# Soil Mechanics

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**Revised by S. van Baars**

VSSD

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# Preface

This book is part of the introductory course of Soil Mechanics in the Department of Civil Engineering of the Delft University of Technology. It contains an introduction into the major principles and methods of soil mechanics, such as the analysis of stresses, deformations, and stability. The most important methods of determining soil parameters, in the laboratory and in situ, are also described. Some basic principles of applied mechanics that are frequently used are presented in Appendices. The subdivision into chapters is such that one chapter can be treated in a single lecture of 45 minutes, approximately.
Comments of students and other users on the material in earlier versions of this book have been implemented in the present version, and errors have been corrected. Remaining errors are the author's responsibility, of course, and all comments will be appreciated.
Several users, from all over the world, have been kind enough to send me their comments or their suggestions for corrections or improvements.
The "double sliding" logo was produced by Professor G. de Josselin de Jong, who played an important role in developing soil mechanics as a branch of science, and who taught me Soil Mechanics.

Zoetermeer, November 2002 Arnold Verruijt

In this new edition several small, but also some major adjustments have been carried through. Not only pressure, instead of tension, but also settlement and volume decrease are defined positive. Besides this, more attention is given to the difference between the failure criterion of Coulomb (based on one normal stress) and the failure criterion of Mohr-Coulomb (based on two principal stresses). Especially the shear tests reflect this difference. My special thanks goes out to Prof.dr.ir. A. Verruijt, who taught me the fundamentals of Soil Mechanics and gave me the opportunity to revise this book to the developments the Geotechnical Engineering is undergoing.

Delft, May 2007 Stefan Van Baars

# Contents

# Part I
# Introduction

# 1 Introduction

## 1.1 The discipline

*Soil mechanics* is the science of equilibrium and motion of soil bodies. Here soil is understood to be the weathered material in the upper layers of the earth's crust. The non-weathered material in this crust is denoted as *rock*, and its mechanics is the discipline of *rock mechanics*. In general the difference between soil and rock is roughly that in soils it is possible to dig a trench with simple tools such as a spade or even by hand. In rock this is impossible, it must first be splintered with heavy equipment such as a chisel, a hammer or a mechanical drilling device. The natural weathering process of rock is that in the long run the influence of sun, rain and wind it degenerates into stones. This process is stimulated by fracturing of rock bodies by freezing and thawing of the water in small crevices in the rock. The coarse stones that are created in mountainous areas are transported downstream by gravity, often together with water in rivers. By internal friction the stones are gradually reduced in size, so that the material becomes gradually finer: gravel, sand and eventually silt. In flowing rivers the material may be deposited, the coarsest material at high velocities, but the finer material only at very small velocities. This means that gravel will be found in the upper reaches of a river bed, and finer material such as sand and silt in the lower reaches.

The Netherlands is located in the lower reaches of the rivers Rhine and Meuse. In general the soil consists of weathered material, mainly sand and clay. This material has been deposited in earlier times in the delta formed by the rivers. Much fine material has also been deposited by flooding of the land by the sea and the rivers. This process of sedimentation occurs in many areas in the world, such as the deltas of the Nile and the rivers in India and China. In the Netherlands it has come to an end by preventing the rivers and the sea from flooding by building dikes. The process of land forming has thus been stopped, but subsidence continues, by slow tectonic movements. In order to compensate for the subsidence of the land, and sea water level rise, the dikes must gradually be raised, so that they become heavier and cause more subsidence. This process will probably continue forever if the country is to be maintained.

People use the land to live on, and build all sort of structures: houses, roads, bridges, etcetera. It is the task of the geotechnical engineer to predict the behaviour of the soil as a result of these human activities. The problems that arise are, for instance, the settlement of a road or a railway under the influence of its own weight and the traffic

load, the margin of safety of an earth retaining structure (a dike, a quay wall or a sheet pile wall), the earth pressure acting upon a tunnel or a sluice, or the allowable loads and the settlements of the foundation of a building.
For all these problems soil mechanics should provide the basic knowledge.

