TAW
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Technical Advisory Committee for
Flood Defence in The Netherlands

Technical Report

Clay for Dikes

1996

TECHNICAL REPORT

CLAY FOR DIKES

Delft, May 1996

The Road and Hydraulic Engineering Institute (DWW) of the Directorate-General of Transport, Public Works and Water Management (Rijkswaterstaat) is the advisory division for technique and environment for road and hydraulic engineering, which does research, advises and transfers knowledge on nature and environmental engineering of the physical infrastructure, water and water defence systems, and supply of raw construction materials, including environmental aspects.
The Hydraulic Engineering Department of the DWW acts as the operational arm of **the Technical Advisory Committee for Flood Defence (TAW)**. DWW commissions the research and prepares the TAW's recommendations.

For questions on TAW's or DWW activities please contact the Road and Hydraulics Engineering Institute (DWW) of the Directorate-General for Public Works and Water Management (Rijkswaterstaat):
PO Box 5044
2600 GA DELFT
The Netherlands
Tel. +31-(0)15 251 84 36
Fax. +31-(0)15 251 85 55

Email: dwwmail@dww.rws.minvenw.nl
Internet: www.minvenw.nl/dww/home/

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1. Reason for and composition of project group
2. Specification of requirements according to RAW methodology (in Dutch) (Dutch Tender Requirements and Specifications); (not included in this report)

Preface

This is the Technical Report "Clay for Dikes', which offers insight into the behaviour of clay as used in dikes. Clay is an excellent material for dikes: it is often sturdy, inflexible and coherent, even under the influence of water.
The conditions for clay in a dike are different than for clay on a horizontal surface, with dike clay being drier. The changes in moisture content and temperature are greater, especially on south-facing banks of dikes. The waterproof nature of clay is true for undisturbed layers under the ground water, but not for clay that is high and dry on a dike bank.

The most important reason for this Preface is that this study into the behaviour of clay and the set-up of the text of this Technical Report date from about 1990.
It became clear then that the erosion resistance of dike banks did not only depend on the quality of the clay; there was also possibly, and even more importantly, influence from good management. After the study of clay, development progressed as a study into the management of dike vegetation. The publication entitled 'Construction and Management of Grassland on River Dikes' by L.M. Fliervoet, September 1992, published by the Association of Water Boards and the Advisory Group on Management of Vegetation gives an excellent overview of the possibilities. When using the current report, careful account must be taken of the effect of vegetation and its management for dike banks and shoulders.
The requirements that are mentioned in this report for clay on dikes are concerned with erosion resistance. The study showed that the upper and lower limits for the permeability of structured clay are only a factor of 10 apart, and it would appear that a limited permeability for structured clay cannot be achieved by the establishment of requirements.

It is possible to distinguish several categories of erosion resistance in clay, and depending on the loading on a bank, a more or less erosion-resistant clay can be applied. When other criteria or the type of management do not justify any other choice, the following suggestions can be used:
Category 1 clay is suitable for outer banks with high loading; at low loading, categories 1 or 2 clay are suitable. For an inner bank with high loading (i.e., a high chance of a large amount of over-topping water) then category 1 clay should be used, but category 2 clay is also perfectly adequate, whereas for low loading even category 3 clay is suitable. For inner dike support shoulders, category 3 clay will usually do the job.

The project group (TAW B6) is convinced that by converting to the new approval criteria, the amount of clay that is eligible for dike construction would be increased, while at the same time clay would be more efficiently applied.
Chairman of 'Clay Club', TAW B6

CHAPTER 1

1 Introduction

1.1 Reason for and aim of study

The Technical Advisory Committee for Flood Defence (TAW) was established to advise the Minister of Transport and Communications on all technical and scientific aspects important for flood water defences. Various guidelines and technical reports have resulted from this task.

The TAW has also initiated some studies on the use of clay as a construction material for dikes. Some years ago, a study was started on the relationship between civil engineering requirements and the desired quality of clay when using it for flood water defences, and the results of this study were reported in 1985-1990 [1 to 10, 12]. A major part of the study was aimed at clay in a top layer with a covering of grassland. Based on this study, and previous studies on clay under a stone setting, requirements have been formulated for top layers under a stone setting.

The reasons for performing this study lie in the fact that previously, for evaluation of the quality of clay, past knowledge and experience has always been used. This means that the composition of the lutum and sand fractions has been the main interest. Comparing the requirements that were then used by various managers showed large differences. In addition, the question was more often raised as to how far non-natural deposited clays, such as Euroclay (clay produced from harbour silt from the Europort in Rotterdam) and 'tarragrond' (soil from industrially processed roots and tubers) could be used in dike construction.

The current report is a Technical Report in which the results of various studies are brought together and placed in some sort of logical context. The aim of the report is to give insight into the properties of clay that are important for dike construction and to give direction to an unequivocal evaluation of clay. Based on the functions to be fulfilled and the material properties, requirements have been adjusted and recommendations are made for the use of clay in dikes.

This report is primarily intended for directly involved technicians in the designing and managing of dikes. In addition, we have attempted to provide insight and information for interested but non-technical people about the problems of applying clay in dikes.

This report is not intended as a scientific work in which a theoretical basis is exhaustively discussed. For this the reader is referred to the research reports that formed the basis for the current report (see References). This report is the so-called 'green' version.

It should be noted that there are still currently various calculation rules missing to be able to accurately quantify the strength of the clay. Therefore, we have worked to provide practical recommendations, in which for most cases a responsible design and management can be established.

This report was prepared under the responsibility of the project group TAW-B6, and the composition of persons in this project group is given in Appendix 1.

1.2 Relationship to current guidelines

This report gives additional information to the previously published Guidelines and reports from TAW and replaces the requirements for clay specified therein. This concerns the following guidelines and reports:

- Guidelines for the design of river dikes, part 1 - the Dutch upper Large Rivers area [23];
- Guidelines for the design of river dikes, part 2 - the Dutch lower Large Rivers area [24];
- Natural and agricultural engineering management of dikes [18];
- Guidelines for methodological selection of dike and river bank coverings [20].

1.3 Contents and arrangement of report

The current report is mainly divided into two sections: the first part deals with descriptions of the properties of clay as a material and the conditions under which it is found in nature and used. The second part is a separate appendix in which a proposal is set out for a draft set of requirements according to RAW methodology (Dutch Tender Requirements and Specifications).

The first part is aimed at the establishment of material requirements important for clay in dikes, based on the properties and the natural conditions that will influence the functioning of the clay in a dike. This part of the report is set out as follows:
Chapter 2 gives a short description of the material 'clay' and from several aspects how clay is used in the construction of dikes, and the concept of 'soil structure' is introduced here, with this chapter forming the central theme of the report. Chapter 3 describes in detail the composition and properties of clay, in which a division is made between clay as a <u>mineral soil fraction</u> and clay as <u>natural soil</u>. The latter means the civil engineering properties that are important for the use of clay in dikes. In Chapter 4, attention is given to the use of clay in dikes, with descriptions of the most important functional requirements for each part of the construction, and the required material properties are given. Chapter 5 summarises the requirements established for application of the material clay in dike construction, and also describes various aspects that play a role in testing the quality of clay in that work. Chapter 6 discusses some points for attention during implementation, especially the application and compacting of the clay.

The separate appendix concerns a proposal for the draft set of requirements according to RAW methodology (Dutch Tender Specifications), which can be used as a supplement to Chapter 22 of the RAW definitions 1995 from the Road Foundation CROW [17]. The finalised definitions will be included in a supplement to the RAW definitions 1995.

CHAPTER 2

2 Clay in dikes

2.1 Description of clay

The term 'clay' can be defined in various ways. In this report 'clay' is used as a name for cohesive soil that is mainly made up of fine particles. 'Clay' can also be used as a general term for fine mineral soil particles, such as in 'clayey' soil or 'clay has affinity for water'. This definition will also be used in this report, where necessary.

In the Dutch Standard NEN 5104 [16] , the soil type 'clay' is defined as a *natural soil* with a composition based on the mass percentages of lutum, silt and sand, as shown in Figure 2.1. In this connection, natural soil consists of erosion and breakdown products of natural rocks, that have been brought together again by natural processes. The limits for the various fractions as given in NEN 5104 are:

- sand, equivalent grain diameter greater than or equal to 63 μm and less than 2 mm;
- silt, equivalent grain diameter greater than or equal to 2 μm and less than 63 μm;
- lutum, equivalent grain diameter less than 2 μm;

The term 'equivalent grain diameter' is used because the size of very small particles is derived from the sedimentation rate of particles in water, by which the particles are assumed to be spherical.

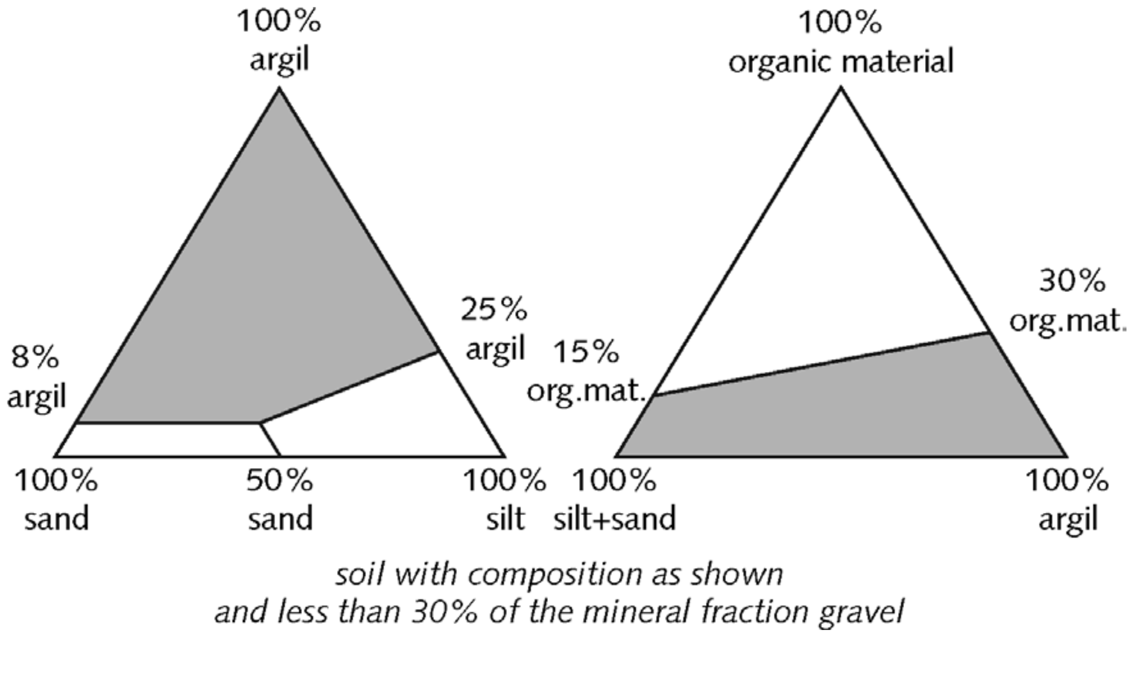

Figure 2.1: Classification of the soil type 'Clay' according to NEN 510(argil=lutum)

Clay is found in various qualities with diverse properties; for example, the properties of a just-excavated plastic grey or blue clay are very different from the sturdy, lumpy agricultural soil that it can also form. The grain-size distribution from both of these clay types can then be almost identical, but the civil engineering properties such as permeability and shape-retention differ considerably. In general it can be assumed that the civil engineering properties of clay change due to the influence of the surroundings in which the clay is found, for example, change in groundwater level, dehydration, etc.

Some characteristic properties of clay are cohesion and the property of retaining water. Cohesion is a consequence of the binding forces between the very fine soil particles; these forces are large in relation to the weight of the particles. The power of clay to retain water is due to the fact that water molecules bind fairly strongly to the surface of the soil particles, and because of the very fine pores in the clay which, due to the high resistance strongly inhibit transport of water through the clay. When no larger pores exist in the clay package, then the clay is still only slightly permeable.

2.2 Using clay for dikes

Clay has been used for dikes for many hundreds of years, especially as a material for top layers and in the core of the dike.

This soil type has been known for ages due to its good erosion resistance and shape retention. These properties are extremely useful for steep banks and if water already laps against the bank. The relatively limited permeability of the material plays an important role for the selection of clay for use in dike construction. Furthermore, clay is usually available in the immediate surroundings in the Netherlands.

Mainly because of these properties, clay is still being used for dike construction, with a clay-containing section having the function of giving soil-mechanical stability to the entire dike body. Figure 2.2 shows the constructive elements in which clay is used.

An important aspect that plays a major role in the consideration of the properties of clay is the presence of the so-called 'soil structure'. A package of clay contains larger pores due to the cracking of the soil and due to biological activity in the soil. Cracking occurs due to shrinking and swelling as a result of the clay becoming wet and dry. Biological activity consists of, for example, burrowing animals (worms, insects, moles) and root penetration from vegetation. The cracking of clay and the biological activity lead to soil structure formation (Figures 2.3 A and B).

