AN OVERVIEW OF THE MECHANICAL BEHAVIOUR OF PEATS AND ORGANIC SOILS AND SOME APPROPRIATE CONSTRUCTION TECHNIQUES

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ABSTRACT

The behaviour of peats and organic soils is usually approached with the concepts and methods developed for inorganic clays. However, important anomalies exist, and these are given emphasis in the present overview of the mechanical behaviour of these soils. Subject headings include index properties and general characteristics, classification issues, variability of deposits of peat and organic soils, one-dimensional behaviour and shear strength. The formation of peats and the history of dealing with peat in the Netherlands are described. The latter is shown to have parallels with the present situation in South-East Asia. Some established and promising new techniques for construction on peats and organic soils are described.

1. INTRODUCTION

Although peats and many other organic soils are notorious for their high compressibility and low strength, they have not received the same amount of interest as has been bestowed on mineral soils. Undoubtedly this is a consequence of the tendency to either avoid building on these soils, or when this is not possible, to simply remove, replace or displace them. Pressures on land-use however are leading world-wide to more development of areas containing such soils, and it therefore necessary to expand the knowledge of their mechanical behaviour, and to devise suitable construction techniques.

This paper gives an overview of some existing knowledge regarding the mechanical behaviour of peats and organic soils. The concepts of behaviour of inorganic clays, having been developed earlier, have often been applied to peats and organic soils, with varying degrees of success. In the main it *is* possible to apply traditional soil mechanics theory to these soils, but there are important "anomalies" which need special consideration. Special attention is given to these peculiarities of peat behaviour, and to the applicability and limitations of methods of characterization, constitutive models and methods of design and engineering analysis commonly employed for mineral soils, as regards their use for peats and organic soils.

Some established and promising new techniques for construction on peats and organic soils are described.

2. FORMATION OF PEAT

Very broadly speaking, temperate climate peats are distinguished according to their genesis in fen, transition and bog peats. Fen peats resp. bog peats are sometimes designated as low-moor and high-moor peat respectively, terms which were introduced by the Dutchmen Vegelin à Claerbergen (1) and Le Franq van Berkhey (2) in the 18th century. Presently, the terms topogenous resp. ombrogenous peats are more often used. Hobbs (3) has a complete summary of the present understanding of the formation and morphology of peats.

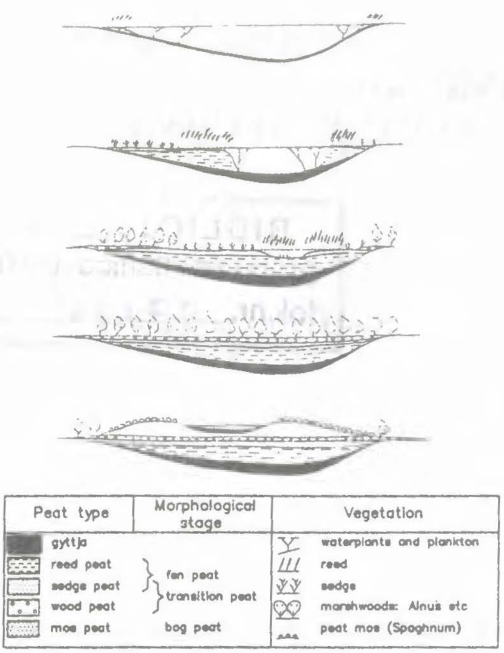

Fig. 1: The Wetland Succession

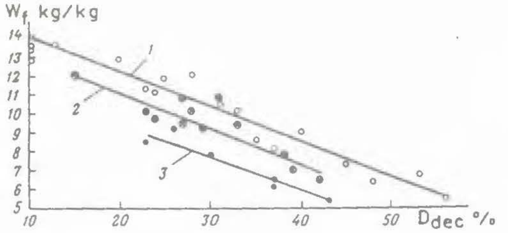

Fig. 2: Water content vs. degree of decomposition. (1) bog peat, (2) transition peat, (3) fen peat. From Amaryan (1993).

Peats generally form in successive stages of the so-called wetland succession, which is illustrated in Fig. 1. In the first rheotrophic stage, a supply of nutrients derived from mineral soils is brought into depressions in the landscape, lakes or basins, by flowing water, allowing the development of eutrophic vegetation such as reeds, rushes and sedges. The remains of this vegetation are conserved under water as fen peat. The early stages of lake filling often involve the deposition of detrital remains of plants and animals brought into the lake, and of floating aquatic plants. These form a deposit known as sapropelium or gyttja. In lime-rich circumstances, lake marls sometimes form above the gyttja before the formation of fen peat. In steepsided depressions, floating mires or Schwingmoor may develop. Lake filling is also referred to as terrestrialization. In contrast, paludification or swamping is the filling of permanently waterlogged basins, hollows etc. The peat itself as it forms raises the water level. The soft deposits beneath the peat are usually lacking.

Transition peat forms on the fen when it grows beyond the level of the ground water. Mesotrophic conditions apply, vegetation commonly comprising trees such as willow, alder and birch. When all contact with the groundwater is lost, the ombrotrophic stage of the bog peats is reached, where spaghnum mosses thriving on rainwater dominate. Heather and cotton grass also occur. Nutrient conditions are oligotrophic. Bog peats may also develop directly on the land surface, and are then referred to as blanket bogs.

Fen peats often have a relatively large mineral content. They tend to be more humified, and have lower water contents than bog peats, which is well illustrated by Amaryan (4), see Fig. 2. Fibrosity of peat decreases as humification increases.

The extensive tropical lowland peats of South-East Asia have likewise formed under both topogenous and ombrogenous conditions. The former are mostly found at the margins of peat swamps, the latter in the centre. The peat-forming vegetation consists mainly of large trees, resulting in a high lignin content which according to Anderson (5) is approximately twice that of the forest/moss-peat bogs of the temperate region. The mineral content is generally very low, especially in the ombrogenous material, and acidity is high.

3. THE HISTORY OF DEALING WITH PEAT IN THE NETHERLANDS, AND THE PARALLELS WITH THE PRESENT SOUTH-EAST ASIAN SITUATION

Peatlands formally covered much of the northern and western Netherlands. In the north, large ombrogenous bogs occurred with topogenous peat lower down. Deep fen peats covered locally by bogs occurred in the western deltaic area of the Netherlands. Reclamation of these latter peatlands started around 1000 A.D. or even earlier, and increasingly intensive settlement took place. The peat was first well above sea level and by digging ditches, drainage by gravity took place and lowered the water table to levels allowing abundant grain harvests. The bogs were probably less fertile and were cut for fuel and brought to the cities. The subsidence and decomposition accompanying the drainage gradually necessitated the construction of low dykes along the rivers, and dams were constructed across the smaller tributaries to protect the area from flooding. First, simple lid-sluices were installed in the dams which automatically opened at low tide to allow drainage. Continuing subsidence and rising sea-levels later necessitated drainage by windmills.

The populace converged on the dykes, especially near the dams (hence Amsterdam, Rotterdam etc. at the confluence of the Amstel and the Rotte with larger rivers) and buildings were usually constructed on the dykes or at their toe. The dykes themselves were often built from the same material they rest on, i.e. peat and organic soil, or in some areas, even from sea-weed which was plentiful there, and so the Dutch have a long history of acquaintance with the peculiarities of these soils. The dykes were regularly heightened and strengthened to offset settlements and rising sea levels, and this process is still continuing.

Unlike other countries therefore, builders in the Netherlands have not been able to escape dealing with peats and organic soils by simply building elsewhere, and this has led to a large body of empirical understanding of the behaviour of these soft soils.

The bog peat has largely disappeared due to decomposition and cutting, and lakes have formed where cutting was continued under the water table. The remaining peat is largely fertile fen peat with a considerable mineral content. The ground water table was traditionally shallow at only 20-40 cm below ground level, keeping subsidence and decomposition within about 2mm/y or 2m in 1000y. The demands of modern agriculture induce the desire for lower ditch levels, but this is accompanied by much greater rates of subsidence.

In the north (the provinces Drenthe and Groningen) large bogs were farmed at subsistence level (buckwheat farming with yearly burning of the tracts to increase fertility) for centuries and also cut for fuel. The latter was practised on such a large scale in the last few centuries and the first half of this century, that the bogs have now disappeared.

Geotechnical engineering in the Netherlands took a natural interest in peats from its very beginnings, with Keverling Buisman (6) e.g. noting the secondary compression phenomenon (or as he preferred to call it, the *secular* compression phenomenon) occurring under dykes near Marken.

Some parallels may be seen in this history of dealing with peat in the Netherlands and what is happening presently in South-East Asia and elsewhere. There, the increase of population is forcing peatlands to be reclaimed and utilized for agriculture etc. The accompanying problems of shrinkage and decomposition will necessitate water management schemes, dykes etc. to be constructed, and may eventually lead to a great deal of the peat disappearing, leaving the barren subsoil to be dealt with. Of course, the problems are more severe: the social pressures to develop the soil in a short time and to obtain high yields are large, at the same time the increased international awareness of the ecological importance of peatlands and tropical forests must be considered, the fertility of the peat and the subsoil is often rather marginal, and decomposition and subsidence can occur at alarming rates. Wayi and Freyne (7) e.g. quote a figure of 60cm shrinkage in the first three months following drainage at Kuk Tea Research Station in Papua New Guinea, and 13cm in the second three-monthly period.

Geotechnical engineering will have to come to grips with its share of these, as we have seen, *old* challenges on a *new* scale, and the old knowledge must therefore be expanded and put to best use.

4. GEOTECHNICAL CLASSIFICATION OF PEATS AND ORGANIC SOILS

4.1 Introduction

There is not one generally accepted system for the classification of peats and organic soils. Andrejko et al. (8) and Landva et al. (9) together list not less than 12 different systems used for the classification of peats and organic soils, based solely on organic content. Their common aspect is the definition of peats at the high end of the organic content scale, organic soils at the low end, and so-called muck in between. The boundaries between these soils are put at widely varying organic contents however. Most of these systems serve soil-scientific, calorific and geologic purposes and have no special significance for civil engineering. It is clear that organic content alone is not sufficient to fully characterize a peat for geotechnical purposes. Other potentially useful classification parameters are: botanical composition, degree of humification, water content, bulk density either dry or wet, specific mass of the compounded organic and inorganic constituents, fibre content and fibre-size distribution, (anisotropic) shrinkage, tension strength, and if at all possible to determine, the Atterberg plasticity limits. Chemical parameters such as pH and contents of organic carbon and carbonates are of interest for special purposes, especially when contemplating soil stabilization techniques such as deep mixing with cements etc. The composition of the organic matter in terms of bitumen, hemicellulose, cellulose, lignin, humic and fulvic acids may also be of interest.

In the following, some comments will be made on the determination of a number of the peat characteristics. Some correlations of peat characteristics with geotechnical parameters will also be given.

4.2 Peat Formulae

The von Post classification system (Hobbs (3) provides an English-language summary) is best known for its definition of degree of humification, going from H_1 for intact, young peat to H_{10} for completely decomposed peat. The method is based on simple manual methods suitable for use in the field. The von Post system also includes classification according to botanical composition, water content, content of fine and coarse fibres, and content of woody remnants. Landva and Pheeney (10) modified Von Post's system, and Hobbs extended it with categories for organic content, tensile strength, odour, plasticity and acidity. Recently, the Dutch ministry responsible for water-management published a first version of guidelines for the geotechnical classification of peat (11). Basically the von Post classification system is adopted, extending it with organic content and designation of the kind of inorganic material encountered. The ten humification degrees are brought back to only four.
In the systems adopted by von Post, Landva and Pheeney, Hobbs and the Dutch ministry, each characteristic is designated by a letter, and the degree to which a characteristic is present, is designated by an index. Thus, with Hobbs,

$$S\ H_5 B_2 F_3 R_1\ W_0 N_3\ TV_1\ TH_2\ A_0 P_1\ pH_0$$

designates Sphagnum (S) moss peat with moderate humification degree (H), water content (B) less than 500%, a high content of fine fibres (F), a low content of coarse fibres (R), no wood (W), a moderately high organic content (N), a low tensile strength in the vertical direction (TV) and a moderate tensile strength in the horizontal direction (TH), no smell (A), a detectable plastic limit (P) and a neutral acidity (pH).
Such formulae are useful for several purposes. When constructed conscientiously, they enable work done on different soils to be compared with more confidence than is possible on the grounds of vague descriptions such as "a hemic Spaghnum muck peat". Further, they contain indications of geotechnical behaviour, and are therefore useful in preliminary assessments of likely field behaviour. If correlated properly with compressibility, stiffness and strength parameters, they also allow a reliable determination of these parameters over the soil body affected by the engineering activities.