## 1.2 History

Soil mechanics has been developed in the beginning of the 20th century. The need for the analysis of the behaviour of soils arose in many countries, often as a result of spectacular accidents, such as landslides and failures of foundations. In the Netherlands the slide of a railway embankment near Weesp, in 1918 (see Figure 1-1) gave rise to the first systematic investigation in the field of soil mechanics, by a special commission set up by the government. Many of the basic principles of soil mechanics were well known at that time, but their combination to an engineering discipline had not yet been completed. The first important contributions to soil mechanics are due to Coulomb, who published an important treatise on the failure of soils in 1776, and to Rankine, who published an article on the possible states of stress in soils in 1857. In 1856 Darcy published his famous work on the permeability of soils, for the water supply of the city of Dijon. The principles of the mechanics of continua, including statics and strength of materials, were also well known in the 19th century, due to the work of Newton, Cauchy, Navier and Boussinesq.
The union of all these fundamentals to a coherent discipline had to wait until the 20th century. It may be mentioned that the committee to investigate the disaster near Weesp came to the conclusion that the water levels in the railway embankment had risen by sustained rainfall, and that the embankment's strength was insufficient to withstand these high water pressures.
Important pioneering contributions to the development of soil mechanics were made by Karl Terzaghi, who, among many other things, has described how to deal with the influence of the pressures of the pore water on the behaviour of soils. This is an essential element of soil mechanics theory. Mistakes on this aspect often lead to large disasters, such as the slides near Weesp, Aberfan (Wales) and the Teton Valley Dam disaster. In the Netherlands much pioneering work was done by Keverling Buisman, especially on the deformation rates of clay. A stimulating factor has been the establishment of the Delft Soil Mechanics Laboratory in 1934, now known as GeoDelft and soon as Deltaris. In many countries of the world there are similar institutes and consulting companies that specialize on soil mechanics. Usually they also deal with *Foundation engineering*, which is concerned with the application of soil mechanics principle to the design and the construction of foundations in engineering practice. Soil mechanics and Foundation engineering together are often denoted as *Geotechnics* or *Geo-Engineering*.


Figure 1-1. Landslide near Weesp, 1918.

## 1.3 Why Soil Mechanics?

Soil mechanics has become a distinct and separate branch of engineering mechanics because soils have a number of special properties, which distinguish the material from other materials. Its development has also been stimulated, of course, by the wide range of applications of soil engineering in civil engineering, as all structures require a sound foundation and should transfer its loads to the soil. The most important special properties of soils will be described briefly in this chapter. In further chapters they will be treated in greater detail, concentrating on quantitative methods of analysis.

### *1.3.1 Stiffness dependent upon stress level*

Many engineering materials, such as metals, but also concrete and wood, exhibit linear stress-strain-behaviour, at least up to a certain stress level. This means that the deformations will be twice as large if the stresses are twice as large. This property is described by Hooke's law, and the materials are called *linear elastic*. Soils do not satisfy this law. For instance, in compression soil becomes gradually stiffer. At the surface sand will slip easily through the fingers, but under a certain compressive stress it gains an ever increasing stiffness and strength. This is mainly caused by the increase of the forces between the individual particles, which gives the structure of particles an increasing strength. This property is used in daily life by the packaging of coffee and other granular materials by a plastic envelope, and the application of vacuum inside the package. The package becomes very hard when the air is evacuated from it. In civil engineering the non-linear property is used to great advantage in a pile foundation for buildings on very soft soil, underlain by a layer of sand. In the sand below a thick deposit of soft clay the stress level is high, due to the weight of the clay. This makes the sand very hard and strong, and it is possible to apply large compressive forces to the piles, provided that they reach into the sand.

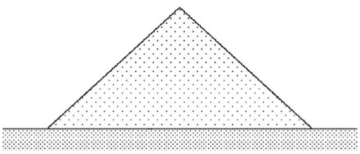

Figure 1-2. A heap of sand.

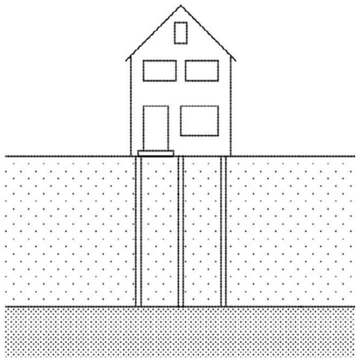

Figure 1-3. Pile foundation.