Clay with a soil structure consists of a composition of larger and smaller mainly angular lumps, so-called 'soil aggregate'. The larger soil aggregates often fall apart into smaller aggregates, and the smallest aggregates, with dimensions of less than 2 mm, are found in and directly under the grass sod (Figure 2.3A).

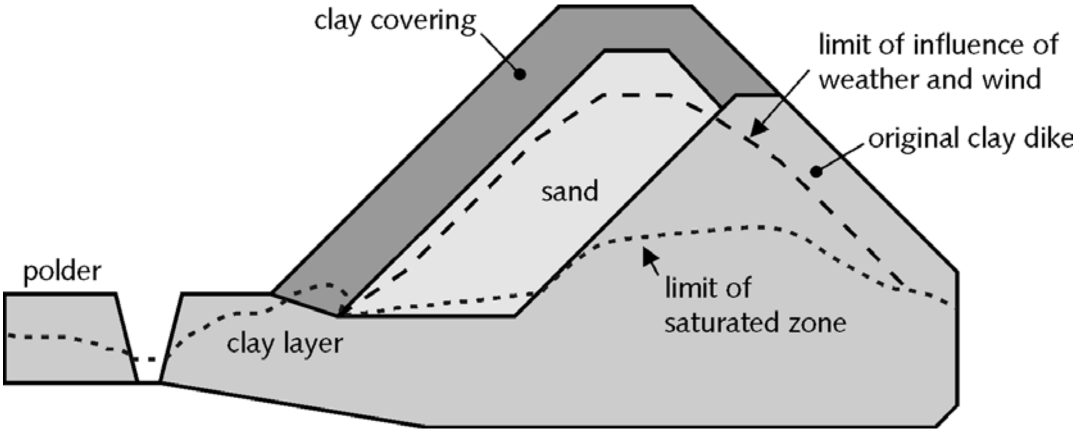

Figure 2.2: A dike profile in which the zone that is permanently saturated in most dikes and the zone in which the weather situation has a greater influence are shown.

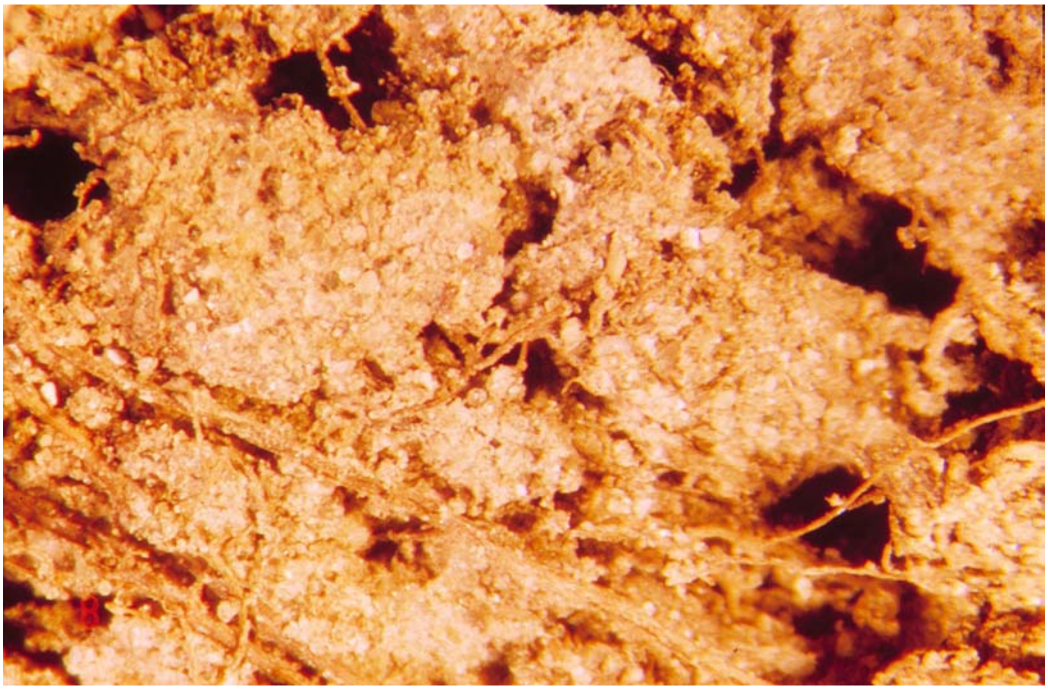

Figure 2.3A: Soil structure in clay of dikes, consisting of cracks, animal tunnels, and soil aggregates. The photograph shows the fine structure in a grass sod.

Large aggregates in the form of more or less angular columns or lumps with dimensions of sometimes more than 20 cm also actually occur under certain conditions

(Figure 2.3B). The aggregates have more or less connections between themselves because they stick together or because, for example, they are held together by roots. The aggregates of clay are often mixed together by burrowing activity and the soil structure is then also only visible if the clay is carefully 'dissected?' by using a knife blade. The outside of the aggregate often has a somewhat different colour and surface texture to that of a freshly broken piece of soil.

Figure 2.3B: Soil structure of clay in dikes. The photograph shows the influence of burrowing animals and root penetration up to 0.7 m deep. The structure underneath is the result of changes in moisture content.

The presence of a soil structure dominates most civil engineering properties of a clay package; the permeability of the package is completely determined by this, and it has an important negative influence on erosion resistance.

In general, all clay in dikes has some sort of soil structure, and insight into the phenomenon of soil structure and its presence in a dike is then also essential.
Soil structure in clay can occur at many places in a dike. As a consequence of climate effects and the influence of weather, soil structure can occur in the outermost 1 to 2 metres of a dike, especially where it remains unsaturated by outside or ground water (Figure 2.2). A soil structure can also be present even in the core of a dike. The effects of soil structure are in general dominant for the properties of clay in and under coverings, and will also have an influence on the function of clay cores in dikes.

Section 3.3 discusses in detail this soil structure and how it originates.

CHAPTER 3

3 Properties of clay

3.1 General

In describing the properties of clay, a distinction must be made between the properties of the material as a *mineral soil fraction* and its properties as *natural soil*.

In the first case, the description covers the composition of the clay mineral, its water-retaining properties and its cohesion. In the second case, the description covers soil structure, permeability, shear resistance, shape-retention, and workability.

The various properties of clay are described in the following sections.

3.2 Clay as mineral soil fraction

In order to be able to understand the material properties of clay and the changes therein, a number of aspects of clay at the microscopic and sub-microscopic levels are important. The major part of the material properties of clay are derived from chemical and directly related physical phenomena.

3.2.1 Composition

Clay consists of small particles of solids, water within which compounds are dissolved and gases. The fine fraction of the particles and the water determine the characteristic properties of clay. The fine particles consist of various minerals and in the Netherlands this is usually always clay minerals, very thin (thinner than 10^{-8} m), flat particles (Figure 3.1). In addition, the fine fraction also contains other minerals such as quartz, some iron and aluminium compounds, chalk, etc. Clay also contains organic materials in the form of the remains of plant and animal organisms (microscopic and larger organisms), fibres, active bacteria and fungi, and organic molecules. Further extensive information can be found in various mineralogy and soil science manuals [31, 46, 47].

Clay in the Netherlands shows variations in the relative amounts of the different fractions of solids such that considerable differences in properties occur. The difference in properties between grey or blue clay and clay from an older clay covering is mainly due to this. The composition of the solids changes under the influence of the surroundings in which the clay is found. The colouring of grey or blue clay, to bright yellow and brown speckled clay is caused by changes in the mineralogical composition (especially by the conversion of iron and manganese compounds), which can change again over time.

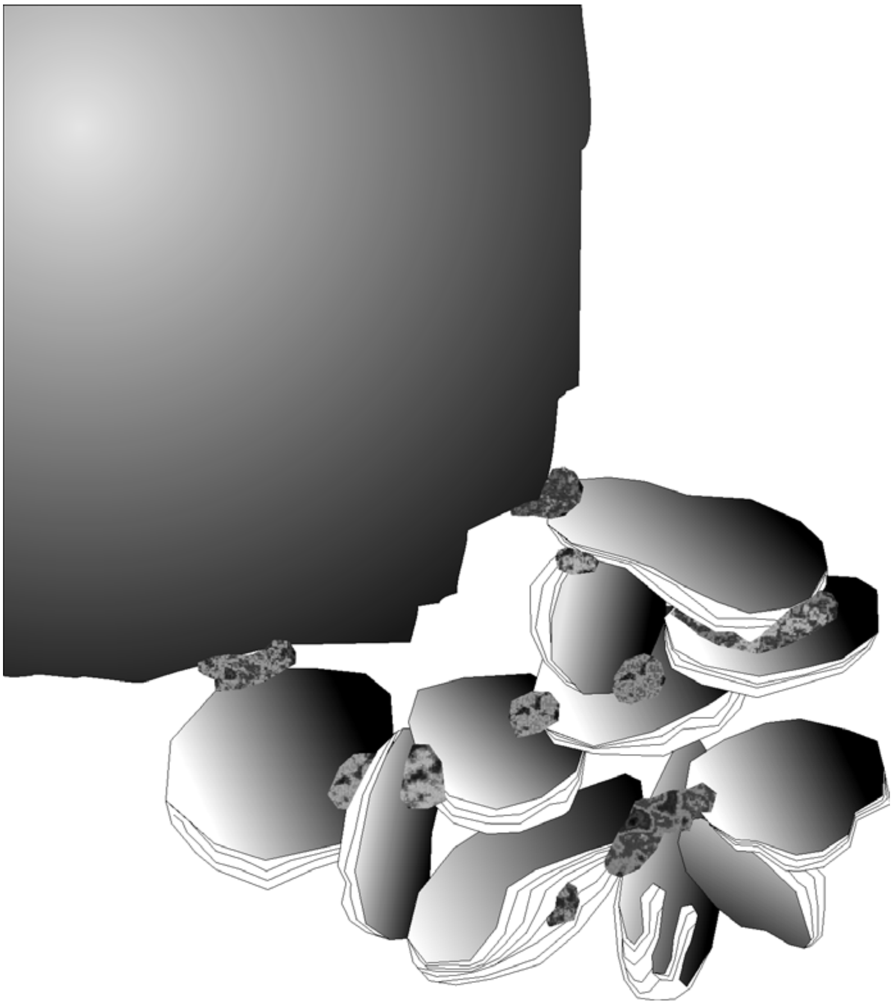

Figure 3.1: Clay particles coupled together and with a sand particle by chemical compounds including iron and organic material.

The minerals concerned have an influence on the water-retaining power of the soil and on the strength of the bonds between the solid particles and therefore on the civil engineering properties such as shape-retention and erosion resistance.

The nature and amounts of the organic compounds present in clay also change. Transformation by micro-organisms decreases the amounts of coarse and fine organic remains. Under anaerobic conditions and if the temperature is less than 10° - 15°C, then this conversion process takes a very long time. The presence of air and higher temperatures greatly increases the rate of degradation, and organic remains in the upper soil are then completely degraded within a few years.

Organic material often occurs in the upper soil as a result of plant roots, fungi, added fertiliser and micro-organisms. Directly under a grass sod, a dynamic balance exists, due to input and conversion of organic matter, in which the total amount of organic materials consists of 3 - 4%. Changes in the amount of organic matter again changes various properties of the clay, including bulk density, water-retention capacity, and deformation.

The so-called 'specific surface area', the total surface area of the outside of the solid particles, is also an influence on the properties of clay. As there are many very small solid particles within clay, the total surface area of the outside of the particles in a certain amount of clay is relatively very large. The specific surface area of the particles of solids in a normal Dutch clay is generally between 40-120 m^2 per gram of soil. The value for sand is often less than 1 m^2. The relationship between grain-size distribution and specific surface area makes it possible to gain insight into the specific surface area of soil by determining its grain-size distribution.

3.2.2 Water-retention capacity

Clay retains a certain amount of water, and this amount depends on the physicochemical properties of the water and clay and from the suction force that the surroundings exercise on the water. Many properties of clay are linked to the water content and changes therein.

Affinity for water

The surface of almost all the solid particles in clay have an affinity for water, which means that water molecules more or less bind to the surface of the particles [53]. Clay even at a temperature of 100°C still retains a small amount of water. Under prolonged dry conditions, the water in a clay covering is distributed in a layer of only a few water molecules thick over the particles of solids. The amount of water that the clay then retains depends on the degree of affinity for water. This affinity is influenced by the surroundings and the composition of the surface of the solids and by any other compounds that are dissolved in the water or adsorbed to the solids. Compounds dissolved in the water also retain the water and clay with a high salt content can, for example, retain a relatively large amount of water.

