and Verstraten; 1985) or a similar approach with the use of a particle sizer (Microscan II). Normally the fraction < 250 microns is defined as micro-aggregates. In the following text we define micro-aggregates as being smaller than 106 microns.

The WDSC method

Equipment Sieving set, balance, 1liter graduated cylinder, peptisator

Method The method is carried out by the following subsequent procedures:
Procedure A: Determination of classical standard size-distribution before pre-treatment to remove carbonates and gypsum, with addition of peptisator.
Procedure B: Determination of classical standard size-distribution after pre-treatment to remove carbonates and gypsum, with addition of peptisator
Procedure C: Shake 25g of the fine earth fraction for 1 hour in 0.5 l. of distilled water. After that fill up to 1 litre and homogenise . Then determine the size distribution of material with an by pipette analyses for equivalent size diameter < 50 mm (Chittleborough 1982; Imeson and Verstraten 1985).
Plotting the difference the grain size distributions obtained by procedure A/B against C will give the micro-aggregation of the soil for the fraction < 50 mm.

The particle sizer method

Comments This method is still experimental. Its advantages are the speed of the analysis and lower subjectivity, which facilitate replication, and the numerical output. However, the method is relatively new and the method has not been applied to the whole variety of soils. Moreover, the required equipment is still expensive.
This method includes also the determination of the total amount of clay and silt, but the results are not the same as found with the classic hydrometer method.

Equipment Particle size analyser (Microscan II), dispersant, ultrasonic probe

Procedure Disperse 3-4 grams of aggregate powder (fraction < 106 microns) in the cuvette until it is fully homogenised, which takes about 60 seconds. A first analysis is made of the water-stable fraction distribution, containing both the primary particles and the aggregated particles. After this run, a second analysis is done on the same sample, which is still in the apparatus. Now 120 seconds of ultrasonic energy is applied to the sample, at a level over 30 Watts (approx. 100 $J.ml^{-1}$). Also a dispersing chemical is added, depending on the type of soil, in standard concentration as used in the hydrometer method:

non-calcaric soils: $Na_4P_2O_7$
slightly calcaric soils: $Na_4P_2O_7$
calcaric soils: Calgon, NaOH

After this second run, two groups of particle size are available: the group of the water-stable aggregates with primary particles and the group of primary particle alone. By subtracting both curves, the aggregation per size class can be found. The full procedure is described in Cammeraat & Imeson (in prep.)

4.13b Aggregate stability

Equipment sieve with 2.8 mm, 4mm and 5 mm meshes, droplets generating apparatus, 1.0 pF tray

Method An adapted method of Low is used, as described by Imeson and Vis, (1984). It is important that 0.1 g drops are used and that the fall height is standardised at 1 m.. Two times 20 aggregates, 4 to 5 mm in size, are used. They can be separated during the aggregate size distribution analysis. It is very important that they are analysed as quickly as possible after sampling as aggregate stability changes during storage. A comparison of pre-wetted and dry aggregates is useful. One set of 20 aggregates is pre-wetted during 24 hours at pF= 1.0. The other set of 20 is used air-dry. Each aggregate is positioned on the 2.8 mm mesh sieve. Let drops of water fall exactly on the middle of the aggregate until its falls apart and is washed through the mesh. Count the number of drops until the aggregate is falling apart. Repeat this analyses for the two sets of 20 aggregates (air-dry and at pF= 1.0).
The results can be plotted into a stability diagram. When the aggregate is very stable stop counting after 200 droplets. When the majority of the aggregates is too stable for the drop test other methods should be used like the ultrasonic method.

4.14 Saturated hydraulic conductivity @

Comment The saturated hydraulic conductivity is an important parameter for the description of the hydrology by means of Darcy's law. It represents the highest apparent rate of laminar flow through a representative area of soil of which the continuous pore space is entirely filled with water. Therefore, the rate of saturated Darcian flow can be considered as the maximum if macro-pores are absent. The saturated hydraulic conductivity can be linked to the apparent flow rate under unsaturated conditions through the relative hydraulic conductivity $k_r(\theta)$, which can be calculated from the soil moisture retention curve.
The saturated hydraulic conductivity is severely influenced by preferential flow paths in the soil. Consequently, samples for laboratory tests are seldom representative for the process scale, which explains the large variability that is usually observed (CV= 2-3, see section 2.7). For the determination of the saturated hydraulic conductivity on a relevant scale, it is recommended that it is determined *in situ*. Several in-situ tests are described in the literature. A distinction can be made between tests that are located above the groundwater table (e.g. the inverse auger hole test, see below) and those that measure the reaction of the groundwater system directly (well-pumping tests).

The inverse auger hole test is a quick and easy method to determine the saturated hydraulic conductivity above the groundwater table. The method is described by Kessler and Oosterbaan (1974). The determination is suitable for the unsaturated zone near field capacity. When the soil is dry and shrinkage cracks are present, the test may overestimate the saturated hydraulic conductivity.
The method does not use any casing and is therefore only applicable to soils that support a free-standing borehole to the required depth (maximum of 2 m). Test procedures for cased boreholes above and below the groundwater table are available for the participants if required but are not described here for the sake of brevity.

Equipment Auger, float (with indicator), ruler or measuring tape, water, cylinder or bottomless bottle, stopwatch

Procedure Make a hole in the soil with the auger. The depth is arbitrary and may be based on earlier observations from the soil profile. However, make sure that the depth of the borehole is at least several times the diameter of the auger.
During the test, the diameter of the borehole should not change. To prevent spalling and the collapse of the borehole, it is advisable to secure the mouth of the borehole with a plastic tube of 50 - 100 mm that fits snugly into the borehole. To test the hydraulic conductivity under saturated conditions, the borehole must be saturated several times prior to the test. Again, to avoid collapse, it is recommended to saturate the profile from the bottom of the hole upwards by using a piece of hose pipe and funnel. In this manner, refill the hole as many times with water until the surrounding soil is saturated. Allow the hole to drain and then measure the total depth (z_0) and the radius (r) of the hole. For the depth, the inserted tube provides a fixed and reliable reference level.

Refill the hole and repeat until the drop in the water level becomes constant. Usually, it suffices to saturate the entire profile three times prior to the measurement.
For the measurement, refill the hole entirely and lower the float. Start the measurement as the water level reaches the lower end of the inserted tube (t_1). Measure the draw-down of the water level, taking the top of the inserted tube as reference, as often as possible or, if the level decreases more slowly, at regular intervals. A reasonable sample frequency is once every 10 s for the beginning of the test when the draw-down is rapid. With the progression of the test, the water level generally falls more slowly and this frequency may be relaxed.

Calculation Make a table with time (t) against water depth (z). Make a third column with the water height, z"= z_0 – z. Plot $_{10}$log(z") against t . Linear segments of the resultant curve indicate that for that particular zone the saturated hydraulic conductivity is constant. The saturated hydraulic conductivity can be calculated with the following equation (Kessler and Oosterbaan; 1974):

$$K_{sat} = 1.15\, r \, \frac{\log(z_1'' + r / 2) - \log(z_2'' + r / 2)}{t_2 - t_1}$$

Where K_{sat} is saturated hydraulic conductivity; z''_1 and z''_2 [m] are water heights in the bore-hole at time 1 and 2: t_1 and t_2 [s]; r = bore-hole radius [m].

Alternatively, a loglinear slope, α, can be fitted to the observations of a particular layer using least-squares. In that case, $K_{sat}= 1.15 \cdot r \cdot \alpha$.

It is recommended that the saturated hydraulic conductivity is determined for each layer of the soil profile or schematisation separately. If this is not possible, it should be calculated separately for every straight section of the plot of log(z") vs. t (Figure 2) Under the assumption that the saturated hydraulic conductivity decreases with depth, the value should be calculated first for the lowest layer. Subsequently, the saturated hydraulic conductivity of the next layer is calculated. For lateral flow, this value represents the arithmetic average of the saturated hydraulic conductivity of this and the underlying layers. Thus, the calculated value can be corrected with the observed depths over which the points form a straight line in the loglinear plot

$$K_{sat}1 = \frac{1}{z1}\left(\hat{K}_{sat} \cdot z - \sum_{2}^{N} K_{sat} i \cdot zi\right),$$

Where z is the total thickness under consideration (z= Σ z1,z2, ..zN), z1 is the thickness of the uppermost layer, $\hat{K}_{sat}$ is the total saturated hydraulic conductivity and ksat1 is the true hydraulic conductivity for the uppermost layer.

An example of a draw-down curve is given below. In the figure the calculated and corrected K_{sat} values are given for three parts of the profile where the curve is straight.

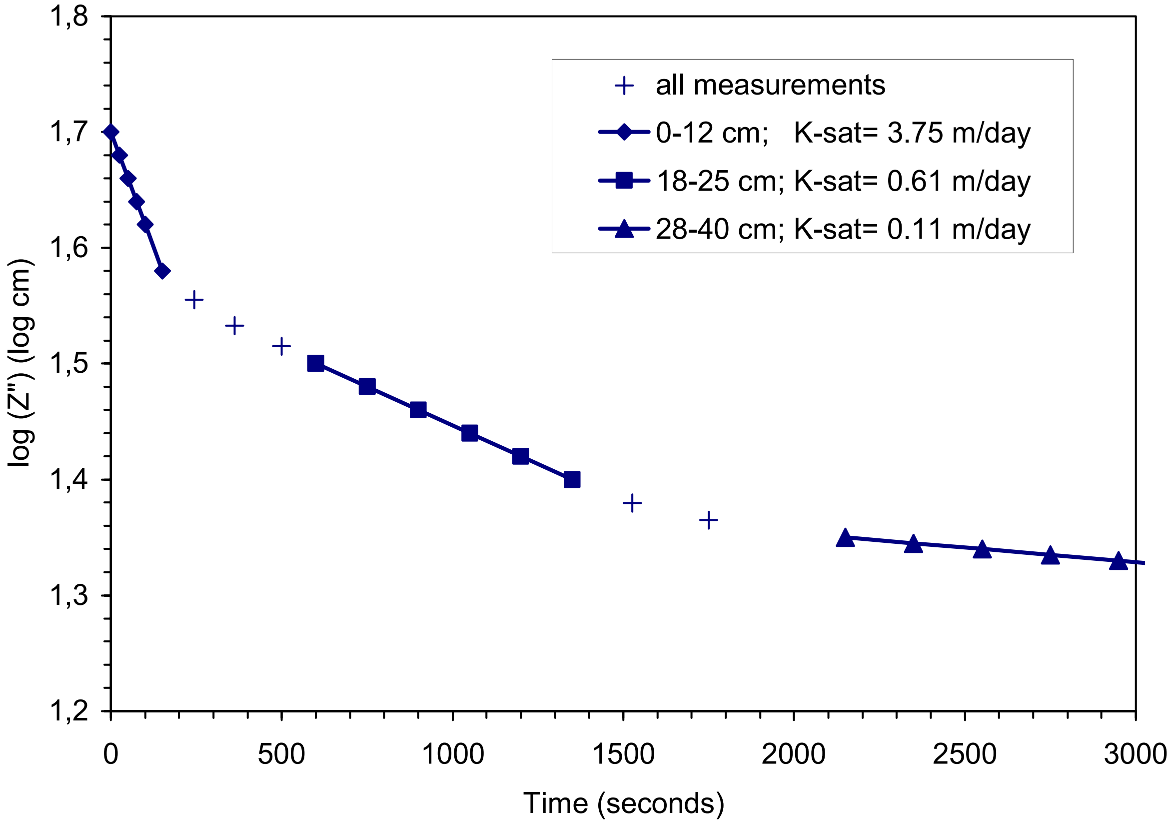


Fig. 2. Example of K-sat determination using the draw-down curve.

4.15 Infiltration characteristics @4,6,7

General Infiltration into the soil creates a zone of wetted soil over the original dryer material. The division between the two is called the wetting front, although the difference between the two zones is not always sharp or straight. The propagation of the wetting front is governed by the diffusivity at its front and a vertical gravitational component as described by the Richard's equation. This propagation manifests itself at the surface as the rate of infiltration, f, i.e. the amount of waterslice entering the soil over a given period [$L \cdot T^{-1}$].

During the initial stages of the infiltration, the diffusivity speeds the propagation of the wetting front into the soil. It becomes less important when the wetting front is well-advanced into the soil and the gravitational term gains in relative importance. Ultimately, infiltration is entirely dependent on the gravitational component and the infiltration rates decreases asymptotically to a minimum value (Figure 3). This value represents the infiltration capacity, f_c. This is the maximum amount of water that a soil can accommodate after a prolonged period of wetting and infiltration can thus be described as a decay function from f_0 at t= 0 to f_c at t= ∞.

Under the boundary conditions of the head-controlled tests, the rate of infiltration is a continuous function (Figure 3). For rainfall simulations of a uniform intensity, i, greater than the infiltration capacity, the function becomes step-like as shown. Initially, the rate of infiltration equals the intensity but the cumulative infiltration affects the diffusivity at the wetting front and the potential rate of infiltration decreases. As soon as the rainfall intensity exceeds the potential rate of infiltration, the latter becomes the actual infiltration. The rainfall excess starts to pond on the surface and may generate runoff, q. The elapsed time between the start of the simulation and the moment at which the break in the infiltration curve occurs is called the time to ponding, t_p [T]. From t_p, the rate of infiltration follows the potential curve. Because the offset between the potential cumulative infiltration, F, and the actual infiltration, $I= i \cdot t_p$, the infiltration curve is shifted in time (Figure 4).

Figure 3: Decay of infiltration rate with time. f* denotes the potential infiltration rate, which occurs under ponded conditions. The actual infiltration rate, f, for intensities, i, greater than the infiltration capacity, f_c, equals i until ponding occurs at t= t_p. The generated runoff is the rainfall excess, q.
From t_p, the actual infiltration can be obtained from the difference between the applied rain and the rainfall excess that is collected as runoff. For the cumulative infiltration, this relationship is shown. The actual infiltration rate for t> t_p is the derivative of the cumulative infiltration with time, i.e. F(dt)= f= I-q. A plot of the rainfall intensity versus the time to ponding is called the infiltration envelope. It forms the threshold above which runoff is likely to occur (Dunin, 1976).

