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Consolidation settlements of tropical peat domes by plantation development

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Summary
Settlement of tropical peat domes after cultivation for agriculture is the result of oxidation and compaction components above the ground water table, and consolidation below the ground water table. This report studies the consolidation component, making use of an advanced geotechnical compression model. An example case of plantation development on a peat dome in SE Asia is constructed, and geotechnical parameters are deduced from laboratory tests on tropical peat in SE Asia. The model calculations reveal that during the initial development phase in which the ground water table is lowered to more than 1.5 metres below the peat surface, over 1 metre subsidence by consolidation can occur in a matter of months assuming a peat thickness of 10 metres. As ground water table depths decrease, first mainly as a result of the subsidence itself and at a later stage maybe also due to water management efforts, consolidation of the peat below the ground water table comes to a complete stand-still. This is explained in geotechnical terms by the relatively large degree of unloading following the rise in ground water level, and leads to the conclusion that after the first year of drainage, further subsidence stems wholly from processes above the water table, i.e. oxidation and compaction.

Deltares References
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Content

1 Introduction

More than half (24.8 Mha) of the global area of tropical peatland is in SE Asia (56%), mostly in Indonesia and Malaysia. Owing to the considerable thickness (mean >5 m) of the peat in these two countries they contain 77% of the entire tropical peat carbon store (Page et al., 2011). In Peninsular Malaysia and the islands of Sumatra and Borneo, some 60% of peat swamps were partly or completely deforested by 2007, usually accompanied by some form of drainage, and only 10% remained in pristine condition (Miettinen et al., 2012a). Some 5 Mha were under agricultural use in 2007, of which 45% (2.3 Mha) was large-scale oil palm and pulpwood (Acacia) plantations. The area of large-scale industrial plantations had increased to 3.15 Mha by 2010 (12% increase per year since 2007, excluding smallholder plantations and other forms of land conversion), and that this high expansion rate is likely to continue unless land use planning policies are changed.

It has long been known that drainage of peatlands causes irreversible lowering of the surface (subsidence or settlement) as a consequence of consolidation, peat shrinkage or compaction and biological oxidation, with the latter resulting in a loss of carbon stock. In peatland areas as different as the Fenlands of the UK, the Netherlands, Venice Lagoon in Italy, the Everglades and Sacramento Delta in the United States and Lake Hula in Israel, a total subsidence of 200 to 600 cm occurred over 40 to 130 years, bringing surface levels close to or below sea level (Schothorst, 1977; Hutchinson, 1980; Stephens et al., 1984; Hambright and Zohary, 1998; Gambolati et al., 2003; Deverel and Leighton, 2010). In all of these cases, peat oxidation is reported to be the main cause of subsidence. In recent years, rapidly increasing peat carbon losses from drained SE Asian peatlands have been found to contribute substantially to global greenhouse gas emissions (Hooijer et al., 2006, 2010; Couwenberg et al., 2010; Murdiyarso et al., 2010).

Land subsidence in drained peatlands is due to three main processes (modified from Hooijer et al., 2012):

1. Oxidation: decomposition of peat in the aerated zone above the water table owing to breakdown of organic matter, resulting in carbon loss through release of gaseous CO_2 to the atmosphere, and to a lesser extent through removal as DOC in drainage water (most of which will ultimately degas as CO_2 or CH_4 to the atmosphere). This process, acting alone, does not increase bulk density of the peat and could in fact decrease it.
2. Compaction and shrinkage: volume reduction of peat in the aerated zone above the water table. Compaction results from the pressure applied on the peat surface by heavy equipment; shrinkage occurs through contraction of organic fibres when peat dries. These two processes cannot usually be separated in practice and they are considered together as ‘compaction’. Both processes lead to an increase in peat bulk density.
3. Consolidation: the compression of saturated peat below the water table owing to loss of buoyancy of the top peat, increasing loading (downward pressure) on the peat below. The initial rapid process is partly controlled by the speed at which water from pores in the peat can be removed under pressure. Slower consolidation processes that may continue in the long term (sometimes collectively referred to as ‘secondary’ consolidation) are a function of a set of physical peat parameters describing its viscoplastic or ‘creep’ characteristics.

1.1 Problem statement

Although the processes causing subsidence in peatland areas are well known, their relative contribution over time remains unclear. It is generally reported that, after a brief initial period following drainage in which the peat surface subsides rapidly, and mostly through consolidation below the water table (Andriesse, 1988; Kool et al. 2006), further land subsidence in following years is caused almost entirely by the processes of oxidation and compaction above the water table, and consolidation may be neglected (Kasimir-Klemedtsson et al., 1997). This principle has been applied in numerous studies that have analysed subsidence rates and changes in peat bulk density (BD) above the water table to determine the relative contribution of oxidation to this process, in temperate climates (e.g. Schothorst,1977; Van den Akker, 2008; Deverel and Leighton, 2010; Leifeld et al., 2011) as well as tropical climates (Stephens and Speir, 1969; Wösten et al. 1997; Couwenberg et al., 2010; Hooijer et al. 2012).

The subsidence/BD method has been applied widely since at least the 1950s. Initially the main interest was in subsidence projections as part of land suitability projections. This was the basis, for instance, for the conclusion that peatland drainage could not lead to sustainable agriculture in the USA Everglades and Sacramento Delta because oxidation is dominant in peat soils (Stephens and Speir, 1969; Galloway et al. 1999, Deverel and Leighton, 2010). As the method became applied more frequently in the tropics, there have recently been some questions on whether the assumption of subsidence being caused solely by oxidation and compaction above the water table was fully justified. Recently, Hergoualch and Verchot (2011) suggested that as much as 99% of subsidence in tropical peatlands could be consolidation. On this basis, they question the validity of the subsidence method for carbon loss quantification.

Besides the applicability of the subsidence/BD method for carbon loss assessments, knowing the contribution of consolidation to land subsidence is critical also for assessment of the slowdown in subsidence rate and increase in flood risk in time, which is required in assessments of land suitability for agriculture. If the contribution of oxidation to subsidence is high, the slowdown of subsidence rates will be relatively low (as there is little densification of the top soil) and CO_2 emission will also be relatively high.

This approach to quantifying carbon loss will be strengthened by accurately quantifying the consolidation component of subsidence. To our knowledge, there has to date been no thorough geotechnical assessment of this aspect of subsidence in relation to carbon loss assessments and long-term subsidence projections. The study presented here has been set up to fill this gap, as part of the ongoing Deltares research programme into the global implications of land subsidence (Erkens et al., 2012).

1.2 This study and report

In this study, we isolate consolidation from other factors that contribute to subsidence. Our results must be seen as the physically possible contribution of consolidation to subsidence. We calculate consolidation below the water table in peat soils, from the moment of drainage. We do this for peatlands in SE Asia that have received much attention in recent years (Page et al., 2011).

The focus of this study is especially on identifying the rate of consolidation after the initial phase of drainage and rapid consolidation. During that initial phase, measurements of subsidence and other parameters are rarely possible. Studies of subsidence and carbon loss usually focus on conditions in established agricultural landscapes, more than 5 years after drainage, so therefore the key question that needs to be answered is: ‘what is the consolidation rate 5 or more years after drainage’?

This report presents the following:

- An assessment of key parameters and characteristics that control consolidation.
- Calculations of consolidation according to different scenarios for water table depth and peat depth using an advanced geotechnical compression model.
- An evaluation of what calculation results mean for applicability of the subsidence/BD method for determining carbon loss from drained peatlands.

To ensure that the results presented here are fully usable in further studies, the contents of this report will also be published in a peer reviewed paper.

2 Example case

The example case of a tropical peat dome development is constructed from observations of typical plantation developments in Indonesia. Guidance is given by descriptions of peatland development in SE Asia (Andriesse, 1988; DID Sarawak, 2001; Hooijer et al., 2005, 2008, 2009, 2012).

The peat below the ground water table is assumed to be highly fibrous and only slightly decomposed, i.e., fibric to hemic in the Soil Taxonomy (1999) classification as is the norm in most peatlands in SE Asia (Page et al. 2011).

Parameters needed for the calculation of consolidation are peat thickness, various density indices of the peat, the permeability of the peat and of the underlying substrate, the history of loading of the saturated soil below the ground water table by changes in water table depth, and the geotechnical compression parameters of the peat.

The typical peat thickness in the Acacia and oil palm plantations in Indonesia considered here is between 3 and 10 m (Page et al. 2011; Hooijer et al., 2012). A thickness of 10 m is used in the example case, but consolidation settlement and peat thickness are more or less proportional (as will be discussed), so that settlements for other thicknesses can easily be estimated from those presented here.