However, it is clear that quite some expertise is required to construct these formulae, and quite some discipline as well to carry it through for each and every borehole of an entire site investigation. For many purposes, simpler methods will inevitably be sought. If one's interest is only local, it is possible to correlate geotechnical properties such as permeability, voids ratio, compressibility, stiffness and strength with a few simple characteristics such as water content, organic content or bulk density, and the complicated peat formulae are therefore not always necessary.

4.3 Degree of Humification

Von Post's H_n-scale is adapted to pure peats containing little or no mineral matter. Its use in organic soils with more than 20-25% mineral matter is difficult. As a result, various coarser scales have now been devised with only 3-5 degrees of humification. Well-known is the soil taxonomic scale employing the terms fibric, hemic and sapric as an indication of degree of humification. Magnan (12) presents the French system of classification for organic soils. The 10 degrees of humification of Von Post are reduced to 3 classes for fibrous, semi-fibrous and amorphous peats resp. It is interesting to note the similarity of this system to a modern Swedish system (Larsson (13)). The Dutch system referred to earlier has 4 classes of humification.

The Canadian Radforth classification system (14) has 17 categories describing the structure of pure peats. The 17 categories are further classed in three groups: "amorphous-granular", "fine-fibrous" and "coarse-fibrous". It is not clear whether there is a direct linkage of these categories and groups with the degree of humification, but certainly the term "amorphous-granular" is often taken to mean strongly decomposed peat.

Apart from giving an impression of the probable state of the fibres in the peat, and thus of shear strength, the degree of humification is not an important quantity for establishing correlations with geotechnical parameters. It has been used to correlate quantities such as bulk density (Clymo (15)), liquid limit and natural water content (Hobbs). These correlations are all very approximate, showing only very generally that bulk density increases with H_n and that liquid limit and natural water content increase with decreasing H_n, and they are of little use when it comes selecting parameters for design.

4.4 Loss on Ignition and Organic Content

Extensive research has been carried out directed at the accurate determination of the organic content of peat. Consensus has not been reached, neither with respect to the methods nor the details of any given method. Sometimes, various methods are recommended for different purposes such as for calorific potential or identification of clays etc. (Andrejko et al.(8))

Wet ashing techniques involving immersion of the sample in caustic solutions are complicated and expensive. Amongst the dry ashing techniques can be distinguished the low temperature ashing (100-150 °C) in oxygen passing through a microwave field, the more usual medium temperature ashing in a muffle furnace between 375 and 600 °C, and high temperature ashing, primarily of use for coal research. Betelev (16) presents a method for determining the organic content of soils and rocks based on dry combustion at 500°C in an oxygen or air stream. The quantity of CO_2 production is measured by a gas analyzer. The method is economical and can also be applied to eg. oil-polluted soils.

Ashing techniques yield the ash content, which is the complement of the Loss on Ignition (or simply: ignition loss). The relation between ignition loss and organic content has also been the subject of much research. Clay minerals and carbonates in the peat are subjected to thermal dehydration up to high temperatures during ashing, thus progressively increasing the ignition loss above the organic content at increasing temperatures.

Medium temperature ashing is most useful for geotechnical purposes. A temperature of 550 °C is most common and is specified e.g. by A.S.T.M. (17). It should be held until a constant mass is achieved, but a standard period of e.g. 5 hours can be adopted. Skempton and Petley (18), while adopting this temperature, studied the influence of higher temperatures. Clay minerals and carbonates continue to lose mass up to 800 °C resp 650 °C, and ideally a temperature of 800 °C should be employed together with corrections based on the amount of clay mineral and carbonates. Clearly such a complex procedure would act as a deterrent to large-scale determinations of ignition loss and Skempton and Petley choose 550 °C to keep dehydration losses within acceptable limits without having to employ corrections.

Skempton and Petley also investigated the relation between ignition loss and organic content. They found

$$H = 1 - 1.04(1 - N) \tag{1}$$

where H =organic content and N = ignition loss, both expressed as a ratio rather than as a percentage. For engineering purposes, the difference between both is negligible above 25% organic content. Many correlations of engineering properties with either organic content or ignition loss exist, but given their nearness and the ease of determination of the one (ignition loss) and the difficulty of determining the other (organic content), correlations with ignition loss are preferred.

Many index characteristics and geotechnical parameters of organic soils correlate well with ignition loss on a local scale, and together with its easy determination, this makes it a valuable characteristic to know. Obviously though, in pure peats there is not much point in establishing time and again that ignition loss is near 100%, and in these soils other characteristics are of more importance.

4.5 Water Content

There is a general fear that the standard drying of soil at 105 °C during 24 hours will lead to charring of the organic components in peat, thus producing too large figures for water content. Lower temperatures, between 50 and 95 °C are therefore advocated by some. Skempton and Petley investigated these effects, and concluded that the loss of organic matter at 105 °C is insignificant, while drying at lower temperatures retains small amounts of free water. The temperature of 105 °C is therefore recommended.

4.6 Specific Gravity

Specific gravity in organic soils is affected by the organic constituents, and cannot simply be set to somewhere near 2.65-2.75 as in mineral soils. Cellulose has a specific gravity of approximately 1.58, while for lignin it is approximately 1.40. These low values reduce the compounded specific gravity of organic soils. The variability of organic content and organic constituents in any peat deposit requires its separate determination whenever voids ratio is to be calculated.

Use of automatic helium gas displacement pyconometers allows cheap and fast determination of specific gravity. Kerosene is usually used in fluid displacement methods, but for peats, Delft Geotechnics has more satisfactory experience with hexane.

Skempton and Petley produced a very sharp correlation between specific gravity of a suite of peats and organic soils and their ignition loss, and fitted the relation by

$$\frac{1}{G_s} = \frac{1 - 1.04(1 - N)}{1.4} + \frac{1.04(1 - N)}{2.7} \qquad (2)$$

where G_s is compounded specific gravity and N is ignition loss. The figures of 1.4 and 2.7 correspond to the separate specific gravities of the organic and inorganic fractions respectively. Ignoring the correction between ignition loss and organic content (equation (1)) which has evidently been applied in equation (2), Den Haan (19) fitted results of specific gravity tests on Dutch organic soils and peats directly to ignition loss, see Fig. 3 and equation (3).

$$\frac{1}{G_s} = \frac{N}{1.365} + \frac{(1 - N)}{2.695} \qquad (3)$$

The correlation between specific gravity and ignition loss is very close. Specific gravity can therefore be obtained from ignition loss with a large degree of confidence, and the more complex determination of specific gravity can be dispensed with. Older data in the literature often indicate significant differences with these correlations (some values being only slightly higher than unity) and should be treated with suspicion.

In establishing correlations as in Fig. 3, it is important that both characteristics be measured on the same piece of material. Peat deposits are so extremely variable that quantities measured on material only centimeters apart, need not have any correlation. In this particular case, it is quite easy to homogenize a dried sample by pestle and mortar, and take one subsample for specific gravity testing, and another for ignition loss. If this sample is first cut to fit an oedometer ring, bulk densities and water content are also established on the same material, extending the possibilities for determining reliable correlations.

Due to the high lignin content of the tropical wood peats, it may be expected that the figure of 1.4 or 1.365 in equations (1) and (2), will be somewhat lower for those peats.

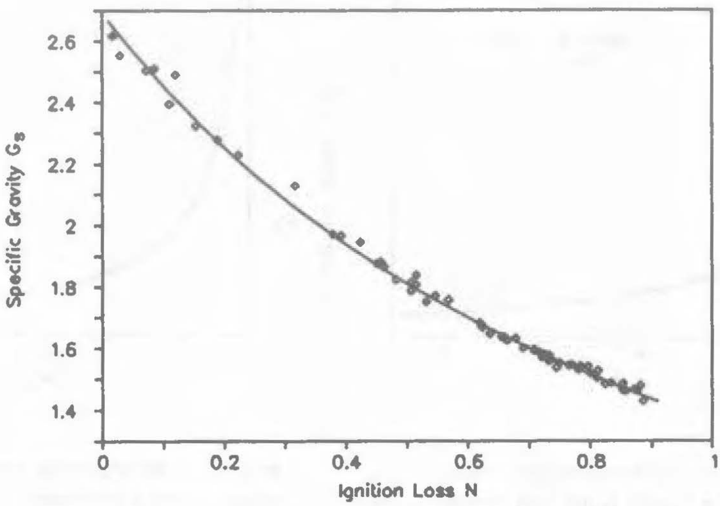

Fig. 3: Correlation of specific gravity and ignition loss, Dutch organic soils

4.7 Atterberg Limits

The fibres in peat make determination of the Atterberg limits difficult, and results depend strongly on the methods used to prepare the samples. In very fibrous material the test is impossible. Skempton and Petley put the boundary at approximately H_3 for the liquid limit and H_5 for the plastic limit. From their tests on a variety of British peats, they noted that all the peats plotted in a band crossing the plasticity chart at a rather low angle, implying that the organic matter contributes greatly to water-holding capacity, but much less so to plasticity. A rather good correlation of liquid limit with ignition loss was found, and the strong influence of the latter on the former emerged from the correlation:

$$w_L = 0.50 + 5.0N \qquad (4)$$

where w_L is liquid limit, and N is ignition loss, both expressed as a ratio. Liquid limit in peat can be quite high, up to 500% having been measured by Skempton and Petley. Hobbs quotes values between 200 and 600% for fen peats, and between 800 and 1500% for bog peats.

The usefulness of the Atterberg limits for determining geotechnical parameters was already questioned by Hosang and Locker (20), although Hobbs and also Farrell et al. (21) present a correlation of liquid limit of peats (up to 1300% water content) with the compressibility parameter C_c.

4.8 Correlations

The geotechnical literature provides many correlations of the characteristics described above, with each other and with geotechnical parameters describing e.g. compressibility and secular compression, permeability, undrained strength etc. Hobbs compares correlations from a number of different sources where identical characteristics had been correlated, which is useful to determine the possible deviation due to differences in soil type. In a few cases, only small differences exist for soils from widely different localities. The relationship between bulk dry density with natural water content is such a case. In Fig. 4 this relationship is shown for soils in the peat district of the central Netherlands. For the one part these were taken along a 30 km stretch of a freight railway planned through the "Betuwe" region between the Rotterdam harbour and the German hinterland, while the remainder is from a single boring in Polder Zegveld in a 7m thick peat deposit.

The fit shown in Fig. 4 is given by

$$\rho_d = 0.872\,(w + 0.317)^{-0.982} \qquad (5)$$

Amazingly, similar correlations given by Farkas and Kovács (22) and by Kabai and Farkas (23) for Hungarian peats, and by Marachi et al. (24) for Californian peats, are very near the Dutch result, as shown in Fig. 5.

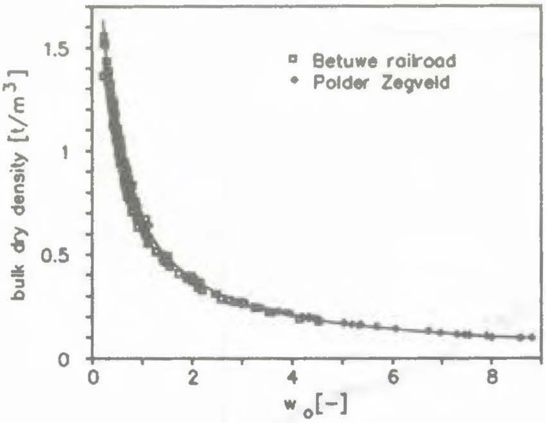

Fig. 4: Correlation of natural water content and dry density for Dutch peats and organic soils

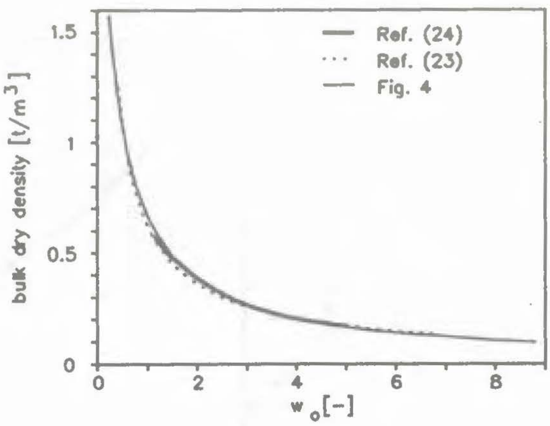

Fig. 5: Comparison of various dry density - water content correlations

It might be expected that similar good correlation exists between the bulk wet density and natural water content, as wet and dry density are simply related by

$$\rho_w = \rho_d (1 + w) \tag{6}$$

Hobbs has a diagram showing this not to be the case however. At high water contents, any minor difference in dry density is magnified in the wet density due to the high values of the factor (1+w) in eq. (6).

The samples used for Fig. 4 were taken more or less at random from boreholes which were sunk at regular intervals along the stretch of the Betuwe railway crossing the fen peat area. Fig. 6 shows that the complete spectrum of peats and organic soils is represented, with organic contents ranging from 90% to virtually zero. Results from a peat profile from another location (Polder Zegveld near Woerden) are also shown. They have low density but fit well with the results along the railroad.