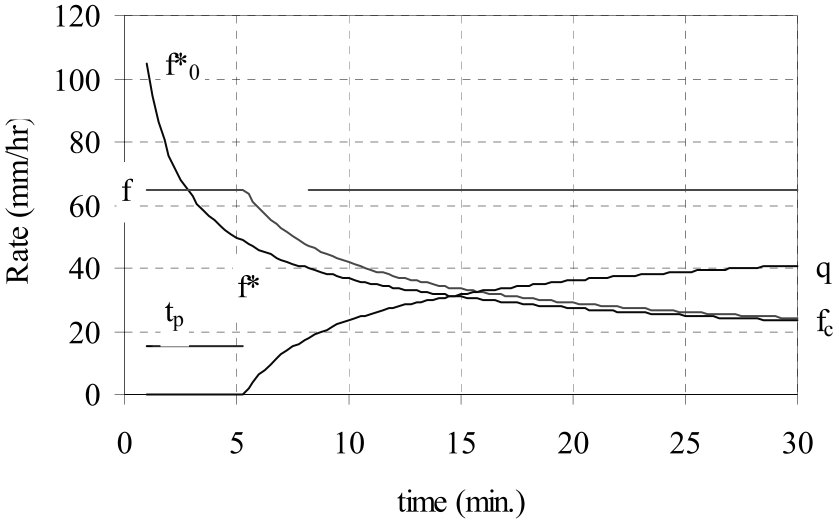


Fig. 3. Typical Infiltration curve, with infiltration rates, runoff rates and time to ponding

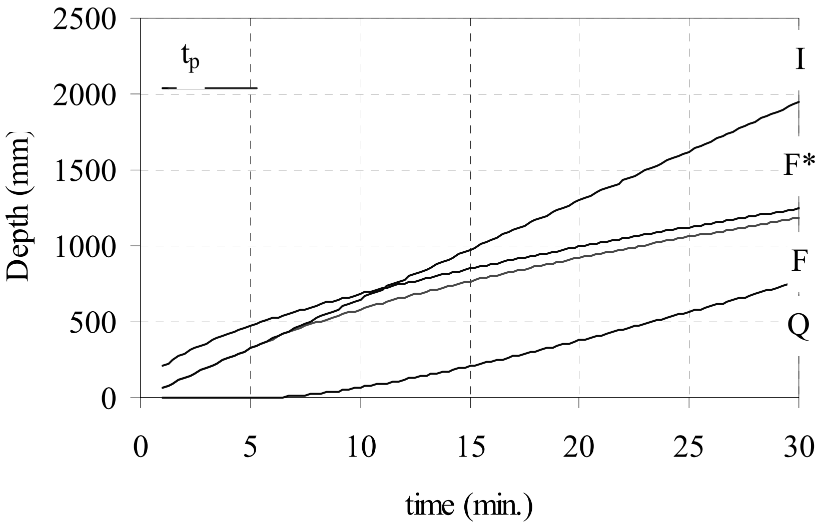


Fig. 4: Cumulative amounts of Figure 3, with totals for the elapsed time denoted by capitals

Philip (1957) devised an approximate solution to describe the process of infiltration. This solution ignores the vertical head due to gravity in the diffusivity term. It describes the rate of infiltration by two parameters, A and S

$$f = \frac{S}{2\sqrt{t}} + A$$

This equation is directly applicable to head-controlled tests and to rainfall simulations when ponding has occurred. The two parameters have a physical explanation. A is related to the gravitational term and thus to the saturated hydraulic conductivity, k_s. It has identical dimensions, [$L \cdot T^{-1}$], and $A = M \cdot k_s$. For most soils, $\frac{1}{3} < M < \frac{2}{3}$ when the elapsed time, t, is not too large. If t is large, Philip's solution is not accurate because of its simplification of the diffusivity term. A is never a reliable estimate of the saturated hydraulic conductivity if the diffusivity, is large, for example in dry soils. The diffusivity is represented by S, which is called the sorptivity [$L \cdot T^{-\frac{1}{2}}$]. The time-dependency of the contribution of the sorpitivity is captured by the square root of the elapsed time since the start of the infiltration, t. The values of the sorptivity can be inferred from the plot of f versus $\sqrt{t}$. It is the slope of the cumulative infiltration, ΔF over $\Delta\sqrt{t}$, during the initial phases of the infiltration. A can be calculated from substituting this value into the formula of f at a later stage of the infiltration.

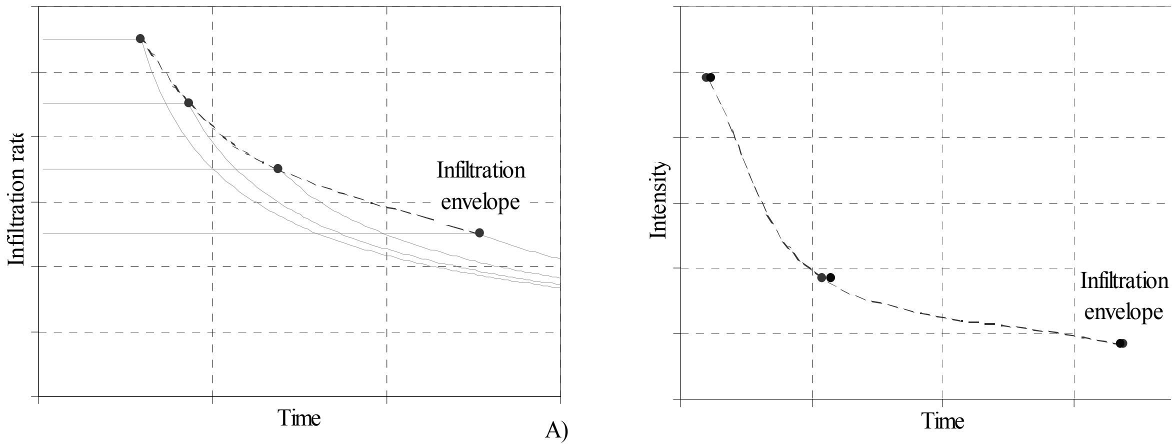


Fig. 5. Experimental results with fitted curve to the cumulative infiltration, I. Derived infiltration characteristics A and S are respectively 3.9 cm·hr^{-1} and 1.1 cm·t$^{-\frac{1}{2}}$.

A complication arises as the sorptivity S (and to a lesser extent A) is dependent on the antecedent moisture conditions. More elaborate equations like those of Richard and Green & Ampt (1911) only partially overcome this problem as they require additional information to estimate the suction at the wetting front in the soil. Because of its simplicity, Philip's solution remains a popular description of the infiltration process. Notwithstanding, many other solutions and embellishments exists. For a full review of the differences and similarities between the various solutions, one is referred to Kutílek & Nielsen (1994). All solutions identify infiltration characteristics or parameters that are related respectively to the diffusivity term and the gravitational component.

A variety of methods is used to determine the infiltration characteristics of a soil. These include head-controlled infiltration tests like ring infiltrometer tests and pemeameter tests as well as rainfall simulations (Hendrickx, 1990). A word of caution is needed on the use of these tests. Head-controlled tests measure the maximum infiltration rate under imposed boundary conditions. Such boundary conditions are often artificial and with the limited area tested a large number of samples is required to capture the variability in surface conditions. Even then, validity is not ensured as head-controlled tests with ring infiltrometers may miss the effects of surface crusting due to mechanical disturbance and slaking.

Rainfall simulations result in less disturbance and are more apt to simulate natural processes, such as runoff generation and sealing. Moreover, because of the larger area tested, they are capable of including surface heterogeneity. However, it must be realised that the rainfall intensity and drop impact lie outside the natural limits and that the infiltration characteristics are related to the rainfall intensity applied. Moreover, rainfall simulations lump the spatial variability in the infiltration over the

entire plot. Consequently, they yield an apparent infiltration that is scale-dependent and not an absolute quantity.
All in all, rainfall simulations are to be preferred although head-controlled tests may still be a valid means to determine the ultimate infiltration capacity of homogeneous and isotropic soil of sufficient depth. Likewise, shallow inverse auger tests (section 4.14) may be used. Double ring-infiltrometers should not be used to estimate the sorptivity for comparisons of head-controlled tests and rainfall simulations reveal that the values for the sorptivity differ substantially between the methods. It appears that head-controlled tests do not return realistic estimates of the sorptivity and are consequently of little use to estimate the generation of runoff.

Descriptions of the head-controlled double ring infiltrometer test and rainfall simulation tests are given below.

4.15a Rainfall simulation

Comment Many types of rainfall simulators of varying size are available but a broad distinction can be made between nozzle-type and drip-plate types. These are briefly introduced here. If simulators of another design are used, one should verify that the distribution of rainfall intensity and drop size over time and space is consistent and lies within natural limits.
As some soils are sensitive to dispersion or swelling when cat-ions are added, demineralised or rainwater must always be used .A chemical analyses of water used in the simulator should always be made and an indication of constant water purity can be obtained by measuring its conductivity during the tests.

Two proposed designs of the two types of rainfall simulators are:

1. The small nozzle-rainfall simulator as designed by Calvo (1990) that applies water to a circular plot at a single rainfall intensity;
2. The drip-plate (Amsterdam type simulator) as described by Bowyer-Bower and Burt (1989); figure 6.

Fig 6. Portable rainfall simulator of Amsterdam type. Ready for use in the Petralona hills, in N Greece. Soil surface is covered with plastic to prevent wetting of surface while setting up the simulator. The rainfall dripping plate is 100 x 50 cm in size. Below the plate a randomiser is attached.

Type (1) is amenable and can be used at many locations, either under different conditions or as replicate. Type (2) offers the possibility to apply different rainfall intensities in the range from 10-70 $mm \cdot hr^{-1}$. This allows the construction of the infiltration envelope from which the sorptivity and hydraulic conductivity of the topsoil can be determined by means of curve-fitting.

Because of the variability of the infiltration characteristics, a large number of replicates is needed for every vegetation or geomorphological unit. A number of three locations under similar conditions is the absolute minimum, if the results are to be more than anecdotal value. Moreover, duplication of the tests over time may be needed as the infiltration rates are highly dependent on soil moisture conditions and may vary with seasonal changes in vegetation cover. Although described here as a one-off measurement, infiltration characteristics will show a large seasonal variability and it is recommended that measurements be made at least at two moments in time: at the end of the dry season when the soil can be taken to be at wilting point and during the wet season when the soil is at field capacity.

Equipment Besides the rainfall simulator, a collector of the runoff is required for both types of rainfall simulator. This can consist of a gutter or through for rectangular surfaces or a ring with outlet for circular surfaces
Additional equipment that is needed are a wind shield, (demineralized) water for the experiment, small rain gauges for the determination of the rainfall intensity, receptacles of various sizes to collect the runoff and sediment, field scales (accurate to 0.1 g or 1.g dependent on plot size/runoff quantities), a graduated cylinder and a chronometer. Dyes may be used as tracer to monitor the penetration of the wetting front or to estimate the runoff velocity on the plot.

Method After selection of the plot, the collector for the runoff should be installed flush with the soil surface and adequately sealed to prevent any leakage into the underlying soil. A good seal can be obtained with water-based sealants (e.g. acrylate kit) that is sprayed or brushed onto the surface. This seal should be fully hardened before the experiment and it is recommended that plots are installed at least one day in advance. The collector should also be sloping to ensure the routing of the runoff and entrained sediment during the experiment. To avoid settlement during the experiment it can be fixed with quick-setting cement. The projected area of uniform rainfall should overlap the plot from which the runoff is collected. For the type (1) simulator described by Calvo, the plot area would be circular and 0.5 m in diameter. For the Amsterdam type (2), it would measure 30 by 50 cm. Vegetation should be removed before the test to prevent interception of the applied rainfall.
Before the simulation, the surface of the plot has to be described and a bulk sample taken in duplo for the gravimetrical soil moisture content. Additionally, samples of known volume can be taken to determine the bulk density and porosity that include the micro- and macro-structure of the soil. Valuable information may be obtained from the SWRC that can be determined for samples from the plot or for those of the geomorphological unit as entity. This is recommended when the bulk density is likely to change during the simulation (swelling soils, freshly tilled surfaces) or macro-pores exist. This should be done in the direct vicinity of the plot. In any case, this procedure should be repeated directly after the test on the plot itself to determine the moisture content and to obtain the necessary soil properties. Also, a trench should be dug along the longitudinal and transversal axis of the plot to expose the penetration of the wetting front along a quadrant of the soil. If multiple runs are done on the same surface, destructive sampling should be postponed till the last run and the penetration of the wetting front may be studied for the respective runs from smaller, less disturbing trenches along the perimeter of the plot.

The infiltration characteristics can be determined from either a single experiment at a constant intensity, i, or from the infiltration envelope constructed from multiple experiments at different, uniform intensities. In both cases, the intensity must exceed the infiltration capacity. Before the experiment, a uniform rainfall intensity should be chosen as far as possible in a range between 20 and 80 $mm \cdot hr^{-1}$. The intensity can be determined exactly after the experiment from the rain gauges. This uniform intensity must be maintained for the entire duration of the experiment. During the experiment, the time to ponding must be estimated. The moment of t_p is difficult to estimate since runoff may start from certain areas of the plot before the cover of stagnating water is complete. A conservative estimate would be to take the time of constant runoff rates but this can be erroneous. It will underestimate the time to ponding when the slope of the plot is high and highly permeable zones exist. It will overestimate t_p when the surface detention and roughness are high and the gradient of the plot low. It is recommended, therefore, that the following quantities are determined during the experiment when runoff can be generated:

- Rainfall intensity and duration;
- Time at which the following fractions of ponding are achieved: 5%, 10%, 15, 25%, 50%, and 75%;
- Time to runoff (≈ 100% ponding);
- Runoff rate.

The fractional areas of ponding need to be estimated by an experienced operator. The runoff rate can be measured as totals collected over discrete, constant time intervals. These intervals should be of sufficient length to obtain significant values, e.g. 2 minutes. It is to be preferred that the weights of the collected samples are measured directly in the field after which the samples can be discarded or kept if the sediment concentrations are high. The sediment concentrations can then be determined in the laboratory from the residue of the evaporated sample. The infiltration rate is consequently given by f= i-q (see above). This is the preferred method but, if no run off can be generated, an alternative may be to vary the rainfall intensity (if possible) to maintain the degree of ponding at t_p. This would require a constant lowering of the intensity due to the decaying nature of f. The moments of changes in the intensity are noted and the average infiltration rate is determined from the volume of water applied over the successive periods.

The duration of an experiment will depend on the infiltration capacity of the soil and the applied rainfall intensity. The purpose is to obtain a constant runoff rate which must be maintained for a certain period of time. Even when this rate is achieved, every experiment should be maintained for a minimum total duration of 30 minutes.

Calculation For t> t_p, the sorptivity can be determined form the plot of the cumulative infiltration F vs. √t. The gravitational component, A, can then be calculated from the rate of infiltration during the later stages of infiltration.
The infiltration envelope can also be plotted and the values of A and S fitted to it trough the following formula, derived by Kutílek (1980) from Philip's solution

$$t_p = \left(\frac{S}{A}\right)^2 \frac{2i_r - 1}{4i_r(i_r - 1)^2}$$

Where i_r= i/A.

Because the infiltration rate is relatively insensitive to A over the periods considered in rainfall simulations it should be preferred to calculate A and S individually for each rainfall simulation. Equation can then be used to check the theoretical time to ponding for the mean values of S and A with the observed times.

Reporting The following results of rainfall simulation tests should be presented.

- Time of year and site description, including slope angle, present and antecedent weather conditions, vegetation cover and a statement whether the plot has been stripped of vegetation prior to the test or not;
- Initial and final volumetric moisture content, porosity and bulk density;
- Rainfall intensity and duration (total volumes of water used can be included as cross-validation);
- A qualitative description of the process of infiltration and patterns of runoff during the test;
- A qualitative description and image (graph/photograph) of the wetting front;
- Plots of the infiltration and runoff, both as rate and as total;
- Plots of the cumulative infiltration vs. √t;
- Explanation of the method used to calculate A and S with results.

<u>4.15b Double ring infiltrometer</u>

Comment The double ring infiltrometer consists of two concentric rings which are driven carefully into the soil to avoid disturbance. Both are flooded and a negligible positive head is maintained during the tests from a constant supply vessel. The outer ring is used only as a buffer to alleviate boundary effects between the wetting front and the soil. Of the inner ring, the volume of water supplied by the vessel is recorded at regular intervals throughout the test. This gives the cumulative infiltration, F, or broken down over time increments, the infiltration rate, f.
Although the results of the infiltrometer ring can be described by Philip's solution, the flooded conditions are not representative for natural conditions and the results should be treated with caution (see above). Notwithstanding, the results can yield information on the saturated hydraulic conductivity.
A derived method from the ring infiltrometer test is the constant supply test to determine the saturated hydraulic conductivity of crusted surfaces. In this test, a constant supply over time of intensity i is maintained and the resulting wetted area recorded. For the actual procedure and the associated equations one is referred to Boiffin & Monnier (1985). No ring is needed and no head is applied which removes some of the constraints on the validity of ring infiltrometer test.

Equipment Ring infiltrometer consisting of outer and inner ring, two supply vessels, of which one graded.

Method Before the test, a site description must be made as mentioned under 4.15a.
The inner ring is carefully driven a few centimeters into the soil, after which the outer ring is inserted in like manner. The outer ring is filled with water from the supply vessel until the surface between the outer and inner ring is completely flooded. Then, the inner ring is flooded from the graded supply vessel. Likewise, the head in the inner ring must be as small as possible but high enough to ensure complete ponding. From the moment of ponding, t= 0, the outflow from the supply vessel is recorded at frequent intervals (30 s). The test is continued until the infiltration rate achieves a constant rate and sampling intervals may be increased in the later stages of the test. The test should last for at least 30 minutes.