The substrate underlying the peat in Indonesia varies mostly from sandy clays and silt and clay loams, mainly deposited in fluvial (backswamps) or coastal (mangrove) environments (Staub and Esterle, 1994). The substrate applied in calculations is assumed impermeable, implying that all lateral water transport required to accommodate consolidation must be through the peat itself.

Hydraulic conductivity in SE Asia peatlands varies widely, from 1 to over 100 m d^{-1} (Ritzema, 2007). Values for fibric peat, which is commonly found in the deeper peat deposits, are at the high end of this range. In Acacia plantations on deep peat in Riau, Hooijer et al. (2009) found values between 50 and 200 m d^{-1}. Conservatively, a value of 10 m d^{-1} will be used in this paper, and it is shown that this value is still sufficiently high to be able to disregard the effects of hydrodynamic retardation of consolidation.

Bulk density of fibric/hemic peat in SE Asia with low mineral content, before plantation drainage, is in the range of 0.06 to 0.10 Mg m^{-3} (mass of dry material relative to total soil volume) (Page et al., 2011, Hooijer et al., 2012). In these cases, there are no indications of a systematic trend with depth. A value of 0.065 Mg m^{-3} will be taken for the state of the peat immediately prior to forest clearing. This value increases during consolidation to values of approximately 0.075 as measured by Hooijer et al. (2012) below the ground water table for plantations in Riau and Jambi.

It is the weight of the unsaturated peat above the water table that causes consolidation of the peat below it. This weight is determined by the volume and wet bulk density of the peat. Profiles of soil moisture in plantations on peat in Jambi, Indonesia are shown in Figure 1. The moisture content as a percentage of total weight is in the range 80 to 90%, averaged over the unsaturated zone. An average value of 80% is taken during the initial stages of drainage to calculate wet bulk density, while 85% is used during the exploitation stages with decreased depth to ground water.

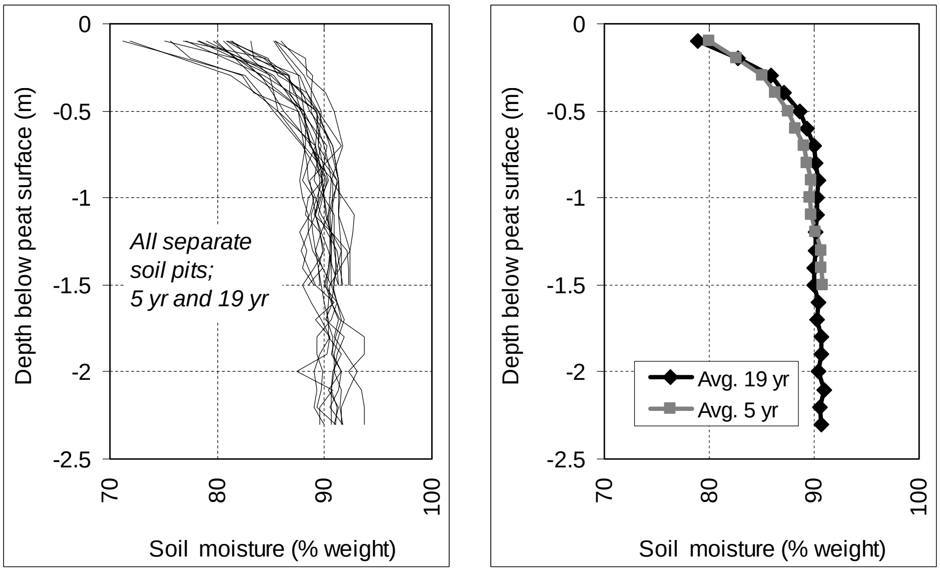

Figure 1 Profiles of soil moisture content as determined in oil palm plantations in Jambi, Indonesia, 5 to 19 years after drainage. These are the same locations where subsidence and bulk density were studied as described in Hooijer et al. (2012). Average water tables were approximately 0.55 m, but averages for individual locations at the time of sampling varied between 0.4 and 1 m.
Left plot: individual profiles, in different seasons, each consisting of three replicate samples at 10-20 cm intervals in soil pits. Note that there is seasonal variation, but soil moisture contents (by weight) below 70% were not found in any location.
Right: profiles for 5 year old and 19 year old plantations, averaged over seasons and locations. Note that the average profiles are nearly identical, despite the difference in land use and duration of drainage.

It should be noted that water content in most of the unsaturated soil is quite stable near field capacity most of the time, for several reasons: i) frequent and intense rainfall events regularly replenish soil moisture; ii) it appears that vegetation on this peat (including Acacia and oil palm) mostly uses water from the saturated zone without much affecting moisture content in the unsaturated zone. In prolonged dry periods the soil moisture content in the top few decimetres is observed to drop to below 80%, but this has a limited effect on the longer-term average wet bulk density as applied in consolidation calculations.

The change in ground water table depth depends on the water management strategy adopted during the various stages of development. This is the largest source of loading on the peat below the ground water table and therefore of subsidence by consolidation. The weight of the forest also contributes some load. The history of loading during the formation of the peat dome must also be accounted for. In particular, low water tables during drought conditions will have contributed to the initial state of the peat before forest clearing and further development. It is assumed that extreme dry spells occurred every 10 years, with a water table depressed to 1 m depth for 1 month during extreme drought events (Usup et al. 2004; Hirano et al. 2012; Jaenicke et al. ,2010). Less extreme but more frequent drought events will hardly contribute to further densification of the peat. During peat dome formation, the presence of forest with a weight of 500 Mg ha^{-1} is assumed. Over an estimated 3000 years of peat dome creation, the extreme drought conditions would total a number of 25 years.

An initial period of gradual and incomplete forest clearing prior to plantation development is assumed to take place over a 10 year period (Miettinen et al., 2012b). The average depth to ground water table in this period is taken as 0.25 m and the weight of forest is assumed to have reduced to 250 Mg ha^{-1}. Less severe droughts with a depression of the ground water table to 0.5 m during 2 months every year, and a single severe event with a depression to 1.0 m during 2 months in one of the ten years are assumed to occur.

Plantation development begins with the construction of a network of drainage canals through the peat dome, to increase density and bearing capacity of the soil. Two scenarios are defined for the plantation development. In the best practice scenario, water table depth is lowered to 1.5 m during the first year. Water table depths then decrease, largely because the peat surface is lowered by subsidence towards the water table, but also partly because efforts may be made to bring up ground water levels through construction of retardation dams. Note that in the initial period of plantation development, canals are without water management structures because i) they are the main access route, for staff and resources, ii) it is the intention of plantation managers to keep water levels low to rapidly increase density and bearing capacity of the top soil, and iii) creating such structures takes time and resources. During the second and third years, 1.0 m water table depth is assumed. Finally, during plantation exploitation, after year three, an average water depth of 0.7 m depth is assumed. This depth is assumed to be maintained to the end of the considered period, 20 years after the start of plantation development.

This scenario matches the one seen in Acacia plantations for which subsidence rates and carbon loss were reported by Hooijer et al. (2012), as explained in Hooijer et al. (2008; 2009; 2012) and in the ANNEX to this report.

A second scenario which is considered to be closer to common practice in most Indonesian plantations is also defined. The first year ground water level is now at 2 m depth, the second and third year level at 1.5 m and in the following years it is also at 0.7 m.

3 The geotechnical compression model

In this study we apply the isotache model by Den Haan, which was specifically developed for use with highly compressible peats and organic clays (Den Haan, 1996; Den Haan and Kruse, 2007). The model is used widely in The Netherlands, and is implemented in the D-Settlement geotechnical software code. Common applications are the calculation of settlements of embankments, structures and sand fills placed on soft ground, and subsidence and heave following changes in ground water levels. Note that the term 'settlement' is used in geotechnical engineering not only for the vertical movement of structures built on soil, but in general for any vertical movement associated with changes in vertical effective stress and with increasing time, and in this respect the term is synonymous with the geological term 'subsidence'. Note further that neither term is strictly limited to ground surface movements and both can therefore vary throughout the depth of a soil profile.

The present isotache model is similar to the model defined by Yin and Graham (1994), but is more suited to highly compressible material by employing logarithmic or natural strain rather than linear strain. The advantages of using the former will become apparent when oedometer test results on tropical peat are presented further on.

A summary of the isotache model is now given.