Fig. 6 shows that pure peats with very high ignition loss do not occur in these areas, and also shows that lower density in the natural (unloaded) state correlates well with higher organic content. The lack of pure peats and the preponderance of soils with high organic content has led Dutch engineers to put the boundary between peat and organic clay or organic silt/sand at the low value of approximately 20% organic content.

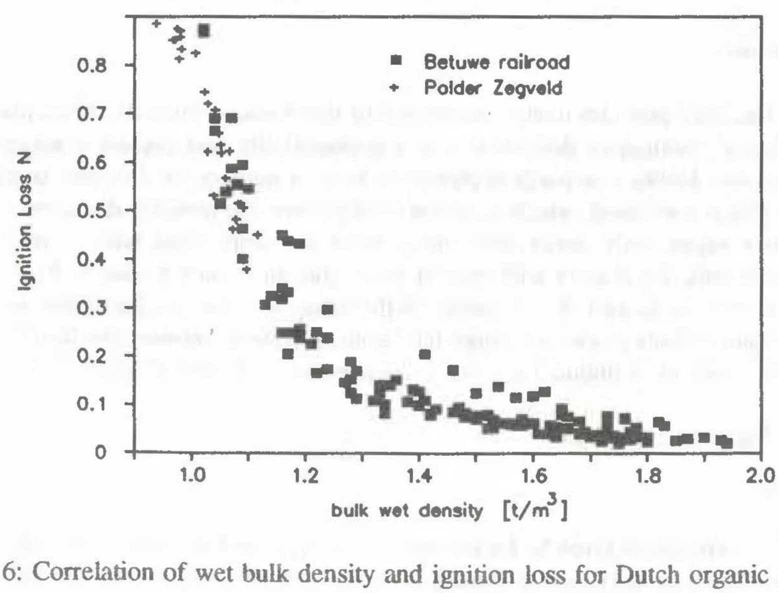

Fig. 6: Correlation of wet bulk density and ignition loss for Dutch organic soils

Very pure peats with negligible (less than say 5%) mineral content are likely to be more difficult to characterize by correlations developed for organic soils with an appreciable mineral content. There is a case for making a distinction between "pure peats" and "peats and organic soils", and Landva et al. (9) e.g. suggest to designate pure peats by the term "Radforth peat".

Fig. 7 depicts the relationship between voids ratio e_o and natural water content w_o for the Betuwe railroad project. Such a close correlation as obtained in the figure, requires that water content and specific gravity be determined on the same material, as discussed earlier. Hobbs brings similar correlations from a number of sources together, and Farkas and Kovács (22) also have such a correlation for Hungarian peats.

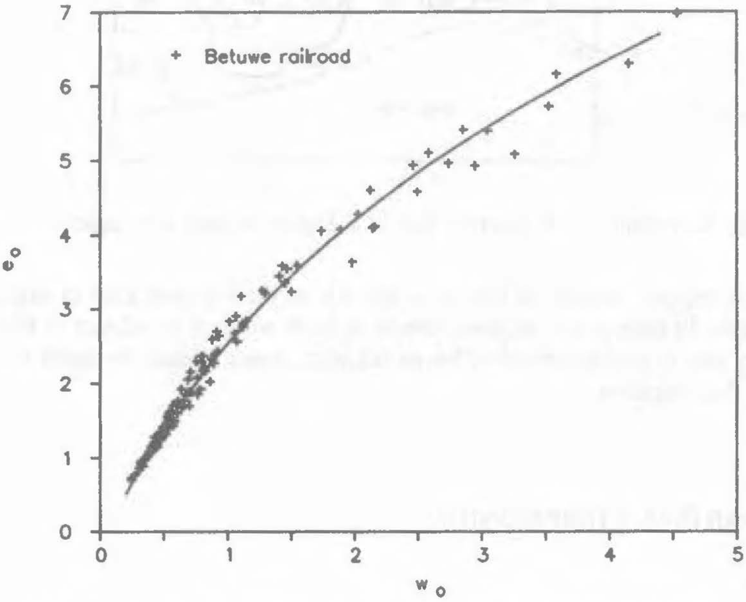

Fig. 7: Correlation of initial water content and voids ratio for Dutch organic soils

The fit in Fig. 7 is expressed by:

$$e_o = 30.65 \left[\frac{w_o + 0.88}{1.12} \right]^{0.116} - 30 \qquad (7)$$

This relationship is bound to be dependent on the type of soil, as e_o and w_o are interrelated through specific gravity and degree of saturation. Some of the deviation between the various correlations reported in the literature may be due to differences in the method of determination of specific gravity as mentioned earlier.

Parameters describing non-linear permeability and compressibility are known to correlate well with initial voids ratio. The good correlation between e_o and w_o of course indicates that such parameters might as well be correlated with w_o.

5. VARIABILITY OF PEAT DEPOSITS

Both laterally and vertically, peats show large variability. Borings taken by Sikder (25) at 2m centres in a peat area in Delft yielded strong variations in loss-on-ignition N as shown in Fig. 8 (X: location of borehole, Y: depth below surface). The vertical scale in the figure is 10 times larger than the horizontal scale. As the areas of equal ignition loss in the figure are approximately circular, it may be concluded that the vertical variability is ten times more intense than the lateral variability. This extreme variability on the decimeter resp. meter scale probably also exists at larger and smaller scales as well. Predictions of peat behaviour will have to account for this variability.

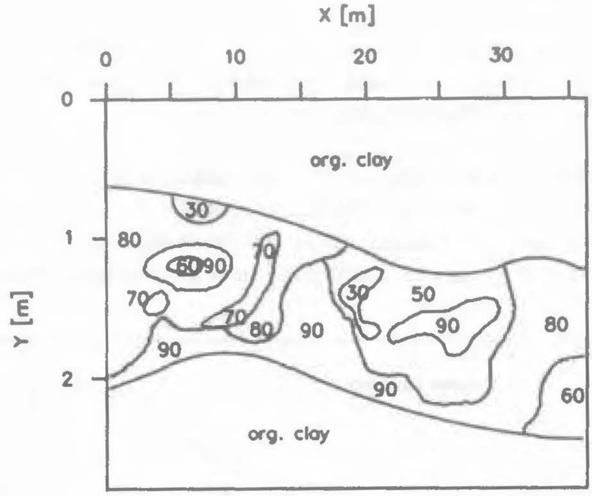

Fig. 8: Variability of ignition loss in a Dutch organic soil deposit

This kind of variation in organic content of course is specific to the fen peat kind of organic soil common in the central Netherlands. In pure peats, organic content at least will not be subject to large variations, but peat structure may vary due to alternation of different botanical types, coarse elements such as tree trunks, and varying degrees of humification.

6. ONE-DIMENSIONAL COMPRESSION

6.1 Introduction

Methods of design and calculation for one-dimensional compression generally follow those used for inorganic clays, but it is necessary to take account of some anomalies in the behaviour of peats and organic clays. The main anomalies concern the anisotropy and non-linearity of permeability, the strong stiffening of the material at large compression, and the strong secular (or secondary) compression. Some remarks will be made on each of these issues in the following.

The conventional method of one-dimensional settlement calculation is to use parameters such as C_s, C_c or m_v to calculate the primary compression, use c_v, the Terzaghi degree of consolidation U and the drainage distance to calculate the time to end of primary compression and the development of compression during primary, and finally to use parameters such as C_α to calculate secondary compression which is assumed to proceed linearly on the logarithm of time scale after end of primary. Not withstanding the simplicity of this method, it can be surprisingly accurate in inorganic clays if used carefully, as shown by the large amount of work done by Mesri in this respect. In peats and organic soils the method may also be effective, but at present it is becoming more and more clear that the one-dimensional compression of soft soils is better described by models relating *rate of strain* to stress (vertical effective stress) and density (or voids ratio e.g.). One such model will be described briefly below.

6.2 Permeability

Values of permeability measured on small oedometer samples cannot be trusted to accurately forecast the development of primary compression. Peat is extremely variable, mass structural features are not represented by small samples, the anisotropy of permeability is not accounted for, and gas contents may not be equal in the sample and in the field. The initial permeability can be quite high in peat, and is enhanced by the generally much higher horizontal than vertical permeability.

There has been much debate about the validity of the scaling law for time during primary compression,

$$\frac{t_f}{t_s} = \left[\frac{H_f}{H_s}\right]^i \quad (8)$$

where t is time, H is drainage distance, s denotes sample and f denotes field, and i=2 in the conventional Terzaghi theory. Comparison of field and laboratory measurements has indicated that i may be smaller than 2, a value of 1.5 often being mentioned. The anomaly could be due to any of the features mentioned above, while Hobbs suggests that the vertical permeability may be much higher in the field than measured in the oedometer. The large decrease in permeability with increasing compression (non-linear permeability) is further not generally accounted for when considering eq. (8).

There exists a widespread pessimism about the possibilities of accurately forecasting the development of settlement and pore pressure dissipation during the primary phase in peats and organic soils. Modern settlement models however have no difficulty in accounting for anisotropic and non-linear permeability and it should be possible to combine field and laboratory tests to evaluate anisotropy and non-linearity of permeability. Clearly though, much remains to be improved in this respect.

6.3 Natural Strain

The voids ratio - logarithm of stress graph is not linear but convex in peats and soft organic clays. This makes the conventional C_c parameter inefficient: it is useful only over a predetermined, limited stress range. By simply replacing strain by *natural* strain, the virgin relationship is again rendered linear in many cases. Thus the *natural* compression index *b* which is the slope of the virgin curve in *natural* strain vs. ln σ'_v, describes the complete virgin range adequately.

Natural strain is obtained by the integration of increments of deformation relative to the momentary dimension. Thus,

$$\varepsilon^H = -\int_{h_o}^{h} \frac{dh}{h} = -\ln(h/h_o) \quad (9)$$

The superscript H commemorates Hencky as the first to apply this measure of strain, although Röntgen (of X-ray fame) appears to have first proposed it.
Common engineering strain differs from natural strain in that deformation is related to the *initial* dimension h_o. Common (or Cauchy) strain is denoted by ε^C and is related to natural strain through

$$\varepsilon^H = -\ln(1 - \varepsilon^C) \quad (10)$$

Lefebvre et al. (26) made use of natural strain to obtain linear relationships between tangent modulus and effective stress for James Bay peats. They showed that this leads to a linear relationship between natural strain and logarithm of effective stress. Earlier, natural strain had been introduced in soil mechanics by Lundgren (27), Juárez-Badillo (28) and Butterfield (29). Den Haan (30) shows that a very wide range of soil types are adequately formulated by natural strain rather than common strain. Therefore, there is sufficient backing at present to abandon the conventional ε^C - logσ'_v formulation in favour of the ε^H - logσ'_v formulation, replacing compression index C_c by *natural* compression index *b*.

A consequence of using natural strain is that ultimately, at infinite stress, volume becomes vanishingly small. This is expected in a hypothetical sense: not only the voids, but also the solids compress at high stress. It is likely that solids volume decreases before all voids are compressed, and voids ratio would probably also approach zero only at infinite stress.

6.4 The Compression - Time Relationship

Secondary strain is severe in peats and cannot be as easily ignored as is often done when dealing with more firm soils. Secondary compression occurring after the hydrodynamic primary period, is conventionally described by a linear voids ratio - log*t* relationship with slope C_α. It is easy to show that this slope does not

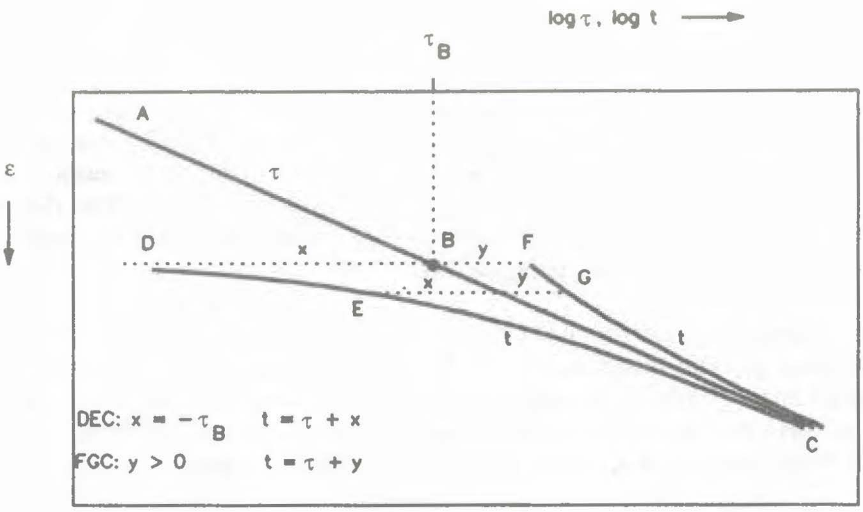

Fig. 9: Distortion of settlement curve by resetting of time zero

reflect a fundamental property of the soil. Consider the case in Fig. 9 that a linear ε^C -log τ relationship is being measured along AB (where τ denotes time) and that at B a very small extra load is applied. Consolidation would be very quick and extra settlements negligible. Nevertheless, time t would now be measured from the start of the new loading, and the new relationship would be DEC. Although nothing substantial has changed in the loading conditions, and compression would proceed further along BC in terms of the old time frame τ, a substantially different curve emerges in terms of the new time frame t.