### 1.3.2 Shear

In compression soils become gradually stiffer. In shear, however, soils become gradually softer, and if the shear stresses reach a certain level, with respect to the normal stresses, it is even possible that failure of the soil mass occurs. This means that the slope of a sand heap, for instance in a depot or in a dam, can not be larger than about 30 or 40 degrees. The reason for this is that particles would slide over each other at greater slopes. As a consequence of this phenomenon many countries in deltas of large rivers are very flat. It has also caused the failure of dams and embankments all over the world, sometimes with very serious consequences for the local population. Especially dangerous is that in very fine materials, such as clay, a steep slope is often possible for some time, due to capillary pressures in the water, but after some time these capillary pressures may vanish (perhaps because of rain), and the slope will fail.

A positive application of the failure of soils in shear is the construction of guard rails along highways. After a collision by a vehicle the foundation of the guard rail will rotate in the soil due to the large shear stresses between this foundation and the soil body around it. This will dissipate large amounts of energy (into heat), creating a permanent deformation of the foundation of the rail, but the passengers, and the car, may be unharmed. Of course, the guard rail must be repaired after the collision.

### 1.3.3 Dilatancy

Shear deformations of soils often are accompanied by volume changes. Loose sand has a tendency to contract to a smaller volume, and densely packed sand can practically deform only when the volume expands somewhat, making the sand looser. This is called *dilatancy*, a phenomenon discovered by Reynolds, in 1885. This property causes the soil around a human foot on the beach near the water line to be drawn dry during walking. The densely packed sand is loaded by the weight of the foot, which causes a shear deformation, which in turn causes a volume expansion, which sucks in some water from the surrounding soil. The expansion of a dense soil during shear is shown in Figure 1-4. The space between the particles increases.

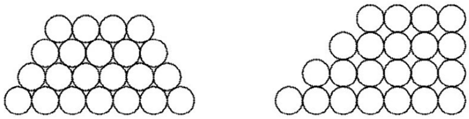

Figure 1-4. Dilatancy.

On the other hand a very loose assembly of sand particles will have a tendency to collapse when it is sheared, with a decrease of the volume. Such volume deformations may be especially dangerous when the soil is saturated with water. The tendency for volume decrease then may lead to a large increase in the pore water pressures. Many geotechnical accidents have been caused by increasing pore water pressures. During earth quakes in Japan, for instance, saturated sand is sometimes densified in a short time, which causes large pore pressures to develop, so that the sand particles may start to float in the water. This phenomenon is called *liquefaction*. In the Netherlands the sand in the channels in the Eastern Scheldt estuary was very loose, which required large densification works before the construction of the storm surge barrier. The sand used to create the airport Tjek Lap Kok in Hongkong was densified before the construction of the runways and the facilities of the airport.

### 1.3.4 Creep

The deformations of a soil often depend upon time, even under a constant load. This is called *creep*. Clay in particular shows this phenomenon. It causes structures founded on clay to settlements that practically continue forever. A new road, built on a soft soil, will continue to settle for many years. For buildings such settlements are particular damaging when they are not uniform, as this may lead to cracks in the building.

The building of dikes in the Netherlands, on compressible layers of clay and peat, results in settlements of these layers that continue for many decades. In order to maintain the level of the crest of the dikes, they must be raised after a number of

years. This results in increasing stresses in the subsoil, and therefore causes additional settlements. This process will continue forever. Before the construction of the dikes the land was flooded now and then, with sediment being deposited on the land. This process has been stopped by man building dikes. Safety has an ever increasing price.
Sand and rock show practically no creep, except at very high stress levels. This may be relevant when predicting the deformation of porous layers form which gas or oil are extracted.

### 1.3.5 Groundwater

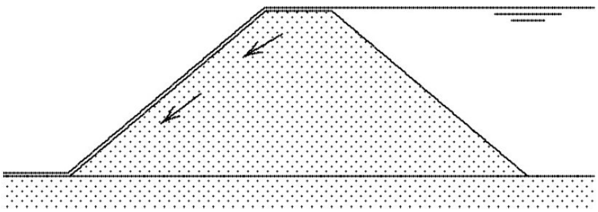

Figure 1-5. Overflowing dike.