Strains are taken as natural or Hencky strains, given by

$$\varepsilon^H = -\ln(1-\varepsilon)$$

where ε is common, linear strain. It is therefore also given by

$$\varepsilon^H = -\ln(v/v_0)$$

where v is specific volume (1 + e), and by

$$\varepsilon^H = \ln(\rho_d / \rho_{d0})$$

where ρ_d is the dry bulk density, and e is voids ratio.

Strain is considered to have a viscoplastic or creep component and an elastic component. Total strain, and total rate of strain is simply the summation of elastic and creep strains and strain rates:

$$\varepsilon^H = \varepsilon^H_{vp} + \varepsilon^H_{el}$$

$$\dot{\varepsilon}^H = \dot{\varepsilon}^H_{vp} + \dot{\varepsilon}^H_{el}$$

where the superimposed dot signifies rate, and the indices vp and el signify the viscoplastic and elastic components.

Elastic strains occur in concord with changing vertical effective stress σ'_v as

$$\varepsilon^H_{el} = a\ln(\sigma'_v / \sigma'_{v0})$$

$$\dot{\varepsilon}^H_{el} = a\dot{\sigma}'_v / \sigma'_v$$

while viscoplastic strain rate can be derived from sustained viscoplastic strain and present stress by

$$\dot{\varepsilon}_{vp}^{H} = \frac{1}{c}\left(\frac{\sigma_v'}{\sigma_p}\right)^{(b-a)/c} \exp(-\varepsilon_{vp}^{H}/c)$$

Here, a, b and c are soil constants, and σ_p is the preconsolidation pressure.

Compression problems are solved incrementally in time, with in each time step the rates of strain being calculated first from the present state of stress and strain, and then adding rates and multiplying by the size of the time increment. During outflow of pore water, Darcy flow can be combined with the constitutive equations given above. Under constant load, outflow gradually reduces to small rates and vertical effective stress becomes almost constant. The first phase of significant outflow is known as the hydrodynamic or primary phase, and the outflow results in elastic and viscoplastic strains. The second phase, known as the secondary phase, consists of little outflow and ongoing viscoplastic or creep strains.

An important feature of isotache models is the ability to accommodate creep ageing, which is the process of increasing preconsolidation pressure due to the on-going volume decrease by creep. A large load maintained for time τ (days) increases the preconsolidation pressure by a factor

$$\xi = \tau^{c/(b-a)}$$

This factor is used to estimate the preconsolidation pressure resulting from the extreme droughts during the formation of the peat dome. These occur to an accumulated duration of 25 years, and with the choice of a, b and c parameters to be detailed in the following, ξ = 1.4 is obtained. The load during these droughts corresponds to the weight of the soil and water above the depressed ground water table (1 m depth) and the weight of the forest, and therefore comes to 11 kPa. The preconsolidation pressure immediately prior to the start of forest clearing is then 15.4 kPa.

The initial stress at the commencement of forest clearing is taken as corresponding to a water table depth of 0.1 m, and 500 tons ha^{-1} of forest. That is 1.6 kPa. The preconsolidation pressure is 13.8 kPa higher, and this value is applied at all depths of the consolidating layer to obtain preconsolidation pressure. That is, the initial stresses in the layer which increase with depth due to the (submerged) self-weight of the peat, are increased with the value of 13.8 kPa to obtain the preconsolidation pressure.

4 Geotechnical parameters

Very little data exists in the literature on the compressive properties of high water content tropical peat. Duraisamy et al. (2007) present data of fibric, hemic and sapric peat from the western coast of peninsular Malaysia. However, initial bulk density was in the range 0.14 – 0.17 Mg m^{-3} for the fibric peats, and higher for the hemic and sapric peats, and therefore not comparable to the much lower values encountered in the peat domes studied here of approximately 0.075 Mg m-3 (Hooijer et al. 2012). It should be noted that bulk density values well over 0.1 Mg m^{-3} are rare in peat below the water table with carbon content over 40% (Page et al. 2011; Warren et al. 2012).

High water content peat with bulk densities lower than 0.1 Mg m^{-3} was encountered at a site near Berengbenkel in Central Kalimantan, Indonesia. This site was chosen for the construction of trial embankments built as preparation for the construction of the Palangka Raya to Banjarmasin national highway. Rahadian et al. (2001) describe the site investigation and field and laboratory data interpretation. These trial embankments were performed in the context of the Memorandum of Understanding (1996 - 2001) between the Ministry of Public Works of the Republic of Indonesia and the Dutch Ministry of Transport, Public Works and Water Management, which was directed at development and knowledge exchange on area development and construction in low lying areas. The oedometer tests performed in this investigation are presented below.

The peat is described as dark brown, highly fibrous with root traces and a von Post degree of humification of H2 – H5. The site investigated had a length of 450 m and the surface peat layer had thicknesses varying from 2.5 to 11 m. A total of 10 oedometer tests on peat were executed on piston samples obtained from 4 boreholes. Standard 24 h incremental loading tests were performed up to loads of 640 kPa or more. The drainage condition was varied between vertical and horizontal. Gravimetric data and compression parameters of the oedometer samples is given in Table 1.

Table 1 Overview of oedometer tests on Berengbenkel (Kalimantan) peat

Borehole – sample nr.	drainage direction V / H	depth below surface	unit weight	water content	bulk density	specific gravity of solids	e_0	b	$\rho_{d,ref}$
		m	kN m^{-3}	[-]	Mg m^{-3}	[-]	[-]	[-]	Mg m^{-3}
1-02-2A	V	1.8	9.43	9.32	0.093	1.77	17.9	0.328	0.037
1-02A-2	H	1.9	9.92	9.21	0.099	1.77	16.8	0.257	0.056
2-01A-1	V	0.75	9.83	11.65	0.079	1.64	19.6	0.860	0.002
2-01A-6	H	0.8	9.84	9.57	0.095	1.64	16.2	0.300	0.053
2-02A	V	1.8	9.72	9.85	0.092	1.53	15.7	0.302	0.051
3-01A-4	V	0.75	9.70	16.45	0.057	1.5	25.4	0.524	0.011
3-02B-2	V	2.13	9.72	10.38	0.087	1.62	17.5	0.228	0.051
5-02B-3	H	2.3	9.97	10.83	0.086	1.62	17.8	0.258	0.050
5-03B-2	V	5.25	10.17	13.67	0.071	1.69	22.8	0.222	0.039
5-03B-3	H	5.3	10.28	13.26	0.074	1.69	21.9	0.275	0.040

The acceleration of gravity is taken as 9.78 m s^{-2}. The temperature of the ground water is taken as 28 °C and consequently ground water density is 0.996 Mg m^{-3} and unit weight of water is 9.74 kN m^{-3}. It should be noted that these numbers are somewhat lower than in temperate zones.

No distinction is made between tests with V and H drainage directions. The drainage parameters are of less interest, as in field conditions rates of drainage are very high, and with the short drainage lengths in the tests, drainage is also very quick.

The relationship between bulk density ρ_d and water content for all samples is shown below. It conforms well with the relationship given by Den Haan (1997) where it is shown to apply to many different peat formations world-wide:

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

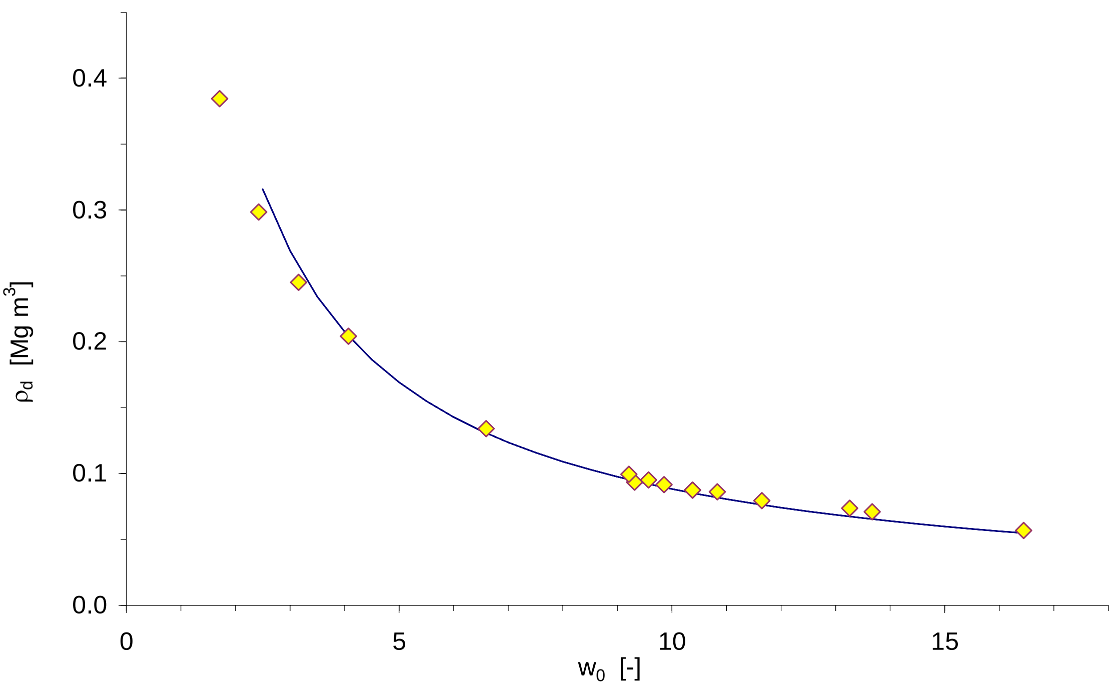

Figure 2 Correlation of initial dry bulk density and water content of Berengbenkel peat and organic soils