Calculation and Reporting The infiltration capacity obtained from a double ring infiltrometer test is a maximum close to the saturated hydraulic conductivity. It can be calculated from Philip's solution as described above.

From the test, the infiltration, both as rate and total with time, should be reported. Also, a site description as described under 4.X should be included. The wetting front may be excavated and sampled for a qualitative description.

4.16 Atterberg limits / plasticity index [-; %] @1,2,7

Comments The Atterberg limits are indicative for the consistency of a soil. They delimit several states of consistency that occur as gradually more water becomes interspersed between the soil particles. The Atterberg limits are the linear shrinkage, LS, the plastic limit, PL, and the liquid limit, LL, which are expressed as gravimetric moisture contents. They form respectively the upper limits at which the soil behaves as a solid, a semi-solid, or a plastic material. Below the liquid limit, the soil behaves as a liquid as the water films around the soil particles become too large to allow for any attraction between them. The difference between the liquid limit and the plastic limit is known as the plasticity index, PI. This is the range over which the material would experience irrecoverable or plastic deformation under an imposed load. The difference between the the ambient gravimetric moisture content and the plastic limit is used to calculate the liquidity index, LI, which is expressed as a percentage of the plasticity index. The liquidity index gives the distance that separates the soil from its liquid state, in which case it loses its strength entirely.

<u>4.16a Plastic limit</u>

Equipment Glass plate (500x500mm), spatula, demineralised water, 425 micron sieve, 3 mm diameter rod, sample, moisture content tins, riffle box, mass balance (accurate to 0.01 g) resolution)

Method (BS 1377) Prepare a homogeneous and representative sample by passing the material through the riffle box or by quartering. Dry the sample in the oven at 105°C and pass it through the 425 micron mesh by means of dry-sieving. A total sample of 500 g dry mass is required to determine the Atterberg limits.
Take 20 g of sample, add some demineralised water and mix thoroughly for 10 minutes to form a plastic material. Mould it into a ball and roll this gently between the palms of the hands until small drying cracks appear. Halve the sample and divide the two parts into four quarters. This gives a total of 8 pieces, but keep each group of four together Take one of the pieces and store the others temporarily under a cover, e.g. an overturned moisture tin, to avoid evaporation.
Gently take the lump between the fingers and roll it to a thread of 6 mm in diameter. Place it on the clean and smooth surface of the glass plate and roll it with the fingers of one hand under a gentle and even pressure over the glass plate. Continue until the thinning thread crumbles at a diameter of 3 mm exactly (use the rod as reference). If the thread crumbles before this diameter is reached, then reform the 8 parts into a new ball, add a small quantity of water (only a few drops!) and repeat the procedure by rolling the sample into a thread. If the diameter of the thread becomes less than 3 mm, regroup the sample, knead lightly to remove the excess water and start over again. The procedure should be repeated until the thread crumbles at 3 mm exactly. Crumbling means that shearing over the width and length of the thread due to a decreasing moisture content only. Cracking due to uneven deformation does not count.
All 8 pieces should be tested in this manner and the procedure repeated if any part does not comply with the 3 mm specified. Store the threads under a cover to prevent evaporation.
Once a satisfactory thread has been formed from the individual parts, the four quarters of each sub-sample are placed in a numbered moisture tin and weighed immediately. The moist weight, mW, of both tins is noted. Subsequently, place the tins in the oven at 105°C for 24 hours and determine the dry weight, dW, as well as the mass of the dry, clean moisture tins, tW, once emptied. Calculate for both samples the gravimetric moisture content, (mW-dW)/(dW-tW) (section 4.4). If the values differ by more than 0.005 (-) or 0.5%, the results should be discarded and the test repeated. If the difference is 0.005 or less, the average of the two values should be taken and reported as the plastic limit.

4.16b Liquid limit (BS 1377)

Equipment Glass plate (500x500 mm), spatula, demineralised water, sample, moisture content tins, cone penetrometer with standard cone (80 g), brass sample cup (55 mm diameter, 40 mm deep), stopwatch

Method Take about 300 g of the prepared sample and mix this with demineralised water on the glass plate in order to obtain a homogeneous paste, just wet of the plastic limit. For clayey materials, leave this paste overnight in an airtight container to allow full permeation. Remix thoroughly, if left overnight, and paste the sample into the sample cup without entrapping any air or compaction. Smooth the surface. Place the cup in the cone penetrometer and lower the cone until it just touches the surface. Zero the dial gage and release the cone for 5 seconds. Read the dial gage. If the penetration is less than 15 mm, remove the sample from the cup, add a small amount of water and repeat the procedure until a penetration of 15 mm or more is achieved. Clean the cone between penetrations.
If the penetration exceeds 25 mm, remove the sample and add some dry soil. If a penetration between 15 and 25 mm is achieved, refill the impression of the cone with some of the paste without entrapping air. Re-position the cone, zero the dial gage and release the cone again for 5 seconds. Read the dial gage. If the measurements differ by more than 1.0 mm, empty the moisture tin and the sample cup and start once more by mixing the sample and filling the sample cup.
If the measurements differ by 0.5 mm but less than 1.0 mm, repeat the test by removing some material and refilling the hole. If the three consecutive readings differ by less than 1.0 mm, the test is successful.
If the second reading differs by less than 0.5 mm from the first penetration, the third penetration is not required.
Note the average penetration and scoop some material (approx. 10 g) from the sample cup into a numbered moisture tin. Weigh this immediately and place it in the oven.
The test is repeated at different moisture contents until at least three sets of penetration and moisture content are obtained within the range from 15 to 25 mm. Only add small amounts of water each time.

The gravimetric moisture contents are determined by drying the samples at 105°C for 24 hours. The gravimetric moisture contents are plotted against the mean penetration. A best fit of a straight line to the data should be drawn. By definition, the liquid limit is then the gravimetric moisture content at 20 mm penetration.

Remark An alternative method to determine the liquid limit is by means of the Cassagrande apparatus. The results of this method are, however, less reproducible and the outcome is even more affected by the skill of the operator than the cone penetrometer. For this reason, the determination of the liquid limit by means of the cone penetrometer should be preferred.

4.16c Linear shrinkage (BS 1377)

Equipment Glass plate, spatula, demineralised water, sample, circular linear shrinkage mould, mould oil, vernier callipers

Method A mass of 150 g prepared sample is required. Lubricate the mould with the oil and wipe off any excess. Mix the sample with demineralised water to a homogeneous paste just dry of the liquid limit. Fill the mould with the paste without entrapping any air and level the surface. Place the mould in an oven at 105°C for at least 24 hours. Remove the sample from the oven and allow it to cool in a desiccator. The shrunken length of the sample, DL, is determined by taking the average of two or three measurements. If the sample is broken, the parts are fitted together before measurement. The linear shrinkage is then calculated as 1-DL/L, where L is the total length of the mould. This is identical to the moisture content at which the soil particles are in full contact and the material can be considered as a solid.

Calculation The plasticity index, PI, is simply the difference between the liquid limit and the plastic limit, PI= LL-PL. Together with the LL, the plasticity index can be used to classify fine-grained soils (Casagrande, 1949; BS 5930).
The liquidity index, LI, is given by LI= (W-PL)/(LL-PL), which is 100% if the soil is at its liquid limit for its natural moisture content, W. The material can then be expected to behave as a liquid. It becomes zero when W equals the plastic limit and the material is then in a semi-solid state.
An additional measure is the activity index, AI. This is the plasticity index divided by the proportion of the fraction smaller or equal to 2 micron. This gives an indication for the clay mineralogy as active clays like smectites can have a higher activity at lower clay content (Skempton, 1953).

Reporting All values are reported as whole percents or in hundredths. Only when the values are lower than 10% or 0.10, a third decimal is reported. Also, the fraction by weight of the soil passing the 425 micron sieve is reported.

4.17 Effective shear strength & Root strength @1,2,7

Root reinforcement is only apparent when soil samples are tested both with and without roots. The following gives a brief description of the commonly used direct shear test.

4.17a Effective shear strength without root reinforcement

Comment The conventional direct shear test is a relatively simple method to determine the shear strength of a soil. It can be performed in a drained or undrained and consolidated or unconsolidated fashion. For natural slopes, the consolidated-drained (CD) test is the most appropriate as it determines the maximum available shear strength of the soil that governs the long-term stability of the slope (effective stress). The test is usually performed in the laboratory on sample sizes ranging from several tens to hundreds of square centimeters. Here, the laboratory procedure is described. However, because of its simple design, a field version of the direct shear apparatus can be used to test larger and more representative samples.

Direct shear tests can be performed on unsaturated soil samples at the ambient moisture content and on fully saturated samples. In the former case, negative pore pressures (matric suction) and cementation or organic bonds can contribute to the shear strength. This contribution will be present in

the results as an apparent cohesion. Under fully saturated conditions, their influence is much reduced and the results can be taken to represent the long-term shear strength. Thus, tests should be performed on saturated samples unless there is evidence that failure occurs under unsaturated conditions as well.
For the determination of the shear strength, the resistance of the soil against shearing is mobilised under a constant rate of strain (strain-controlled test).
Equipment Direct shear apparatus and shear box

Method This is a general description of the test. For detailed information, refer to the manual of the direct shear apparatus or to more elaborate test descriptions in Head (1983) or Vickers (1986).

The direct shear box consists of two halves, placed on top of each other, that before the test are held together by screws. Within this shear box, a soil sample can be placed that extends below the seam between the two halves. On this sample, a constant vertical load is placed, usually by means of a dead-weight. This load acts normal to the horizontal division between the two halves of the box. Along this division, the lower half can be displaced at a constant strain rate once the fixing screws are removed. Thus, an artificial slip plane is created along which the sample is sheared. Under the influence of the imposed normal load, a resistance will develop that is measured as a reaction force (shear force). The mobilised shear force increases with the deformation until a maximum is reached at which the material is no longer capable to sustain the deformation and the sample will fail. The maximum can be determined from a stress-strain plot. The maximum of mobilised shear strength defines the shear strength of the soil. By expressing both the normal load as the shear force as stresses, the mobilised resistance becomes independent of the scale of the sample. The shear resistance is then expressed as the shear strength that describes the Mohr-Coulomb failure criterion by means of the cohesion, c, and the friction angle, ϕ, i.e. $\tau_f = c + \sigma \tan\phi$, where σ and τ_f are respectively the normal stress and the mobilised shear stress at failure. For effective strength, these parameters are primed by convention, i.e. c' and ϕ'.

In the case of a cohesive soil, the sample is cut from an undisturbed block sample with a sample former. Such samples will be relatively undisturbed and can be considered to represent the actual strength on the sample scale
For granular materials, the sample must be reconstituted directly in the direct shear box and the strength will be representative for the frictional strength at the degree of compaction achieved. Direct shear tests on remoulded and reconstituted samples of clayey material are only indicative for the strength of the soil. It should be reported whether the direct shear test has been performed on disturbed or undisturbed samples.

Undisturbed samples for direct shear tests are usually saturated in advance. When the material is loaded, either by the placement of the normal load or shearing, part of the applied force will be imposed on the pore water. The resulting excess pore pressures are detrimental for the mobilisation of the frictional strength. To avoid this, the sample must be consolidated prior to the test and the strain rate kept low enough, i.e. below the saturated hydraulic conductivity. To facilitate drainage, porous stones and perforated retention plates are used on either side of the sample to provide easy pathways for the excess water.
The gap width between the shear box halves should be large enough to allow the movement of particles over each other without spilling the sample. A width of at least 2 times the mean particle diameter is a reasonable estimate for uniform to well-graded soils. The sample dimensions should be at least six times the diameter of the largest particles present to avoid unrealistic shear strengths due to boundary effects. This restricts the use of normal shear boxes to particles < 2mm.

Calculation & reporting For the determination of the cohesion and friction angle, several tests at different normal loads are required. By plotting the mobilised shear stress against the normal stress, the Mohr's envelope can be constructed, either graphically or by a least-squares linear fit. Its slope is the tangent of the friction angle, $\tan\phi$, and its intercept is the cohesion. At least three points are needed to construct the envelope but, given the variability in shear strength, it is recommended that at least 10 points, i.e. two samples at 5 normal loads, are available for each soil layer to characterise the shear strength without root reinforcement.

In addition, the dilatancy of the material could be provided with the stress-strain plots.

Remarks Multi-stage tests, in which the normal stress is increased near the point of failure and the test continued after consolidation, are allowable in the case of material shortage under the following conditions. The sample size should at least be 100 x 100 mm, the cumulative strain should not exceed the 20% of the sample length and the final normal stress should be duplicated in a single-stage test. Thus, the number of samples can be decreased to a minimum of 6 (Table 6). A total of 12 tests is performed on 6 samples. It is decided to reproduce the central normal load and the lower normal load three instead of two times. For least squares, the central load gives a good estimate of the error in the friction angle whilst the error of the lowest load is more representative for the cohesion, which represents the largest error term of the regression equation.

Table 6: Minimum sample number to obtain duplicated test results from multi-stage direct shear tests

σ-increment	1	2	3	4	5
Sample 1	■		■		■
Sample 2	■	■		■	
Sample 3	■	■	■		
Sample 4			■		
Sample 5				■	
Sample 6					■
Number of tests	3	2	3	2	2

Multi-stage tests tend to underestimate the maximum shear strength that can be mobilised and can therefore be deemed as conservative estimates. However, because of the confinement of the sample and the imposed artificial shear plane, single-stage tend to overestimate the true angle of internal friction, as determined by triaxial tests (see for a description section 4.17) by 2° approximately (Lambe & Whitman, 1979). Although opposite in sign, the resulting errors will not cancel each other out entirely and the shear strength determined may be biased on either side of the “true” value. It is recommended therefore to use a limited number of triaxial tests to verify the shear strength without root reinforcement from the direct shear tests. From the triaxial test, the Mohr’s circles (see below) can be plotted. The normal and shear stress at failure can be calculated with the c’ and ϕ’ of the direct shear tests. The test results should be re-evaluated when the failure points from the triaxial test plot outside the Mohr-Coulomb envelope by a given significance level (e.g. α= 0.05 or 0.10 two-tailed). Three triaxial tests would suffice and these tests will also serve to determine the elastic properties of the soil that are needed for numerical stability modelling (section 4.17). Although triaxial tests would be the preferred method to determine the shear strength, they are more time-consuming than direct shear tests and sample preparation may be difficult. Moreover, as the mobilised shear strength is representative for the weakest zones of the sample, the triaxial test may underestimate the root reinforcement of the soil on the field scale if roots are present. In the direct shear test, roots are usually sheared perpendicularly and the mobilised shear strength can be taken to represent the maximum of the available root strength as aggregated on the sample scale. Thus, the reinforcement of the soil by roots can be determined by shearing soil samples with and without roots. For this, direct shear tests are the most appropriate, both in the field and the laboratory.

<u>4.17b Root reinforcement</u>

Comment Roots contribute to the shear strength of the soil by their intrinsic tensile strength and the resistance against pull-out along the soil-root interface. In its simplest form, this contribution can be represented as an additional cohesion term, Δc’.

The contribution of roots can also be determined by direct shear tests. This is a maximum value as the displacement will be perpendicular to the roots for a horizontal sample and the deformation consequently the largest. However, in the laboratory, the length over which the roots are embedded in the soil is not necessarily representative for the true reinforcement as it is likely that the roots are truncated at the lower and upper end of the sample. In-situ tests might be more representative as they do not alter the depth by which roots extend below the shear plane. Moreover, by testing larger samples in the field, it is obvious that a larger, more representative part of the root system is tested.

Therefore, direct shear tests in the laboratory should only be used to characterise the contribution of the smaller root systems.
In-situ tests can be used to determine the shearing resistance of a shallow root system over a larger sample volume (150 x 150 mm) or to determine the contribution of a single larger root (tap root). Currently, no normal stress can be applied and root reinforcement can only be determined as the additional cohesion term $\Delta c'$.