A special characteristic of soil is that water may be present in the pores of the soil. This water contributes to the stress transfer in the soil. It may also be flowing with respect to the granular particles, which creates friction stresses between the fluid and the solid material. In many cases soil must be considered as a two phase material. As it takes some time before water can be expelled from a soil mass, the presence of water usually prevents rapid volume changes.
In many cases the influence of the groundwater has been very large. In 1953 in the Netherlands many dikes in the south-west of the country failed because water flowed over them, penetrated the soil, and then flowed through the dike, with a friction force acting upon the dike material. see Figure 1-5. The force of the water on and inside the dike made the slope slide down, so that the dike lost its water retaining capacity, and the low lying land was flooded in a short time.

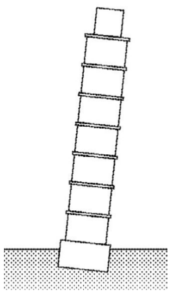

Figure 1-6. Pisa.

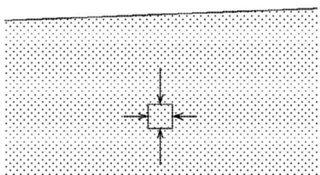

Figure 1-7. Stresses.

In other countries of the world large dams have sometimes failed also because of rising water tables in the interior of the dam (for example, the Teton Valley Dam in the USA, in which water could enter the coarse dam material because of a leaky clay core). Even excessive rainfall may fill up a dam, as happened near Aberfan in Wales in 1966, when a dam of mine tailings collapsed onto the village.
It is also very important that lowering the water pressures in a soil, for instance by the production of groundwater for drinking purposes, leads to an increase of the stresses between the particles, which results in settlements of the soil. This happens in many big cities, such as Venice and Bangkok, that may be threatened to be swallowed by the sea. It also occurs when a groundwater table is temporarily lowered for the construction of a dry excavation. Buildings in the vicinity of the excavation may be damaged by lowering the groundwater table. On a different scale the same phenomenon occurs in gas or oil fields, where the production of gas or oil leads to a volume decrease of the reservoir, and thus to subsidence of the soil. The production of natural gas from the large reservoir in Groningen is estimated to result in a subsidence of about 50 cm.

### 1.3.6 Unknown initial stresses

Soil is a natural material, created in historical times by various geological processes. Therefore the initial state of stress is often not uniform, and often even partly unknown. Because of the non-linear behaviour of the material, mentioned above, the initial stresses in the soil are of great importance for the determination of soil behaviour under additional loads. These initial stresses depend upon geological history, which is never exactly known, and this causes considerable uncertainty. In particular, the initial horizontal stresses in a soil mass are usually unknown. The initial vertical stresses may be determined by the weight of the overlying layers. This means that the stresses increase with depth, and therefore stiffness and strength also increase with depth. The horizontal stresses, however, usually remain unknown. When the soil has been compressed horizontally in earlier times, it can be expected that the horizontal stress is high, but when the soil is known to have spread out, the horizontal stresses may be very low. Together with the stress dependency of the soil behaviour all this means that there may be considerable uncertainty about the initial behaviour of a soil mass. It may also be noted that further theoretical study can not provide much help in this matter. Studying field history, or visiting the site, and talking to local people, may be more helpful.

### 1.3.7 Variability

The creation of soil by ancient geological processes also means that soil properties may be rather different on different locations. Even in two very close locations the soil properties may be completely different, for instance when an ancient river channel has been filled with sand deposits. Sometimes the course of an ancient river can be traced on the surface of a soil, but often it can not be seen at the surface. When an embankment is built on such a soil, it can be expected that the settlements

will vary, depending upon the local material in the subsoil. The variability of soil properties may also be the result of a heavy local load in the past.
A global impression of the soil composition can be obtained from geological maps. These indicate in the first place the geological history of the soils. Together with geological knowledge and experience this may give a first indication of the soil properties. Other geological information may also be helpful. Large areas of Western Europe have, for instance, been covered by thick layers of ice in earlier ice ages, and this means that the soils in these areas have been subject to a preload of considerable magnitude.
An accurate determination of soil properties can not be made from desk studies. It requires testing of the actual soils in the laboratory, using samples taken from the field, or testing of the soil in the field (*in situ*). This will be elaborated in later chapters.

## *Problems*

**1.1** In times of high water in the rivers in the Netherlands, when the water table rises practically to the crest of the dikes, local authorities sometimes put sand bags on top of the dike. Is that useful?

**1.2** Another measure to prevent failure of a dike during high floods, is to place large sheets of plastic on the slope of the dike. On which side?