The specific gravity of the solid peat material $G_s = \rho_s/\rho_w$ appears not to have been determined on the oedometer material itself. Peats are heterogeneous to the extent that dry weight should be determined on each sample after an oedometer test, and G_s can then be determined on a subsample after homogenization by pestle and mortar. The voids ratios given in the table are consequently not highly accurate.

The consolidation curves for all tests are shown below. Two scales are used: the voids ratio and the natural logarithm of the bulk density, both plotted against applied vertical stress. It is noticeable that in the lower plot of Figure 3, the post-yield section of the plots are more or less linear, whereas voids ratio in the first depiction produces convex curves. The logarithm of bulk density on the vertical axis in the second depiction corresponds with natural strain, as described earlier, while in the first depiction the voids ratio on the vertical axis can be transformed to linear strain. The two figures therefore show the advantage of using natural strain rather than linear strain for describing the compression of highly compressible soils.

While the voids ratio can also be transformed to natural strain through the logarithm of specific volume, as discussed earlier, in the present case the voids ratio values are possibly not accurate. For this reason, and for the purposes of interpretation of behaviour and choice of parameters, the second representation is favoured.

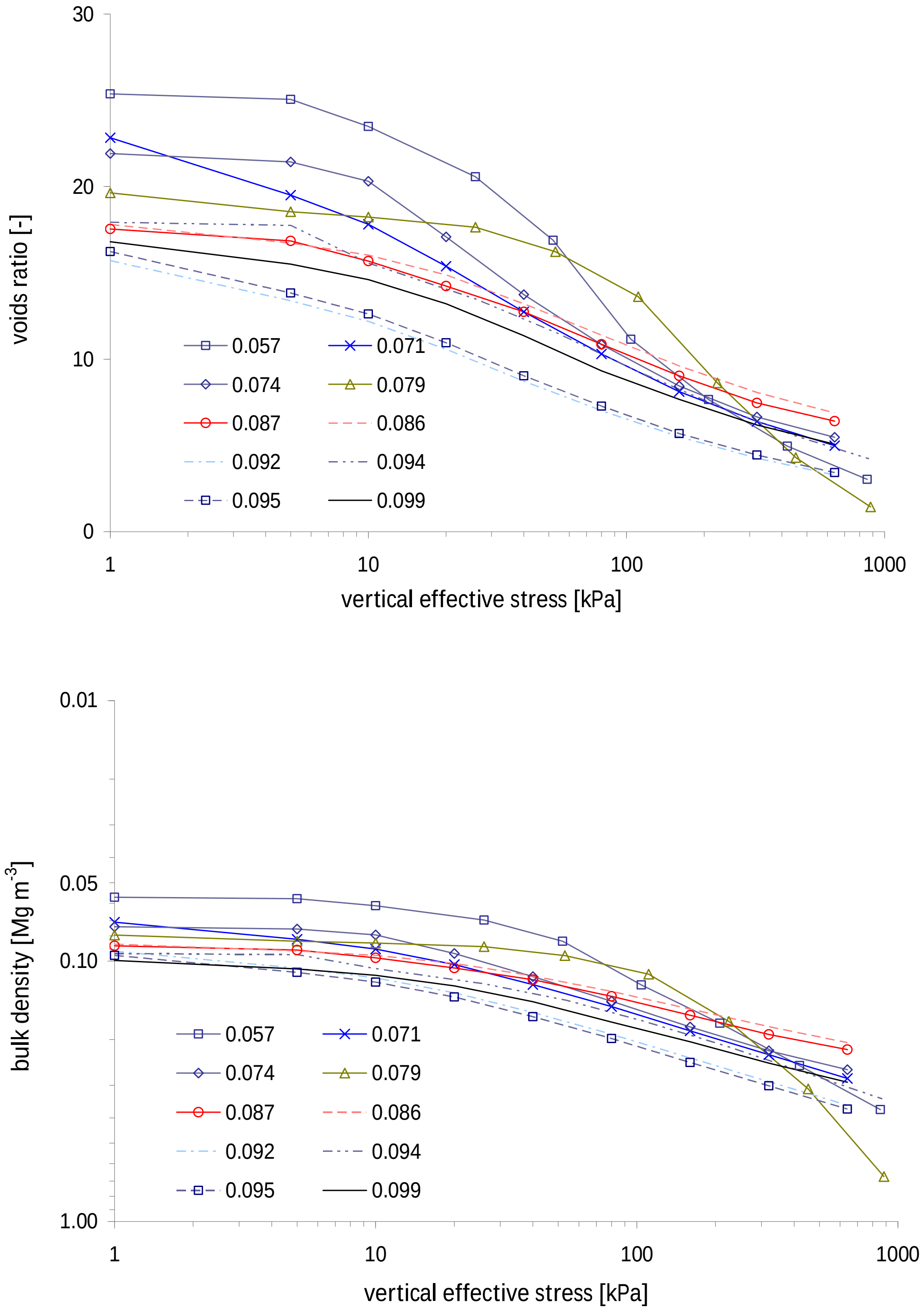

Figure 3 Compression curves of oedometer tests on Berengbenkel (Kalimantan) peats. (a) voids ratio vs. vertical effective stress (b) dry bulk density versus vertical effective stress. Legend: initial dry bulk density in Mg m^{-3}.

The legend gives the initial bulk density of the samples. The initial voids ratios are all above 15 and therefore very high. Two samples (ρ_d = 0.057 Mg m^{-3} and 0.079 Mg m^{-3}) were taken at shallow depths (0.75 m) and these have high yield stresses. It is likely that the high yield stresses are due to desiccation stresses. The higher yield stress of the denser sample points to more desiccation.

Otherwise, the tests appear to be quite consistent. The virgin, post-yield slopes appear to be quite constant when the logarithm of bulk density is plotted against the logarithm of stress. A straight line representation is given by:

$$\ln \rho_d = \ln \rho_{d,ref} + b \ln \sigma_v'$$

with the slope being given by b and $\rho_{d,ref}$ being the cut-off bulk density at a stress of 1 kPa. These parameters are given in Table 1 and are correlated in the figure below. The virgin slope varies from b = 0.22 – 0.33 for the deeper samples, and 0.52 – 0.86 for the two shallow samples.