Equipment & procedure see section 4.16a. A detailed description of the in-situ direct shear test is given in section 5.9.

Note in-situ tests will be carried out by the team of Nottingham Trent University. Facilities for direct shear tests are available at Utrecht University and (presumably) at NTU. Geotechnical consultancy firms will provide direct shear tests and triaxial tests on a commercial basis.

4.18 Soil elastic properties @1,2,7

Comment The elastic behaviour of the soil must be characterised for numerical modelling of geomechanics. Whereas static slope stability assessments rely on the limiting-equilibrium concept from the theory of plasticity to simulate failure, numerical FE and FD models simulate the interactions between stress and strain dynamically. In order to convert strain into stress and vice versa, the elastic behaviour of the soil is used. When applied over short periods and distances, this will result in reasonable estimates of the deformation.
Young's modulus, E [kPa, MPa], and Poisson's ratio, ν [-], describe the elastic behaviour of solids. Young's modulus is the ratio of the imposed stress, σ, [kPa] over the recoverable linear strain, ε ($\Delta L/L$),

$$E = \frac{\sigma}{\varepsilon}.$$

By definition, compression is taken as positive.

Poisson's ratio is needed to calculate the volumetric strain that is associated with the shortening or extension of a sample. It is defined as the ratio between the strain in any direction perpendicular to that of ε and this value. For cylindrical samples of homogeneous soils, ν is defined with respect to the radial strain, ε_r,

$$\nu = -\frac{\varepsilon_r}{\varepsilon}.$$

The minus sign is introduced as the sample will expand laterally under compression. Poisson's ratio varies between 0.5 for undrained conditions for a saturated soil to 0.1-0.4 for drained conditions.
For the calculation of the elastic properties, the linear strain and the applied stress should be known. For this, the triaxial test is the most suitable as the applied stresses are principal stresses (i.e. working on planes experiencing only true deformation). The elastic properties should be determined under drained conditions and for saturated samples, the change in volume can be established from the drained pore water.

Derived elastic properties are the shear modulus, G, and the bulk modulus, K [both in units of stress]. The first describes the shear strain on planes where the normal stress is zero, the second relates the volumetric strain to the average stress condition. They are respectively defined as

$$G = \frac{E}{2(1+\nu)},$$

and,

$$K = \frac{E}{3(1-2\nu)}.$$

The shear modulus is independent of the drainage conditions and can, if necessary, be estimated from direct shear tests as the ratio of the shear stress over the shear strain for the initial straight section of the stress-strain graph.

Equipment Triaxial apparatus

Method This description provides only an outline of the consolidated drained triaxial test as the test is fairly complex and the equipment is not widely available.
In the triaxial test, a cylindrical sample is placed in a triaxial cell. The sample should at least be twice as high as the diameter. The sample is protected by a rubber membrane that seals it from the water that surrounds it in the cell. This water is pressurised to provide an all-round confining pressure σ_3, which is the minor principle stress. At the top and bottom, the sample is covered by porous disks to facilitate drainage. To shorten the drainage paths, a filter paper mesh is usually placed on the outside of the sample. To evacuate water, the base and top, formed by a cap, are fitted with tubes. By means of these tubes water can also be driven through the sample in order to achieve full saturation. On the top of the sample, a spindle is placed that can move freely in the vertical. The spindle is linked to a gear box that provides a constant strain-rate. Between the spindle and the sample, a gauge is present that measures the axial stress that is present. This axial stress is the deviator stress $\Delta\sigma$ and added to σ_3, it gives the value of the major principal stress σ_1.
Prior to the test, the sample is saturated and consolidated at a constant confining pressure (σ_3). Once saturation and consolidation are complete, the sample is loaded at a constant strain rate that ensures drained conditions throughout the test. The axial shortening of the sample and the mobilised deviator stress are recorded at 0.2 mm intervals whilst the confining pressure is kept constant. In addition to the axial strain and the deviator stress, the volume change, as measured by the drained pore water, is recorded as well.
The test is continued until the sample fails. Alternatively, the sample may be unloaded at an arbitrary point of the test. In the latter case, the sample can be subjected to a number of loading and unloading cycles although, as a rule of thumb, the total axial strain should not exceed the 10%. For common sample heights of 75 and 140 mm respectively, this means a range of 8 and 14 mm respectively over which the sample can be loaded and unloaded.

Calculation The elastic or Young's modulus is defined as the slope for the linear section of the stress-strain graph of pure deformation. E is thus calculated as the ratio of the increment in the major principal stress σ_1 over the resulting axial strain. This can be done for either the section over which the stress-strain curve is more or less straight or for the pressure of interest if known. A more or less objective method to calculate Young's modulus is the secant method which uses the strain and stress difference between the origin of the stress-strain curve and the point located at one-third of the major principal stress at failure.
Under cyclic loading, the axial strain will exhibit hysteresis as the sample will experience some irrecoverable plastic deformation. In that case, the slope of the reloading stage, between its lowest point and that where it rejoins the original stress-strain curve, can be considered as indicative for Young's modulus. Generally,

$$E = \frac{\Delta\sigma_1}{\varepsilon_a} = \frac{\Delta\sigma_1 \cdot L}{\Delta L},$$

Where L is the original length of the sample, ΔL is the change in sample length, ε_a is the axial strain and $\Delta\sigma_1$ the increment in the major principle stress.

For the determination of Poisson's ratio it is essential to know the volume change, ΔV, for the range over which Young's modulus has been determined. Therefore, the volume change should be recorded at a high resolution. From the volume change, the radial strain can be calculated if the volumetric and axial strain are known

$$\varepsilon_v = \varepsilon_a + 2 \cdot \varepsilon_r .$$

Where ε_v is the volumetric strain, $\Delta V/V$, V being the original sample volume .

This assumes that the deformed soil can be described as an ideal cylinder. This holds for brittle soils but not for ductile soils that will barrel. However, the error that is introduced is negligible over the range that the soil deformation is purely elastic. Substituting the equation for $\nu = -\varepsilon_r/\varepsilon_a$, Poisson's ratio is then simply calculated from

$$\nu = \frac{1}{2} \cdot \left(1 - \frac{\varepsilon_v}{\varepsilon_a}\right).$$

The elastic behaviour of a soil sample in the triaxial apparatus may be different from that of the soil in the field when the soil is heterogeneous or anisotropic. Field tests such as pressure meters and plate bearing tests could be used as an alternative, if desired.

4.19 Groundwater monitoring @@

General Pore pressures have potentially a large influence on slope stability. Groundwater measurements are therefore essential for the calibration and validation of slope stability models.

4.19a Open (stand pipe) piezometer

Comment This is the simplest type, consisting of a filter and access tube that are installed in a borehole at a known depth. The filter is placed in a body of fine sand or gravel to provide easy access for groundwater to the pipe. In contrast, the borehole is sealed with bentonite to form an impervious boundary for surface water along the entire or partial length of the access tube. Where no bentonite is used, backfilled original material is placed between the tube and the wall of the borehole. The groundwater level in the pipe can be checked manually or recorded automatically by means of a pressure transducer and data logger. The method is cheap and flexible. Different lengths can be used and installed with relative ease by means of a hand auger. The disadvantage of the method is that it measures head which must be translated to pore pressures which is not straightforward in the case of (semi-)confined or perched water tables. The direct connection between water in the pore space and in the tube also makes the response of the system slow. This can be partly resolved by reducing the volume of the stand pipe but even then the response of an open stand pipe piezometer in material of low permeability will be seriously attenuated.

4.19b Closed (Cassagrande type) piezometer

Comment Closed type piezometers are more expensive than open piezometers but overcome some of the inherent problems of the latter. They can be driven into the soil and thus are in direct contact with the original material Moreover, there is no direct contact between the water in the soil and in the piezometer and thus pore pressures rather than head are measured. In the past, the pressure was measured by a manometer but nowadays pressure transducers are standard. The volume of water in the piezometer is very small which makes their response nearly instantaneous. Because of these advantages, closed type piezometers are in principle ideal for geotechnical investigations. The reason, however, why their use is still limited in the research of natural slopes can be explained by the higher costs. When substrate conditions are poorly known, it may be advantageous to invest in a larger number of observations along the slope and at different depths., in which case the costs of closed type piezometers becomes prohibitive. Most natural slopes are also free-draining, which reduces the difference between the head as measured by a open standpipe piezometer and the pore pressure experienced in the soil. For this reason, closed type piezometers are predominantly used on artificial slopes and embankments where especially during construction the pore pressure conditions may be excessive due to the imposed loads.

5. DETAILED CHARACTERISATION OF VEGETATION

5.1 Percentage cover of vegetation and height [$m^2 \cdot m^{-2}$]; [m] @

Comments Information on cover and canopy height will be recorded periodically throughout the field period. This information is needed to relate transpiration rates to growth and to water depletion patterns in the soil. It is of ecological interest in relation to seasonal differences in the soil water-temperature regimes. The canopy also intercepts rainfall which affects the net input into the soil.

The observations concerning the cover and height of the vegetation are to be carried for each of the measurement areas (section 2.2).

The proposed procedure for the determination of the vegetation cover is a modification of the Braun-Blanquet method (Braun-Blanquet, 1952 & 1961; Van der Maarel. 1980). It is proposed that the characterisation is made on the basis of the dominant species. For generalisation purposes, these species may be grouped according to the functional types, listed below.

Equipment Square grid 1 x 1 m with 0.05 x 0.05 m spacing wires

Procedure Record at monthly intervals cover and average height of the dominant species for the two sub-areas for non-destructive vegetation sampling. Over the 5x5 m, position the grid within the 1 squared meter and record the species with the estimated or observed frequency. Where a square sample area is not possible (e.g. dense forests), sample the vegetation along transects with a similar area or larger, depending on the variability (see Section 3).
For each plant, note its species name, abundance and average height. It is worthwhile to create a repository of the species that are encountered on the site. The observations can be used to group the vegetation in functional types. To this end, record those units that approximately 10% of the cover or more and note the species contributing the highest cover values in each functional type.
In the destructive vegetation sampling quadrants, the cover should be estimated at the start of the work, before any other destructive measurement will be carried out or litter traps or bags are put into position.

<u>5.1a Classification of functional types</u>

For the characterisation of the vegetation, a classification of fifteen (15) functional types is used

1. Winter-annuals
2. Drought deciduous perennial grasses
3. Winter deciduous perennial grasses
4. Drought deciduous herbaceous perennial
5. Winter deciduous herbaceous perennial
6. Drought deciduous shrubs < 50 cm in height
7. Winter deciduous shrubs < 50 cm in height
8. Evergreen shrubs < 50 cm in height
9. Drought deciduous shrubs 50 - 200 cm in height
10. Winter deciduous shrubs 50 - 200 cm in height
11. Evergreen shrubs 50 - 200 cm in height
12. Drought deciduous trees and shrubs > 200 cm in height
13. Winter deciduous trees and shrubs > 200 cm in height
14. Evergreen broad leaved trees and shrubs >200 cm in height
15. Coniferous trees and shrubs >200 cm in height

For cultivated fields, additional categories may be added if the crops can not be accommodated by this classification. A note should be made on the record sheet, of any list that is not complete.

<u>5.1b Cover estimation</u>
In each quadrant, the cover should be estimated for each 5x5 cm or 10x10 cm grid cell.

The classification can be based on cover abundance scales (e.g. the Domin scale). Especially when the smaller 5 cm x 5 cm grid size is used, the following categories provide a rapid assessment of the vegetation cover: Calculate an average value for each quadrant from the grid estimates.

Estimates of vegetation cover per grid square
0%;
Around 25%
Around 50%
Around 75%
100%

The area without vegetation is either bare or covered by litter. On this basis, a further distinction can be made in the following classes of which the percentage cover should be estimated per quadrant

- Bare soil: no cover of dead or living vegetation or canopy and hence fully exposed to the sky;
- No litter present but sheltered by overhanging canopy
- Litter covered without canopy
- Litter covered with canopy.

Litter is defined here as all dead plant material that is detached from the plant's stem.

5.1c Height estimation

When estimating cover, record the heights of the canopies of the functional types and the vegetation in its entirety per quadrant. For trees, the procedure is described separately in section 5.8b For the other functional types within the quadrant, the height should be rounded to the nearest 0.5 cm.
Where the canopy is open and the upper surface undefined, choose an arbitrary position as the top of the canopy and use this position throughout the measurement period.

5.2 Tree location and dimensions @

Comment When trees are present on a site, it is important to map the position of all trees. Also the measure tree height, projected canopy area and diameter at breast height (DBH) must be measured. In the case of coppiced trees, the stump position, maximum height and diameter of the newly re-sprouted crown, should also be measured. It is vital to obtain information about the stand history (tree age, planting regime, year of coppicing *et cetera*).

The tree dimensions are needed to calculate certain vegetation characteristics like the LAI, either directly or indirectly. In the latter case, empirical relationships between the desired, difficult-to-measure parameters and the tree dimensions are used. Generally, the tree dimensions are easier to measure in the field and can be used as proxy. The three dimensions that are the most needed are the diameter, the height of the vegetation and the projected canopy area.
It is suggested that all three variables are determined if any of them is needed for a particular reason (e.g. for tree winching). From these data, a relationship might be found between these variables and other parameters of interest. Per measurement area, the variables should also be determined for a substantial and representative fraction of the trees present. Per species, a minimum of 15 or all trees should be measured.

Equipment Tachymeter or GPS, measuring tapes (2), Abney level or Vertex instrument, ranging staff, 4 pegs and poles, rope

Procedure Map tree locations using either a tachymeter or a high resolution GPS system. X, Y, and Z-co-ordinates of each tree should be recorded.
Measure the circumference of the tree (DBH, [m]) at breast height (1.5 m). If the shape of the tree trunk is very irregular, measure three times, at 1.5 m and at a small distance above and below this height, and average.

Measure tree height as the vertical distance from the bottom of the stem to the top of the canopy. This can be done with an ipsometer or tachymeter. The simplest method uses the tangent of the angle between the horizontal and the sighting line and the distance to calculate the height. To this end, the observer positions himself at a location wherefrom the crown and the base of the tree are visible. Ideally, the vertical angle, α, between the observer and the tree should be kept at 45°. In no case should it be lower than 30° or higher than 60° as the resulting error will be large (over 5% at ±1° accuracy). An assistant positions himself with the ranging staff at the base of the tree with the ranging staff whilst holding the measuring tape between himself and the observer. At the line of sight of the observer, the horizontal distance, x, to the tree is measured, as well as the difference in elevation from the ranging staff, z_0. Subsequently, the vertical angle to the top of the canopy, α, is measured by the observer.
Estimate the projected canopy area. Position one of the pegs at a known distance, L, from the heart of the tree in the prevalent wind direction. The length L is arbitrary but should be sufficiently large, say 5 m. Position the second peg at a horizontal distance 2L from the first in a line straight through the tree (or just beside it). Fix the two measuring tapes at the two pegs and mark a distance of x= ½·√2·L on each of them (if L= 5 m, x= 3.5 m). Position the third peg at the point in the horizontal plane where the two measuring tapes intersect at the marked distance. Repeat on the other side, which should result in a square area (Check the diagonals 2L).
Position the poles at the outer point of the canopy along the lines through the two opposing pegs. Measure the horizontal distance between the opposing poles as the diameter of the canopy.

Calculation Calculate the diameter (= circumference/π). The height of the tree, h, can be calculated from

$$h = z_0 + x \tan\alpha \, .$$

For the projected canopy area, average the two diameters measured (D). Calculate the projected area of the canopy as A= $\frac{1}{4}\pi D^2$. Also calculate the ratio of D1, the diameter parallel to the prevalent wind direction, and D2.