**1.3** Will the horizontal stress in the soil mass near a deep river be relatively large or small?

**1.4** The soil at the bottom of the sea is often much stiffer in the Northern parts than it is in the Southern parts. What can be the reason?

**1.5** A possible explanation of the leaning of the Pisa tower is that the subsoil contains a compressible clay layer of variable thickness. On what side of the tower would that clay layer be thickest?

**1.6** Another explanation for the leaning of the Pisa tower is that in earlier ages (before the start of the building of the tower, in 1400) a heavy structure stood near that location. On which side of the tower would that building have been?

**1.7** The tower of the Old Church of Delft in Holland, along the canal Old Delft, is also leaning. What is the probable cause, and is there a possible simple technical solution to prevent further leaning?

# Part II
# Soil and stresses

# 2 Classification

## 2.1 Grain size

Soils are usually classified into various types. In many cases these various types also have different mechanical properties. A simple subdivision of soils is on the basis of the *grain size* of the particles that constitute the soil. Coarse granular material is often denoted as gravel and finer material as sand. In order to have a uniformly applicable terminology it has been agreed internationally to consider particles larger than 2 mm, but smaller than 63 mm as *gravel*. Larger particles are denoted as *stones*. *Sand* is the material consisting of particles smaller than 2 mm, but larger than 0.063 mm. Particles smaller than 0.063 mm and larger than 0.002 mm are denoted as *silt*. Soil consisting of even smaller particles, smaller than 0.002 mm, is denoted as *clay* or *luthum*, see Table 2-1. In some countries, such as the Netherlands, the soil may also contain layers of *peat*, consisting of organic material such as decayed plants. Particles of peat usually are rather small, but it may also contain pieces of wood. It is then not so much the grain size that is characteristic, but rather the chemical composition, with large amounts of carbon. The amount of carbon in a soil can easily be determined by measuring how much is lost when burning the material.

| Soil type | min. | max. |
|---|---|---|
| Clay | | 0.002 mm |
| Silt | 0.002 mm | 0.063 mm |
| Sand | 0.063 mm | 2 mm |
| Gravel | 2 mm | 63 mm |

Table 2-1: Grain sizes.

The mechanical behaviour of the main types of soil, sand, clay and peat, is rather different. Clay usually is much less permeable for water than sand, but it usually is also much softer. Peat is usually is very light (some times hardly heavier than water), and strongly anisotropic because of the presence of fibers of organic material. Peat usually is also very compressible. Sand is rather permeable, and rather stiff, especially under a certain preloading. It is also very characteristic of granular soils such as sand and gravel, that they can not transfer tensile stresses. The particles can only transfer compressive forces, no tensile forces. Only when the particles are very small and the soil contains some water, can a tensile stress be transmitted, by capillary forces in the contact points.

The grain size may be useful as a first distinguishing property of soils, but it is not very useful for the mechanical properties. The quantitative data that an engineer needs depend upon the mechanical properties such as stiffness and strength, and these must be determined from mechanical tests. Soils of the same grain size may have different mechanical properties. Sand consisting of round particles, for instance, can have a strength that is much smaller than sand consisting of particles with sharp points. Also, a soil sample consisting of a mixture of various grain sizes can have a very small permeability if the small particles just fit in the pores between the larger particles.
The global character of a classification according to grain size is well illustrated by the characterization sometimes used in Germany, saying that gravel particles are smaller than a chicken's egg and larger than the head of a match, and that sand particles are smaller than a match head, but should be visible to the naked eye.

## 2.2 Grain size diagram

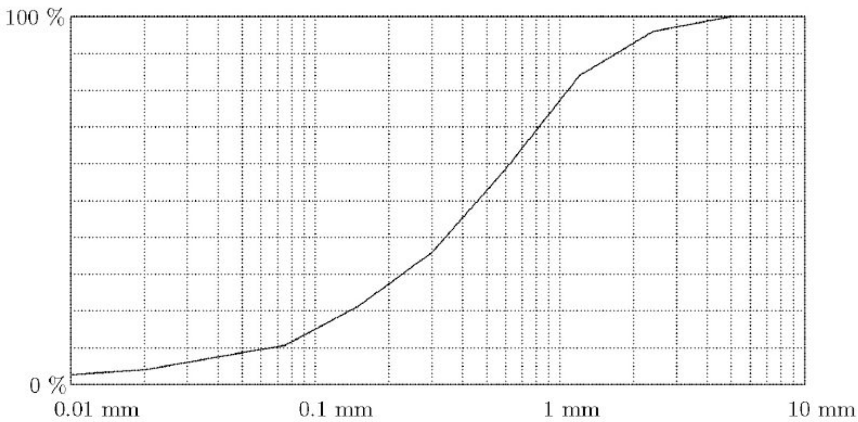


Figure 2-1. Grain size diagram.