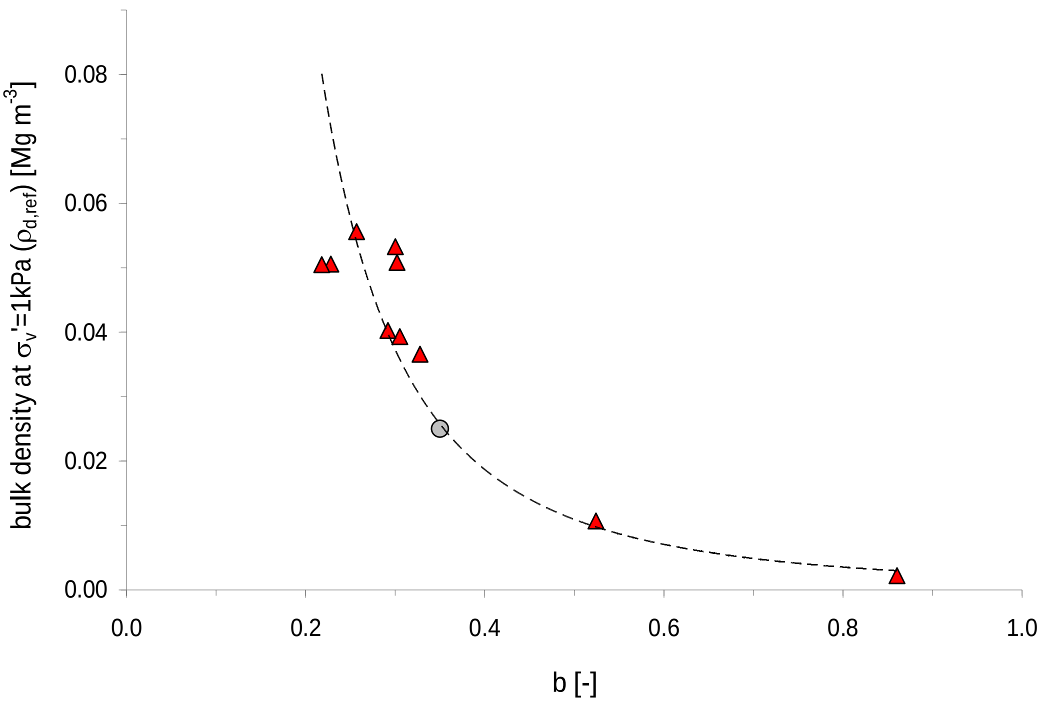

Figure 4 Correlation of the straight line fit parameters to the post-yield, virgin oedometer compression curves in Figure 2(b). Triangular markers: individual tests. Dot: chosen parameter combination.

The density of the deeper samples, 0.07 - 0.10, is in the same range as measured by Hoojer et al. (2012) in Sumatra plantations during exploitation. The yield stress of these tests is quite low, between 7 and 12 kPa, while in the plantations higher values are expected due to drainage to 1.5 m or more. That is, the stresses the Berengbenkel material has endured are lower, but the density is equal. Possibly therefore, the material is intrinsically more dense than in the studied plantations. The surface material on the other hand is possibly intrinsically less dense, as even with the high yield stresses due to dessication, the density is still less than or equal to that in the studied plantations.

A virgin curve as shown was chosen which is within the range of the measured virgin curves, when these are back-extrapolated below their preconsolidation pressures. The chosen curve has a value b = 0.35 and a cut-off value of bulk density at a stress of 1 kPa of 0.025 Mg m^{-3}. The bulk density on this curve at the preconsolidation pressure of 15.4 kPa estimated above, is equal to the assumed value immediately prior to forest clearing, 0.065 Mg m^{-3}. The position of this curve within the range of the measured curves for the Berengbenkel peats, and its compliance with the expected yield stress and density in the plantations, validates its choice for the present calculations.

It is quite common to take the a-parameter and c-parameter (for elastic behaviour and viscoplastic behaviour respectively) as ratios of the b-parameter. The a/b ratio is taken as 0.05. Ratios of 0.2 to 0.1 were found for the tests described above, with the ratio decreasing with increasing initial bulk density, but the a-parameter was determined in one large unloading step from maximum load to 5 kPa. Smaller unloading as in the example case will result in smaller a-parameter, and the ratio of 0.05 is considered justified.

The tests yielded c/b ratios of approximately 0.03 to 0.035. These are very low when compared to values often quoted for temperate-zone peats. The ratio c/b is equal to the well-known ratio C_α / C_c which is usually approximately 0.04 in inorganic clays, and well above 0.05 in peats and organic clays. This is also discussed by Duraisamy et al. (2007) who nevertheless also found quite low ratios (0.02 - 0.04) for Malaysian peats. They surmise that this might indicate deviant behaviour of tropical peats relative to temperate-zone peats, for which more data is available, and that more research involving long-term consolidation of tropical peats is needed. Both findings nevertheless justify for the present to assume a low value of 0.035 for the present calculations. However, a value of 0.06 is also applied to investigate the sensitivity of the calculated subsidence to this figure.

A final choice concerns that of G_s, the specific density of the solid peat material. This is taken as 1.5, close to that of the cellulose and lignin constituents of the peat. Higher values are only likely when mineral matter is mixed with the peat, but the high water contents and low bulk densities point to very pure peat without a significant inorganic component, as is also reported by Hooijer et al. (2012) who report ash content being below 2%.

5 Rate of Consolidation

The observed response of ground water depths to changes in drainage conditions, for example by the construction of drainage canals or changes in the water levels in drainage canals, is quite immediate, and only slight variation exists in ground water depths between drainage canals. This points to a high permeability, as already discussed. A conservatively low value of the permeability coefficient is taken as 10 m d^{-1}. Taking one-way drainage, a layer of 10 m thick, and the compressibility parameters a and b, an estimation can be made of the response time of the consolidating layer below ground water level. Terzaghi's consolidation theory has 93% adaptation to a load change at a dimensionless time factor T = 1. This factor is related to true time by:

$$t = T L^2 / c_v$$

where L is drainage length (10 m) and

$$c_v = k / \gamma_w m_v$$

The compressibility is chosen conservatively at the initial stress at midplane in the layer (2.8 kPa) in combination with the elastic compressibility a-parameter, and at the midplane preconsolidation pressure (16.6 kPa) in combination with the b-parameter. Therefore, with:

$$m_v = d\varepsilon / d\sigma'_w = (a \ or \ b) / \sigma'_v$$

This calculation yields response times of 0.6 days (initially) and 2 days at the preconsolidation pressure. At higher stresses it increases. These values are sufficiently high to disregard Terzaghi's hydro-dynamic retardation, the slow transfer of load from the pore water to the contacts between solid particles and fibres as the pore water drains off. This was verified in comparative calculations where the hydrodynamic effect was turned on and off.

6 Loading scheme

The total bulk density of the soil above the ground water table is calculated from the total water contents of 80% in the initial stages and 85% in the exploitation stage. With G_s = 1.5, values of 10.48 and 10.29 kN m^{-3} are obtained.

The ground water level changes from the beginning of forest clearing (-10 years) up to 20 years of plantation development and exploitation (+20 years), translated into loads through the above total bulk densities, are shown below. The two scenarios are those of best drainage practice and common drainage practice as discussed in chapter 2. Note that the slight water table lowering associated with initial forest clearing in the 10 year period preceding plantation development is modelled by a series of annual water level changes, while one extreme drought event is assumed to occur halfway through this stage.

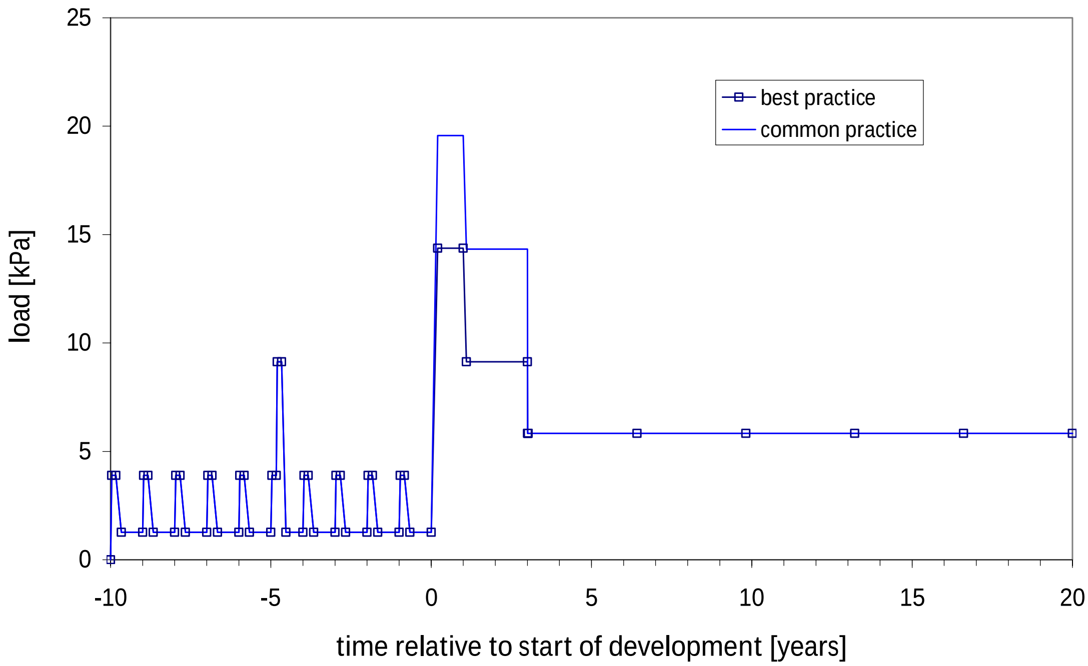

Figure 5 Loading scheme for best drainage practice and common drainage practice.