Reporting Report the coordinates of the tree to the nearest 0.1 m. The location of the trees may be shown in the detailed field mapping (1:250). If it is not feasible to represent all trees on this scale, tree densities may be used per stand or otherwise delineated units.
Report per stand of trees the age of the trees, the vitality and land use history. Also include a description of the characteristic tree shape when this is different from the natural form (e.g. in case of coppicing).
Report per tree the diameter at breast height to the nearest 0.01 m. The number of trees and the average and standard deviation of the DBH should be listed per stand with the same precision.
Report the height of each tree to the nearest 0.1 m. Also list the average and standard deviation per stand.
Report the projected area to the nearest 0.01 m^2 and also list the totals of the surface area and the projected areas over the entire stand to the nearest 1 m^2. Report the ratio between D1 and D2 per tree and its mean and standard deviations in two decimal units (0.01 [-]).

Remark If a more detailed description of the projected canopy is desired, it can be mapped using the reference grid of the pegs and the pole + measuring tapes. Depending on preference, grid distances or pole coordinates can be calculated. The first has the advantage that the canopy could be mapped to scale directly in the field on graph paper.

5.3 LAI (leaf area index) [$m^2 \cdot m^{-2}$] and shoot & leaf arrangement @

General The LAI is the area of the leaf surface over the projected ground surface of the canopy. It is needed to describe plant-atmosphere relationships like carbon-uptake, interception and evapotranspiration. The LAI can be determined directly from the specific leaf area and indirectly from radiation measurements below and above the canopy.
For the first method, the specific leaf area should be determined on fresh leaves, within 24 hours of collection. As the specific leaf area might change over time, it should be determined every time plant

material is collected for biomass determination (section 5.4). Because of the temporal changes in biomass and LAI, both should be determined for each season. This method yields exact measurements of the leaf area but suffers from two drawbacks. First, the measurements of the specific leaf area have to be extrapolated to obtain a measure of the LAI of a plant or stand. Second, the method is destructive and labour-intensive. Consequently, it is mostly suitable on a limited scale as reference method for the indirect determination of the LAI from radiation measurements.
The indirect measurement of the LAI uses optical devices (photo-sensitive cells etc.) to capture the incoming radiation below the canopy. Such techniques use relationships like the Beer-Lambert law to estimate the LAI from measurements of incoming global radiation (LI-COR, 1990). To calculate the interception of the radiation by the canopy, incoming radiation is measured at locations under the canopy compared to measurements above the canopy. The following description is based on the LI-COR LAI 2000 device which allows for a rapid assessment of canopy structure and is available at the University of Amsterdam (LI-COR, 1990, Welles & Norrman, 1991). However, other methods and devices may be equally suitable if the sampling method is designed to restrict the influence of the underlying simplifying assumptions (see below).
The indirect method by means of optical devices has the advantage that the method is time-efficient and non-destructive. It can be applied to any vegetation type below which the optical device can be placed, the leaf size is large compared to the sensor and a realistic number of measurements suffices to capture the variability in canopy density. It is, however, based on a second-order relationship and the results, therefore, approximate only. The main assumption is that the leaves are randomly arranged in the canopy. As a result, the cover is assumed to be uniform over the entire area under consideration whereas in reality leaves will cluster around the stem and branches. Under this assumption, also the apparent angle of the leaves (mean tilt angle) is calculated from which shoot and leaf arrangement can be induced.
Deviations from the assumed randomness may result in erroneous values of evapotranspiration and interception on a local scale. The estimated LAI may also be biased because of the underlying empirical relationships. The solution would be to replace the general relationships for more detailed, local relations. However, this would involve destructive sampling and this is not always feasible or desirable.
Destructive sample is the only possible technique to determine the LAI when an optical device can not be used (e.g. herbaceous vegetation covers). In theory, the method could provide exact estimates of the leaf area and that of the projected canopy. However, it is doubtful that, with the tedious labour involved, the results are more accurate than that of the indirect sampling with optical devices. It should be noted that neither method is capable to take the arrangement of leaves in the canopy into account. This error is more serious in the case of deciduous and broad leaf vegetation of which the arrangement is more prone to rain and wind and the cover in many cases changes over the year. The arrangement of coniferous vegetation is less prone these disturbance but suffers more from the fact that the method measures predominantly the projected area of shoots than that of the needles (Gower and Norman, 1991). Gower & Norman (ibid.) suggest a method to eliminate this bias in the measurement of the LAI of conifer stands with the LI-COR LAI 2000.

5.3a LAI determination of trees or forest canopies

Comment The non-destructive sampling with the LI-COR LAI 2000 device provides adequate estimates of the LAI. The device uses a wide-angled fisheye lens (zenith cut off angle74°) to measure the distribution of light and shade. The view is divided into five concentric sensors that each sample an area with a different angle and pathway along which the incoming radiation falls through the canopy. Because the large angle over which the canopy is sampled, a single measurement at one location suffices to integrate the spatial arrangement of leaves and in addition to the LAI, the orientation of the foliage can be estimated.
To eliminate the effect of reflectance or transmittance by leaves, only light with a wavelength between 320 and 420 nm is passed to the sensor for which both values are minimal in comparison to the direct incoming light. Sampling under overcast or clouded skies can further reduce the influence of reflectance and transmittance. Consequently, the foliage is assumed to be black and measurements above and below the canopy can be directly related to estimate the fraction of intercepted light. For the analysis of the data, the following additional assumptions are made (LI-COR, 1990)

- The foliage elements are small compared to the area of view;

- The foliage is randomly distributed within a certain foliage containing envelope (projected canopy area);
- Foliage is azimuthally randomly oriented.

These assumptions are not in agreement with the true distribution of foliage within the canopy but in practice they can be overcome using proper measuring techniques. Moreover, even if the assumptions are not exactly met, the deviations are slight and do not seriously affect the results.

The measurements with the LAI 2000 can be interpreted for an entire stand with a continuous canopy or for isolated shapes like bushes or trees. In the latter case, information on the shape of the tree or shrub must be provided (see manual for details; LI-COR, 1990).

Equipment LI-COR LAI 2000 device (2x)

Method For the sampling of a single feature, the projected canopy area should at least have a radius from the position of the sensor that is three times the plant height. Otherwise, neighbouring vegetation or clear sky may be erroneously included in the calculated LAI. If this is not the case, restrict the field of view of the apparatus with the caps supplied for this purpose or by discarding information from the outer concentric layers (i.e. reducing the angle of view). For single features, also measure the vertical distance to the top and bottom of the canopy at several horizontal distances from the main stem. This is necessary to correct for the height of the canopy which cancels out of the equation when the height, z, is uniform throughout a stand.

Measure the direct incoming radiation (preferably diffuse radiation on an overcast day), which is called the *above (canopy) measurement*. These measurements can be taken at the beginning and end of a series of measurements *below* the canopy or sampled frequently at a location where the view is unobstructed by canopy. In the former case, the two above measurements are averaged to provide the reference for the below measurements, in the latter case, the measurements are merged and the measurements referenced on a moment-to-moment basis. This reduces the influence of changing weather conditions and the latter mode is, therefore, preferred It requires, however, two sensors and the corresponding logger unit.
Under the canopy, sample frequently at regular intervals along a transect or sample at random locations (using a GPS for referencing). There is no minimum number of sample points. For a complete stand, a safe number would be the ratio of the total area over the average projected canopy area. For single features, a measurement at either side of the stem would suffice when the stem itself is barred from the field of view (see above). Because of the assumption that the leaf size is small to in comparison to the area of view, the nearest canopy elements must be removed three times their size from the sensor at a 30° angle.

Calculation The LAI can be calculated directly from the data with the software provided. For the LAI and leaf angle the mean and standard error are returned. Recalculation of the defaults values with the software provided may be necessary in the case of anomalous plot sizes or for a single canopy, for which the necessary measurements on the vegetation height must be provided.
The program also returns the average fraction of visible sky, both per sample rings of the device and integrated over the total field of view.

Reporting . A canopy description should accompany each LAI estimate. This should provide information on vegetation type/species, geo-referenced location, plot size, the height and shape of the tree(s), weather conditions and a measurement protocol. This measurement protocol should include the type of reference *above* measurements (interpolated begin/end measurements or frequent sampling with sample rate), restrictions of the field of view per series of measurements, if used, and the nature and number of *below* measurements.
For each stand or plot, the LAI and tilt angle of the foliage as returned by the program should be reported with mentioning its standard error, method of calculation and number of data pairs used. Also, the fraction of visible sky should be reported

5.3b LAI of the vegetation < 2 meter high.

Comment The procedure is identical to the one described above although the restrictions on plot size and vegetation height will be more restrictive. The LAI 2000 device can be used whenever the minimal distance of three times the leaf size can be observed and inserting the instrument below the canopy cover does not create gaps of its own. If this is not possible, the destructive method must be used.

Equipment LI-COR LAI 2000 device, *or*, Leaf area meter, clippers etc. and analytical scales.

Procedure For the use of the LAI 2000, see section 5.3a. If this method is not appropriate, use the following destructive method:
Remove from a known surface area that is representative for the vegetation type all above-ground plant tissue. Weigh this material to determine the wet plant biomass (see also section 5.4). Separate all foliage from this plant material and weigh this fraction. Take a representative sub-sample of the foliage and determine the surface area of each leaf (with an automatic leaf area meter, if possible). Multiply the total area of this sub-sample with the ratio between the total sample and the sub-sample of the foliage. Divide the total area by the surface area in order to obtain the LAI.

Reporting Mention whether the destructive or a non-destructive method has been used. If the LAI 2000 or similar device is used, report the values mentioned under 5.3a. If destructive sampling is used, mention the fraction of the different sub-samples and the measured area of foliage for the sub-sample with its composition and number of leaves analysed. In all cases, a canopy description as described in section 5.3a must be included.

Remarks From a conservation point of view, destructive sampling may not be desirable at every site.
Under the assumption that the foliage is randomly distributed, the LAI can be used to calculate the volume of the canopy. This offers a possibility to measure the (above-ground) biomass (see below) indirectly by means of the LAI 2000 or similar devices. Once a relationship between the canopy volume and the total biomass is established by means of destructive sampling, it can be applied in those instances in which only the LAI is determined and the total biomass inferred from it.

5.4 Spatial pattern of vegetation and within-unit variability @

Comment The determination of vegetation patterns is used for the establishing the spatial distribution of assemblies of functional types (vegetation units). This is essential for the generalisation of the acquired data. Information on the within-unit variability can be readily obtained if an optical device like the LI-COR LAI 2000. This would allow the recognition of the influence of uncertainty in the vegetation parameters on the model outcome.

Equipment measurement tape, LI-COR LAI 2000

Measurements The spatial pattern of vegetation height, biomass, and LAI are determined, by using the measurement methods as described in the previous sections.
The spatial structure will be determined by sampling in sampling quadrants (for dimensions see section 2.5) along contour lines on the measurement area. This can be repeated for 5 contour lines along the slopes. For each contour line 10 sample quadrants should be taken.
The results can be transferred into a spatial distribution function:

species density = f (altitude).

5.5 Biomass determination [$kg \cdot m^{-2}$] @

Comment This section provides the determination of the destructive method to measure the biomass of vegetation and litter. This method can be applied to sample individual vegetation plots or used to determine the relationship between biomass and LAI in order to determine the biomass indirectly and non-destructively over larger areas with similar vegetation.

Biomass will vary seasonally with the different time of emergence of different species. Also, the relative contribution of the root biomass to the total biomass will vary over time. Therefore, it is recommended that the biomass is determined for areas that are representative for the vegetation in both composition and size. It should be determined at different moments (e.g. seasonally) and the total biomass should be broken down into the following components: root biomass, stem & leaf biomass and litter biomass.
For woody vegetation, the biomass, both under- and above-ground, must be determined from a minimum sample number of 15 trees. For the herbaceous vegetation, the sample can be lumped.

5.5a Root biomass

Comment This is the underground biomass of the vegetation. For the interpretation of the results, it is essential that the volume of soil from which the roots are extracted is known.

Method For woody vegetation, root biomass is determined from samples that are obtained after the description of the root architecture or tree winching (Section 5.6 and Chapter 6). For herbaceous vegetation, the total weight of the sample is determined. Roots are cleaned from the adhering sediment by wet-sieving after which the material is dried in an oven at 60°C for three days. Total weights are reported as bulk value or subdivided into several species or diameter classes when appropriate.

5.4b Above-ground biomass (stem and leaves)

Comment This is the above-ground biomass of the living vegetation.

Equipment Measuring tape, stakes, garden clippers, pruning shears, knives, sample bags (polyethylene or cloth for large samples), analytical balance and drying oven

Method Delineate the sample area. It should be sufficient to reflect the overall vegetation but must have a minimum size of 50 x 50 cm.
Clip all vegetation to the soil surface. Separate the plants by functional type or by genus or species if required. Also a distinction may be made between living and dead material (excluding litter!). Keep the foliage separate for the determination of the LAI if required. Bag the material and determine its fresh weight, either directly in the field or within 24 hours in the laboratory. Take a sub-sample of the fresh foliage (for LAI determination). Dry all other material in the oven at 60°C until all free water is lost. Meanwhile, determine the specific leaf area of the sub-sample and add it to the stove when done. Extract the dry material and place in a desiccator for 24 hours. Weigh the dry material.

Calculations Calculate the net weights of each sample/species and gravimetric moisture content.

5.4c Litter (in combination with organic matter content)
Comment This is the mass of decomposing organic material on the surface and in the fermentation layer (O horizon).

Equipment Brush, trowel, small garden spade (+ additional equipment in laboratory)

Method Brush the litter from the surface and store in a separate bag. Exclude anorganic material (stones and sediment), either manually or by flotation on a fluid of an appropriate density. Weigh this sample and dry it in a stove at 60°C. Reweigh.
Excavate the O horizon to a measured depth over the 50x50 cm surface so that the volume of soil can be calculated. Dry it in an oven at 60°C. Weigh the dry weight of the total sample, W_D.
If a large fraction of mineral soil is present in the O horizon, then homogenise the soil and take two sub-samples of ± 100 g from the total sample. Determine the exact total weight of these sub-samples (w_T). Remove the organic material with peroxide. Determine the weight of the mineral soil only (w_M). Alternatively, the organic matter content may be used as described under section 4.9.

Calculation Calculate net weights of each sample/species and gravimetric moisture content. Calculate the dry bulk density of the O horizon. Calculate the total mass of dried organic material, W_O, of the O horizon using the mean weights of the sub-samples

$$W_o = \frac{w_T - w_M}{w_T} \cdot W_D.$$

Reporting Report the size of the sample area, as well as a vegetation description with the dominant species. List all masses and moisture contents. Express the dry biomass for the above-ground vegetation, roots and litter as the ratio between the dry mass and the area in units of $kg \cdot m^{-2}$. Do the same for the dry mass of organic material of the O horizon. Also, report the total bulk density and the ratio between organic and mineral soil for the O horizon. Report the biomass per volume for the root zone and express the root/shoot ratio as the fraction between the root biomass and the above-ground biomass (with exclusion of both the litter layer and the O horizon).

5.5 Root architecture @

Comment Descriptions of the root architecture provide information on the development of root systems on slopes and aid to resolve the root force that develops within a root due to strain with respect to the orientation of the slip plane.

5.5a Herbaceous layer and annuals

For root architecture characterisation of herbaceous species, it is easiest to remove a block of soil near the plot, take it back to the laboratory and clean the soil from the roots (either leave the soil to soak overnight, or use a jet of high pressure water). Remove 12 plants of each principal species within that functional class. Root length, surface area, volume (for roots of certain diameter classes), number of tips and forks, and root system topology (Fitter *et al*. 1991), should then be measured using the WinRhizo software (©Regent Guay Systems, Quebec, Canada, 2001; Bouma *et al*., 2000). For perennial species, root architecture only needs to be measured once a year (try to take different sizes of plants). For annual species, it will be necessary to measure root architecture in spring and summer.