This is due to the logarithmic transformation of time. The new time t is equal to τ-τ_B. On linear time scales, DEC would merely shift τ_B left of BC. A shift towards the right of ABC, such as FGC, would occur if for some reason, time after B was measured from a moment earlier (τ_B+y) than the time frame of AB.

An improved formulation of the compression - time relationship of peats (and of many other soft soils) is obtained by assuming that during secondary compression at constant effective stress, ε^H is linear when plotted against logarithm of *intrinsic* time. Intrinsic time is denoted by τ and can be thought of as the time which would have been necessary to achieve the present volume, had the present stress been applied immediately to the soil in its initial state directly after formation. Intrinsic time τ and time t are related by

$$t = \tau + t_r \tag{11}$$

where t_r is a time shift, and thus

$$dt = d\tau \tag{12}$$

so that increments of intrinsic time and time since loading are equal.
Taking the slope of the assumed linear ε^H-ln τ relationship as c, we obtain

$$\varepsilon^H - \varepsilon_o^H = c \ln\frac{\tau}{\tau_o} = c \ln\frac{t-t_r}{t_o-t_r} \tag{13}$$

where o designates the initial condition on the intrinsic time line at the beginning of secondary compression. Note that strain is linearly related to log$(t$-$t_r)$, not to log$t$.

The rate of secondary compression $d\varepsilon^H/dt$ or $\dot{\varepsilon}^H$ is obtained by

$$\dot{\varepsilon}^H = \frac{c}{\tau} \tag{14}$$

Substituting this in Eq. 5 yields

$$\varepsilon^H - \varepsilon_o^H = -c \ln\frac{\dot{\varepsilon}^H}{\dot{\varepsilon}_o^H} \tag{15}$$

This is a linear plot of strain versus logarithm of strain rate. The slope is c here as well as in Eq. 13. This slope c is called the *natural secondary compression index.*

At large values of time t, $t \approx \tau$, and a plot of ε^H against $\log t$ will eventually be linear with slope c at large values of t. However, plots using $\log\tau$ or $-\log\dot{\varepsilon}^H$ are expected to be linear shortly after End of Primary.

Fig. 10 shows compression - time curves obtained in a multiple stage oedometer test on Portage, Wisconsin peat (Edil & Den Haan (31)). Various scales are used to illustrate the advantage of natural strain and strain rate. The second graph improves greatly on the conventional first graph by replacing common strain with natural strain. This shows that not only the virgin compression - stress relationship, but also the compression - time relationship, are improved by using natural strain. In the third graph, time is replaced by strain rate which is simply obtained from the slopes of the second graph. Careful comparison will show that the linear portions of the curves are now longer, thus making determination of the slope c easier. Note that strain rate is reciprocal to intrinsic time; see Eq. 14.

In the second and third graphs in Fig. 10, the fit lines to the consecutive loading stages are more or less parallel once stress is larger than the preconsolidation stress between 50 and 100 kPa. Thus the single parameter c formulates the complete secondary compression behaviour of this peat. The final slope at 400 kPa during prolonged loading steepens however, and this is a phenomenon which needs separate formulation: see the section on tertiary compression.

Not only are the lines in the second and third graphs parallel, they are also more or less equidistant. As the consecutive loads are doubled in each stage, this means the slope b is independent of both stress and strain rate. This is revealed more clearly by replotting the third graph of Fig. 10 in Fig. 11. Here we see that the constant strain rate lines (or *isotaches*) are tolerably parallel. Their slope is the *natural compression index b.*

Fig. 11 however shows that in the area of precompression (below about 70 kPa) the constant strain rate lines are distorted. Also, after unloading at 400 kPa, subsequent reloading also results in distortion of the constant strain rate lines. Therefore, reloading behaviour requires separate formulation.

We conclude that the parameters b and c are powerful descriptors of peat compression. They are defined as

$$b = \frac{d\varepsilon^H}{d\ln\sigma_v'} \tag{16}$$

and

$$c = \frac{d\varepsilon^H}{d\ln\tau} \tag{17}$$

b successfully linearizes stress-strain behaviour in the virgin compression range; c successfully linearizes strain-time behaviour in the secondary compression range. Just how successful and powerful these parameters are is illustrated forcefully in Fig. 12 where Fig. 11 has been replotted on conventional scales. Clearly the conventional description is highly non-linear in the virgin range.

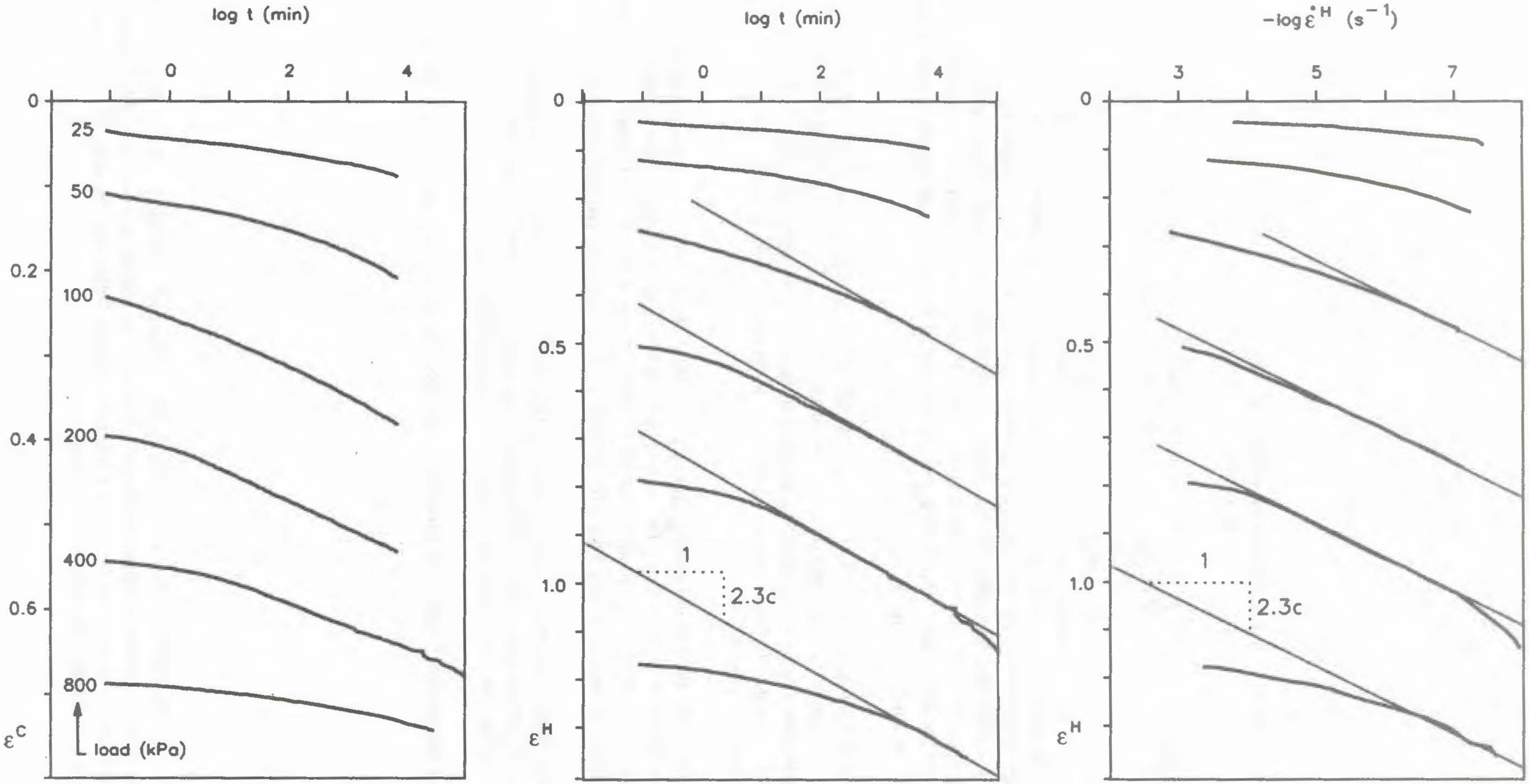

Fig. 10: Middleton Wisconsin peat, incremental loading oedometer test #6. Settlement - time curves on various scales

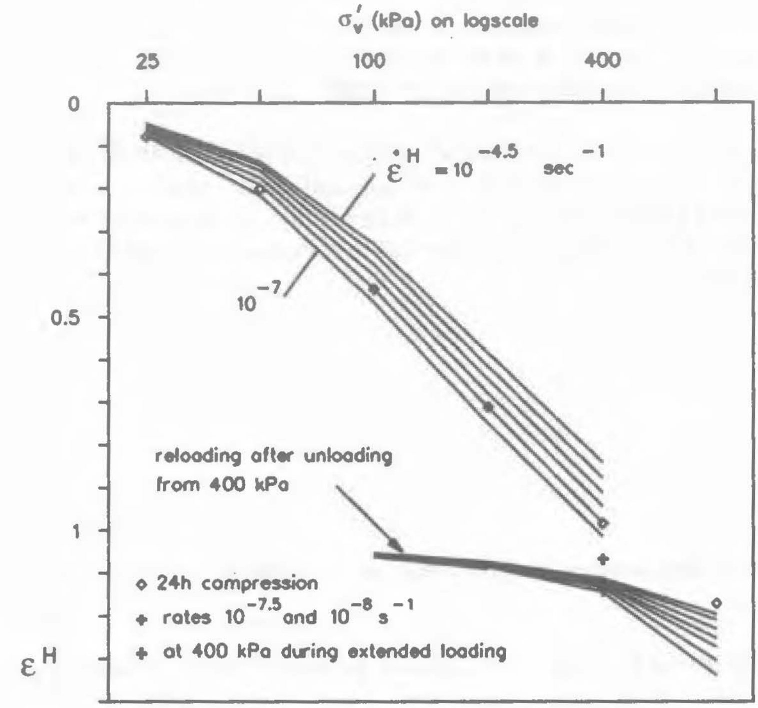

Fig. 11: Middleton Wisconsin peat, oedometer test #6, isotaches for loading and reloading

6.5 The Stress - Strain - Creep Strain Rate Relationship

It appears from Fig. 11 that strain rate is related to stress and strain. Taking only the strain rates in the virgin stress and secondary compression ranges, results in a stress - strain - *creep* strain rate relationship, which is described by

$$\varepsilon^H - \varepsilon^H_o = b \ln \sigma'_v + c \ln\left(\frac{\tau}{\tau_o}\right) \qquad (18)$$

Here, τ_o is a reference value of intrinsic time. ε^H_o lies on its associated intrinsic time line, and follows from

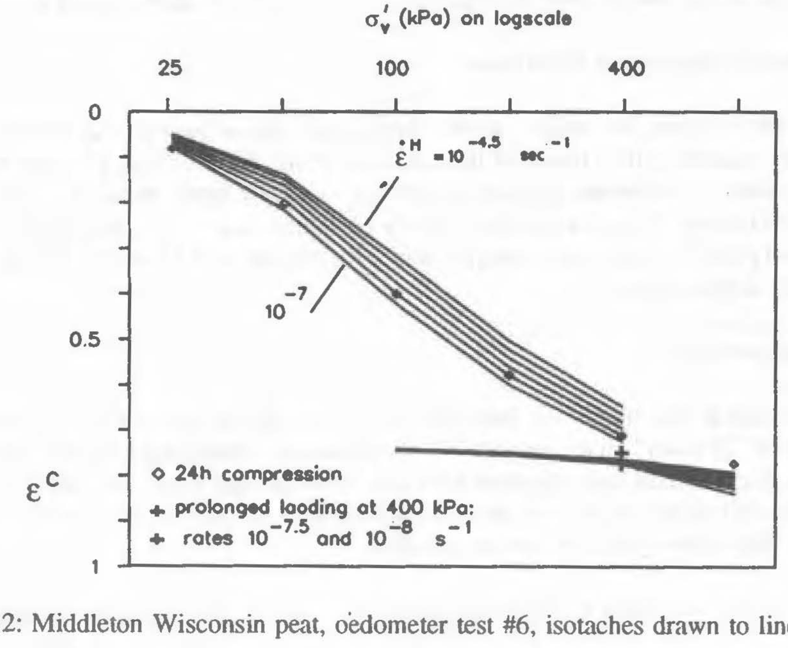

Fig. 12: Middleton Wisconsin peat, oedometer test #6, isotaches drawn to linear strain

backextrapolation of the natural strain scale to σ_v'=1 kPa on this line. τ_o is taken at a natural strain rate of 10^{-7} s^{-1} because this rate often corresponds roughly to the rate at the end of 24h. Much compression data has been reported in terms of 24h, and because 24h curves are essentially parallel to the constant creep rate lines (see Fig. 11), *b* can be determined fairly accurately from standard 24h curves.