Clay also retains water due to the presence of so-called surface tension, which retains water in finer pores and the small corners of larger pores. Surface tension is the consequence of the attraction between the water molecules and a solid surface, by which the water as it were remains linked to the solid surfaces.

Changes in water content

The water pressure in clay above the water table is mainly negative in relation to atmospheric pressure. This negative pressure is usually referred to as 'suction pressure' because clay can 'suck up' water from the water table due to this negative pressure. The water pressure only becomes positive above the water table due to precipitation or infiltration of outside water. The suction pressure is determined by a dynamic equilibrium between the gravitational head of water, the height of the water table, and the shape and size of the pores. In addition, evaporation into the atmosphere plays an important role, and this can take place directly from the soil into the atmosphere or via the vegetation. The amount of evaporation is dependent on, among other factors, the relative humidity of the air.

Close to the surface of a dike, the suction pressure can be often higher than a 100 m head of water in the summer, mainly as a result of the relative high temperature and the suction power of the vegetation. Precipitation and temperature changes can actually allow this suction pressure to vary greatly, and when it rains, it is often less than 5 m.
In winter conditions, in wet periods, the suction pressure in the clay covering of a dike is on average usually less than a 1 m head of water. The suction pressure can be considerably higher only in dry freezing air, especially in banks that face south. The greatest changes in suction pressure take place in the root layer due to changes in precipitation, water extraction by roots, and very large temperature differences.

Variations in the suction pressure in the core of the dike are caused by changes in the positioning of the water table, and by atmospheric effects. The effects of changes in atmospheric conditions are very faint and the variations in suction pressure in the dike core are generally slow and of limited size. The suction pressure in the core of a dike can vary between 0 m to rarely more than a 5m head of water.

There is a constant transport of water through a dike body caused by the changes in suction pressure. In the winter, clay is mainly wetter even if no rain falls. In the summer, clay in coverings dries out due to moisture transport to the atmosphere. When a covering is wet, the water disappears by diffusion to the atmosphere and to the relatively cold core of the dike.

The suction pressure of a dike varies at every place in the dike body between certain values over the longer term. The representative values for suction pressure as mentioned earlier can be found in the core of the dike, between a 1 and 5 m head of water in the zone well above groundwater level. In the outermost 1 to 2 metre of the dike profile, there is a greater range of average suction pressure and in the variation around the average (see also Figure 3.3). The suction pressures measured in three summer periods in the upper 30cm of a grass bank appeared to be more than a 10cm head of water. At a depth of 40 to 70cm, it appeared to be this level in a little less than half of the determi-nations. A suction pressure of a 10 m head of water (pF = 3) for the summer period has been selected as a suitable representative value for grass banks in the Netherlands.

Provisional findings suggest that this value is also a suitable representative value for clay under stone settings, but that the suction pressure under a stone covering changes less quickly.

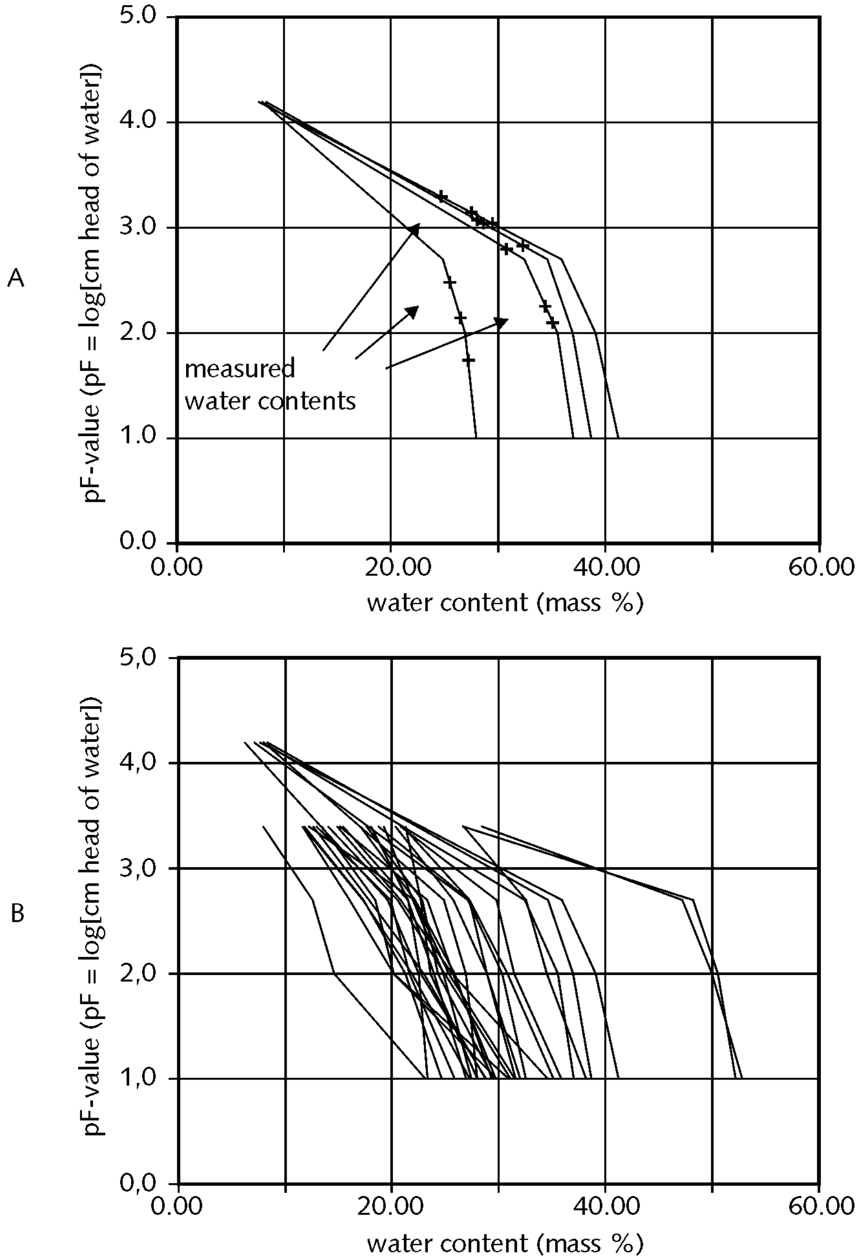

Figure 3.2: A: pF curves showing the water contents measures in the Spring, Summer and Autumn.
B: Some pF curves of clay from clay coverings [7]

The amount of water that is retained in clay under different conditions depends on the suction pressure and the retention capacity of the clay. This amount is shown using a pF curve in Figure 3.2, for which:

pF = $\log_{10}$ (suction pressure in cm head of water).

The pF curve is important information for clay under unsaturated conditions.

Figure 3.3 shows some measured water contents on dikes of clay under grass covering and the related suction pressures.

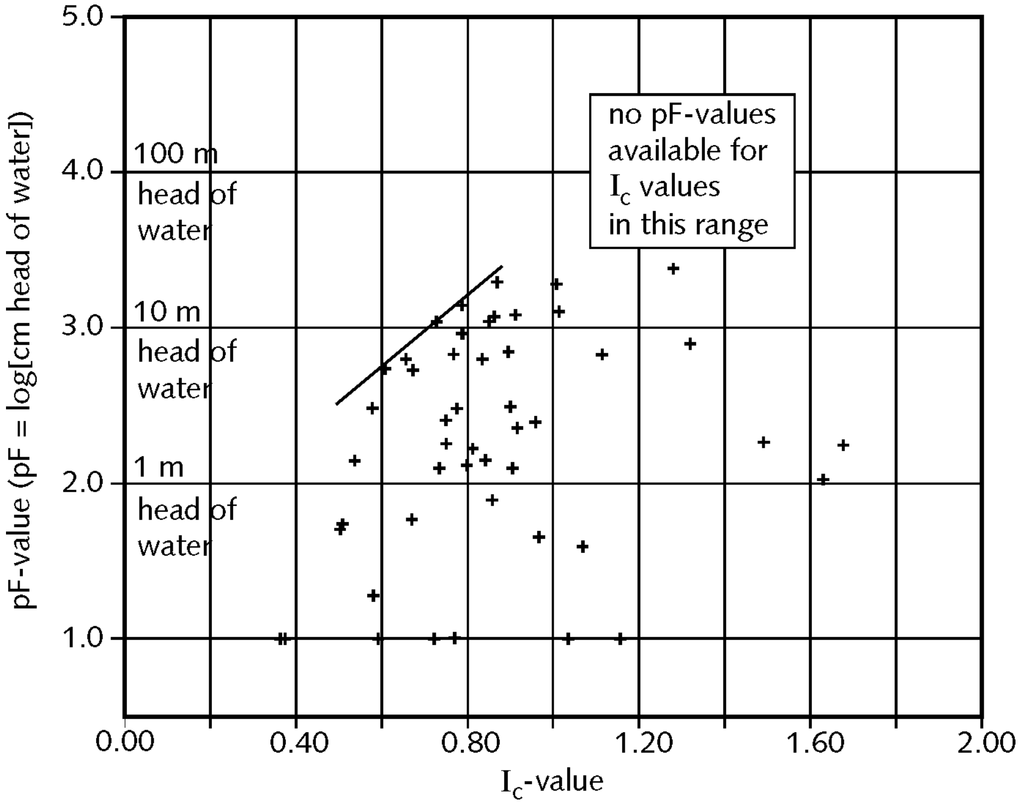

Figure 3.3: Suction pressures and water contents determined for clay in covering layers of dikes with grass, in the Spring, Summer and Autumn.

<u>Water content versus Atterberg limits</u>

The Atterberg limits (flow and plastic limits) are a measure of the plastic properties of soil, in which the physical properties of the solids play an important role. In general, the water-retaining capacity of clay, as mentioned above, is determined by the physicochemical properties of water and solids and by the shape and size of the pores. For suction pressures greater than about a 5m head of water, the amount of water retained by the dike is mainly determined by the properties of the surface of the solids. The size and shape of the pores are relatively unimportant. The water-retaining capacity of clay due to suction pressures greater than about a 5m head of water also then show a link to the Atterberg limits.

A decreasing water content increases the sturdiness of the saturated clay, because among other factors the particles lie close together. A further decrease of the water content leads to the clay behaving more like a plastic solid than a thick fluid. The water content during kneading at the transition point between thick fluid and plastic clay depends mainly on the binding of water to the clay particles. This binding can change by, among other factors, changes in the composition of the ions and molecules. The water content at this transition is an indication of the direct and indirect binding of water to the clay particles and is called the *flow limit*. The flow limit gives insight into the physicochemical properties of the surface of the solids and of the water. The flow limit is in practice a useful classification test for clay, because the civil engineering properties have a direct link to these physicochemical properties.

As the clay becomes even drier, the limit is reached at which stirred cohesive soil can suddenly transform into a plastic state. The water content from this test is called the *plastic limit*. This classification test also gives insight into the binding between particles which involves water. The plastic limit is relatively low if the soil contains few particles that are smaller than 10 - 20 μm.

The difference between the flow and plastic limits is called the plasticity index (I_P) and this value gives insight into the amount by which the clay is sensitive to differences in water content. For sandy clay, the flow limit is relatively low, and the plasticity index is then usually also low. The plastic limit can be high for some clay types relative to the flow limit, from which the plasticity index is also relatively low. There is a lot of water in this type of clay that does not contribute to the soil's so-called 'cohesion'. The average lower limit for the relationship between the plastic and flow limits for clay in dike construction is given by the so-called A line in a plasticity diagram (Figure 5.1).

As mentioned earlier, there is a definite relationship between, for example, the Atterberg limits and the physicochemical properties of clay. The maximum amount of water that clay can retain with somewhat greater suction pressures can be estimated using a certain relationship between these limits, the so-called consistency index (I_c). This index indicates how the water content of clay is related to the flow and plastic limits, and is defined as follows:

$$I_c = \frac{w_l - w_n}{w_l - w_p} = \frac{w_l - w_n}{I_p}$$

where:
I_p = plasticity index
w_l = flow limit
w_p = plastic limit
w_n = available water content*
 * in percentage mass compared to dry material

For a relatively high water content and therefore a low consistency index, clay deforms easily. If the available water content lies close to the plastic limit, the clay will no longer quickly deform 'plastically'. Several items thus influence the degree of compacting of the clay and the consistency index is therefore a good indication of the workability of the clay (see also section 3.3.6). This index is then also used in this report to limit the water content of clay when applying it and working it.

The water content of clay with an I_c of 0.75 is thus a good approximation to the maximum water content for a suction pressure of 10 m head of water (Figure 3.4). The water content of clay in the core of a dike well above the water table is calculated using a water content of clay with an I_c of 0.6 [33].