5.5b 3D root characterisation of woody vegetation

General Three-dimensional descriptions of the root mass of woody vegetation can be made with laser and radar technology. Commercially available are respectively the Fastscan and Fasttrak systems (3D Space Fasttrak system manufactured by Polhemus, 1993: www.polhemus.com). The Fasttrak radar equipment is the least expensive of the two and has been used extensively by groups within ECO-SLOPES. The vast resource of skill and knowledge that has been acquired cannot be condensed in a short description. Everyone with specific questions is kindly referred to Michael Drexhage of the INRA in Nancy, France (drexhage@nancy.inra.fr).

With the radar equipment, the position of a passive sensor, consisting of a bobbin, in a low magnetic field is determined. This magnetic field is emitted by an electronic device, consisting of a sphere in which three bobbins are placed on three orthogonal planes (X, Y, and Z). The magnetic field has a standard radius of 2 m but an extension can be purchased to increase its radius to 4 m. The emitted signal is received by the sensor that is connected a central unit. This passes the sensor's position to a computer for data storage and processing. The equipment only tracks the position of the sensor in a single or *operational* hemisphere (either X^+, X^-, Y^+, Y^-, Z^+ or Z^-), which has to be defined beforehand. Six variables define the position of the sensor at any time: First, the X-, Y- and Z-co-ordinates in the operational hemisphere. Second, the positioning angles of the sensor, ψ, θ and ϕ. ψ is the azimuth within the horizontal plane. Its range is -180° to 180°and the zero angle coincides with the X+ axis. ψ increases counter-clockwise and negative values are confined to the Y^- plane. θ is the vertical angle, measured as the enclosed angle between the sensor and the horizontal plane. The range is –90° to 90°. By definition, 90° is the vertical angle pointing upwards, -90° is the vertical angle pointing downwards. The zero angle coincides with the horizontal plane. ϕ is the roll angle, which is the angle of the sensor with its larger axis.

By tracing the roots with the sensor, a database of Cartesian co-ordinates is built up (digitalisation). This database defines the root system in three dimensions. However, the sample points are located on the bark and must be processed to obtain the position of the marrow. For this, both the diameter and the three angles ψ, θ, and ϕ are needed. During the digitalisation, the diameter of a root and additional information like codes and state descriptions can be entered through the keyboard into the computer. By digitalisation, an accurate 3-D model of the geometry and the topology of a root system can be constructed.
Purpose-built software packages to enter, store and analyse digitised root systems are available. They expand on the methods of plant architecture studies proposed by Atger & Edelin (1995) and Godin *et al*. (1997). Digitalisation of plant roots in three dimensions was pioneered by Sinoquet & Rivet (1997) and Sinoquet *et al*. (1997). They developed the programs *diplami* and *3A*, presented by Adam *et al*. (2000). Both programs enable the storage of additional information, e.g. root diameter, with the 6 variables (co-ordinates and angles) that are retrieved by the equipment. *3A* is an improved version of *diplami* and the most recent. It is the proposed standard for all novice users of the Fasttrack equipment. It is available at ftp.cirad.fr or http://www/cirad/programmes/amap and information can be obtained from sinoquet@clermont.inra.fr.
Visualisation of the 3-D root architecture is possible with *3A* or AMAPMod (Danjon *et al*., 1999 a & b). The latter is a software package for root architecture analysis and allows the user to study the arrangement, ramification and volume of roots. The forthcoming architectural parameters can then be fed into the AMAPSim, which simulates the (development of) root systems. All the programs mentioned are shareware and freely available.

The equipment can be transferred and operated in the field. Therefore, root systems can both be digitised in the laboratory and the field. Only large metal objects and electronic equipment that generate an electromagnetic field interfere with the equipment. Soil has generally no influence and this offers the possibility to digitise roots *in situ.* Small exposures and trenches will suffice as long as they are large enough to position the sensor on a root. In situ measurements do not require the complete excavation of the root mass with the associated risk of distortion and breakage. However, it may be slow and tedious because of the manual clearing soil that is needed to expose the roots. Moreover, it is difficult to digitise roots whilst digging because of the procedure by which the data are ordered (see below and collet@nancy.inra.fr). Both methods are presented here. The equipment and general procedure are, however, very similar and presented first.

For the digitalisation of root systems, several adaptations of the Fattrak equipment are necessary. First, the sensor: this may be either the standard sensor or the optional stylus of different length. The stylus is not weatherproof as the bobbin of the sensor is exposed. One should therefore avoid the use of the stylus in damp weather for corrosion would affect the results negatively. Additionally, although the construction is fairly solid, it is advisable to strengthen the stylus by putting Araldite on the point and waterproofing it. Wrapping adhesive tape around the cable may prevent that it shears due to tension and torsion. This is also a particular problem with the standard sensor or mouse that is supplied with the equipment. To avoid this, a low-cost adaptation has been suggested by Lagane (2001) by which the cable is made expendable. It also offers the opportunity to add a switch to the set-up. This allows the user to make isolated measurements rather than the continuous tracking by the standard equipment. The consequent data files are economic and a direct link between the automated measurements of the root system and the manual readings of the diameter that have to be entered separately from the keyboard (Figure 7).
Every sensor has an offset, which is the distance between the point on the root surface and the origin of the bobbin. For the stylus, this distance is automatically registered, for the adapted sensors it has to be measured and entered before the start of the digitalisation.

For field measurements, a portable power source is required for the equipment. A standard diesel car battery suffices to power the equipment for a day (12V, 64 Ah). A converter is needed to change the 12 V DC of the battery to 220 V AC at 50 Hz (e.g. Radio Spares Statpower ProWatt 250i/12).
The emitting sphere is best placed in a protective cage made out of plywood. Connections should be made with plastic nuts and bolts or dowels to avoid disturbance of the magnetic field. The cage can also be used to reposition the sphere in exactly the same position, for example when measuring a

root system in the field over several days. To this end, it is to be joined to a wooden base plate that is securely fixed in the field by wooden stakes.

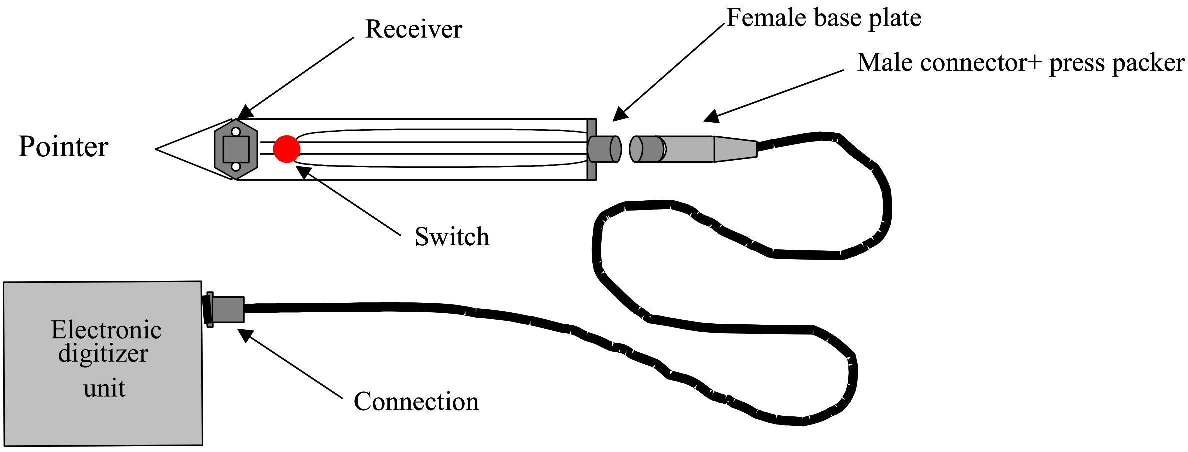


Fig. 7: Design of the custom-built sensor (Lagane, 2001)

Equipment For the excavation or extraction of the root system:

Extraction with heavy machinery for ex situ digitalisation:
- Tractor, mini-caterpillar or harvester with winch;
- High power water jet cleaning system ("Kärcher");
- Wire rope, shackles, lifting strops.

Excavation by using water:
- Tanker and hose pipe (from public service or fire brigade).

Excavation by using air stream (especially suited for in situ digitalisation):
- Pneumatic excavator (e.g. Soil Pick: http://www.mbw.com/pick.htm);
- Air hoses;
- Air compressor;
- Plastic tarpaulins;
- Sticks and boards.

For all methods the following is needed:
- Labels and staple gun;
- Camera;
- Shovels and spades in different sizes;
- Hand tools (saws, screw drivers, chisels, brushes etc.);
- Shears and scissors;
- Plastic sheets, bags and packaging material;
- Appropriate safety equipment (hard hats, goggles,protective clothing, boots).

For the digitalisation:
- 3D SPACE Fastrak Digitizer, preferably the long range version with sphere, registration unit and mouse or stylus;
- plastic setsquare as reference
- A computer (portable), with Windows 95 or higher, running the program *3A;*
- Measurement tape;
- Plastic vernier calliper and thread-counter.

Optional:
- Cage for the sphere;

- Car battery and converter 12V-220V or small petrol generator.
- Abney level and compass or similar to measure aspect and slope angle.

For the analysis of the data:

- Computers with Windows 95 or higher and LINUX operating system supporting spreadsheet program (Excel or Quattro) and AMAPMod.

General procedure

Excavation: For the excavation of the root system, various methods can be used, depending on the size and strength of the root mass and whether complete exhumation is required, for example when the digitalisation will be performed in the laboratory (*ex situ*). Uprooting is the quickest method. The selected trees have to be felled, leaving a 1-m-high stump. Stem and crown dimensions are to be measured. The north side of each tree at the ground level and the direction of the slope at ground level have to be marked at the stump. The main lateral roots are to be exposed at the stem-root base by careful excavation before winching the stumps over. A 1-m-deep soil trench is to be carefully dug 1 m from the stump by a caterpillar tractor with a mechanical shovel fit with a special tooth (Drexhage et al. 1999). A chain is to be attached to the stump and connected to the shovel of the tractor. The root system must be then pulled over slowly but some roots may snap and remain buried. These have to be excavated and tagged for reconstruction in the laboratory. The stem is cut (horizontally) from the root plate at the root collar.
A less destructive method, which is equally applicable to in situ measurements, is the use of an air spade (Soil Pick) or water jet. The water jet is quick but requires large quantities of water on site and a means to evacuate stagnating water from the pit. Therefore, the first method is preferable as it is easier to use. Moreover, it leaves the root system clean and dry. It is essential that the root system is free of dirt to avoid decay. If possible, digitalisation should be immediate to avoid desiccation and distortion of the root system.
The extracted root system must be linked to the topography (N azimuth, slope). As the root system loses its bearing to these conditions, some reference must be applied. It suffices to insert three small nails in the stump at opposing sides (N, E, S or W). They will not influence the measurement. Besides the reorientation of the root stump in the laboratory, they can also help to link field measurements on the topography to the root system by transformation, provided that all three markers are both digitised in the laboratory and in the field.

Measurements: As measurements are confined to one hemisphere it is advisable to install the equipment in such a manner that the hemisphere encompasses the entire root system or that the necessary changes are minimal.
Before the start of the measurement, test the accuracy. It is negatively influenced by disturbances of the magnetic field and erroneous values for the sensor offset. The following steps help to assess the accuracy:

- Stability: successively remote click ([F7] in *diplami*) the receiver in a place where measurements may be warped (for example hung from a branch near the digitisers electrical alimentation), after clicking 10 or so times the co-ordinates should not have varied by more than 0.1 cm. From this measurement, one can also infer the influence of the wind on the measurements;
- Precision: measure an object of known size – the plastic setsquare in the equipment list or any gauge of reasonable length - in the three orthogonal directions of the sphere (X, Y & Z);
- Sensor offset: measure 10 times the same point whilst tilting the sensor in different directions. If the error is a large, you should check the offset definition in *diplami* or *3A*.

Digitalisation abstracts a root into segments in the shape of truncated cones where the ends can be ellipses: After the first point, each point marks the node of a segment whose base is located at the level of the preceding click. This determines the sequence of the digitalisation. Measurements start from the stump's collar, and follow the pivot (1^{st}-order) until the first ramification (2^{nd}-order). This ramification is followed up till the first 3rd order root, this ramification is then described and so on. With each ramification, the branching root must be described fully, before returning to the main one.

Usually many 2nd-order roots insert themselves on the pivot. So, as not to over-estimate the length and the volume of the root, it is advisable to define a series of virtual discs on which to insert a certain number of the 2nd-order roots (discs 2 or 3 cm in thickness were used for 5 year old pines). It is assumed that all roots inserted on one disc are of the same depth. For the pivot, it is advisable to position the sensor towards the North, by directing it perpendicular to the stump axis. The larger diameter of the stump raises the uncertainty in the position of the segment centre and by digitising with the sensor bearing north decreases the error in the length, and thus in the volume.

It is necessary to digitise with the sensor orientated perpendicularly to the main axis of the root. With the measured diameter, this allows to reconstruct the position of the root pith.
The points on the root should approach the architecture of the root as accurately as possible. Thus, at bends, it is necessary to locate several points close to each other. On the other hand, if the root keeps to the same direction and the diameter decreases regularly, two points at each end are enough. When the distance between two points of measurement is small compared to the diameter, the length and especially the volume of the root will be overestimated. The resulting errors will appear as small zigzags on the 3D picture.

The size of the roots that have to be digitised depends on the purpose. For ECO-SLOPES, only roots with a diameter of more than 5 mm at their base included. Smaller roots may be removed before the start of the digitalisation. This creates space to manoeuvre between the larger roots.

During digitalisation, the root diameter is measured with a plastic vernier calliper at every co-ordinate. The diameter is measured at a resolution of ½ mm for roots smaller than 5 mm and at a resolution of 1 mm for larger roots. The diameter of finer roots can be measured with a thread-counter.
Below a certain root diameter (e.g. 1 mm), roots are not to be measured. Ramifications of a root into these small roots can be included qualitatively by entering them as a code (e.g. S1 and S2 for one- or two-way ramifications).
For circular roots, one measurement of the diameter suffices. For oval roots, the minimum and maximum diameter have to be determined but make sure that the diameter pair corresponding to the co-ordinate can be retrieved later on. Figure 8 summarises the sequence of digitalisation. In this example, roots n°1 to 18 are inserted at the same level into and around the pivot forming a table; root n°19 is inserted further down the pivot and root n°25 is deepest of 2nd order roots. The figure schematises half a root system.

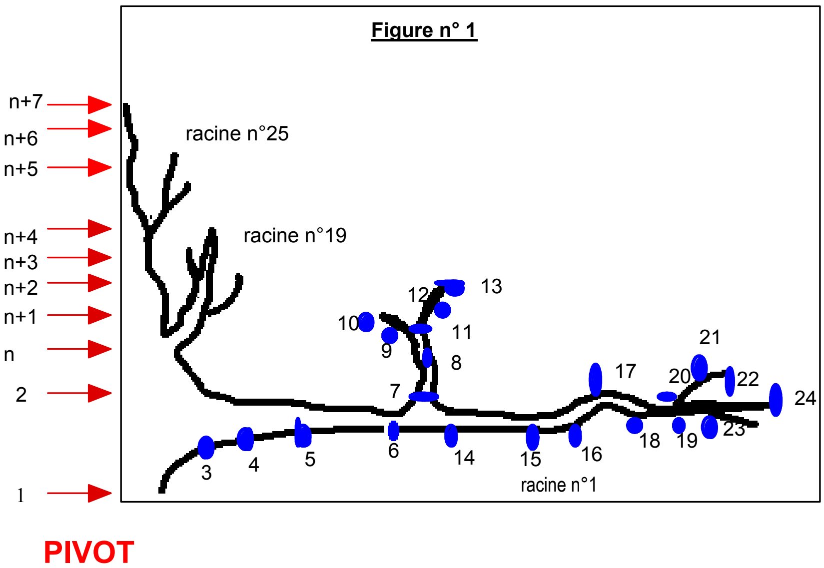


Fig. 8: Sequence of digitalisation of a root system

Points 1 and 2 are first digitised hence defining a cylinder into which will insert roots 1 to 18. Then are digitised points 3 to 24 defining root n°1. Roots n°2 to 18 are measured in this way and the tap root is returned to by clicking points n and n+1. Root n°19 is measured inserting itself into the new cylinder defined on the pivot and so for all roots inserting themselves onto that cylinder. Measurements continue for the pivot by clicking points n+2 to n+5 and so on. It should be realised that in practice the majority of roots are broken off. When this is not the case 0 or 1 (mm) can be the last diameter.