The system of parallel lines determine creep rate $\dot{\varepsilon}^H$ as a function of natural strain and effective stress. They form a background pattern to the development of stresses and strains which is assumed to be valid in the primary (or hydrodynamic) period as well as the secondary period. In the primary period, strain rate then is assumed to consist of the sum of creep rate and rate due to compression induced by an increase in effective stress. For this, it is assumed

$$d\varepsilon^H = a\, d\ln\sigma_v' \tag{19}$$

and therefore

$$\dot{\varepsilon}^H = \frac{a}{\sigma_v'}\frac{d\sigma_v'}{dt} + \frac{c}{\tau} \tag{20}$$

The increase in effective stress induces a large increase in creep rate as well as being associated with a rate of strain itself.

This equation is dubbed the "*a-b-c model*". The relevant parameters for the Middleton peat sample are

$$a = 0.05$$
$$b = 0.384$$
$$c = 0.043$$
$$\varepsilon_o^H = -1.408$$

Combining the chosen stress - strain - strain rate equations with Darcy flow and the continuity equation, it is possible to calculate combined primary and secondary deformations following surface loading of peat deposits. The permeability of the soil must be known to calculate Darcy flow, and is taken as a function of voids ratio by means of

$$k = k_o\, 10^{-e/C_k} \tag{21}$$

A compression model utilizing the equations described here, has been programmed. A full code is available in Den Haan (32), and a demonstration version together with a short description and a number of worked exercises, is available on the internet at hhtp://www.delftgeot.nl/so by downloading consef.exe and consef.wp.

6.6 Unload/Reload Compression Behaviour

Fig. 11 suggests that on reloading, the stress - strain - creep strain rate relationship is different than during first loading. The laws governing the change of the relationship are not yet clear. It is necessary to obtain formulations for the change in the relationship at any arbitrary stress or strain, to enable a general model to be constructed in which loading stages can be alternated by unloading stages. The preloading technique often used over soft soils and peats is an obvious example calling for extension of the theory. Work is in progress to improve the models in this respect.

6.7 Tertiary Compression

Wilson et al. (33) postulated that, due to the intricate and complicated cellular structure of fibrous peat, it would exhibit not only "primary" and "secondary" consolidation characteristics, but also tertiary and quaternary etc. characteristics. Edil and Dhowian (34) and Dhowian and Edil (35) found that in standard oedometer tests on fibrous peat at low stresses, the normally straight secondary tail of the ε - log-time curve eventually steepened. They named this tertiary compression.

To avoid confusion with the well-known continuous steepening *towards* the secondary tail on application of small load increments (so-called Type III curves), the following definition should be adopted: *after* a long secondary stretch during which $\log\dot{\varepsilon}$ decreases equally with increasing log-time, $\dot{\varepsilon}$ gradually decreases less quickly. Usually, $\dot{\varepsilon}$ still decreases during tertiary compression, only less so than expected from further extrapolation of the secondary tail. Bishop and Lovenbury (36) showed examples of creep tests on London clay and Pancone clay where $\dot{\varepsilon}$ actually suddenly increases in the secondary stage. Kabbaj et al. (37) have ascribed this to the passing of the minimum voids ratio previously experienced in the geological history of the clay.

Hansbo (38) found a steepening ε - log-time plot but showed that no special transition appears when plotted on ε - t scales. However, the criterion to consider is whether the final slope is equal to or larger than C_α for large load increments. In the former case, steepening is probably associated with small increments, as described earlier. A case of the latter may be seen in tests by Krieg and Goldscheider (39) on a Dutch peat. The final slope of the test at 40 kPa is a factor 4 higher than at higher pressures.

Field occurrences of tertiary compression have also been noted (Candler and Chartres (40); Simic (41)). Edil and Fox (42) observed both field *and* laboratory tertiary compression for a test fill in Middleton, Wisconsin.

The existence of tertiary compression has become somewhat controversial. However, from other materials it is known that creep curves sometimes exhibit a wavy course, possibly due to structural perturbations (Feda (43)). There is clearly a need for careful study of this topic.

6.8 Correlations of v_l and b with Ignition Loss

Values of v_l and b determined for Dutch peats in the Polder Zegveld, and for other oedometer tests on peats reported in the literature, are correlated with ignition loss in Figs. 13 and 14. The degree of correlation is reasonable, but could be improved by developing local correlations, and diversifying the relationship for different botanical peat types. Fig. 15 shows that the equation

$$\frac{b}{G_s N} = 0.28 \pm 0.028 \qquad (22)$$

where G_s is specific gravity and N is ignition loss, yields reasonably accurate results for Polder Zegveld peats. Specific gravity of course can be taken as a function of N according to equation (3).

The creep rate index c is related to the creep stress index b by the same interrelationship as given by Mesri for C_α resp. C_c . As with Mesri, values of approximately 0.05 - 0.06 are found for c/b in peats and organic soils.

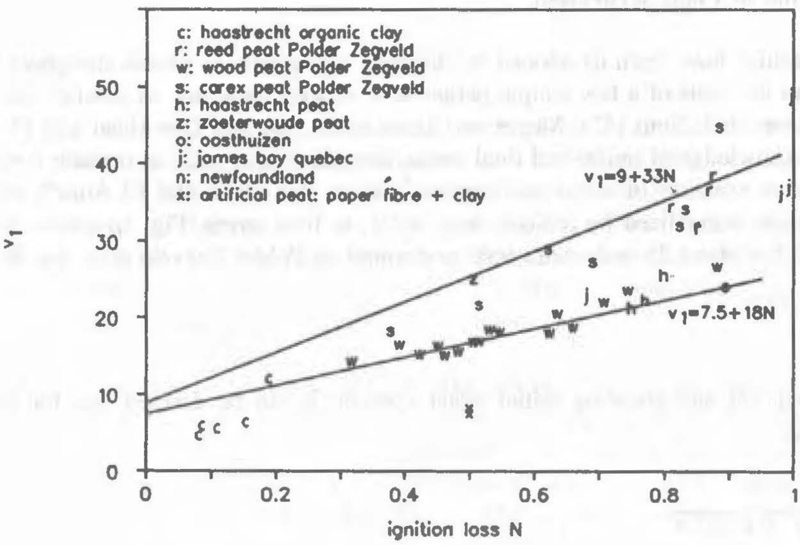

Fig. 13: Correlation of compression parameter v_1 with ignition loss for peats and organic soils

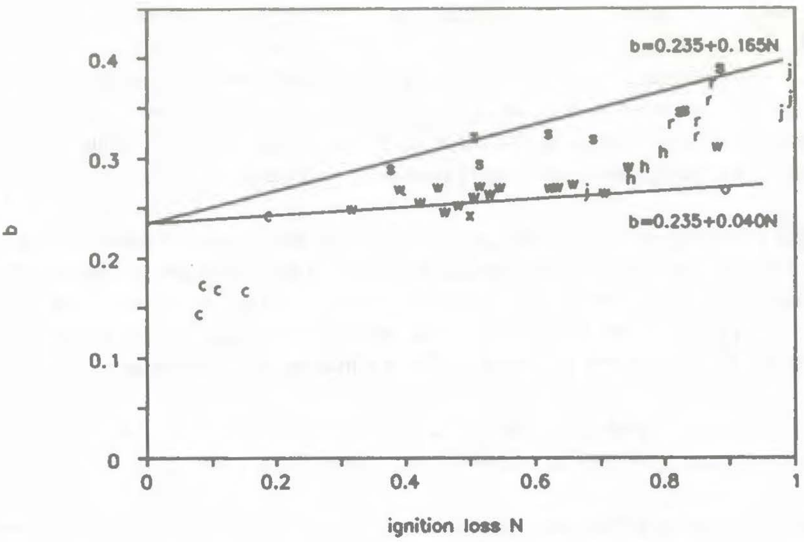

Fig. 14: Correlation of compression parameter b with ignition loss for peats and organic soils

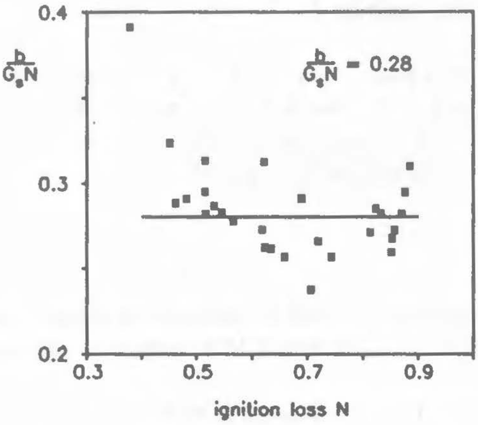

Fig. 15: Polder Zegveld peats, correlation formula for natural compression index b

6.9 Estimation of Final Settlement

Many simple formulae have been developed by different researchers to enable designers to easily estimate final settlement on the basis of a few simple parameters. Among these are Al-Khafaji and Andersland (44), Flaate (45), Carlsten (46), Noto (47), Meyer and Dereczenik (48) and Den Haan and El Amir (49). These formulae require knowledge of initial and final stress, and parameters such as organic content, natural water content, and relative volumes of water and organic matter. Den Haan and El Amir's (49) method relates natural water content normalized by ignition loss, w/N, to final stress. Fig. 16 shows that a fairly unique curve is obtained. For about 25 oedometer tests performed on Polder Zegveld peat, the fit curve is given by

$$w/N = 26.7\,\sigma_v'^{\,-0.437} \tag{23}$$

Combined with eq. (3) and knowing initial water content, it can be derived that for loads in the virgin compression range

$$\varepsilon = \frac{w_o - w}{w_o + 0.371 + 0.362\,N} \tag{24}$$

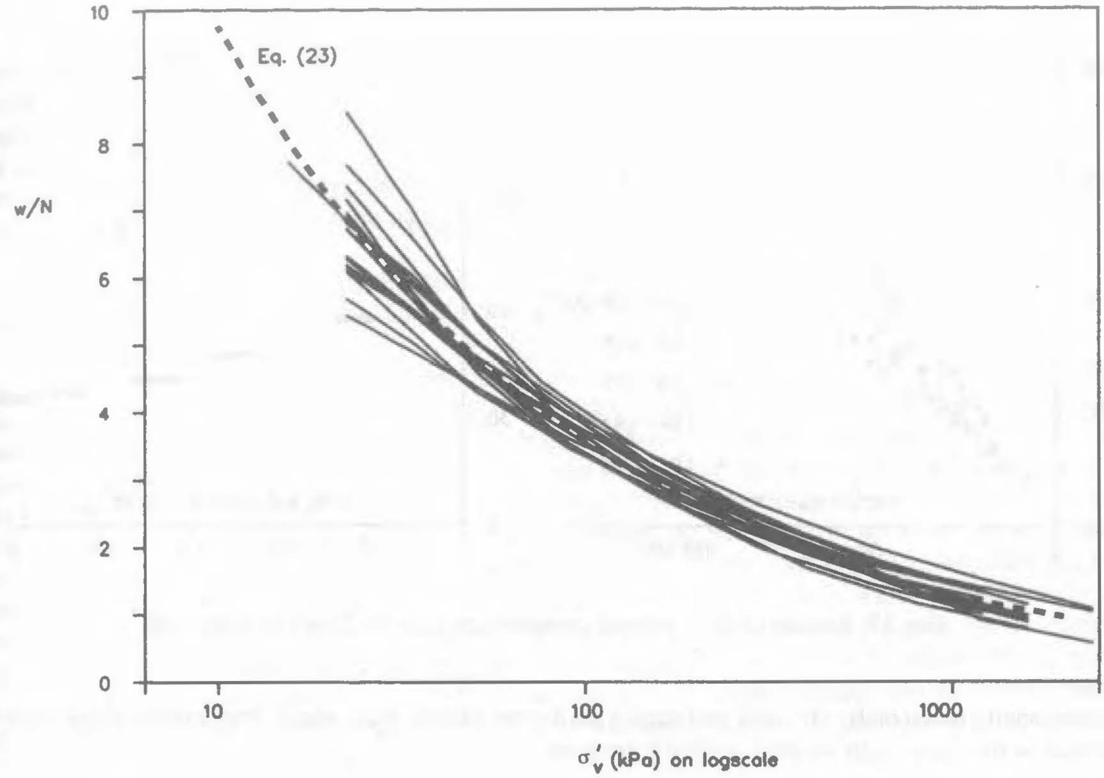

Fig. 16: Polder Zegveld peats, w/N - logσ'_v for 10^4 d loading

where w, the final water content, can be calculated from eq. (23). The curves in Fig. 16 and equations (23) and (24) are valid for a loading duration of 10^4 days, i.e. virtually for long term settlement.