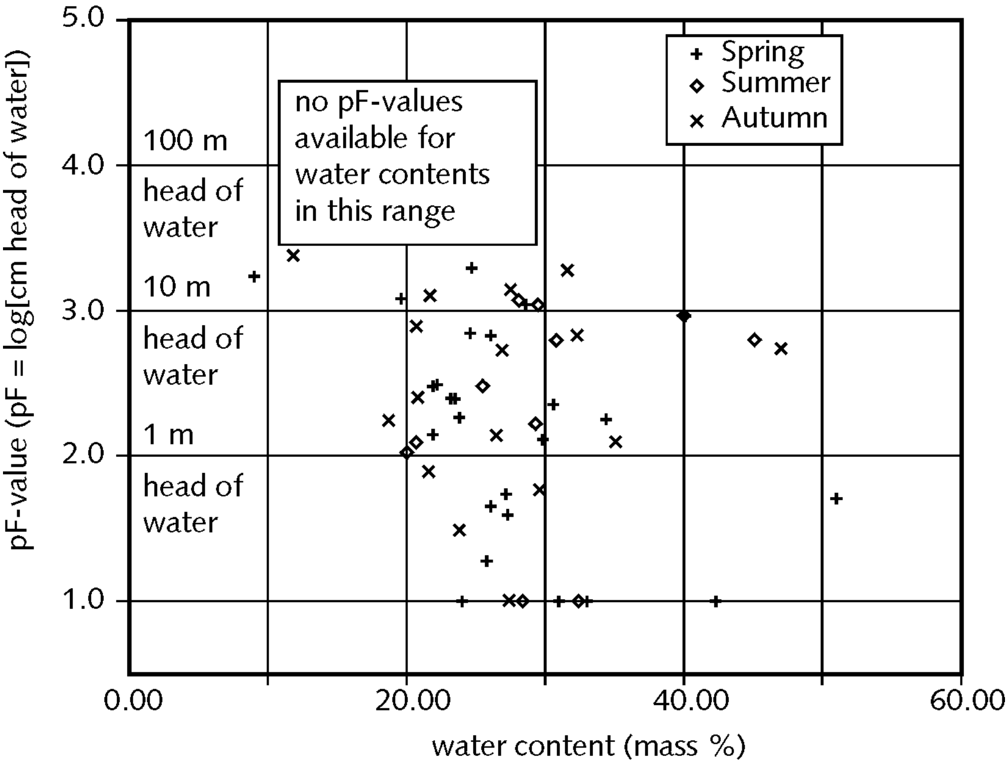

Figure 3.4: The consistency index of clay in clay coverings of Dutch dikes and the suction pressures (pF values) thereby determined. The I_c is for pF = 3 higher than approx. 0.75.

3.2.3 Cohesion

The cohesion of clay is caused for an important part by the affinity of the particles for water. Water molecules bind to these particles, by which they form a link between the particles. In addition, the binding of water molecules to dissolved compounds is also important for cohesion. Due to the mobility of water molecules, cohesion remains as a result of binding between water molecules even if clay is heavily kneaded. The Atterberg limits and the consistency index also play a major role here (see section 3.2.2). A large amount of water that does not contribute to the cohesion of the soil is found in clay types with a relatively high plastic limit in relation to the flow limit and thus a relatively low plasticity index.

A decreased water content increases the cohesion of saturated clay because the particles then lie closer together. The clay then behaves in a more plastic manner than as a thick fluid. Further dehydration leads to decreased plasticity.

In addition to the affinity of the solid particles for water, the cohesion in clay is also partly the result of direct linking of mineral and organic compounds in the soil to each other. These bonds occur mainly in minerals and organic materials that are fixed chemically to the surface of more than one particle and therefore link the particles together like cement. This 'cementation' causes relatively very strong bonds, by which the soil becomes sturdy to hard. Cementation bonds are mainly formed after several hours or sometimes even years. The bonds are not very flexible and are therefore broken during larger amounts of deformation. The previously mentioned iron and aluminium compounds form an important category of these cementing materials and are often the cause of the increase in the strength of blue or grey clay that comes into contact with air. In addition, many converted organic compounds function as cementing material.

3.2.4 Influence of coarser fractions

The somewhat coarser fraction in clay (the fraction bigger than 10 - 20 μm) influences the properties of clay, such as its bulk density, permeability and deformation. If soil in the unsaturated zone contains many coarser particles (more than 60 - 70%), the fine fraction distributes itself in a layer around the coarser particles, especially at the points of contact. A soil such as this has a relatively low specific surface area. It consists of a skeleton of coarser grains on which fine material is lying and in which the larger pores remain open between the grains.

If there are few coarser grains present in a clay (i.e., a clay with a high specific surface area), then these drift as it were in one mass of fine particles. In that case, the coarser fraction has relatively little influence on properties such as permeability and shear formation. The grain-size distribution of clay gives an insight into the influence of the coarser fraction and is partly therefore of importance for the evaluation of the clay.

3.3 Clay as natural soil

When considering the properties of clay as a natural soil, this concerns mainly civil engineering properties such as water permeability, erosion resistance, shape retention, etc. These properties can vary a great deal after application of the clay, and this is dependent on, among other factors, the surroundings and the method of application. These properties and the direct background to them will be briefly discussed in the following paragraphs.

As already indicated in Chapter 2, the *soil structure* has an essential influence on the various civil engineering properties. Consequently, in this chapter, we shall first give ample attention to this soil structure before going further into the various civil engineering properties.

3.3.1 Soil structure

Clay shrinks and expands due to drying and wetting, and these changes are directly connected to changes in the water content of the clay. The change in water content in unsaturated soil is, as described in section 3.2.2, caused by differences in suction pressure. Clay in the unsaturated zone undergoes thereby volume changes due to changes in suction pressure. The relative volume change in this sort of clay is about half the change in water content (expressed in mass percentage).

The shrinking and expanding of soil in the unsaturated zone is linked to the formation of cracks. When soil shrinks, 'pull' cracks appear; when it swells, shear areas appear in the ground. The larger shrinkage cracks are mainly vertical, also in a dike bank; smaller shrinkage cracks and the shear areas can be found in all orientations. Crack formation produces a soil that consists of aggregates of various dimensions. The composition of these cracks and aggregates, together with pores and aggregates made by animals, is called the *soil structure*.

The development of this soil structure is on the one hand dependent on the properties of the clay, such as the interaction between the clay particles and water, and on the other hand on factors in the surroundings that determine change in suction pressure. In addition, burrowing activities of earthworms or larger animals also play a role, by which the shape and size of aggregates and cracks continually change. The soil structure under and in the grass sod is then also rather dynamic: new aggregates are continually being formed and then collapse again.

The soil structure can be more or less clearly developed. For a strongly developed soil structure, we can talk of aggregates that are clearly individually recognisable and that show few connections with each other. Such a marked structure develops from continuous movements due to expanding and contracting, or from a single very strong shrinkage, after which the large splits that occur are not filled in again. Rapid changes in water content, e.g., due to rainfall, cause many small cracks and therefore a fine soil structure. In the uppermost decimetres under the grass sod on a dike bank the structure is usually very strongly developed and consists of relatively small aggregates with dimensions of millimetres to centimetres. The aggregates are often linked to each other by roots (see Figure 2.3A). At greater depths under the grass cover and in clay layers under stone settings, the aggregates are often less clearly recognisable. The dimensions there are sometimes more than 10 cm and there is often still some cohesion present between the aggregates.

In clay that becomes wet very regularly, under the influence of the tide, such as clay under a stone covering below the high-water line, a soil structure is formed only in the uppermost centimetres to decimetres of the clay and the structure is often less easily visible.

Within a period of a few years, a clear soil structure forms under a grass sod to a depth of more than 0.8m. The available observations show that in a period of 5 years a clearly recognisable soil structure can occur under a stone setting, and that after 10 - 15 years the soil structure is present everywhere. A strong soil structure can develop even in clay under asphalt [37].

When clay with a high water content is brought on above the water table, the water content will decrease until it reaches equilibrium with the suction pressure in the surroundings. The clay will therefore shrink once only, together with the formation of large cracks. In the upper soil, these cracks do not last long due to homogenisation by burrowing animals and root activity. Below a few decimetres under ground level these cracks remain for many years; such 'fossil' cracks have been found in the core of a dike more than 10 years after its construction [33].

It should be clear that the presence of soil structure is a major influence on the water permeability of clay layers. A top layer of clay will have a considerably greater permeability than tests based on clay samples have shown.

Soil structure is not only found in the cover layers of a dike; it can also be found deeper in the dike body. For example, if a dike is intermittently increased in height, some of the various layers will have once been surface layers and therefore will have soil structure. In that case, such a dike consists of a stack of layers of soil with a particular soil structure (Figure 3.5).

Worm tunnels, etc., sometimes also penetrate deep into the dike and result in soil structure formation (see Figure 3.6). At greater depths in the core of a dike, soil structure has been found that was the result of root penetration from growing vegetation on the dike. There is very often a soil structure present even in the core of a dike due to these types of situations. This also has consequences for the water permeability of the entire dike body..

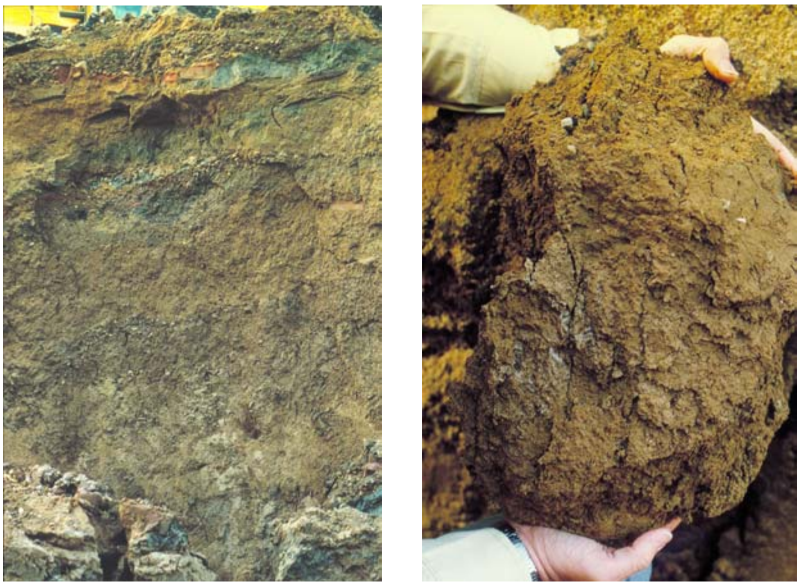

Figure 3.5: Soil structure in the core of a dike that was hardly attacked after an increase in height. A: Increment recognisable in low-level construction Erlecom Dam. B: Lump of soil structure from 1.5 m deep, from the lowest layer of Figure 3.5 A.

Figure 3.6: Worm tunnels in a dike core at Hank, 2 m below the crown: the worm tunnels were found in large numbers up to 0.6 m above the local groundwater level.

In section 3.2 we mentioned that the water content for a consistency index (I_c) of 0.6 gives an indication of the maximum water content for clay in the core of a dike well above the water table. An indication of the maximum water content for clay in a covering is the water content for a consistency index of 0.75. When the clay is applied, if the water content is higher than that of the indicated consistency index values, then there will be a once-only decrease in the water content after construction. This decrease in water content results in the above-mentioned volume shrinkage and crack formation.

The formation of soil structure considerably limits the composition of a clay layer and a network of coarse pores will occur. The civil engineering properties of a clay package with a soil structure therefore differ strongly from those of individual aggregates from such a package. In structured soil, surface water can infiltrate rapidly and a great deal of water can be drained off through the large cracks and tunnels. The soil structure formation is favourable and often even essential for vegetation and other soil life, considering that aeration is greatly improved and roots can find an easier way into the soil.
Sand inclusions in a clay package lead to the same effects as the cracks in the soil structure. The composition of a clay package is broken up by sand inclusions, and the permeability of a sand inclusion is also many times greater than that of the clay itself. Sand inclusions also influence the formation of soil structure, by facilitating the entry of oxygen and the drainage of water. Strong discoloration can often be seen around sand lenses due to precipitation of iron and manganese compounds.

3.3.2 Microstructure

As well as the previously discussed soil structure formation, changes in water content also affect the so-called 'microstructure' of clay. This microstructure refers to the spatial composition the smaller and larger soil particles. Decreasing the water content of a grey or blue clay, or of a mineral dredging slurry, brings the particles very close together and this tighter packing creates very tight bonds between the particles, so that they only break apart if the clay is made wet again. The effect of this close packing is considerably strengthened by the presence of the cementing materials discussed in section 3.1. Repeated changes in water content strengthen the close order of the particles and make the clay stronger.

In general, clay is already considerably stronger one summer season after being dug up due to the changes in composition and microstructure. The aggregates in a clay in a dike covering have a strength against shearing after a few years that is often many MPa (i.e., c_u value of laboratory paddle test). Clay in an unsaturated zone in the core often has an undrained shear strength much higher than 100 kPa. Fine-grained mineral dredging slurry can be transformed into very strong clay within 2 to 4 years by exposure to the atmosphere. The changes that then take place in a dredging slurry, or in grey or blue clay, are often called 'ripening'. The effects of the changes in microstructure of 'ripe' clay are destroyed again by intensive kneading.