Digitalisation is a painstaking process that asks for good bookkeeping. It is recommended that a list of codes is designed beforehand that specifies the type of ramification, root branching order and state of the root (healthy, diseased, rotting or rotten etc.). The measurement and coding system described by Danjon (1999a) can be used as reference.

The data can be analysed with AMAPMod, which is especially conceived for this purpose. It requires a LINUX platform. AMAPMod couples an architectural database with Markov chains that describe branching probabilities. It is described extensively in two articles by Danjon *et al*. (1999a & b). Included functions are the description of ovally roots, localisation and characteristics of slides and segments taken during the measurement, topology, characteristics individual of each root, cross-sectional areas, characteristics of roots intercepting a slope and their distribution in space. User-defined functions can, however, be easily included. So is there no function for volume measurement in AMAPmod and the actual calculation has to be defined by the user. ; it is the user who defines the exact mode of calculation.

AMAPmod is also a powerful graphical tool. It makes it possible visualise root systems in all the positions and to indicate by colour for example anatomises in green and rotten parts in blue. Roots can be integrated in a landscape with Landmaker. Functions were written under Splus for graphs and final variable calculations in Danjon *et al*. (1999a & b). Users may use these programs in a similar way to present the resulting data.

Ex situ measurement of entire root systems
The main problem with ex situ measurements is to position the root system without affecting the results. Several methods can be used dependent on the size of the root stump:

- Small root systems without or with aerial parts: attach the root at the level of the trunk base with rucksack type straps, and/or with adhesive tape to a post (but risk of disturbing the measurement of horizontal roots situated on the side attached to the post) or on a frame with an overhanging rail.
- Average sized root systems (Danjon 1999b): The root system is positioned on a plate (non metallic) located at approximately 70 cm in height. The plate was previously levelled. Northern azimuth of the root system materialized on the stump is positioned on the plate's (X^+) axis that is the prolongation of the sphere's X+ axis. It is sometimes possible to make an alignment stump/sphere. If this is not the case the NS axis of the stump should be parallel with the sphere's OX axis. The root system is reversed (earth side towards the top, trunk/sky side downwards). It is fixed on the plate by a screw in the centre, and with straps to limit rotational movement of the stump during measurements.
- Large root systems: stumps of several hundreds of kilos were positioned on concrete blocks with an crane. The stump was repositioned with wooden wedges placed between the stump and the concrete blocks and fixed on poles stuck in the ground with self-tightening links of *Colson* type.

For small root systems it is possible to number all the 2nd-order roots from one to N with horticultural sticker labels placed at their base. It is advisable to always follow the same rule: numbers follow a north to west spiral and gradually go up the pivot according to the root insertion origin. It is possible to measure long roots with a decameter and with a vernier calliper (diameter every 20 cm for example), their positioning is recomputed by AMAPmod (cf. Danjon and al. 1999 a and b). For the bigger root systems, it is better to progressively cut out measured roots, to free measurement space and to avoid measuring the same root twice.

For digitalisation, the most practical set-up is achieved when the ball is well positioned horizontally and the north is in the X+'s direction. The OX-axis of the sphere coincided with the north and can be used as the reference mark to define the system in which one will work.
For the digitalision, one should proceed as explained under the general procedure. For the practical details about the set-up of the installation, one is referred to the Fasttrak Manual.

In situ measurement of root systems
For measurements in situ, however, some more plots are recommended. A roof of plastic tarpaulins against rain should be built using neighbouring trees as supports (Figure 9). Wooden sticks should be placed and fixed beneath roots to stabilise the root system during the measurements. The root measurements start beginning on the root stump and with an easily accessible horizontal main root. After measuring the entire main root with all its side roots, the root should be cut at the root stump to get access to the remaining roots. All structural roots are thus progressively digitised.

Fig. 9. Provisional shelter for the in situ digitalisation of root systems

Digitisation of roots on a slope departs from the general case as the X-axis must be perpendicular to the maximum inclination. The long-range 3D Space Fasttrak should be located horizontally on the upward side of the tree with its down-slope direction perpendicular to the X+ axis (see Figure 10). If the recording software 3A is used, the setsquare has to be installed horizontally (using a level) on the slope within the hemisphere. In this case, the setsquare is the reference and should not be removed. In the case of difficulty in the evaluation of the slope direction, the best reference is the geographical North, meaning the X+ axis perpendicular to the north direction.

Fig.10. Alignment of the orthogonal planes for in situ digitalisation on slopes

In the latter protocol, it is necessary and easy to reference the root system with the north and the horizontal plane. The horizontal plane can be determined by means of a large vernier calliper on which two, perpendicular spirit levels are placed (Figure 11). The calliper, kept level in the horizontal plane, is rotated until a compass positioned on the fixed calliper side points to the north. Two nails, hammered in the tree, at the same distance indicate north and south. Through these two points runs the horizon plane. In this way, after the excavation, the tree root system can be orientated towards the north and the horizontal plane.

Fig. 11: Referencing of the root stump using spirit levels and compass

Reporting For each root system, the report should include the following:

Descriptions of

- Excavation method used;
- Soil conditions;
- Tree and local vegetation.

Data on

- DBH and projected canopy area;
- Slope angle and aspect.

List of

- Co-ordinates of the pith as well as the diameter and branch order.

Graphs of

- Field sketch and photos;
- Plan view of the root system indicating the north and direction of slope;
- Photos of excavated root system in situ and repositioned;
- 3-D reconstruction of the root system.

6. BIOMECHANICAL CHARACTERISATION OF TREES

6.1 Tree Winching Experiments

Purpose of experiments @

In the Eco-slopes project, several different tree species growing on slopes will be subjected to winching for measurements of stem and root strain and to find the maximum overturning moment. Strain gauges will be attached to the tree stem and roots, and forces will be applied to the stem in three directions – up-slope, down-slope and cross-slope. Values obtained from the strain gauges will be used to determine longitudinal strain, stem stiffness and modulus of elasticity (Young's modulus). After these measurements are complete, the maximum load required to overturn the trees will be measured, and overturning moment will be related to tree, slope and root characteristics. Overturning moment and tree mechanical characteristics will be used to quantify the dissipation of wind forces from the stem into the soil, and in the development and validation of tree stability and biomechanical models by Eco-slopes partners.

Required equipment

- Mechanical or manually operated winch (Hit-Trac 16 or equivalent);
- Cable;
- ***Slings;***
- ***Karabiners and shackles;***
- Tape measure;
- Camera with flash (preferably digital);
- Inclinometers (eg http://www.geomechanics.com/pdf/900.pdf);
- ***Dynamometer/load cell, capable of measuring loads up to 2 tonnes;***
- ***Chainsaw;***
- ***Rope;***
- ***Spade;***
- ***Strain gauges (Kyowa or equivalent);***
- ***Strain data logger (Kyowa SMD 10A or equivalent);***
- ***Switch and Balance unit (VMG SB10 or equivalent);***
- Pulley;
- Wire, terminals for strain gauges;
- Glue (Loctite 401 or equivalent); and
- Assorted tools including pliers, wire cutters, and a soldering iron.
- Safety equipment, including safety helmets, gloves for handling wire rope, boots with steel toe-caps, tree climbing equipment, chainsaw protective clothing.

Method

Tree Selection

A subject tree is selected based on a predetermined set of criteria such as species type, size (height and diameter) and location on a slope. Initially, a visual inspection is required to determine tree suitability, and difficulties associated with removing the tree including the location of neighbouring trees. It is necessary to chose a tree located within relatively close range of others (to which winching equipment may be secured). It is also necessary to chose a tree sufficiently spaced from others such that it may be winched without coming into contact with them. Criteria established within the Eco-Slopes project require trees of the following diameters to be winched:

- Small trees, diameter: 15cm
- Medium trees, diameter: 20cm
- Large trees, diameter: 30cm

Apparatus configuration

The tree winching apparatus is arranged as depicted in Figure 12. A sling is wound around the subject tree stem at a height equal to half of the total tree height. Using shackles and karabiners as required, high tension cable is then attached to the sling, and fed to a winch and dynamometer (used to measure cable tension). The winch may be either mechanical or manual, depending on tree size. The winch is secured to the base of a neighbouring tree of equal or greater size using a sling. The neighbouring tree should be located at a distance greater than the height of the subject tree (separation distance, x – Figure 12). Prior to the commencement of winching, any slack in the cable is taken up, although not such that the stem of the subject tree begins to bend, and the angle of the cable is recorded relative to horizontal.

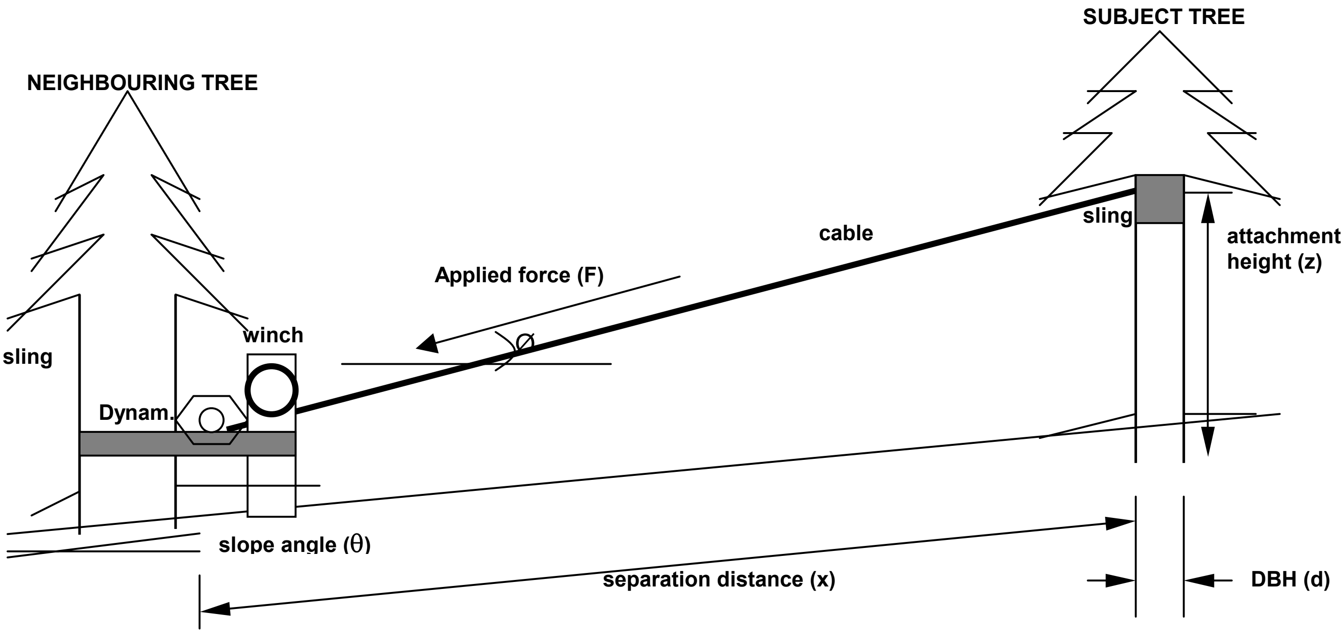
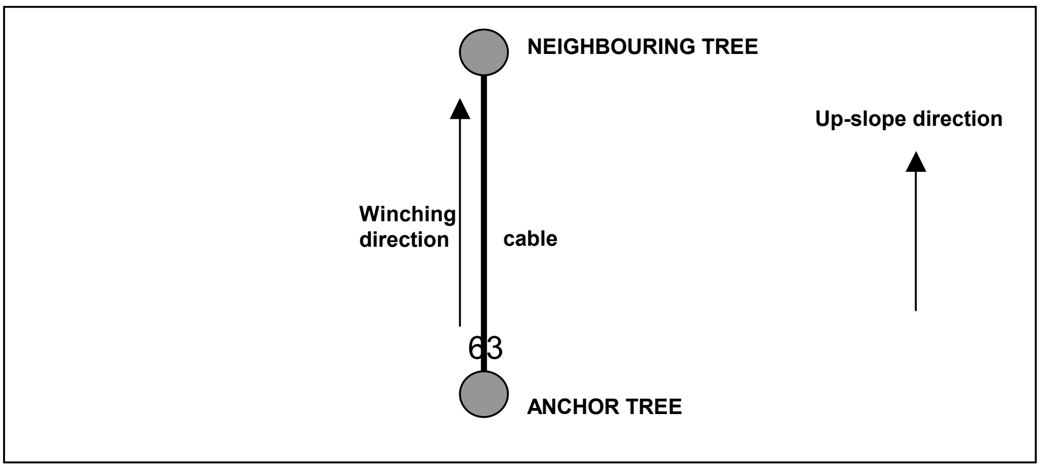


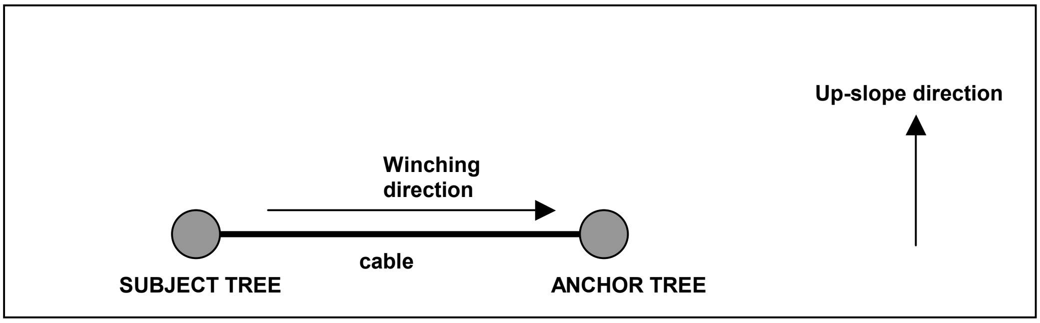
Figure 12. Assembly of apparatus for tree winching

Note: When trees are pulled down-slope it is necessary to arrange the cable and winch system such that winching is not conducted in a direct line with the area that the tree could potentially fall should stem breakage occur. The following aerial views (Figure 13) depict the recommended apparatus configuration for the three directions of load. Any surrounding vegetation that is likely to interfere with the experiment should be removed prior to commencement. If an offset arrangement is used as shown in figure 13c, the load cell should be placed at the end of the cable at the subject tree. Suitably long output leads should be installed on the load cell to allow for this.