The size of the particles in a certain soil can be represented graphically in a *grain size diagram*, see Figure 2-1. Such a diagram indicates the percentage of the particles smaller than a certain diameter, measured as a percentage of the weight. A steep slope of the curve in the diagram indicates a uniform soil, a shallow slope of the diagram indicates that the soil contains particles of strongly different grain sizes. For rather coarse particles, say larger than 0.05 mm, the grain size distribution can be determined by sieving. The usual procedure is to use a system of sieves having different mesh sizes, stacked on top of each other, with the coarsest mesh on top and the finest mesh at the bottom. After shaking the assembly of sieves, by hand or by a shaking machine, each sieve will contain the particles larger than its mesh size, and smaller than the mesh size of all the sieves above it. In this way the grain size diagram can be determined. Special standardized sets of sieves are available, as well

as convenient shaking machines. The example shown in Figure 2-1 illustrates normal sand. In this case there appear to be no grains larger than 5 mm.
The grain size distribution can be characterized by the quantities $D_{60}$ and $D_{10}$. These indicate that 60 %, respectively 10 % of the particles (expressed as weights) is smaller than that diameter. In the case illustrated in Figure 2-1 it appears that $D_{60} \approx 0.6 \text{ mm}$, and $D_{10} \approx 0.07 \text{ mm}$. The ratio of these two numbers is denoted as the *uniformity coefficient* $C_u$,

$$C_u = \frac{D_{60}}{D_{10}}. \tag{2.1}$$

In the case of Figure 2-1 this is about 8.5. This indicates that the soil is not uniform. This is sometimes denoted as a *well graded soil*. In a *poorly graded soil* the particles all have about the same size. The uniformity coefficient is than only slightly larger than 1, say $C_u = 2$. For particles smaller than about 0.05 mm the grain size can not be determined by sieving, because the size of the holes in the mesh would become unrealistically small, and also because during shaking the small particles might fly up in the air, as dust. The amount of particles of a particular size can then be determined much better by measuring the velocity of deposition in a glass of water. This method is based upon a formula derived by Stokes. This formula expresses that the force on a small sphere, sinking in a viscous fluid, depends upon the viscosity of the fluid, the size of the sphere and the velocity. Because the force acting upon the particle is determined by the weight of the particle under water, the velocity of sinking of a particle in a fluid can be derived. The formula is

$$v = \frac{(\gamma_k - \gamma_w)D^2}{18\mu}, \tag{2.2}$$

where $\gamma_k$ is the volumetric weight of the particle, $\gamma_w$ is the volumetric weight of the fluid, $D$ is the grain size, and $\gamma$ is the dynamic viscosity of the fluid. Because for very small particles the velocity may be very small, the test may take rather long.

## 2.3 Chemical composition

Besides the difference in grain size, the chemical composition of soil can also be helpful in distinguishing between various types of soils. Sand and gravel usually consist of the same minerals as the original rock from which they were created by the erosion process. This can be quartz, feldspar or glimmer. In Western Europe sand mostly consist of quartz. The chemical formula of this mineral is $SiO_2$.
Fine-grained soils may contain the same minerals, but they also contain the so-called *clay minerals*, which have been created by chemical erosion. The main clay minerals are kaolinite, montmorillonite and illite. In the Netherlands the most frequent clay mineral is illite. These minerals consist of compounds of aluminium with hydrogen, oxygen and silicates. They differ from each other in chemical composition, but also in geometrical structure, at the microscopic level. The microstructure of clay usually