3.3.3 Permeability

The permeability of clay after application increases strongly due to the occurrence of cracks and animal tunnels, as mentioned in section 3.3.1. During a study, the measured infiltration rate for water at many locations on dikes was 10^{-5} to 10^{-4} m/s, with measurements being taken from the early Spring up till Autumn. The variation in infiltration rate on a dike bank was greater just a short distance apart that would be expected based on seasonal variations.

The process of compacting poured clay makes it much less permeable. The permeability of well compacted clay covering on a dike was less than 10^{-6} m/s shortly after application. In the first six months after application, the permeability increased to about 10^{-5} m/s, which is a ten-fold increase as a result of almost invisible cracks formed by the clay drying out.

The infiltration rate was measured at two locations, in the deeper-lying parts of a dike [33] and, at both locations, the infiltration rate was also about 10^{-5} m/s. The core material consisted in one case of sandy clay and in the other of clay that was perforated by worm tunnels to about 60 cm above groundwater level. At six existing dikes from which a part of the core was dug clear, only one gave the impression that structure formation and material properties from a part of the dike were such that the bulk permeability was significantly lower than 10^{-5} m/s [33].

Based on the above, it does not seem possible to influence the permeability of clay coverings in the longer term by applying a certain type of natural clay. The permeability of the clay top layers will almost always lie between 10^{-6} and 10^{-5} m/s for the above reasons.

3.3.4 Erosion resistance

Various mechanisms can be distinguished that are responsible for the erosion of clay in dikes; for example, the dispersion of fine particles in water, the sweeping along of particles under the influence of the flow of water, and the forces from breaking waves. How these mechanisms work depends on the loading and the structure in the clay.

Fine particles in clay can under certain conditions be taken up without any flow of water; the clay dissolves (i.e., disperses) them, so that the particles and the dissolved material attract so much water that their underlying coherence is lost. This form of erosion works very slowly in most Dutch clays, but can be important under changing fresh-salt water conditions. Erosion under a hard covering can also occur partly by this mechanism in erosion-resistant clay in the longer term and its function is then affected (e.g., from the effect of channel formation under a stone setting).

The flow of water in the soil can loosen individual particles and small aggregates, and this phenomenon is observed as more or less regular wear of the surface. As is well known, this mechanism quickly leads to a large amount of damage due to water flow in sand, and in sandy clay this erosion mechanism quickly leads to damage. Using a laboratory erosion test apparatus, the erosion of various types of soil that have no root penetration can be compared. It appears that soil with more than 40% sand is eroded very quickly by relatively limited flow rates and even soil with a plasticity index lower than 18% erodes quickly. A low level of fine particles is also indicated by a similar plasticity index.

The sticky clay types, with a flow limit higher than 45%, do not suffer from a large amount of erosion by water running along them. Water can flow at a speed of 8 m/s along such a clay for several hours without causing more than 1 to 3 mm of wear, if the soil is well compacted or has been in the unsaturated zone for a long time. Only some clays in a study, with a flow index higher than 45% showed strong erosion, but these all had a relatively low flow limit in relation to the plastic limit. It was also observed that a number of samples with a relatively limited sand content but with a flow limit lower than 45% showed relatively strong erosion. The findings from the laboratory erosion test apparatus agree with results from large-scale tests and with field observations of erosion damage. They also agree with those from large-scale tests in 1992 on erosion in clay with a high flow limit [51].

In Chapter 5, the findings from various studies have been combined into a number of requirements that are characteristic for the erosion resistance of clay. The Atterberg limits and the sand content are used to distinguish **three categories of clay**; see Chapter 5 for a more extensive discussion.

If soil has a strongly developed fine soil structure, then also with sticky clay, erosion can occur by the disappearance of smaller aggregates, just as with erosion of sand. In contrast to sand grains, small aggregates can be anchored very strongly to each other by roots (Figure 2.3) by which the grass sod becomes relatively erosion-resistant.

Little erosion is caused as a result of the flow of water on banks with grassland vegetation. Water flowing over such a bank even causes almost no erosion on relatively sandy clay, but the grass sod must be in compacted condition. It must be noted that significant damage can still occur to the grass mat of grass-covered banks. This damage occurs mainly, where it is visible, in the zone where waves break and where other forces are operating than those from over-topping water (e.g., as a consequence of driftwood). Tests on grass mats with very sandy soil show that damage by waves occurs very slowly or not at all in compacted grass mats when these waves (Hs) are lower than 0.2 to 0.3 m.

An important erosion mechanism for wave attack is the force as a result of breaking waves [27, 43]. For clay with a soil structure, the breaking away and disappearance of soil aggregates are an important form of erosion from wave attack. The lumps can be swept away by a variety of mechanisms, which are related to the build up of pressure in the bank as a result of the wave action, the forces on the bank from breaking waves and the consequential water movement over the bank [32]. The large-scale tests performed in 1992 on clay with soil structure showed that this manner of erosion was the main cause of damage from waves of 1 m (Hs) in otherwise erosion-resistant clay [51, 52]. The results of rough calculations suggest that actually this form of erosion probably hardly ever occurs with waves of less than 0.5 m [32].

Damage develops faster due to the interaction between the various involved erosion processes. In a relatively short time, holes larger than 0.8 m deep can form in clay without a grass sod with soil structure. Figure 3.7 shows an example of the damage that occurred in the Delta-flume tests in 1992 on clay without a grass sod.

Large-scale tests also in 1992 were performed with waves of 1.5 m (Hs) on clay with a grass sod and a bank slope of 1:4 [52, 38]. These tests showed the protective nature of a good grass sod: a large amount of damage only occurred to the clay with a soil structure after the grass sod on the clay had been severely affected. In this test, local weak areas could be seen only after more than 16 hours of wave loading. Over-topping of more than 5 l/m per second generated during the tests also caused no noticeable effect on the inner bank.

In general it can be suggested that high waves can cause great damage in a short time in the zone above average high water in clay without a grass sod or hard covering. Low waves can only cause damage in poorly erosion-resistant clay if it is not adequately protected by a covering. It can be noted that over-topping water only causes damage on clay with little erosion resistance and that does not have an adequately compacted covering. Clay from the unsaturated zone shows a much greater erosion resistance in laboratory tests than will occur due to the loads from over-topping.

Figure 3.7: Damage caused by erosion of lumps from a clay layer with soil structure formed under a stone setting. The clay is in the form of lumps eroded out of a hole that is 0.4 m deep. Some lumps show brown patches due to iron compounds.

3.3.5 Shape retention

Shape retention is mainly of importance for the clay that is worked in thick packages in the core of a dike. The firmness of a package of clay directly after application depends very closely on the water content and the amount that the package is compacted. The firmness increases in most cases after application (see section 3.2.1). A possible exception to this is a dry worked clay that is compacted intensively, and such a clay can, if applied close to the groundwater, be temporarily somewhat less firm. It is apparently not possible that a change from salt to fresh water environment, or vice versa, has important effects on the strength of well-compacted clay. The shear resistance and compression properties of compacted clay can therefore, immediately after application, be indicative for the shape retention.

The deformation properties of a certain type of clay are, immediately after application, dependent on many factors. There are no clear relationships available between classification test results and deformation properties of clay, thus a quality evaluation based on this relationship can also not be proposed. The deformation properties on application can be determined using the normal soil mechanics tests because the water content of the clay during application is usually known and the degree of compacting can be specified. Reduction in the water content of a clay core that was applied in a too wet state can reduce the volume of the clay by several percent (apart from consolidation by loading from above from the soil body). Clay in the unsaturated zone of the core usually becomes firm to hard with time.

As mentioned earlier, a soil structure occurs in the core that also often limits the internal cohesion of the core and strongly increases its permeability. This change of properties also has an influence on the shape retention properties of the clay.

3.3.6 Workability

The workability of clay is of great influence on the manner in which the clay can and will be applied and compacted. It influences therefore to a large extent the functioning of a clay package in a dike. The erosion resistance and shape retention of a clay top layer that has just been applied depends strongly on the degree to which the clay has been compacted, as explained in the previous sections.

In order to be able to work the clay it should be as plastic as possible so that the lumps can be compacted together into a cohesive whole by the earth-moving machines. The clay must, in contrast, also be sufficiently hard to be able to offer enough bearing capacity to cope with the tyres and tracks of the machines, and the soil should not remain sticking to the machines in very thick lumps.

The firmness and stickiness of clay are closely related to the water content, as also is the workability. The workability is often indicated by the water content in relation to the Atterberg limits and the consistency index, I_c (see section 3.2.2). When clay is very wet, its workability will be limited due to its stickiness and limited strength. In contrast, when clay is very dry, the lumps are often so hard that compacting is only effective in the uppermost centimetres.

In general, clay is at its best desired packing density for working with when the water content lies close to the plastic limit, that is between the plastic and flow limits. If the consistency index is 0.6 then the clay is easy to work with; a lower consistency index usually leads to more difficult working possibilities.

Compacting of clay with a water content near the plastic index requires a relative high load. Vehicles with tyres, or the scoop of an hydraulic crane, can only compact adequately the top one to two decimetres of this type of clay. Bulldozers can generally adequately compact this sort of clay to a greater depth. Compacting of a clay layer must be evaluated for the effect on the underside of the compacted layer.

The workability can be strongly and negatively influenced by an excess of water on the edge of the lumps and at the contact surface between the tools and the clay. Some heavy rain showers can considerable limit the workability of the clay, while the shower may have increased the overall water content of the clay package by very little.

Finally, it should be noted that the water content, as well as having an influence on the workability, also affects the formation of soil structure. As already discussed in section 3.2.2, if the water content of a clay during working is much higher than the representative water content of the clay in position on the dike, then large shrinkage cracks will occur in the clay body and these will not disappear.

In general, the water content required for working of clay in the core and in the covering of a dike (see Chapter 5) almost always leads to a reasonably good working situation

CHAPTER 4

4 Clay in functional sections

4.1 General

In the design of a dike and its different clay sections, there are various aspects that play important roles. Considering the local situation, these could be, for example, the geometry of the dike, the orientation of the banks and the type of management. Many of these aspects fall outside the scope of the current report and, for design, the reader is then also referred to guidelines and assistance from the TAW.

In Chapter 3 the properties of the material and the changes therein as a consequence of factors in the surroundings, for clay as a mineral soil item and for clay as natural soil were extensively discussed. In the current chapter, the aspects are described that are concerned with the use of clay as a material, with attention being given to the possible influences of the surroundings which must be taken into account. A distinction has been made between the functional sections to which clay is applied in a dike:

- clay in top layers;
- clay in dike cores;
- clay in ‘clay-boxes’.

A top layer means both for inner and outer banks, and also horizontal top layers on foreshores for inhibiting the percolating water.
Requirements and recommendations are given for the clay to be used in the various functional sections.

4.2 Top layers

A clay top layer is applied on or close to the surface of the dike, which in practice usually means clay layers on the bank of the core of a dike, covered with grassland or a stone setting. The top layer functions to protect the core against damage, with the clay mainly fulfilling the function of limiting permeability and usually also acts as the substrate for the covering.

For clay worked as a top layer, the following constructions are considered in this section:

- top layer on bank under a grassland covering;
- top layer on foreshore to inhibit percolating water;
- top layer on bank under a 'hard' covering.

Figure 4.1 shows a summary of these functional sections. The layers lie at or close to the surface of the dike and therefore the weather and atmospheric conditions have a major influence. The fact that close to the surface of a dike the suction pressure in the summer is often more than a 100 m head of water as a result of the relatively high temperature and the suction force of the vegetation was explained in section 3.2.2. In the summer, due to rain and temperature changes, the suction pressure can change wildly.

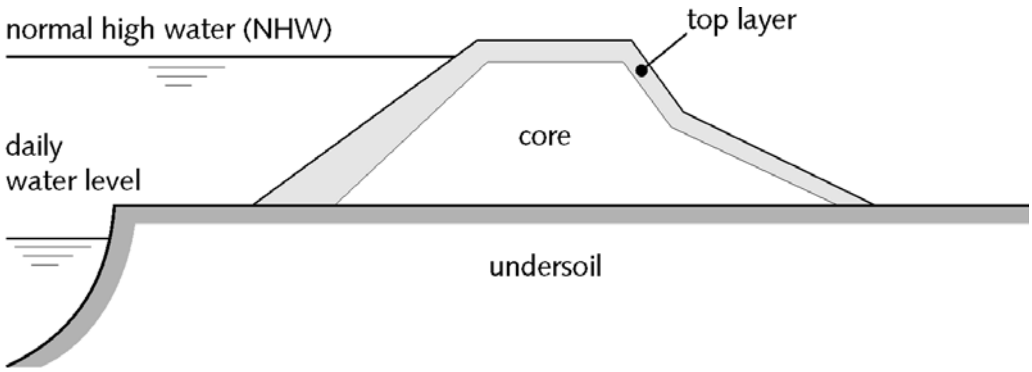

Figure 4.1: Functional sections of a flood water defence dike

The representative figure of a 10 m head of water (pF = 3) has been established for grassland banks in the Netherlands in the Summer (Figure 3.3). This figure is also valid for the suction pressure under a stone setting, although it does not change so quickly and the effect of vegetation is absent. Therefore, the water content at the time of construction must not be higher than this value.