7 Calculated subsidence

The subsidence of the 10 m thick consolidating layer under the ground water table is shown in Figure 6. The calculated bulk density profiles, and the effective vertical stress versus linear strain at midplane (that is, at 5 m nominal depth) are given in Figures 7 and 8.

During forest clearing prior to plantation establishment, effective stresses do not exceed the maximum values attained during historic extreme droughts, and therefore strains are limited and elastic in nature. The only permanent subsidence is due to the average drainage depth increasing to 0.25 m rather than the 0.10 m assumed before the commencement of forest clearing. Significant consolidation results from the drainage activities that accompany plantation establishment. These are highly dependent on the depth of drainage. While in the common drainage scenario canal levels are only 0.5 m deeper than in the best practice scenario (2 m versus 1.5 m), consolidation is 0.80 m larger (1.89 m versus 1.09 m).

During and after the first year development stage, water levels are brought closer to the peat surface, finally to a ground water depth of 0.7 m in both scenarios. This entails a reduction of loading on the layers below ground water, and consequently heave of these layers occurs. The heave amounts to 0.13 m in the common practice scenario, and 0.096 m in the best practice scenario. The heave occurs quite quickly, after which no further consolidation occurs.

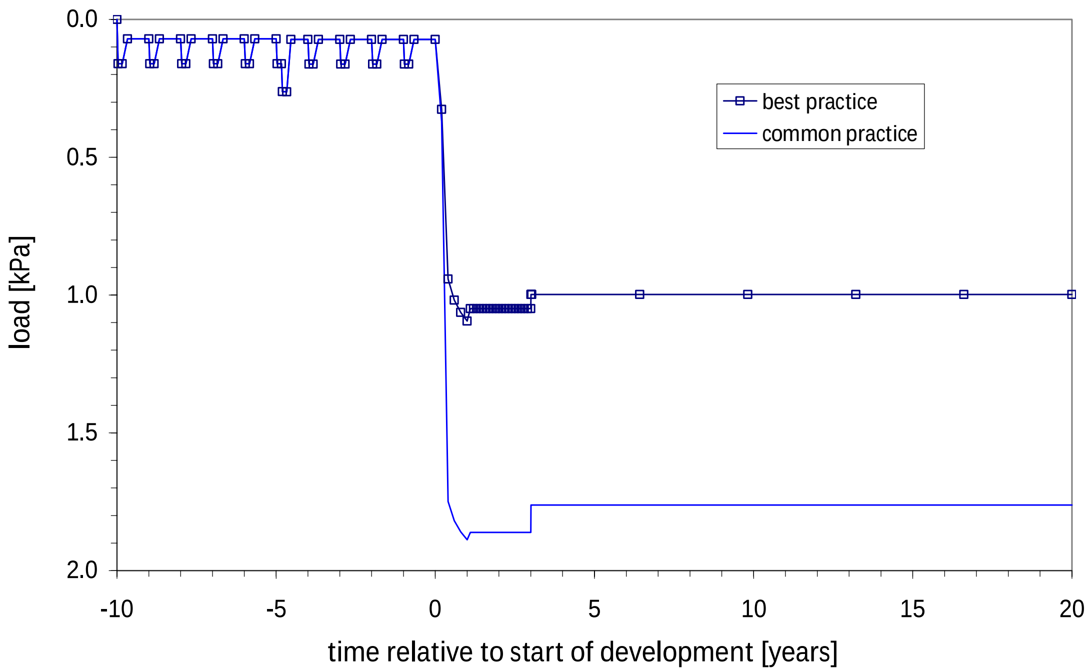

Figure 6 Calculated settlements due to consolidation of a 10 m thick layer of peat, due to the loading shown in Figure 4.

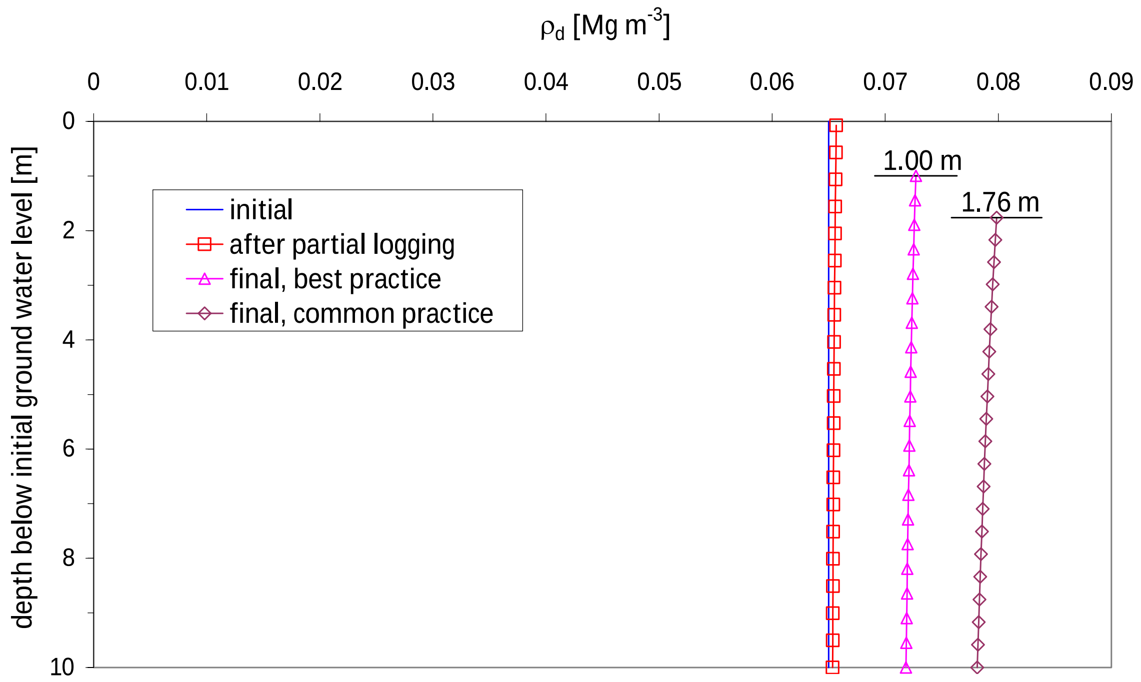

Figure 7 Profiles of dry bulk density in the consolidating layer of peat below ground water table, due to the loading scheme shown in Figure 5.

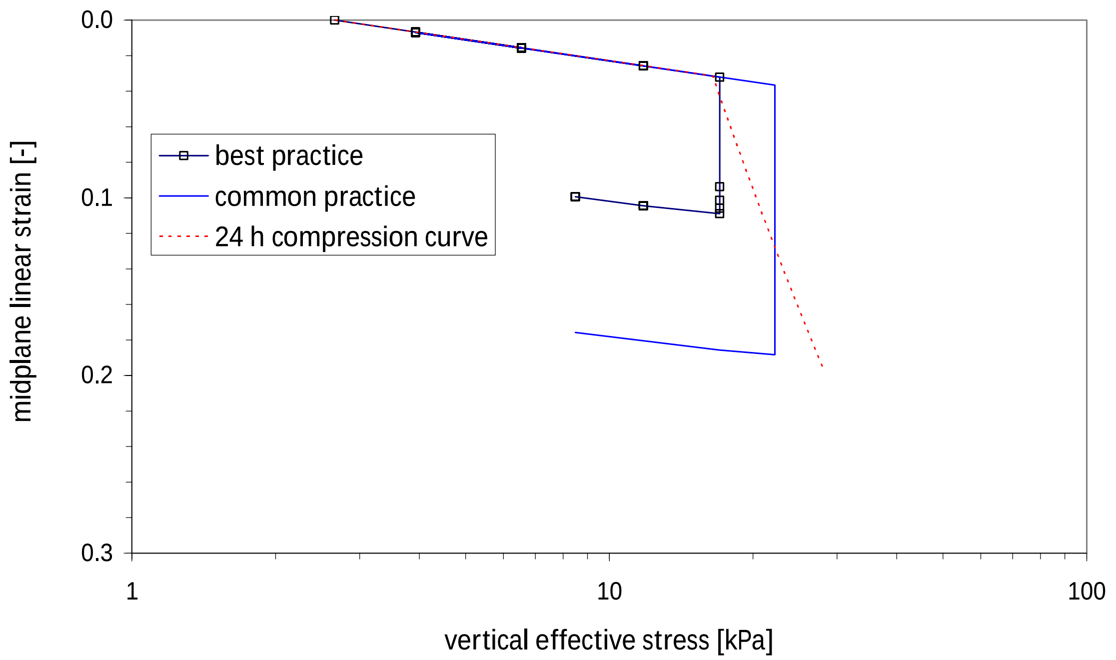

Figure 8 Stress – strain relationships at mid-plane (nominal depth 5 m) of a 10 m thick consolidating layer of peat, due to the loading scheme shown in Figure 5.