A comparative study of all the available formulae for final settlement in peats has not yet been made, although Den Haan and El Amir (49) compared the Al-Khafaji & Andersland method with equations (23) and (24), and with eq. (22), and found only small differences. If this is true for all methods, the most simple could be chosen for use in international handbooks and guidelines for construction on peats and organic soils.

7. SHEAR STRENGTH

Both the undrained shear strength c_u and the effective stress strength parameters c′ and φ′ of many suites of peats and organic soils are *higher* for *higher* natural water content. This may be seen from Fig. 17, which plots 5% axial strain states for consolidated undrained triaxial tests on samples from the Betuwe railroad mentioned earlier. The value of 5% strain is close to peak for most samples. There is a clear tendency for samples with lower density (and therefore with higher water content) to plot higher in the shear stress vs. normal stress graph, and this is confirmed in Fig. 17b where φ′ (fitted to Fig. 17a by linear regression) is shown vs. wet bulk density (cohesion was negligible in all cases).

Similar results have been obtained by Coutinho and Lacerda (50) on organic Brazilian soils. They found φ′ values increasing up to 57° in organic soil with organic content increasing up to 60%, and the c_u/σ'_v ratio increasing up to 0.54. Tsushima and Mitachi (51) experimented with mixes of clay and organic matter, and also found that higher organic content (up to 57% was investigated) correlated with higher φ′ (up to 52°) and higher c_u/σ'_v (up to 0.78). Not only c′ and φ′, but also c_u exhibits this behaviour. Such behaviour is not expected intuitively. The high strengths both in terms of undrained strength ratio c_u/σ'_v and φ′ are reason to reconsider the use of the C.U. triaxial tests for these soils. Possibly fibres of vegetable matter which are present even in organic clays up to a wet bulk density of at least 1.8 t/m^3 in the Betuwe case, are

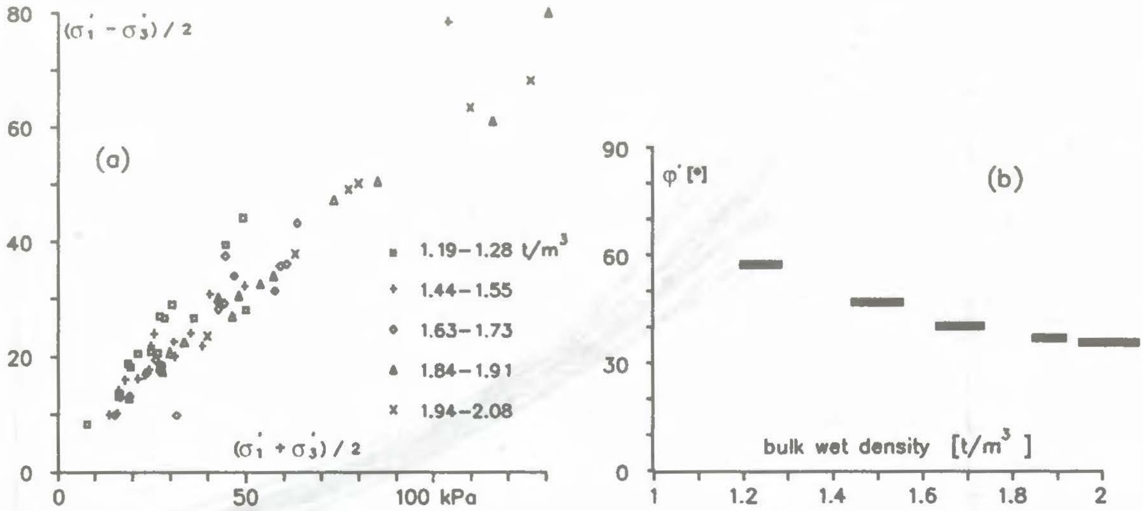

Fig. 17: Results of C.U. triaxial compression tests on Dutch organic soils

predominantly horizontally oriented, and stretch during the triaxial shear phase, thus lending extra resistance to shear in the form of an internal confining pressure.

The triaxial mode of deformation is not a good model of the deformation at failure of most geotechnical problems and certainly not when predominantly horizontally oriented fibres act to resist active shear failure. Other, economically viable methods of shear test must be sought. Candidates are the direct shear test and the simple shear test. In both, the horizontal fibres cannot extend, and the simple shear mode of deformation especially may be a reasonable compromise with that in e.g. a potential circular slip plane under an embankment.

Such a slip plane is usually divided into the active section under the crest, the neutral section under the slope and the passive section under the toe. The C.U. compression test is considered a reasonable model for the active section, and the C.U. extension test likewise for the passive section. The simple shear test models the neutral section, and in inorganic clays, the simple shear strength is a slightly conservative estimate of the average along a circular slip plane.

In peats however the simple shear test is likely to give more conservative estimates of strength still. This is not only because of the fibre-stretching in the active section. The fibres which are compressed in the passive section (and in a C.U. extension test) also increase shear strength.

In summary, it is seen that peats and organic soils exhibit anomalous behaviour with regard to shear strength, with higher natural water content correlating with higher strength. The anisotropic nature of the material is considered to be the cause of the anomaly. Reliable methods to establish the strength parameters, either in terms of undrained or drained behaviour, need to be developed.

More anomalous aspects of the shear strength of peats and organic soils are illustrated by Den Haan (52). They include the following:

* The undrained strength ratio c_u/σ_v' appears to decrease with increasing stress rather than remain constant in the normally consolidated range (Lechowicz (53)).
* Due to longer duration of prior consolidation, φ' decreases, c_u/σ_v' increases and dilatancy decreases. In inorganic clays, no such effect of duration of consolidation is expected.
* The undrained strength decreases after cyclic loading followed by drainage. In inorganic clays, an increase is expected.

8. CONSTITUTIVE MODELLING

Much engineering design for construction on peats and organic soils has been limited to settlement and stability calculations. However the lateral deformations caused by such construction work affects any neighbouring structures, and in the densely populated Netherlands this occurs frequently. Strengthening a dyke will affect buildings on or near the dyke; widening a road will affect the existing road and pipelines and communication cables buried near the toe. This fact has induced research in Holland into improved constitutive models for peat soil to be included in finite element codes.

The main problem is to account for the strong anisotropy of the peat. This is of importance not only for predicting lateral deformations, but in stability problems as well, as discussed earlier.

The most simple method to account for anisotropy is to introduce elastic anisotropy into the constitutive relations in finite element methods. More advanced methods make use of kinematic yield surfaces and boundary surfaces. Topolnicki and Niemunis (54) describe a boundary surface, anisotropic cap model which takes induced anisotropy into account by allowing rotation of the yield surface. The model was developed for clay but has been shown to apply fairly well to peat as well. Three different approaches to the problem have been attempted at Delft Geotechnics, all based on a suggestion by the author (55,56) to superimpose fibre stresses brought about by extension in the direction of the fibres, on the continuum stresses following from equilibrium requirements. Sellmeijer (57) devised an analytical anisotropic model which combines an elasto-plastic matrix with oriented fibres. Molenkamp (58) constructed constitutive equations for a composite material in which both matrix and fibres are given elasto-visco-plastic properties. Teunissen (59) combined an existing elasto-plastic finite element code incorporating both Mohr-Coulomb and modified Camclay models, with a simple fibre model. The so-called overlay method or fraction method is used to combine both laws. The fibre properties are given by Fig. 18a. The fibres have a linear elastic stiffness in their longitudinal direction, limited by a compressive strength (buckling) and tension strength (plastic stretching). Fig. 18b illustrates a strip footing on such a composite soil, and Fig. 18c shows that the bearing capacity is found to depend strongly on the fibre orientation with the horizontal direction. In this particular case, horizontally oriented fibres give the largest bearing capacity. Vertically oriented fibres also give high bearing capacity due to the large buckling strength assumed for the fibres, and other orientations appear to give low bearing capacity independent of fibre angle.

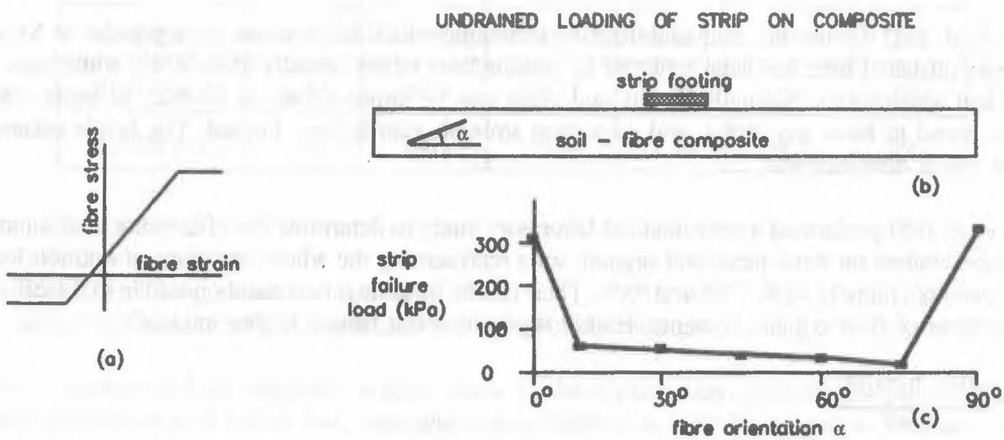

Fig. 18: Undrained bearing capacity of a strip footing on a soil - fibre composite with oriented fibres

The necessary input parameters in Teunissen's model however are not easy to determine, but the method is attractively simple and easily understood. More work should be done to determine correct input parameters, to study unexpected results such as Fig. 18c, and to expand the stress - strain law of the fibres to more realistic relations including the softening effects of progressive snapping of fibres.

Interesting applications of finite element programs to peat problems may be found in Rowe and Soderman (60), Yong and Mohamed (61), and Szymanski (62).

9. APPROPRIATE CONSTRUCTION- AND SOIL IMPROVEMENT TECHNIQUES

9.1 Introduction

Many methods have been developed to deal with the large compressibility and low strength of soft soils, most of which are applicable in peat and organic soils as well. Only a few methods will be discussed briefly, concentrating on the most important established techniques and a few promising new ones.

9.2 Stage Loading and Preloading

The natural fibrosity of peats is helpful in maintaining stability of fills. This can reduce lateral bulging and shear deformations considerably, as long as the rate of loading is slow enough to allow sufficient drainage for the fibre friction to be mobilized. This fibre action can be enhanced by application of fascine mattresses, corduroys and geotextiles.

Vertical wickdrains can help to speed up the drainage, although there has been much debate about the effectiveness of vertical drains in peat. The high initial permeability of peat may render the drains useless. Later in the consolidation process, permeability might decrease to levels making drains effective, but buckling and filter contamination might render them less effective before then.

Preloading remains an economical method of improving the stiffness of the embankment foundations (Carlsten (46)). Stage loading is necessary in most cases, and geotextiles are applied when existing roads are widened to keep the two parts of the embankment together. Use of lightweight fills, "weight-credit construction", are of use in peats even though peat itself is a very light material. Especially where road grades are regularly maintained by constantly applying new layers of asphalt, rehabilitation using light materials is effective. Light weight materials commonly used in construction over peat are baled peat, bark, foamed concrete, expanded clay and expanded polystyrene. Edil (63) further mentions shredded waste tyres, wood chips and sawdust. Corduroys, no longer much used because of high labour costs, nevertheless can be constructed to have better load spreading capabilities than geotextiles. Soil replacement and removal is applied up to depths of 5-6m: Magnan (12). Roads on peat soils are sometimes constructed on piles.

9.3 Deep Stabilization

Åhnberg et al. (64) discuss the deep stabilization technique which has become very popular in Sweden. In recent years unslaked lime has been replaced by cement/lime mixes (usually 50%-50%), while pure cement has also had applications. Strength of silts and clays can be improved up to 30-fold. In peats, only pure cement is found to have any effect, and even then strength gain is very limited. The brittle nature of the stabilized soil is demonstrated.

Odajima et al. (65) performed a very detailed laboratory study to determine the effectiveness of a number of cement-type binders on three peats and organic soils representing the whole spectrum of ignition losses (or organic contents), namely 48%, 77% and 98%. Their results indicate it is certainly possible to "stabilize" such soils regardless of their organic contents. Higher strengths result from a higher ratio of

$$SAC = \frac{SO_3 + Al_2O_3}{CaO} \qquad (25)$$

in the cement, and a higher SAC ratio is needed to obtain the same strength if organic content increases. Fineness of the cement is also of great importance. The latter is expressed in the surface area per unit of mass and is determined by the Blaine test.