13a. Tree winching up-slope



13b. Tree winching cross-slope



13c. Tree winching down-slope

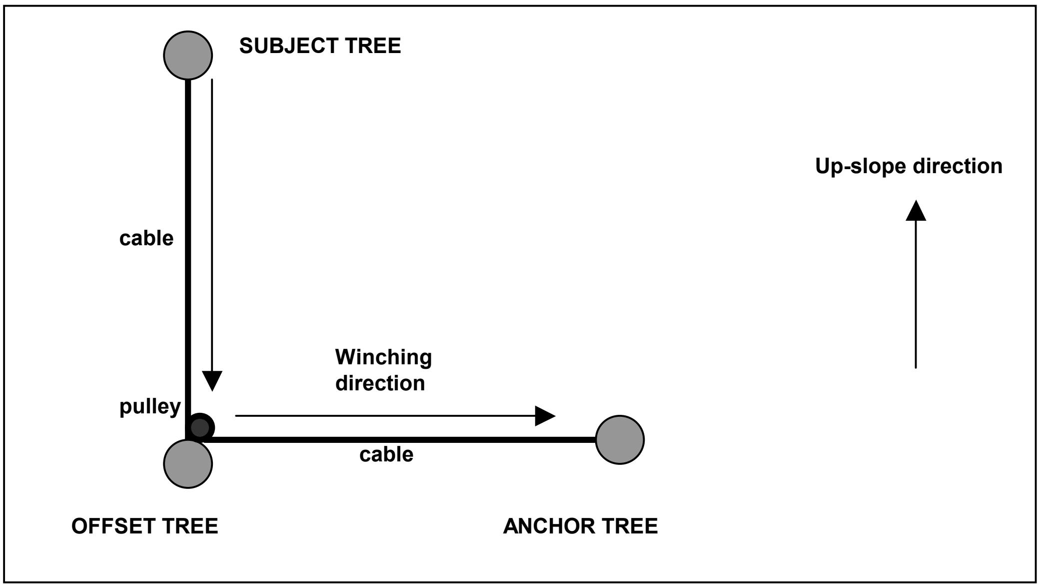


Figure 13. Winching configuration (aerial views)

Measurements

The following values should be measured (using tape measure, inclinometer) prior to the commencement of winching:

- Tree diameter at breast height (DBH), the diameter 1.3m from the base of the tree (d);
- Approximate tree height (H) (accurate measurement when tree is on the ground);
- Angle of cable under tension;
- Average slope angle (θ) – average angle between subject and anchor (or offset) trees;
- Local slope angle – slope angle around subject tree;
- Distance (x) between the base of the subject tree and the anchor tree (neighbouring tree to which cable, winch and dynamometer are attached), or to the offset tree.

Other measurements including exact height of cable and inclinometer attachment can be made once the tree is on the ground if the tree is being uprooted. All recording equipment (data loggers, inclinometers and dynamometer) should be zeroed, or zero offset recorded, before applying the load.

To measure stem deflection under load, two inclinometers are attached to the tree, one at DBH and the other at the height of cable attachment in the tree.

Strain measurements

If strain measurements are to be made, strain gauges should be attached to the tree stem, base and roots of the tree at the following points:

- DBH (breast height – 1.3m) : up-slope, down-slope and cross-slope directions (3 gauges);
- Tree base (just above soil level) : up-slope, down-slope and cross-slope directions (3 gauges); and
- Roots –a large lateral root in each direction (up-slope, down-slope and cross-slope) is chosen, and gauges are placed on the top of the root at distances of 1m and 2m from the tree base.

The method of gauge attachment for both stem and roots is the same. Roots must firstly be exposed by removing surrounding soil with a spade. A section of stem/root bark of area $25cm^2$ (5cm x 5cm) is removed using a chisel, taking care not to damage the wood underneath. Any sap on the wood is carefully removed with a rag. Strain gauges are attached to the centre of the chiselled region using liquid superglue, oriented longitudinally with the stem or root. The gauge wires are connected to the SB unit and data logging equipment, which may be left to rest near the base of the tree, clear of the direction in which the tree is winched. Initial values for each of the strain gauges are recorded prior to the commencement of winching. The diameter of the roots/stem at the point of gauge attachment is also recorded.

Force should be applied incrementally to the tree stem using the winch. As the tree is winched, the magnitude of applied load (F) is recorded, as are readings from the strain gauges and the inclinometers. Increments of applied force should be consistent with stem diameter and should be decided depending on tree characteristics. To avoid damaging the tree before measuring the maximum load for overturning, trees should not be deflected by a horizontal distance that is more than approximately 10% of the pull height. The following can be used as a rough guide:

- Small trees, diameter 15cm: 125N increments up to 500N
- Medium trees, diameter 20cm: 200N increments up to 800N
- Large trees, diameter 30cm: 250N increments up to 1000N

Variations of the direction in which each stem is first bent (either up-slope, down-slope or cross-slope) are essential to ensure no bias in the acquired measurements. At each increment, dynamometer force reading (F) and strain gauge readings are recorded. Trees should not be pulled far enough during the strain gauge measurements so as to damage the stem or roots, but any sounds of stem or root breakage during winching should be noted and pulling should be stopped immediately.

One of two alternate tree-bending scenarios may arise when a moment is applied to the stem of the tree. In the first scenario, the stem bends in an *arc* (Figure 14). This type of bending is characteristic of small and medium sized trees, having highly flexible stems that undergo large deflections under applied load.

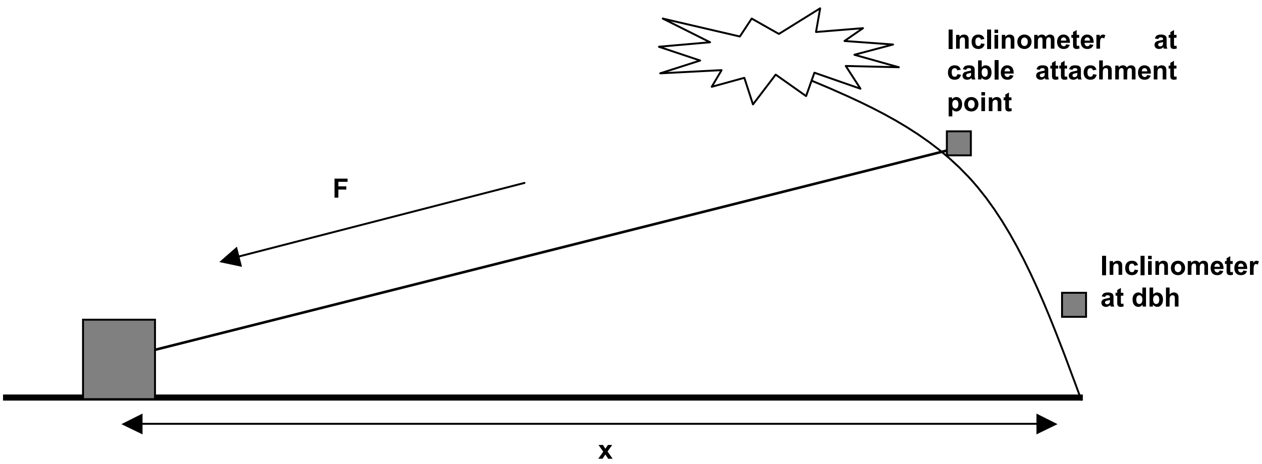


Figure 14. Arc-like stem bending (large deflection)

A second possibility is that the stem remains relatively straight as a moment is applied. This type of bending is characteristic of medium and large sized trees with relatively inflexible stems that only undergo small deflections under applied load (Figure 15).

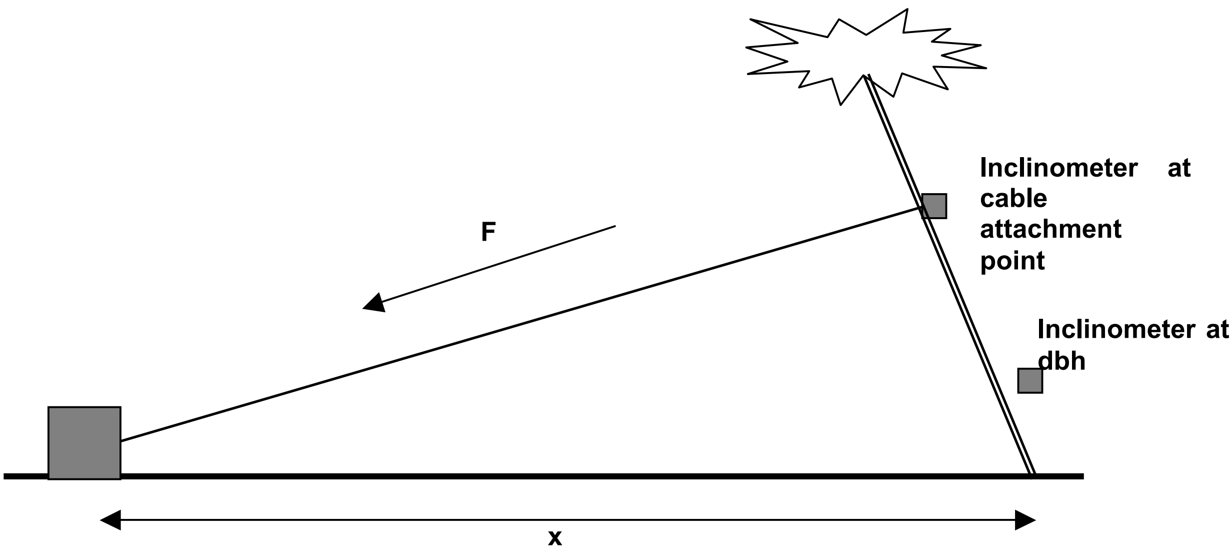


Figure 15. Relatively straight stem bending (small deflection)

Tree overturning

It is necessary to record the maximum load for overturning the tree. If possible, trees should be pulled over in equal numbers up-slope, down-slope and across slope. To avoid damage to strain gauges, it may be advisable to remove them from the tree before overturning. Attach a numbered label to the up-slope side of the tree, and spray paint a horizontal line around the base of the tree before pulling the tree over (these are important for subsequent root architecture measurements). Angles of stem deflection at the time when the maximum load is reached should also be recorded. The most reliable way of doing this is to wire the load cell and both clinometers into the same datalogger. The logger can record the angles when the maximum load is reached. However, the readout should be watched during pulling as a second peak in load can occur after the tree is pulled over if the winch operator continues to pull the tree out of the ground. Digital clinometers usually give output in the range –45° to +45° (with 0° vertically upwards) and may give spurious data outside this range.

Measurements of the tree on the ground

Once trees have been overturned, the diameter of the stem should be measured every 1m up the stem to allow calculation of stem taper and volume. Also, using a tape measure, it is important to record accurately the heights of both inclinometers, cable attachment, height of crown base, and tree height. A 1m central section of the stem should be cut using a chain saw, and weighed on site to allow calculation of stem density and mass. Crown spread should be measured before removing branches. Branches (both live and dead) should be weighed fresh. The easiest method is to build a simple tripod, hang a balance from it, and weigh branches in bundles. If the tree snaps during pulling, this should be recorded, all measurements should be made as before, and the height and diameter of the snap point should be measured.

Soil-root plate measurements

Measurements should be made of the dimensions of the soil-root plate after overturning, but before extracting the stump or cleaning the roots. The plate should be photographed (with a meter scale) from each side (a digital camera with flash is good for this). The following should be recorded: soil depth (at least 3 points), plate width, plate height (preferably top to stem centre, and stem centre to base of crater), maximum lateral root extension, maximum root depth.

Stump removal

In order to extract the stump and root system for measurement of root architecture, it may be necessary to reposition the sling nearer to the base of the stem, such that the stump may then be easily removed from the surrounding soil using a winch. Any large roots which break in this process are collected and temporarily reattached to the root ball. The loss of fine roots (<5mm) may be ignored. Soil can then be removed using hand tools, and/or an airjet or water system.

Who to talk to in case of questions:

Task :	*Contact :*
Strain gauge instrumentation	Alexia Stokes/ M Sharman
Strain gauge measurement / Young's modulus calculation	Alexia Stokes
Tree pulling, clinometers, load cells	Bruce Nicoll
Tree measurements	Bruce Nicoll/Alexia Stokes
Overturning moment calculation	Barry Gardiner/BruceNicoll
Soil-root plate measurement and stump removal	A Stokes/ M Drexhage/ B Nicoll

Measurements checklist

Initial measurements:
DBH
Cable angle
Average slope angle
Local slope angle
Distance from subject tree to anchor tree or offset tree

Strain measurements:
Diameters of stem and roots at attachment points
Positions of strain gauges
Zero offset from strain gauges, load cell and inclinometers
Strain gauge readings (x9)
Load cell readings
Inclinometer readings (x2)

Tree overturning measurements:
Zero offset from load cell and inclinometers
Maximum load from load cell
Inclinometer readings at time of maximum load

Final tree measurements:
Diameter of the stem from ground level every 1m up the stem
Heights of both inclinometers
Cable attachment height
Height of crown base
Tree height
Weight of 1m central stem section
Diameters of both ends of 1m central stem section
Crown spread
Fresh branch weight (live and dead)
Height and diameter of the snap point (if the tree breaks during pulling)

Soil-root plate measurements:
Photographs with scale from each side of soil-root plate
Soil-root plate thickness (at least 3 points)
Soil-root plate width
Soil-root plate height (preferably both top to stem centre, and stem centre to base of crater)
Maximum lateral root extension
Maximum root depth

6.2 Root reinforced soil shear strength @1,2,7

Comment Root reinforcement is only apparent when soil samples are tested both with and without roots.

Equipment Load cell, hydraulic jack, displacement gauge, data logger, shear box, spade.

Method A Select a suitable tree for testing and record its height, diameter etc. (as described in section 5.8). Remove, the top 200mm of the topsoil to expose suitable tree roots for testing. Place the shear box above a root reinforced area and excavate around the outer edge of the box until the top of the box is level with the soil surface. The load cell, hydraulic jack, displacement gauge and data logger are attached to the shear box (Figure 16). Record the initial load on the shear box and apply a horizontal displacement. Observe the mobilised shear force and the horizontal displacement and continue the test until peak load has been reached.

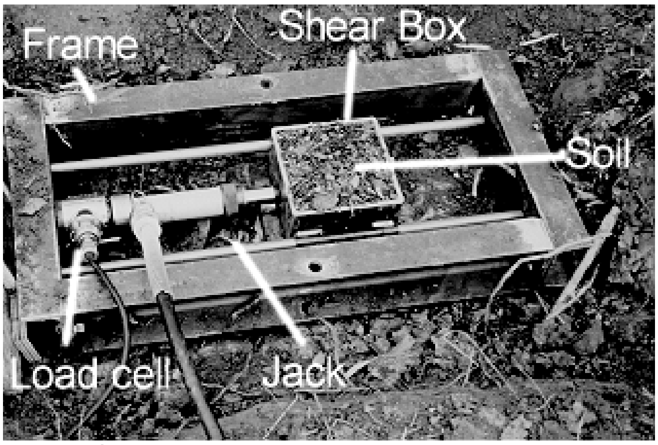


Fig.16. Shear box apparatus

Method B To simulate normal stress, place the shear box over a selected root. This root is clamped to a suitable top plate using the gripping cone (as described in section 5.10; Figure 16). Normal stress is measured using a load cell.


Fig. 17. Combined root and shear apparatus

Reporting and Calculation Analyse the results from the test which are stored by the data logger, to determine peak shear stress and displacement.
Analyse the contents of the soil sample, measuring the diameters and lengths of all roots contained in the sample. Obtain an indication of the strength of the soil by means of a pocket vane or penetrometer and take samples to determine the moisture content and Atterberg limits of the soil.

6.3 Soil-root interaction: Pull-out strength @

Comment The pull-out strength is indicative for the friction that can be mobilised along the soil and root interface. The amount of frictional resistance determines the mode of failure of the roots in the soil by slippage or rupture. Thus, it ultimately controls the contribution of roots to the shear resistance of the soil (Norris and Greenwood 2000).
.

Equipment Load cell, hydraulic jack, displacement gauge, 20mm angular gravel, steel cone, data logger.

Method Expose approximately 200mm of root from the soil and measure the root diameter. Position the cone over the protruding root and fill with gravel. Attach the cone to the load cell and displacement gauge by a metal rod (figure 17&18). Pump the hydraulic jack at a constant rate to give a uniform displacement of 10mm per 60 seconds. Displacement and load are recorded by the data logger and the strain is increased until the root snaps.


Fig. 18. Root pull out apparatus

Reporting and Calculation Calculate the tensile strength (MN/m^2) of the root and the amount of failure strain (%). The tensile strength of the root can then be applied to slope stability analysis to include the effects of vegetation (Norris and Greenwood 2000).

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8. Changes of version 2 in comparison to the Ecoslopes Field Protocol version 1

1. completion of list of contributors
2. improved referencing to figurer and figure numbers
3. corrected version of section 6.1
4. corrected version of section 4.15
5. corrected version of section 2.2 and 2.3