In Figure 7, the calculated bulk density profiles is given at the start of plantation development (after partial logging) and in the final state after 20 years. The initial bulk density prior to the start of partial logging is taken constant throughout the initial depth of 10 m as 0.065 Mg m^{-3}. The partial logging activities result in only a small increase of bulk density, and this is due to the limited depths of drainage during this period, compared to the effects of severe droughts in the pristine period.

The cases best drainage practice and common drainage practice result in final bulk densities of 0.72 and 0.79 Mg m^{-3} respectively, and concur well with the measurements of Hooijer et al. (2012). The settlements associated with both these cases is evident in the lower position of material points relative to the initial state.

The stress – strain curves of the midplane point at a nominal depth of 5 m are shown in Figure 8. As a reference, the 1 day laboratory compression curve is also shown. The initial yield stress is obvious on this curve at the break of slope at 16.4 kPa. The initial state is at 2.7 kPa. The difference in stress is so large that only elastic compression occurs initially, and compression is determined by the a-parameter discussed earlier. When drainage occurs the stress increases, but in the best practice case only up to the yield stress. This is higher than the historical maximum value due to the creep ageing that occurred, and rates of strain near the yield stress are quite high. Maintaining this stress, creep occurs (the vertical downwards section of the curve), fast at first but eventually attenuating. When drainage levels are brought upwards, stress decreases quickly to a degree that creep and viscoplastic effects are no longer important. The strain is again elastic, and therefore the stress decrease results in heave. This is the last section of the stress – strain curve. On it, the changes in drainage level and the effects of time are not visible, simply because only the response is elastic.

The case of common practice in Figure 8 is initially the same as the best practice case, but when the deeper drainage level is applied, stress increase well past the yield stress, and very high rates of compression occur. The downward creep part of the curve is now longer than for the best practice case, and so more creep compression occurs. Likewise, when drainage levels are brought upwards to the same level as in the best practice case, stress decreases to the same level by elastic response, and consequently the heave is greater.

A feature of the stress – strain mapping as in Figure 8 is that at any point in the map, the rate of creep strain can be calculated from the distance to the post-yield 24 h curve. Points above it have increasingly higher rates of creep strain, and points below it increasingly lower rates. The decrease of stress by decreasing drainage depths has the effect of diminishing creep rates to insignificant values.

The slopes of the initial loading branch and of the unloading braches can be calcutaed from the elastic a-parameter. Should a higher value of the a-parameter have been chosen as found from the large unloading branch in the Berengbenkel oedometer tests, more heave would be calculated. The calculated amounts seem high already, when compared to field observations, and the chosen a-parameter is also from this perspective considered appropriate.

8 Discussion

8.1 Considerations regarding the model

With acknowledgment that the precise development of loading and soil properties are not well known, the calculated density profiles in Figure 7 agree quite well with measurements by Hooijer et al. (2012), where values of 0.07 – 0.08 are given for a number of plantations on deep peat, at stages well into the exploitation phase. Agreement also exists with the observed virtual stand-still of consolidation settlements and the related lack of change in dry bulk density below the ground water table after the initial drainage activities. This is easily explained in soil mechanical terms as the effect of induced over-consolidation by the large relative degree of unloading. The latter results from the rise of the ground water table to 0.7 m below ground level, leaving loads which are only 38% (common practice) or 50% (best practice) of the maximum load during first year drainage.

In Dutch geotechnical practice, reservations exist with regard to the prediction of heave and settlement after unloading. Temporary excess loading is often purposely applied in the so-called pre-loading or surcharging technique, to pre-empt creep settlements which would otherwise materialize during the later service-life of structures built above the soil. The effect of unloading the temporary excess load (which often consists of sand-fill) is usually approached conservatively.
A work-around which is considered conservative (that is, to over-predict settlement), is to limit the amount of unloading by a factor of 2. In the present case this would correspond to a final level of the ground water table not at 0.7 m but at 1.35 m (common practice) and 1.1 m (best practice). The calculations for these adaptations yield smaller heave: 0.035 m rather than 0.13 m for common practice, and 0.029 m rather than 0.094 m for the best practice scenario. However, even with this conservative assumption, there is no return to subsidence, and this strengthens the finding that all movement of the layers below ground water table essentially cease.

The effect of unloading is so strong that the precise choice of the a-, b- and c- compressibility parameters is not critical. Other parameter combinations would predict different amounts of subsidence by consolidation during the first years of plantation development, but after bringing up the ground water table to the exploitation depth (0.7 m), compression of the layers below ground water table comes to a stand-still in such cases as well. Given that the chosen parameter combination provides reasonable agreement with what is known of prior and present conditions underneath peat domes and developed plantations (e.g. the development of bulk density) there is little point in varying these choices. Nevertheless, the ratio of c/b, for which 0.035 was used based on what is known of the compression behaviour of tropical peats, has been increased to a value of 0.06, which is better in line with temperate-zone peats. The consolidation settlements following ground water lowering then increase strongly, the heave due to the rise in ground water level is slightly smaller, and finally cessation of movement occurs just as with the lower c/b ratio. For the best practice case, maximum settlement increases from 1.09 m to 1.53 m, and heave decreases from 0.094 to 0.081 m. While the higher c/b ratio does not result in on-going settlements, the higher maximum settlement would produce a larger increase in bulk density than is deduced from field measurements, as discussed earlier, and this is therefore not a realistic case.

The applied geotechnical model is limited to consolidation of layers below the ground water table. It further assumes a constant amount of solid material. The calculations would deal adequately with the consolidation of the layers below the ground water table if no material passes through the ground water table, and the applied loads correspond to the dead-weight of the material above the ground water table. The nominal thickness of 10 m could then be identified as the depth of the peat below ground water level at the moment of the maximum lowering of the ground water to 1.5 m or 2.0 m depth. As the peat consolidates, the load and the ground water table migrate downwards together, and at maximum consolidation, the maximum depression of the ground water would be the sum of depth to ground water and the consolidation settlement.

Lack of data on the absolute level of the ground water table, in contrast to its depth below the surface, prevents a proper evaluation of the course of events sketched above. Nevertheless, it is quite likely that ground water levels are adapted periodically to on-going subsidence of the surface, to maintain a certain depth to ground water.

Should solid peat material pass through the level of the ground water table, either downwards or upwards, the amount of material above the ground water table would change and the load on the consolidating layer likewise. Both effects, change of load and change of the amount of consolidating material, must be considered together. Of further influence on subsidence of the surface is that the material above ground water is subject to suction pressures and shrinkage or compaction, while below it essentially hydrostatic pressures hold. Changes in these pressures cause changes in volume of the peat migrating across the ground water table, and therefore influence measured subsidence.

Where material passes downwards through the ground water table, the model continues to correctly calculate strains in the nominal, initial 10 m of material. The material from above the ground water table is not considered, and neither is the change of load brought about by the loss of this material from the upper zone into the ground water zone. The change of load is likely to be negative, as essentially submergence is occurring. The submerged material itself will probably expand as it enters the ground water zone, as the suction pressures it experienced above ground water are likely to be larger than the effective stresses below ground water level. These effects act to reduce the total settlement.

Such downwards migration of material from the upper soil could occur when consolidation settlements are very quick, and it is quite likely that this occurs during the initial stages of drainage. It will almost certainly also occur during raising of the ground water table.

These effects have been simulated in the present calculations by bringing the ground water level upwards in two steps.

More precise models would address the settlement of the two zones above and below the ground water table together. The suction in the upper zone and the effect of suction on volume change would need to be modelled, as would the vanishing of material and mass due to oxidation. Such a model would need to cope with the relative change in ground water level as settlement advances, and allow step changes due to changes in canal levels. Such models need yet to be developed. In spite of dealing solely with the consolidation below ground water level, the present study is successful in revealing the quick development of consolidation settlements following the initial depression of the ground water table, and their complete stand-still after the ground water level is raised.