The suction pressure in the clay covering of a dike under wet winter conditions is often an average of less than a 1m head of water. In the sod (the layer in which most roots are present) the greatest changes in suction pressure occur by changes in precipitation, water extraction by roots and very large temperature differences.

It is important for top layers on the foreshore for inhibiting percolating water that little shrinkage occurs. The same safe and representative value for suction pressure of a 10m head of water can be used. A lower value can be used, depending on the position of the water table and its variation, and clay with a higher water content can be worked in. It is recommended to maintain a maximum water content for clay that will be worked into the core of a dike.

4.2.1 Design of top layers

Substrate function

The substrate function of a clay layer requires a certain shape retention, depending on the type of covering, and the shape retention of a clay covering immediately after application depends mainly on both the water content and the degree of compacting of the loosely dumped clay (see section 3.3.5).

For a hard covering, the clay must be compacted so that at least the large pores between the lumps are sealed shut, because settling can occur by compaction and gradual internal erosion in the package after insufficient compacting. This can literally undermine the function of a hard covering with time, due to erosion of the underlying clay. A great deal of erosion can occur from wave loading in non-compacted clay under a hard covering and undermining can also occur due to the phenomenon of clay dissolving, as it were, dissolving as discussed in section 3.3.4. Large differences in salt content reinforce this type of erosion; salt-water clay in a fresh-water environment especially is sometimes sensitive to this form of erosion for several years.

The upper soil layer in the zone into which it is intended for roots to grow must not be too strongly compacted in order for the plants to have the opportunity to grow adequate roots. The penetration of grass roots into firmly compacted clay takes so much time that the young roots of newly growing grass obtain too little water and food for the plants to survive. Sod formation is improved by good combinations of food materials, and appropriate water and aeration provision to the top layer. This layer must not dry out too quickly (such as sand) yet it must still be sufficiently aerated for the release of carbon dioxide and other gases. All of this goes together with the type of management of the dike bank.

A grass sod can adjust itself over a period of months to small changes in the bank surface; the grass covering following the changes in the bank surface. A grass sod is therefore less sensitive for local shallow erosion and other slight damage to the bank.

Protection function: inner bank and crown

The design of an inner bank and the crown of a dike are discussed in the 'Manual for Assistance in Constructive Design of River Dikes' from TAW (Handreiking Constructief Ontwerp Rivierdijken), April 1994. In section 3.2.3 'Erosion of inner bank by over-topping' it is indicated how and in what way a sufficiently strong inner bank can be designed, depending on the loading, bank slope, type of grassland covering and the clay category used. This allows selection of the most appropriate clay category for a particular bank.

Protection function: outer bank

The design of an outer bank is dependent, among other factors, on loading (flow and waves), bank slope, type of covering and strength of top layer (substrate and covering). The clay category used has an influence on the strength of the bank. There is no assistance manual yet available for the design of outer banks.

The geometry of a top layer on an outer bank of river dikes is often wedge-shaped (e.g., underside 1:2; upper side 1:3), so that areas likely to suffer from relatively frequent and prolonged loading have a greater resistance against infiltration and erosion (Figure 4.2). The wedge shape is at the same time favourable against shearing of outer banks after a rapid decrease in the outside water level, which can lead to over-pressure. The thickness of the top layer is usually maintained at a minimum of 1 m.

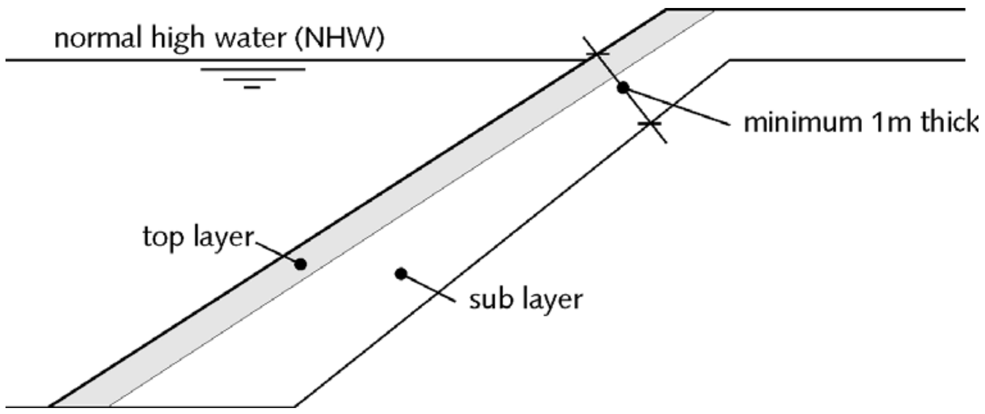

Figure 4.2: Wedge-shaped top layer on outer bank

4.2.2 Examples of top layers

Top layer with grassland covering

A top layer consisting of clay with a grassland covering is a simple and in many situations effective covering construction, especially for river dikes. Figure 4.3 shows a top layer with its distinctive sections.

The function of the top layer is, as mentioned earlier, protection of the core against damage, which requires a good erosion-resistant surface on the dike. The erosion resistance is provided by the interaction between the clay and the vegetation, by which diversity in the vegetation realises a strong sod and this can be achieved by the type of management.

There appears to be a contradiction here, such that stickier clay is more erosion resistant, whereas a strong sod develops better on a poorer clay. For this reason, the top layer is built up of an upper and an under layer. The upper layer of about 0.3 m consists of material on which vegetation can develop well; the under layer consists of erosion-resistant clay (see Figure 4.4).

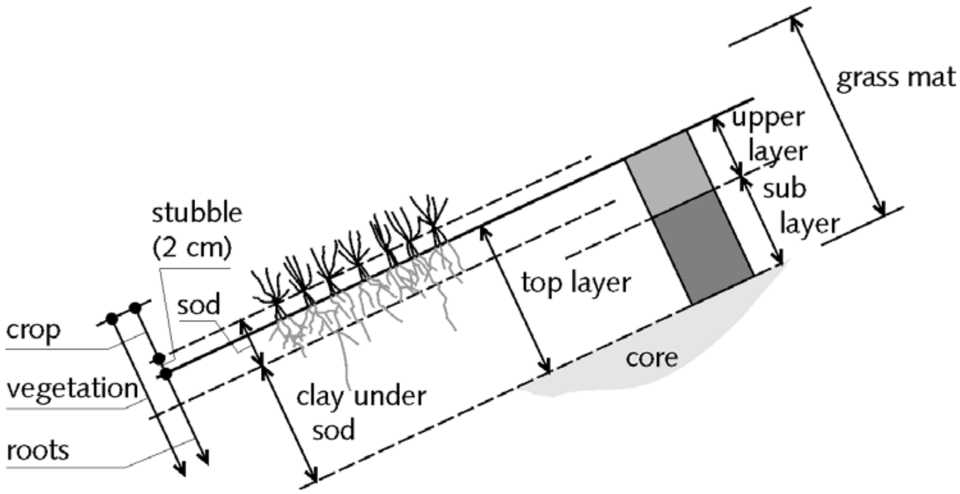

Figure 4.3 Structure of top layer sections

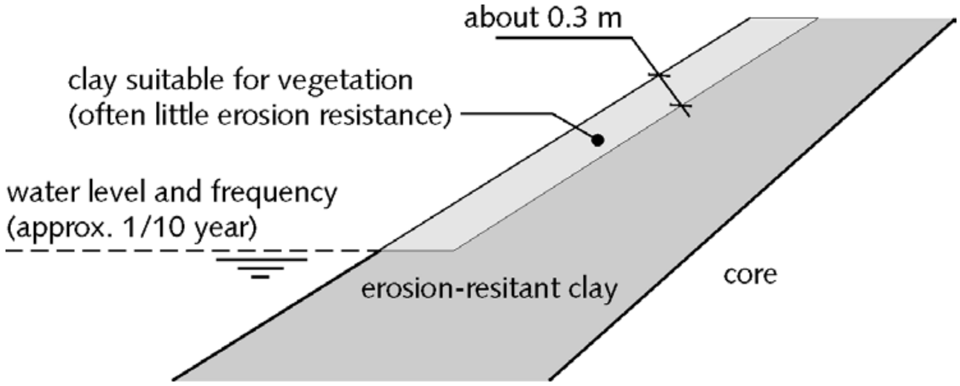

Figure 4.4 Differentiated top layer

Material is also used for the top layer from the old dike when improving dikes, when interesting vegetation is growing there. The TAW is currently studying further the erosion resistance of banks with grassland coverings.

The reports 'Construction and management of grassland on river dikes" by L.M. Vliervoet and 'LNC aspects and management of steep dike banks' in the manual 'Constructive Design' (TAW, April 1994) should be consulted for assistance on management. Note: landscape-, nature- and culture-history- values are abbreviated in Dutch as LNC-values.

The development of a species-rich vegetation on a newly applied bank takes 3 to 5 years and especially immediately after construction when the vegetation has not yet adequately developed a top layer is vulnerable to erosion. For this reason the application of a more sandy top layer on the outer bank, in which a species-rich vegetation can develop, is limited to the parts that lie higher than will be affected by a water level with a frequency of approx. 1/10 years. In the lower parts of the bank, where there is a greater chance that in the winter water will lie against the bank the whole top layer should be made of erosion-resistant clay. The lower part of the bank can also be covered with sods.

There are no indications that the covering of a top layer with growth fostering cellular stone-blocks, that are then filled or over-filled with clay, results in better erosion resistance than grassland vegetation without these stones.

Top layer on foreshore

Top layers on a foreshore to inhibit percolating water must be compacted up to the clay layers in the outer bank of the dike. The layers in the foreshore are not or very rarely loaded by wave impact. The function of this layer is to keep the water away as much as possible by having a very low permeability. As mentioned in section 3.3.3, clay layers with strong soil structure achieve a permeability of 10^{-4} to 10^{-5} m/s, which is a factor of 1 to 100 smaller than the permeability of sand. In top layers on dike banks, this structure formation will always occur, but at greater depth in a horizontal ground level, in which sufficient moisture is available from the under-soil, less structure formation will occur. More sandy clay types will also show less soil structure formation, and these types are also suitable for horizontal compacted clay layers in the foreshore.

Top layer under a 'hard' covering

'Hard' coverings are divided into the following types:

- Closed coverings are impermeable sheet constructions of cement or hot-rolled asphalt.
- Open coverings are permeable constructions, which can further be divided into:
    - Set coverings, such as basalt, or concrete pillars, blocks or stones;
    - dumped crushed stone coverings;
    - sheet constructions of permeable material, such as open colloidal concrete or open stone asphalt.

An under layer of clay will not be selected for a new section of compacted covering; the requirements for such a clay are therefore not discussed.

The clay is brought on immediately under the hard covering or under a filter layer for open covering, and a geotextile can even be applied above the clay.

The clay under a hard covering relies on the erosion resistance of the bare clay because it must ensure sufficient residual strength in the event that the hard covering should collapse. It should be clear that the amount by which a soil structure has developed in the clay determines this residual strength.

In general, erosion will be caused by the water from wave run-up and from precipitation. In open coverings, erosion channels regularly appear in the clay.

Clay under coverings must also be of a good erosion-resistant type (category 1) and must also be well compacted.

4.3 Core material

The most important property of the clay in the core of a dike is its shape retention, which depends on the water content after application, and the amount of compacting; it also decreases in general after application (as mentioned earlier).
When a core at the same time is given the function of limiting consequent damage when the top layer is damaged, then requirements must also be set on the erosion resistance of the clay in the core.

4.4 Buried clay

Buried clay, i.e. a subterranean application of layers of clay intended to close off water-transporting sand layers (‘clay-box’) usually means application in the saturated zone, with the only function of limiting the permeability. The only important properties for the clay are those of compression and workability.
When clay from a saturated environment is worked into a clay-box, it is possible to achieve a much lower permeability than with structured clay; this applies to the section that will be under groundwater level.

CHAPTER 5

5 Evaluation of clay

5.1 Requirements

5.1.1 General

The selection of a certain category of clay that should be used in a particular situation should be made on the basis of the functions that it needs to fulfil and the way in which these functions can be appropriately and efficiently carried out.

This chapter mentions the requirements that clay must comply with in order to fall within a particular category.