resembles thin plates. On the microscale there are forces between these very small elements, and ions of water may be bonded. Because of the small magnitude of the elements and their distances, these forces include electrical forces and the Van der Waals forces.
Although the interaction of clay particles is of a different nature than the interaction between the much larger grains of sand or gravel, there are many similarities in the global behaviour of these soils. There are some essential differences, however. The deformations of clay are time dependent, for instance. When a sandy soil is loaded it will deform immediately, and then remain at rest if the load remains constant. Under such conditions a clay soil will continue to deform, however. This is called *creep*. It is very much dependent upon the actual chemical and mineralogical constitution of the clay. Also, some clays, especially clays containing large amounts of montmorillonite, may show a considerable swelling when they are getting wetter.
As mentioned before, peat contains the remains of decayed trees and plants. Chemically it therefore consists partly of carbon compounds. It may even be combustible, or it may be produce gas. As a foundation material it is not very suitable, also because it is often very light and compressible. It may be mentioned that some clays may also contain considerable amounts of organic material.
For a civil engineer the chemical and mineralogical composition of a soil may be useful as a warning of its characteristics, and as an indication of its difference from other materials, especially in combination with data from earlier projects. A chemical analysis does not give much quantitative information on the mechanical properties of a soil, however. For the determination of these properties mechanical tests, in which the deformations and stresses are measured, are necessary. These will be described in later chapters.

## 2.4 Consistency limits

For very fine soils, such as silt and clay, the consistency is an important property. It determines whether the soil can easily be handled, by soil moving equipment, or by hand. The consistency is often very much dependent on the amount of water in the soil. This is expressed by the *water content* $w$ (see also Chapter 4). It is defined as the weight of the water per unit weight of solid material,

$$w = W_w / W_k \,. \tag{2.3}$$

When the water content is very low (as in a very dry clay) the soil can be very stiff, almost like a stone. It is then said to be in the *solid state*. Adding water, for instance if the clay is flooded by rain, may make the clay plastic, and for higher water contents the clay may even become almost liquid. In order to distinguish between these states (solid, plastic and liquid) two standard tests have been agreed upon, that indicate the *consistency limits*. They are sometimes denoted as the *Atterberg limits*, after the Swedish engineer who introduced them.
The transition from the *liquid state* to the *plastic state* is denoted as the *liquid limit*, $w_L$. It represents the lowest water content at which the soil behaviour is still mainly

liquid. As this limit is not absolute, it has been defined as the value determined in a certain test, due to Casagrande, see Figure 2-2. In the test a hollow container with a soil sample may be raised and dropped by rotating an axis. The liquid limit is the value of the water content for which a standard V-shaped groove cut in the soil, will just close after 25 drops. When the groove closes after less than 25 drops, the soil is too wet, and some water must be allowed to evaporate. By waiting for some time, and perhaps mixing the clay some more, the water content will have decreased, and the test may be repeated, until the groove is closed after precisely 25 drops. Then the water content must immediately be determined, before any more water evaporates, of course.

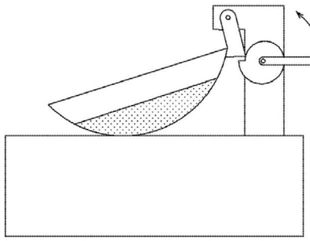

Figure 2-2. Liquid limit.

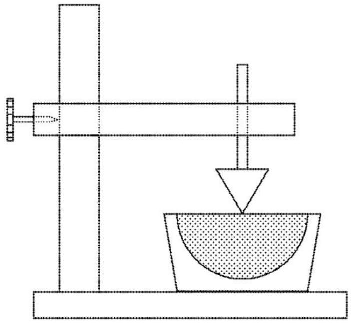

Figure 2-3. The fall cone.

An alternative for Casagrande's test is the *fall cone*, see Figure 2-3. In this test a steel cone, of 60 grams weight, and having a point angle of 60°, is placed upon a clay sample, with the point just at the surface of the clay. The cone is then dropped and its penetration depth is measured. The liquid limit has been defined as the water content corresponding to a penetration of exactly 10 mm. Again the liquid limit can be determined by doing the test at various water contents. It has also been observed, however, that the penetration depth, when plotted on a logarithmic scale, is an approximately linear function of the water content. This means that the liquid limit may be determined from a single test, which is much faster, although less accurate.
The transition from the plastic state to the solid state is called the *plastic limit*, and denoted as $w_P$. It is defined as the water content at which the clay can just be rolled to threads of 3 mm diameter. Very wet clay can be rolled into very thin threads, but dry clay will break when rolling thick threads. The (arbitrary) limit of 3 mm is supposed to indicate the plastic limit. In the laboratory the test is performed by starting with a rather wet clay sample, from which it is simple to roll threads of 3 mm. By continuous rolling the clay will gradually become drier, by evaporation of the water, until the threads start to break.
For many applications (potteries, dike construction) it is especially important that the range of the plastic state is large. This is described by the *plasticity index PI*. It is defined as the difference of the liquid limit and the plastic limit,