Den Haan (66) performed unconfined compression tests on a Dutch peat and an organic clay, using three different cement-type binders. The first was a standard Dutch blast furnace slag cement (A). The second (B) was inspired by the work of Odajima et. al. It consisted of a mixture of 85% blast furnace cement, 14.5% of anhydrite (i.e. dehydrated gypsum), and 4.5% of aluminium cement clincker. The third binder (C) was of the same composition as the second, but was milled to a higher fineness in a ball mixer (capacity 10 liters) during 2 hours. The properties of the binders and their constituents are given in Table 1.

Table 1. Properties of binders A and B and their constituents

	SiO_2 (%)	Al_2O_3 (%)	CaO (%)	MgO (%)	SO_3 (%)	Fe_2O_3 (%)	SAC (-)	Blaine cm^2/g
BINDER A: CEM III/B 42.5	28.3	9.4	46.4	7.1	4.4	2.4	0.30	4375
CEM III/A 52.5	27	11	49	7	3	2	0.29	5280
anhydrite	0,5	-	41.0	3.2	52	-		
CSA aluminium cement	3.6	47.4	38.3	-	7.5	1.4		
BINDER B: 85:14.5:4.5 III/A:anhydrite:CSA	21.8	10.9	47.3	6.1	10.8	1.6	0.46	

The peat originated from Abcoude near Utrecht. The peat had a water content of 697%, an ignition loss of 83.1%, a pH of 5.8 and consisted predominantly of moderately decomposed reed peat. Its specific gravity was 1.44. The organic clay originated from 's-Gravendeel near Dordrecht and had a water content of 108%, an ignition loss of 13.0%, liquid limit 95%, plastic limit 46% and a pH of 6.7. Its specific gravity was 2.38. Soil from a number of borings was first homogenized in a laboratory mixer and then mixed with the binders. 200 kg binder per m^3 of wet soil were applied. Results of unconfined compression test performed on cylindrical test specimens of these stabilized soils is given for 28 days hardening in Table 2.

Table 2. Results of unconfined compression tests on cement-stabilized peat and organic clay.

	organic clay			peat		
	γ t/m^3	Q_u kPa	E_{50} MPa	γ t/m^3	Q_u kPa	E_{50} MPa
BINDER A	1.41	158	47	1.14	990	265
BINDER B	1.43	1827	1550	1.15	776	230
BINDER C	1.42	1661	1060	1.16	966	290

Symbols used in Table 2:

γ bulk density $[t/m^3]$

Q_u unconfined compressive strength [kPa]

E_{50} secant stiffness at 50% of the unconfined compressive strength

The table demonstrates high strengths in most cases. In the organic clay, strength complies with C>B>A, supporting the influence of higher SAC ratio and higher fineness as with Odajima et al. The unblended slag cement A is very much less efficient than the blended cements. It is surprising therefore to discover that A performs much better in the peat than in the organic clay, even better than the blends B and C which have a higher SAC ratio.

The strengths obtained for these Dutch soils are rather higher than for comparable tests on Scandinavian and Japanese soils. It should be possible to obtain reasonable strength with less cement, making the technique economically even more viable. It is now quite likely that the deep mixing technique will come to the Netherlands, to stay. The possible applications of the technique are unlimited. Mass stabilization under high speed railway links will overcome the problem of dynamic vibrations. Widening of highway embankments need no longer damage the existing road. Stability of slopes, revetments and embankments can be improved by deploying the piles as dowels through the potential slip surface.

9.4 Thermal Precompression

A novel method to improve peat is the thermal precompression technique: Edil and Fox (67), Fig. 19a. Peat compresses more quickly under load when it is heated. Two trial embankments, one (A) unheated, the other (B) heated by circulation of water 65°C in temperature flowing through heating wells installed in the peaty subsoil, demonstrate this, Fig. 19b. A significant quasi-preconsolidation effect is induced in the peat, and creep rates are strongly reduced. This may be found to be a cost-effective method of peat soil improvement.

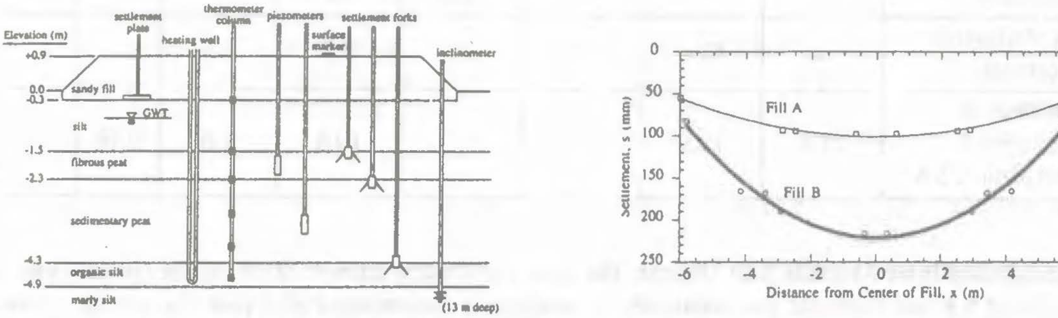

Fig. 19: Cross section and settlement of heated fill (B), compared to control fill (A)

9.5 The "Gap Method"

In Holland the so-called "gap method" has been experimented with to reduce horizontal deformations during widening of highway embankments. The stage construction of the new embankment is performed from the outside inwards, see Fig. 20a, rather than in layers as in the conventional technique. When consolidation of the outside sections has proceeded far enough the middle section, the "gap", is filled. Increased arching and reduced horizontal deformations result: compare Fig. 20b to Fig. 20c. Finite element analyses (Brinkgreve et al. (68)) indicate horizontal deformations of some 60cm for the conventional method, and only 50cm for the gap method.

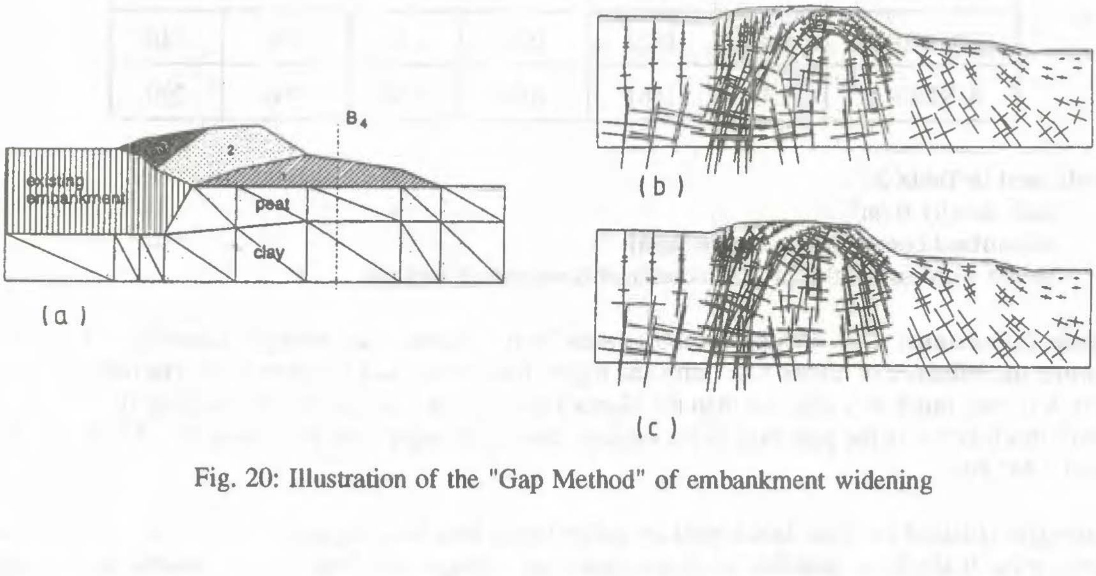

Fig. 20: Illustration of the "Gap Method" of embankment widening

10. SUMMARY AND CONCLUSION

This paper provides an overview of the mechanical behaviour of peats and organic soils, with an emphasis on the anomalies relative to the behaviour of inorganic clays. Some anomalies, outstanding characteristics and research needs are listed below.

* Deposits of peat and organic soils are extremely variable, large differences occurring over centimeters or decimeters. The variability extends throughout all scales up to the kilometer scale in many cases.
* The Atterberg limits are difficult to determine and are not especially useful characteristics.
* Surprisingly good correlation exists in organic soils from all over the world between natural water content and bulk dry density.
* Ignition loss is a very useful characteristic of organic soils. It correlates well with bulk density, specific gravity, and compressibility parameters and possibly also with shear strength parameters.
* Permeability of peats and organic soils is highly anisotropic and non-linear, and usually quite high in the initial state. These characteristics can be accounted for in modern methods of settlement analysis, but there is a need to gain insight in mass characteristics and anisotropy of permeability.
* The conventional C_c compression index is non-linear in peats and organic soils and the natural strain formulation is required to rectify this. The high creep rates in these soils necessitate a more accurate creep model than that based on Buisman's logarithm of time law, and modern stress - strain - (creep) strain rate relationships appear to be the answer. The author's *abc* model incorporates these features with non-linear permeability in the computer program CONSEF.
* Unload/reload behaviour of these soils and the tertiary compression phenomenon require further research.
* Unlike inorganic clays, peats and organic soils exhibit increasing friction angle and undrained strength ratio for *in*creasing natural water content. It is considered that the increasing fibre content is the cause. The high values of these parameters obtained from C.U. triaxial tests makes the usefulness of this test questionable for these soils. The simple shear test is possibly more suited. Anisotropy of strength in these soils must be accounted for in stability analysis and in calculating lateral deformations.
* Of the various constitutive models being developed to account for the fibre-induced anisotropy, the overlay model seems most simple and most promising. Further research in this field should concentrate on this approach.

The paper briefly describes some appropriate construction techniques and soil improvement methods for building on peats and organic soils:

* Stage loading and preloading continue to be reliable and popular. Use of geotextiles and vertical drains can enhance these techniques. Light weight fill materials are a useful alternative.
* Deep stabilization in the form of soil-cement piles and soil-cement mass stabilization are promising new techniques, which contrary to the general expectation some years ago, seem to work well in organic soils and peats.
* Thermal precompression is a promising new technique to obtain quick precompression without using large surcharges, thus preventing large lateral deformations.

The art of building on peats and organic soils is gradually developing into a full-fledged branch of geotechnics. Consensus regarding the determination of index properties, classification and geotechnical taxonomy are needed to enhance exchange of results and concepts. This task was one of the objectives of the Technical Committee on Peat (TC15) of the International Society for Soil Mechanics and Foundation Engineering in the terms prior to 1994, but was not realized. It is not an objective in the present term of TC15, and must be reconsidered in the near future.

Methods for settlement calculation are evolving, and will certainly yield useful results in the coming years. Methods to account for the anomalous shear strength behaviour of peats and organic soils are desperately needed, and too little is being done in this respect. Constitutive modelling of the anisotropy of these soils should be kept as simple as possible, and the overlay model seems very promising it this respect.

The rapid rate of decomposition of peat in tropical conditions once it is drained, poses severe problems and requires special attention. No simple answers are at hand.

REFERENCES

(1) J. Vegelin à Claerbergen, "Vertoog over de veengraverijen", (Treatise on the bog-diggings), Leeuwarden, 1766.

(2) J. le Franq van Berkhey, "Natuurlijke historie van Holland", (A natural history of Holland), 1771.

(3) N.B. Hobbs, "Mire morphology and the properties and behaviour of some British and foreign peats", *Quart. J. of Eng. Geol.*, Vol. 19, 1986, pp. 7-80.

(4) L.S. Amaryan, *Soft soils properties and testing methods.* Rotterdam, A.A. Balkema, 1993, 180pp.

(5) J.A.R. Anderson, "Tropical peat swamps of Western Malesia", *Ecosystems of the world 4B. Mires: swamp, bog, fen and moor, Regional Studies.* Amsterdam, Elsevier Scientific Publishing Company, 1983, pp.181-199.

(6) A.S. Keverling Buisman, "Results of long duration settlement tests", *Proc. 1st Int. Conf. Soil Mech. and Fdn Eng.*, Cambridge, Mass., 1936, pp. 103-106.

(7) B.M. Wayi & D.F. Freyne, "The distribution, characterization, utilization and management of peat soils in Papua New Guinea". *Proc. Int. Symp. on Tropical Peatland*, Kuching, Sarawak, Malaysia, May 1991, pp.28-32.

(8) M.J. Andrejko, F. Fiene & A.D. Cohen, "Comparison of ashing techniques for determination of the inorganic content of peats", *Testing of peats and organic soils*, A.S.T.M. Special Technical Publication nr. 820, 1983, pp. 5-20.