The basis for the classification of clay are three categories of erosion resistance. When clay complies with the criteria for a particular category, in principle the composition of the clay is such that it is already or can be made suitable for application in a dike. Before clay is definitely suitable to be worked into the dike, it must also comply with the requirements for water content (consistency index).

When the clay does comply with these requirements and good compacting is achieved, then an optimum result for the various construction sections can be realised, including permeability, shape retention and erosion resistance.

5.1.2 Description of requirements

The following table shows the requirements that must be checked during evaluation of clay for use in dikes, within the following categories:

Category 1. Erosion resistant.
Category 2. Moderately erosion resistant.
Category 3. Little erosion resistance.

The distinction between the three categories is based on the Atterberg limits and the sand content. In addition, some extra requirements have been added for the other important properties that are valid for all three categories. The requirements are in the area of organic material content, salt content, chalk content, colouring and smell. Furthermore, the current requirements for soil regarding toxicity and environmental effects are also relevant.

Regarding the requirement for the water content for clay in the core of a dike, a distinction is made between a water-impermeable function and clay that simply acts as filler in the core. The first function requires clay with no soil structure from shrinkage cracks, and also drier clay is required.

Table 5.1: Overview of requirements for clay used in dikes

Erosion-resistance category	Limit values for classification tests (all figures are mass % compared to dry mass) w_1 = flow limit $\boldsymbol{I}_p$ = plasticity index $\boldsymbol{I}_p$ = 0.73*(w -20) is the so-called A line in the plasticity diagram (Figure 6.1)
1. Erosion-resistant clay	w_1 > 45 and $\boldsymbol{I}_p$ > 0.73 * (w_1 - 20) and sand content < 40
2. Moderately erosion-resistant clay	w_1 < 45 and $\boldsymbol{I}_p$ > 18 and sand content < 40
3. Clay with little erosion resistance	w_1 < 0.73 * (w_1 - 20) and/or $\boldsymbol{I}_p$ < 18 and/or sand content > 40

For all clay in dikes, the following is also relevant:

Organic material content < 5
Salt content (NaCl g/l soil moisture) < 4
Water content for working : top layer: $\boldsymbol{I}_p \geq 0.75$
core: $\boldsymbol{I}_p \geq 0.60$

and also (because of possible variations in composition):

Chalk content (HCl loss of mass): < 25
No extreme colouring from excavation or drying
(bright red, bright yellow, bright blue or many black patches)
No deviating strong smell (rotten eggs, oily or coal aroma)
The requirements regarding flow limit and plasticity index are shown in Figure 5.1.

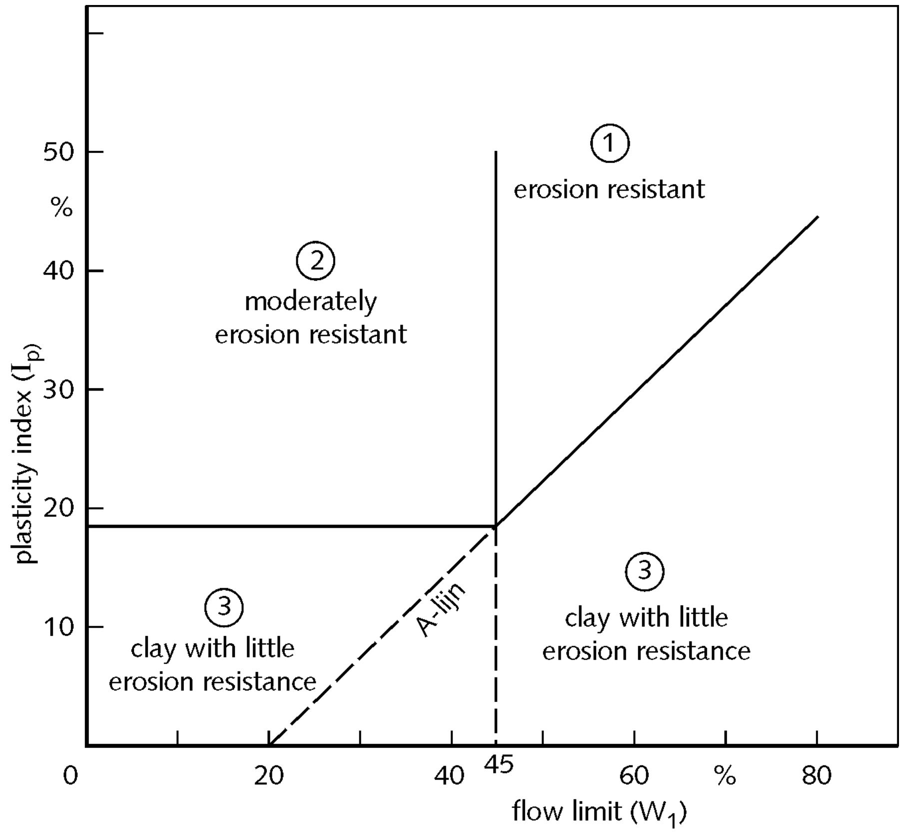

Figure 5.1 Erosion resistance shown as a plasticity diagram; the comparison of the A line is $\boldsymbol{I}_p = 0.73 * (w_1 - 20)$

5.1.3 Differences to previous requirements

Comparison of the requirements described in this report with those from the previous requirements [24] shows that the lutum content is no longer included as an test criterion, because the consistency limits have a better relationship with the behaviour of clay than the lutum content.

The maximum allowable sand content for erosion-resistant and moderately erosion-resistant clays is set at 40%. The previous minimum sand content is no longer applicable.

The maximum allowable organic material content is increased from 4 to 5 %, which is a very small adjustment. The new requirement is only included with the aim to limit shrinkage because degradation of organic material can lead to a volume contraction. The organic material content is also limited by requirements for the water content (consistency limits).

The evaluation according to the old and new criteria are set out in Figure 5.2 for comparison. All samples from the figure comply with the new requirements with regard to sand content. The figure also shows that clay that did not meet approval of the old requirements due to its too high lutum content often now falls into the category of erosion-resistant clay.

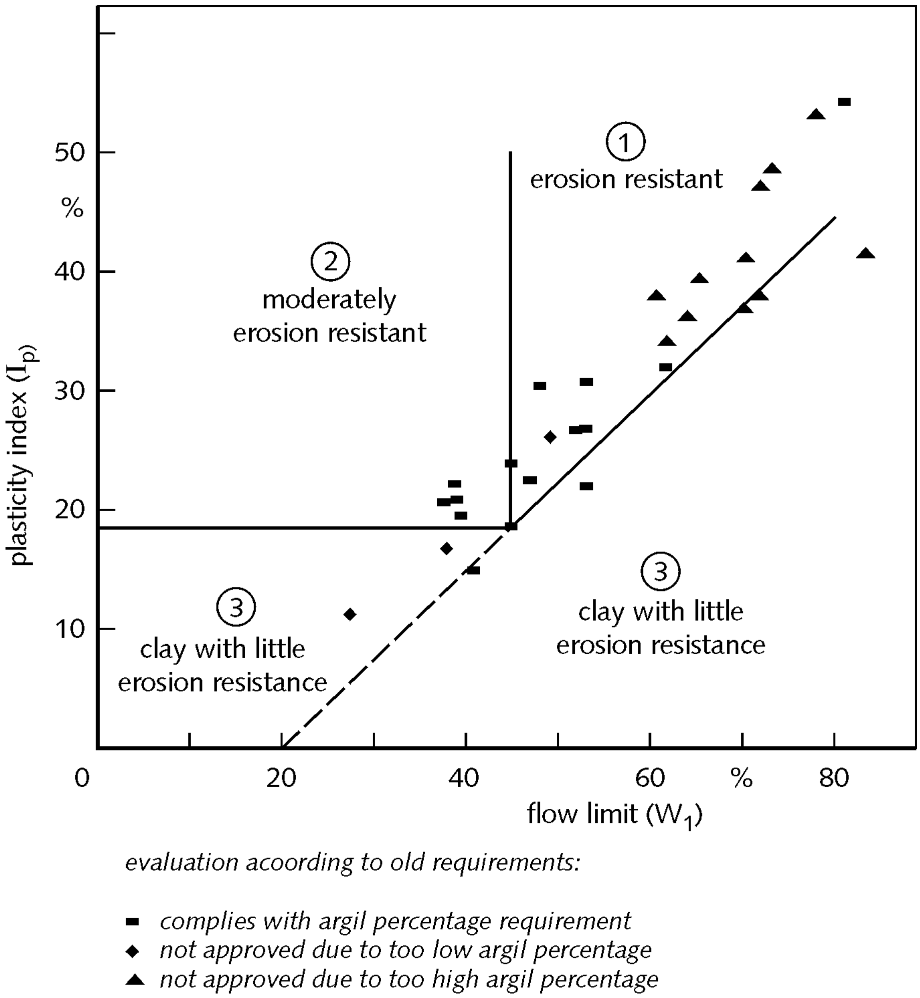

Figure 5.2 Comparison of old and new classification for clay (argil=lutum)

5.1.4 Impurities

Impurities in the clay, whether already present at the extraction location, or having entered the clay during extraction, transport or working up, can act by negatively influencing the clay. Specifically, impurities such as brick debris, wood, roots and other parts of plants, plastic, etc. The functional properties of the clay, such as erosion resistance, water permeability, shape retention, will become considerably worse due to these impurities. Clay may also not contain sufficient quantities of these impurities that they would be damaging to the constructive application of the clay.

The set-up and processing procedure for extraction, storage and transport must be aimed at keeping the various materials apart, and especially the prevention of sandy layers in clay constructions. This is particularly important for the sequence of working and the application of clay layers on a sand under layer. It should be obvious that visible sand lenses and sand layers should not occur in the clay. When a package of clay is seen to contain sand inclusions, then it should be held apart for evaluation and sampled more directly.

Clay to be worked on must also comply with the relevant regulations for chemical impurities; this report does not consider that aspect.

5.1.5 Water content on application

If clay with a higher water content than the representative suction pressure of the top layer is applied, the clay will dry out further and then shrink. This will lead to large cracks that will considerably affect the civil engineering properties of the clay. A maximum water content is prescribed to prevent this when working in a construction section., and this is expressed in the so-called consistency index, I_c (see section 3.2.2).

A requirement for clay for all top layers is that $I_c \geq 0.75$; for clay for the core as filling material $I_c \geq 0.6$. From this, the maximum water content w_{max} is:

$w_{max,top\ layer} = w_1 - 0.75\ \boldsymbol{I}_p$ and $w_{max,core} = w_1 - 0.60\ I_p$.

The optimum water content w_{opt} can then be derived from the Proctor test, as the water content by which the greatest density can be achieved. Compacting of drier clay than this optimum is made difficult by the strength of the lumps of clay, and good compacting of dry clay requires a lot of effort. For this reason, the optimum water content is also looked on as the minimum. For clay, the optimum water content lies 5 - 10% lower than for an I_c of 0.75, and 10 - 15% lower by an I_c of 0.6.

It follows that the water content by which clay can be worked lies above the optimum for efficient compacting (Proctor test) and under the maximum allowable water content :

5.1.6 $w_{opt} \leq w_n \leq w_{max}$Additional remarks

The water content of original blue or grey clay is often too high for the clay to be worked directly into a dike, because this would lead to undesired deformation after some time with large cracks both in the clay covering and in the core of the dike. Such wet clay should be dried before it is applied. Drying under Dutch conditions occurs fastest if the clay is dumped in not too thick deposits above groundwater level. Original blue or grey clay is only dried to the required water content in covering layers in a short time if it is spread out in layers thinner than 1 m.

Instead of using original clay resulting from natural sedimentation, it is also usually possible to use non-naturally sedimented clay, for example, Euroclay (clay produced from harbour silt from the Europoort in Rotterdam) and 'tarragrond' (soil from industrially processed roots and tubers). Clay can also be mixed from a variety of different types of soil.

Account should be taken of several factors when using these types of soil:

- the soil must be sufficiently homogeneous, which means taking account of:
    - sand and other coarse-grained inclusions;
    - coarse impurities;
    - large local variations in properties.
- the chemical and mineralogical composition should not be very different from that of natural soil used for dike construction. If there are larger differences, then the civil engineering functioning of the material must be examined. Important deviations are:
    - salt content;
    - toxic materials (for plants, animal and man);
    - variant organic materials;
    - larger amount of non-stable minerals.

During application of the clay, there is the possibility that sand from elsewhere in the working area gets into the clay package. The sand lenses and layers that then occur have the same effect as the cracks in the soil structure of the clay (see section 3.3.1). These sand inclusions can also be present in clay at locations where it has not formed a soil structure. A clay package with many sand inclusions has the same permeability and erosion properties as clay with a soil structure. The sand inclusions can actually erode very quickly and they should be prevented as much as possible for clay packages for which high requirements have been set.