$$PI = w_L - w_P.$$

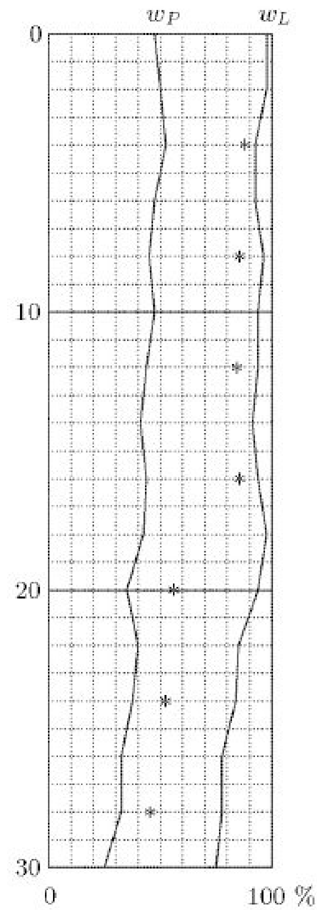


Figure 2-4. Water content.

The plasticity index is a useful measure for the possibility to process the clay. It is important for potteries, for the construction of the clay core in a high dam, and for the construction of a layer of low permeability covering a deposit of polluted material. In all these cases a high plasticity index indicates that the clay can easily be used without too much fear of it turning into a liquid or a solid.
In countries with very thick clay deposits (England, Japan, Scandinavia) it is often useful to determine a profile of the plastic limit and the liquid limit as a function of depth, see Figure 2-4. In this diagram the natural water content, as determined by taking samples and immediately determining the water content, can also be indicated.

## 2.5 An international classification system

The large variability of soil types, even in small countries such as the Netherlands, leads to large variations in soil properties in soils that may resemble each other very much at first sight. This is enhanced by confusion between terms such as *sandy clay* and *clayey sand* that may be used by local firms. In some areas tradition may have also lead to the use of terms such as *blue clay* or *brown clay*, that may be very clear to experienced local engineers, but have little meaning to others.

| Character 1 | | Character 2 | |
|---|---|---|---|
| G | gravel | W | well graded |
| S | sand | P | poorly graded |
| M | silt | M | silty |
| C | clay | C | clayey |
| O | organic | L | low plasticity |
| Pt | peat | H | high plasticity |

Table 2-2: Unified Classification System (USA).

Uniform criteria for the classification of soils do not exist, especially because of local variations and characteristics. The soil in a plane of Tibet may be quite different from the soil in Bolivia or Canada, as their geological history may be quite different. The engineer should be aware of such differences and remain open to characterizations that are used in other countries. Nevertheless, a classification system that has been developed by the United States Bureau of Reclamation, is widely used all over the world. This system consists of two characters to indicate a soil type, see Table 2-2. A soil of type SM, for instance, is a silty sand, which indicates that it is a sand, but containing considerable amounts of non-organic fine silty particles. This type of soil is found in the Eastern Scheldt in the Netherlands. The sand on the beaches of the Netherlands usually is of the type SW. A clay of very low plasticity, that is a clay with a relatively small plasticity index is denoted as CL. The clay in a polder in Holland will often be of the type CH. It has a reasonably large range of plastic behaviour.

The characterization *well graded* indicates that a granular material consists of particles that together form a good framework for stress transfer. It usually is relatively stiff and strong, because the smaller particles fill well in the pores between the larger particles. A material consisting of large gravel particles and fine sand is called *poorly graded*, because it has little coherence. A well graded material is suitable for creating a road foundation, and is also suitable for the production of concrete.

Global classifications as described above usually have only little meaning for the determination of mechanical properties of soils, such as stiffness and strength. There may be some correlation between the classification and the strength, but this is merely indicative. For engineering calculations mechanical tests should be performed, in which stresses and deformations are measured. Such tests are described in later chapters.