(9) A.O. Landva, E.O. Korpijaakko & P.E. Pheeney, "Geotechnical classification of peats and organic soils", *Testing of peats and organic soils*, A.S.T.M. Special Technical Publication nr. 820, 1983, pp. 37-51.

(10) A.O. Landva & P.E. Pheeney, "Peat fabric and structure", *Can. Geot. J.*, 1980, pp. 416-435.

(11) Technische Adviescommissie voor de Waterkeringen, Ministerie van Verkeer en Waterstaat (Netherlands Ministry of Traffic and Water-Management), *Technisch rapport geotechnische classificatie van veen* (Technical report on classification of peat), 1996, 102pp.

(12) J.P. Magnan, "Construction on peat: State of the art in France" *Advances in understanding and modelling the mechanical behaviour of peat*, Rotterdam, Balkema, 1994, pp. 369-380.

(13) R. Larsson, *Behaviour of organic clay and gyttja.* Linköping, Swedish Geotechnical Institute, 1990, Report No. 38.

(14) N.W. Radforth, "Classification of muskeg", *Muskeg Engineering Handbook*, Univ. of Toronto Press, 1969. pp. 31-52.

(15) R.S. Clymo, "Peat", *Ecosystems of the world 4A. Mires: swamp, bog, fen and moor, General Studies*, Amsterdam, Elsevier Scientific Publishing Company, 1983, pp. 159-224.

(16) N.P. Betelev, "Determining of organic matter content in soils and rocks", *Proc. 11th ECSMFE*, Copenhagen, 1995, Vol. 3, pp. 13-18.

(17) A.S.T.M. D 2974, "Test for moisture, ash and organic matter of peat materials".

(18) A.W. Skempton & D.J. Petley, "Ignition loss and other properties of peats and clays from Avonmouth, King's Lynn and Cranberry Moss", *Géotechnique*, Vol. 4, 1970, pp. 343-356.

(19) E.J. den Haan, "Samendrukbaarheid en andere eigenschappen van veen in een karakteristiek West-Nederlands veenprofiel" (Compressibility and other properties of peat in a characteristic Western Netherlands peat profile), *Delft Geotechnics, report CO-305862/3*, 1989.

(20) J.R. Hosang & J.G. Locker, "Discussion to: Ignition loss and other properties of peats and clays from Avonmouth, King's Lynn and Cranberry Moss". *Géotechnique*, 1971, Vol. 4, pp. 416-418.

(21) E.R. Farrell, C. O'Neill & A. Morris, "Changes in the mechanical properties of soils with variations in organic content", *Advances in understanding and modelling the mechanical behaviour of peat*, Rotterdam, Balkema, 1994, pp. 19-25.

(22) J. Farkas & M. Kovacs, "Volume change of peats. *Proc. 2nd Baltic CSMFE*, Tallinn, 1988, Vol. 1, pp.42-47.

(23) J. Kabaj & J. Farkas, "Strength and deformation tests of Hungarian peats. *Proc. 2nd Baltic CSMFE*, Tallinn, Vol. 1, pp. 48-54.

(24) N.D. Marachi, D.J. Dayton & C.T. Dare, "Geotechnical properties of peat in San Joaquin delta", *A.S.T.M. S.T.P. 820*, pp. 207-217.

(25) S.H. Sikder, *Variability of geotechnical properties of peat*, MSc thesis, ITC Delft, 1994.

(26) G. Lefebvre, P. Langlois & C. Lupien, "Laboratory testing and *in situ* behaviour of peat as embankment foundation", *Can. Geotech. J.*, 1984, pp. 322-337.

(27) H. Lundgren, "Dimensional analysis in soil mechanics". *Acta Polytechnica Scandinavica*, Vol. 237, Civ. Eng. & Build. Constr. Series 4/10, 1957, pp. 73-107.

(28) E. Juárez-Badillo, "Compressibility of soils", *Proc. 5th Symp. Behaviour of Soil under Stress*, Vol. 1:A2/1-35. 1965, Bangalore, Indian Institute of Science.

(29) R. Butterfield, "A natural compression law for soils (an advance on e-log p')", *Géotechnique*, Vol. 29, No. 4, 1979, pp. 469-480.

(30) E.J. den Haan, "The formulation of virgin compression of soils", *Géotechnique*, No. 3, 1992, pp. 465-483.

(31) T.B. Edil & E.J. den Haan, "Settlement of peats and organic soils", *A.S.C.E. Geot. Spec. Publ. No. 40*, Vol. 2, pp. 1543-1572.

(32) E.J. Den Haan, "A simple compression model for non-brittle soft clays and peat", *D.Sc. thesis "Vertical Compression of Soils"*, Delft *University Press*, nov. 1992, pp. 61-95.

(33) N.E. Wilson, N.W. Radforth, I.C. MacFarlane & M.B. Lo, "The rates of consolidation for peat", *Proc. 6th ICSMFE*, Montreal, 1965, Vol. 2, pp. 407-411.

(34) T.B. Edil & A.W. Dhowian, "Analysis of long-term compression of peats", *Geot. Eng. S.E. Asian Soc. Soil Eng.*, No. 10, 1979, pp. 159-178.

(35) A.W. Dhowian & T.B. Edil, "Consolidation behaviour of peats", *Geot. Test. J.*, No. 3, 1980, pp. 105-114.

(36) A.W. Bishop & H.T. Lovenbury, "Creep characteristics of two undisturbed clays", *Proc. 7th ICSMFE*, Mexico, 1969, Vol. 1, pp. 29-37.

(37) M. Kabbaj, F. Oka, S. Leroueil & F. Tavenas, "Consolidation of natural clays and laboratory testing", *A.S.T.M. S.T.P. 892*, 1986, pp. 378-404.

(38) S. Hansbo, "Experience of the use of vertical drains for speeding up consolidation of peat", *Proc. 2nd Baltic CSMFE*, Tallinn, 1988, Vol. 1, pp. 150-157.

(39) S. Krieg & M. Goldscheider, "Some results concerning the development of K_o during one-dimensional creep of peat", *Advances in understanding and modelling the mechanical behaviour of peat*, Rotterdam, Balkema, 1994, pp. 71-76.

(40) C.J. Candler & F.R.D. Chartres, "Settlement measurement and analysis of three trial embankments on soft peaty ground", *Proc. 2nd Baltic CSMFE*, Tallinn, 1988, Vol. 1, pp. 268-272.

(41) D. Simic, "Strength and consolidation behaviour of a soft organic clay from a mangrove swamp in Ecuador", *Proc. 10th ECSMFE*, Florence, 1991.

(42) T.B. Edil & P.J. Fox, "Field test of thermal precompression. *A.S.C.E. Geot. Spec. Publ. No. 40*, 1994, Vol. 2, pp. 1274-1286.

(43) J. Feda, *Creep of soils and related phenomena.* Amsterdam, Elsevier, 1992, 422pp.

(44) A.W.N.Al-Khafaji & O.B. Andersland, "Compressibility and strength of decomposing fibre-clay soils", *Géotechnique*, Vol. 31, No. 4, 1981, pp. 497-508.

(45) K. Flaate, "Setninger i torv-jordarter", *Statens Vegvesen, Veglaboratoriet,* Report nr. 93, 1968.

(46) P. Carlsten, "Peat: Geotechnical properties and up-to-date methods of design and construction", *State-of-the-art report, 2nd Baltic CSMFE, 1988, Varia nr. 215*, Swedish Geotechnical Institute, Linköping.

(47) S. Noto, *Peat Engineering Handbook,* Publication of the Hokkaido Development Agency, Prime Minister's Office, Japan, 1991.

(48) Z. Meyer & M. Dereczenik, "Non-linear model of terminal settlement of peat", *Advances in understanding and modelling the mechanical behaviour of peat*, Rotterdam, Balkema, 1994, pp. 89-94.

(49) E.J. den Haan & L.S.F. El Amir, "A simple formula for final settlement of surface loads on peat", *Advances in understanding and modelling the mechanical behaviour of peat*, Rotterdam, Balkema, 1994, pp. 35-48.

(50) R.Q. Coutinho & W.A. Lacerda, "Strength characteristics of Juturnaiba organic clays", *Proc. 12th ICSMFE*, Rio de Janeiro, 1989, pp. 1731-1734.

(51) M. Tsushima & T. Mitachi, "Influence of consolidation duration on shear characteristics of organic soils", *9th S.E. Asian Geot. Conf.*, Bangkok, 1987, Vol. 4, pp. 65-72.

(52) E.J. den Haan, "Theme report on special problem soils / soft rocks. Part I: Peats and Organic Soils", *Proc. 11th ECSMFE*, Copenhagen, 1995, Vol. 9, pp. 139-156.

(53) Z. Lechowicz, "An evaluation of the increase of shear strength in organic soils", *Advances in understanding and modelling the mechanical behaviour of peat*, Rotterdam, Balkema, 1994, pp. 167-180.

(54) M. Topolnicki & A. Niemunis, "Numerical simulation of stress-strain behaviour of peat for biaxial deformations at plane strain", *Advances in understanding and modelling the mechanical behaviour of peat*, Rotterdam, Balkema, 1994, pp. 253-266.

(55) E.J. den Haan, "Veen, een grondmechanisch probleem", (Peat as a geotechnical problem soil), *Delft Geotechnics, report CO-416731/24*, 1987.

(56) E.J. den Haan, "Enkele ideeën over modelvorming veen" (Suggestions regarding constitutive modelling of peat), *Delft Geotechics, report CO-305866/2*, 1989.

(57) J.B. Sellmeijer, "Ansiotropic peat model", *Advances in understanding and modelling the mechanical behaviour of peat*, Rotterdam, Balkema, 1994, pp. 211-230.

(58) F. Molenkamp, "Investigation of requirements for plane strain element tests on peat", *Advances in understanding and modelling the mechanical behaviour of peat*, Rotterdam, Balkema, 1994, pp. 181-202.

(59) J.A.M. Teunissen, "Numerical modelling of peat", *I. S. Hiroshima: Compression and consolidation of clayey soils*, Rotterdam, Balkema, 1995, Vol. 1, pp. 367-372.

(60) R.K. Rowe and K.L. Soderman, "Geotextile reinforcements of embankments on peat", *Geotextiles and Geomembranes*, 1985, Vol. 2, pp. 277-298.

(61) R.N. Yong & A.M.O. Mohamed, "Nonlinear stress analysis of muskeg via finite element", *Can. Geot. J.*, Vol. 28, 1991, pp. 613-629.

(62) A. Szymanski, "The use of constitutive soil models in consolidation analysis of organic subsoil under embankment", *Advances in understanding and modelling the mechanical behaviour of peat*, Rotterdam, Balkema, 1994, pp. 231-240.

(63) T.B. Edil, "Immediate issues in engineering practice", *Advances in understanding and modelling the mechanical behaviour of peat*, Rotterdam, Balkema, 1994, pp. 403-414.

(64) H. Åhnberg, C. Ljungkrantz, C. & L. Holmqvist, "Deep stabilization of different types of soft soils", *Proc. 11th ECSMFE*, Copenhagen 1995, Vol. 7, pp. 167-172.

(65) H. Odajima, S. Noto, J. Nishikawa and T. Yamazaki, "Cement stabilization of peaty ground with consideration of organic matters", *Proc. Int. Workshop on Eng. Characteristics and Behaviour of Peat*, Sapporo, 1995, pp. 133-141.

(66) E.J. den Haan, "Strength gain of a Dutch organic clay and a peat by stabilization with various cement-type binders", *Delft Geotechnics, report nr. CO-366340/27*, 1997.

(67) T.B. Edil & P.J. Fox, "Field test of thermal precompression", *A.S.C.E. Geot. Spec. Publ.*, No. 40, Vol. 2, pp. 1274-1286.

(68) R.J. Brinkgreve, P.A. Vermeer & E. Vos, "Constitutive aspects of an embankment widening project", *Advances in understanding and modelling the mechanical behaviour of peat*, Rotterdam, Balkema, 1994, pp. 143-158.

BIOGRAPHY

Evert den Haan is a member of the Strategic Research Department of Delft Geotechnics, which he joined in 1978. In 1994 he obtained a D.Sc. degree on a study of the vertical compression of soils. Part of this work was awarded the 1993 Geotechnical Research Medal of the British Institution of Civil Engineers. A 1994 paper on "Settlement of Peats and Organic Soils" of which he is co-author, was acclaimed an Outstanding Geotechnical Paper by the North American Geotechnical Community.
Present scientific interests regard various aspects of the behaviour of soft clays, peats and organic soils such as one-dimensional compression, creep, shear strength, finite element modelling, and laboratory and centrifuge testing. Soil improvement techniques of organic soils and peats are also a major topic of interest. E.J. den Haan is a member of the Dutch Royal Institute of Engineers and serves as secretary of the Technical Committee TC15 on "Peats and Organic Soils" of the International Society for Soil Mechanics and Foundation Engineering.