Clay from existing dikes is often worked into new dikes, if it has been excavated. Old dikes usually have a very heterogeneous structure with a great variation in soil structure both longitudinally and across. Clay from old dikes must therefore be selectively excavated and then used. Clay in existing dikes is heterogeneous and structured. In the older dikes, structure formation has been found down to great depths in the core. The properties associated with this have consequences for the functioning of an old dike body as a part of a new flood water defence.

5.2 Testing

5.2.1 Procedure

The evaluation of the quality of the dredging to be worked is based on visual inspection, taking of samples and testing, and four phases can de discerned:

- preliminary inspection;
- testing during production;
- visual inspection on delivery, taking of samples, and testing;
- definitive testing after working.

Preliminary inspection and testing during production take place under the responsibility of the contractor. Based on this preliminary inspection, the management can determine whether they trust the contractor to supply the appropriate clay in sufficient quantities on time. Inspection and testing during production allows management to have a finger on the pulse for the supply of the clay.

Management then gives approval of the material to be worked based on the data provided by the contractor. The management are free at any time to take samples and to examine them (either themselves or by third parties) in order to be able to determine whether the clay complies with the requirements.
Testing of the supplied clay takes some time and this means that the results are usually not known before the clay has been worked. The management can give permission for the material to be worked on the basis of a visual inspection by the supervisor and/or on the basis of data provided by the contractor. The costs of testing samples means that not all packages of clay are tested and a large amount of the supplied clay will pass a visual inspection only.

If there is doubt on the quality of the clay from the visual inspection, it is worthwhile taking samples for testing. The approval for working of the material is on condition that, if a definitive test shows that the clay does not comply with the requirements, the contractor will remove the non-approved clay at his own cost and exchange it for suitable material.

By testing after working, the clay is tested on whether it complies with the requirements set, including the water content (I_c) and the compacting of the clay in the work. This testing takes place after working and is done by or on behalf of the management. This evaluation or testing then also determines the acceptance of the working, by which the quality must comply with the set requirements.

5.2.2 Visual inspection

The following aspects are of importance during visual inspection of the material supplied to the works (see Table 5.1):

- extreme discolouration;
- strong deviating smell;
- homogeneity;
- impurities;
- sand content;
- chalk content;
- consistency/hardness.

Care should be taken during visual inspection that the clay does not show extreme discolouration (bright red, bright yellow, bright blue, or many black patches). The soil also must not have a strong aroma, such as that of rotten eggs, oil or coal. The clay also must not contain any foreign objects, such as brick debris, plant roots, wood, etc., in such amounts that these could be damaging to the constructive application of the clay. Furthermore, the clay should be homogeneous, with no concentrations of sand or sand-rich material.

Soil can be classified according to the Dutch Standard NEN geotechnics 5104, for which the lutum, silt and sand contents and the amount of organic matter of a sufficient number of samples is estimated. NEN 5104 uses the triangular relationships lutum-silt-sand and organic matter-lutum-silt+sand for classification. The estimates of the amounts can be made by the supervisor or a soil expert. The material is rubbed through the fingers, and carefully examined visually. On the basis of experience, a reasonable estimate of the various fractions can be made and the soil can be classified.

The sand content and plasticity limits are of special importance for evaluation of the erosion sensitivity of the clay. The lutum content is no longer applied in the new requirements. An estimate of the sand content (either above or below 40) is easily achieved, and an adequate estimate for plasticity index is no longer needed.
The draft report 'Testing systems for grass mats' (TAW A3) established that, for evaluation of the erosion sensitivity of the supplied material, on the basis of a visual inspection, classification into category 1 (erosion resistant) is not possible. A guideline for this classification is the estimated sand content, and clayey sand and very sandy clay belong in category 3. Clay may not be classified into a better category than category 3 using this visual inspection method.

The chalk content can be determined using a simple test. Diluted hydrochloric acid (10% HCl) added to a crumbled sample results in effervescence. The amount of effervescence is a measure of the chalk content.

- chalk-free reaction is not audible or visible;
- chalk-poor reaction is audible and not visible to clearly audible with bursts of effervescence;
- chalk-rich strong and prolonged reaction.

The consistency or hardness of the clay can be determined using the hardness indications according to Sowers. In Table 5.2 an overview is given of the hardness classification and the simple-to-apply test

Table 5.2 Hardness indications according to Sowers

Hardness indication	Undrained shear strength [kPa]	Simple field identification test
very soft	< 12.5	presses between the fingers with a closed fist
soft	12.5 - 25	easily pliable with fingers
sturdy	25 - 50	pliable with fingers under strong pressure
stiff	50 - 75	fingers can be pressed in under strong pressure
very stiff	75 - 100	almost impossible to press in with fingers
hard	> 100	almost impossible to press in a pencil point

5.2.3 Taking samples

No mixed samples must be taken for the preliminary inspection for determination of the clay category, because this is intended to gain an impression of the distribution of the properties at the place of extraction. Mixed samples can be used for determination of the chemical impurities, as far as that is allowed in the regulations.

The preliminary inspection at the extraction site or in the depot should consist of the following:

- a representative number of drillings by an expert;
- three representative samples taken per soil layer for each clay category to be supplied. The total number of samples depends on the surface and thickness of the soil layers to be sampled;
- accurate description of the soil structure and the drilling locations.

Based on this preliminary inspection, it can be decided whether to excavate selectively for the various categories of clay.

According to 'Set-up of indicative soil study' from the Association of Dutch County Councils of 1986 [26], it is advised in the first instance to collect mixed samples, consisting of a maximum of 3 unmixed samples, for studying the degree of impurity. The total amount of samples must be adjusted to the question of how much chemical impurities can be expected (historic study). If it appears from one or more samples that the impurity requirements are exceeded, then a further study can be performed in which the extent of the impurities (in the surface, at depth, and the degree of impurity) can be established.

Testing during extraction takes place in the same way as the preliminary inspection by or on the responsibility of the contractor. The extensive nature of this study during the extraction shall be in relation to the non-homogeneity of the clay, as a result of the preliminary inspection and the method of excavation.

When the clay is delivered to the site, a visual examination is made either by or on behalf of the management and by which random samples are taken. When the visual inspection raises doubts as to compliance with the requirements, the samples taken may be tested. If part of a load suggests non-compliance then that part of the load can be marked as a part-load and random samples can be taken from it. Evaluation of the part-load is the same as for the complete load. When the part-load can be kept separate from the remainder of the load, then management can give permission for the part evaluated as good or approved to be worked.

With regard to checking the degree of compacting, the following remarks can be made: The volume of the bore samples for determination of the degree of compacting is relatively small compared to the dimensions of the lumps or aggregates. Selection of the place at which the bore samples are taken is therefore important. A check can be made along the walls of an excavated trench through the whole of the compact layer whether after compacting large pores or holes are still present. This information can be used as an indication for determining the place for the bore samples.

The set-up of the definitive testing after working must be determined for each project, by which the amount of study depends on the test results of the preliminary inspection, the testing during production and the weather conditions during working.

5.2.4 Testing

During the process, from extraction of the clay up to and including working of the clay, samples are taken from the clay (see section 5.2.1). These clay samples must comply with the requirements shown in Table 5.1. Furthermore, requirements are set for water content of the clay during application, in connection with the occurrence of contraction and in connection with good compacting (see section 5.1.5). After compacting, the dry density must be at least 97% of the Proctor density for the available water content (see section 6.2).

In order to check whether the clay conforms to the set requirements, standardised tests are used. The flow and plastic limits, the plasticity index, and the sand, chalk, salt and organic matter contents are important for studying the erosion sensitivity of the clay.

The flow limit is determined using the Casagrande apparatus, and is defined as the water content at which a V-shaped groove made using a standard knife just closes after the container is lifted up and allowed to fall down 25 times. The plastic limit is defined as the water content by which it is just still possible to roll out the clay into strips of 3 mm. The flow and plastic limits are determined according to test 15 of the standard RAW definitions 1990 (Dutch Tender Requirements and Specifications). The plasticity index is defined as the difference between the flow and plastic limits.

The sand content of the clay can be determined using test 2 from RAW 1990. The density of the clay and the water content are determined according to test 4.4, and the Proctor density according to test 5 of the standard RAW definitions from 1990.

CHAPTER 6

6 Aspects of implementation

6.1 General

In addition to the requirements for clay as discussed in the previous chapters, there are a number of aspects that deserve attention during implementation that can influence the functioning of the clay. These points for attention are described in a separate appendix, in which draft standard usage-description regulations for clay in dikes are formulated according to RAW systematics (Dutch Tender Requirements and Specifications). After publication of the Standard RAW Definitions 1995, in which the draft standard usage-description regulations are expected to be included, those are to be used and the concept regulations attached here will no be longer valid. For the definitions, the situation of 'implementation in the dry' will be used.

The most important points for attention during implementation of the clay are:
- compacting of clay;
- impurities in the clay.

6.2 Application and compacting

The influence of the water content on the workability of clay has been discussed in section 3.3.6. Some general aspects that are important for application and compacting will be discussed below.

Clay that has been transported for working in a dike consists of loose pieces and lumps, of which the dimensions depend on the composition, the moisture situation and the method of extraction. The aim of compacting is to work these lumps together so that the large pores and holes are pressed closed.

In order to achieve optimal compacting, the clay must be applied in layers no more than 0.40 m thick, each of which is compacted separately using a bulldozer.

By riding the clay up against a slope a larger gravity component exists by which more effective compacting is achieved. Compacting using a machine with tyres produces too great a contact pressure directly under the tyres, unless very low tyre pressures are used. Using the scoop of an hydraulic crane also does not lead to good compacting.

Clay must not be worked while frozen, because good compacting is then not possible.
After compacting, the dry density must be at least 97% of the Proctor density (one-point Proctor test) for the available water content. In the case of too firm

compacting, sheet formation, mixing and kneading together can occur, which cause loss of firmness of the clay and root penetration takes place with great difficulty and very slowly. For these reasons the clay to be applied over the work should be spread out evenly.

The clay should be worked such that no puddles can remain on the clay after precipitation. The clay layers must be applied so that it drains well.

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Appendix 1

1. Contract for and composition of project group. Composition of project group

The project group TAW-B6, 'Approval specifications for clay for dike construction' consisted of the following persons:

D.C. van Ooijen (chairman)	Directorate General for Public Works and Water Management
J.A. Muijs (secretary)	Directorate General for Public Works and Water Management
J. Dekker	Soil Mechanics Delft
L.M. Fliervoet	Agriculture University Wageningen
G.J. Flórián	Heidemij Advies B.V./Delft Technical University
G.A.M. Kruse	Soil Mechanics Delft
G.J. Laan	Directorate General for Public Works and Water Management
C.I.J.M. Liebrand	Agriculture University Wageningen
K.V. Sykora	Agriculture University Wageningen
M. van Zetten	Directorate General for Public Works and Water Management

The members of the project group all come from hydraulics or natural engineering backgrounds and are closely involved with improving river dikes.

The studies that are the basis of this report have been performed by or on contract to the Road and Hydraulics Engineering Institute of the Directorate General for Public Works and Water Management.

G.J. Flórián was succeeded by W.A. de Haan in 1992.

K. Zuurman (Heidemij Advies B.V.) and A. Hakkers (Building Contractor Hakkers Werkendam B.V.) were included in the sub-group for preparation of the RAW definitions, together with members of the project group.

Appendix 2

Specification of requirements according to RAW methodology (in Dutch)

(Dutch Tender Requirements and Specifications); (not included)

General information

In 1965, the Netherlands Technical Advisory Committee for Flood Defence (TAW) was inaugurated by the Minister for Transport, Public Works and Water Management. This committee was established as a reaction on the flooding of part of the city of Amsterdam as a result of a dike failure.

TAW is now functioning for almost 4 decades. Its tasks have remained the same, namely:

- giving the Dutch Minister of Transport, Public Works and Water Management (asked or on own initiative) advice on matters concerning safety against flooding;
- preparing handbooks and technical reports for the dike managers (water boards), and;
- overall guidance of the ever needed research (on technical aspects of water defences as well as on the technical background of the safety approach).

To realise these tasks, the committee consists of representatives of the three governments that play a role in water defences (State, Provinces and Water Boards), and specialists from universities and private enterprise. An independent chairman and secretary at the water policy directorate of the ministry complete the TAW. TAW is advised by four committees: Technical affairs, Safety matters, River systems, Coastal systems.
TAW does not have an own budget; the Road and Hydraulic Engineering Institute from the Ministry carries out the work.

For questions on TAW's activities please contact the Road and Hydraulics Engineering Institute (DWW) of the Directorate-General for Public Works and Water Management.:

PO Box 5044
2600 GA DELFT
THE NETHERLANDS
Tel. +31 15 251 84 36
Fax. +31 15 251 85 55
Email: tawsecr@dww.rws.minvenw.nl