Where peat thickness is less than the thickness of 10 meters assumed here, a more or less linear relationship with the settlements predicted here is found from the calculations. This is due to the lack of hydrodynamic retardation, and the low self-weight of the peat, which produces only very slight gradients of effective stresses with depth.

8.2 Implication of the model results

This paper has considered the consolidation settlements of peat below the ground water table following the conversion of tropical peat domes to industrial plantations. It is found that considerable consolidation settlements occur especially in the first months after development of plantation drainage, and that the extent of these consolidation settlements depend strongly on the degree of drainage, that is on the lowering of the groundwater table that is abruptly applied. In practice, this is at least 1.5 metres. The thick layer of moist, but unsaturated, peat that is thus created, generates tremendous loading on the underlying peat, which is compressed rapidly as a result by over one metre (assuming an initial peat thickness of 10 metres). As ground water depths decrease in the following months, first as a result mainly of the subsidence itself and at a later stage also to some extent due to water management efforts, slight heave (i.e. uplift of the top of the peat column below the water table) occurs, although this appears not to be noticeable in measurements of the position of the peat surface as it is compensated by high rates of peat volume loss due to oxidation and compaction above the water table. Following this initial phase, the peat column below the water table has stabilized and no further movement occurs. The peat is overconsolidated to a degree at which viscoplastic effects (creep) are unnoticeable. Only by the renewed application of large loads would significant compression re-occur, for example by deep drainage or the construction of road embankments.

Acknowledging that the precise development of loading and soil properties during plantation development in SE Asian peatlands are not accurately known, the density profiles resulting from the consolidation settlement calculations presented here agree sufficiently well with measurements by Hooijer et al. (2012), where values of 0.07 – 0.08 are given for a number of plantations on deep peat, to be confident in the finding that consolidation ceases soon after plantation development.

This finding is easily explained in soil mechanical terms as the effect of induced over-consolidation by the large relative degree of unloading. The latter results from the rise of the ground water table to 0.7 m below ground level, leaving loads which are only 38% (common practice) or 50% (best practice) of the maximum load during first year of plantation drainage.

Only two water table depth scenarios are presented here, both for a single set of physical peat parameters. The outcomes show that: i) there is no conceivable situation in which peatland development for agriculture will not require sudden and major lowering of water table; ii) such drainage will always cause overconsolidation of the peat when water table depths are subsequently reduced, and iii) this will in all cases mean that further consolidation will be negligible.

It also proved unnecessary to present calculations for more than one peat thickness. Where peat thickness is different from the 10 metres assumed in this assessment, a more or less linear relationship with the settlements predicted here can be assumed. This is due to the lack of hydrodynamic retardation, and the low self-weight of the peat, which produces only very slight gradients of effective stresses with depth.

For this study, consolidation was isolated from the other factors that contribute to subsidence, namely compaction and oxidation of the peat (both above the groundwater level). In reality these processes all operate together, and at the same time. Already during initial water level lowering, the unsaturated part of the soil will shrink and oxidise, at high rates even though the contribution to subsidence will be relatively small compared to the rapid consolidation. When water table depths are reduced, and consolidation rates approach zero, oxidation and compaction become the only contributors to subsidence.

This lack of consolidation is also substantiated by Figure 9. It shows that increasing thickness of peat does not correlate with increasing subsidence. Consolidation settlement, occurring as it does over the full thickness of the peat below ground water level, increases with increasing peat thickness (in an approximately linear fashion as shown above). Such an increase being absent from Figure 9 points to small consolidation settlements and a dominance of settlement in the unsaturated zone above ground water level.

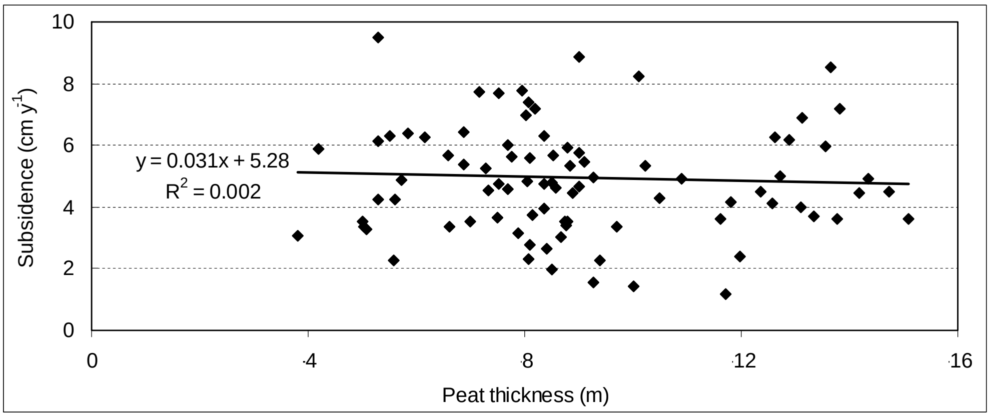

Figure 9 Annual subsidence rate in Acacia plantations plotted against thickness of the peat layer, for locations with average water table depths between 0.5 and 1 m. The very low R^2 value of the regression line indicates that no relation exists between peat thickness and subsidence rate. Such a relation would be expected if consolidation of the peat layer as a whole would be a significant contributor to subsidence.

The current assessment shows that the assumption of negligible consolidation certainly applies to situations where the water table depth is suddenly increased, and then allowed to be reduced again. In some situations, however, the water table is gradually lowered and water table depths may not be increased much because consolidation causes the peat surface to closely follow the water table. Such a situation may exist in some peatlands in SE Asia that remain forested but where the draining effects of logging, road construction and nearby plantations affect water levels. Until the consolidation implications of such a gradual drainage scenario are further investigated, it is therefore recommended that surface subsidence is only used as a measure of carbon loss in those tropical peatlands that have undergone sudden and major drainage. This condition applies to nearly all areas drained for agriculture, including failed agricultural schemes such as the Ex-Mega Rice Project area in Central Kalimantan. But it may not apply to forested peatlands well away from major canals.

9 Conclusion

This paper has set out to investigate the possible contribution of consolidation settlements to the subsidence of plantations which are newly established on tropical peat domes. A geotechnical approach has been followed by applying an advanced compression model to an example case of a tropical peat dome. The process of consolidation is followed from the pristine condition, through the period of partial logging, on to the development phase with deep drainage, followed by decreased, stable drainage depths during exploitation. The model calculates settlements (or subsidence) due to the compression of the saturated zone under the ground water table. Geometrical data such as peat thickness and drainage levels, and material properties such as peat density and permeability of the peat and substrate is chosen to represent typical peat dome developments in SE Asia, and geotechnical consolidation parameters are determined from oedometer tests on tropical peat soil.

The results of the calculations show clearly that

- significant consolidation settlement occurs immediately following the start of deep drainage. Consolidation settlements of almost 2 m are possible for a 10 m thick layer of peat during the first year of deep drainage. Best practice drainage methods can reduce this to approximately 1 m.
- once drainage depths decrease, either due to the subsidence itself or by obstructing flow in drainage channels to regulate the ground water table within desired limits, consolidation settlement essentially ceases. The calculation applies these measures as a step-loading, and calculates heave (rising) of the peat layer in response to the laod reduction. Once the heave is complete, no return to ongoing settlement by viscoplastic effects ('creep') is calculated.

The consolidation settlements calculated for the example case follow well-estabiished geotechnical principles. The initial large consolidation settlement is simply a result of the large loads developing above the ground water table when deep drainage is applied. The heave after raising the ground water levels is due to the unloading of the peat it brings about, and the lack of subsequent settlement is due to the large degree of unloading.

Above the ground water table, oxidation and compaction of the peat occur. The subsidence / bulk density method for calculating carbon loss assumes that after initial drainage, oxidation and compaction are the sole contributors to subsidence, and that no further consolidation settlement occurs. The results of the geotechnical calculations in this paper underscore this approach, but possibly only when the initial drainage is followed by a substantial decrease in drainage depth. More research is needed to investigate the geotechnical effects of drainage depths maintained constant from the initial state onwards.

10 Acknowledgement

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A ANNEX Water table depths in tropical peatlands drained for agriculture

A.1 Water table depths prior to plantation development

As elsewhere, peat in SE Asia develops in conditions that are water saturated for most of the time. Average water levels in natural conditions are around or just above the peat surface. They are highly variable in time however, even without anthropogenic drainage, as rainfall amounts vary seasonally. Especially in the central and southern parts of Sumatra and Kalimantan, where most SE Asian peatlands occur and where periods of rainfall deficit of three months or longer are common between May and October, water levels in undrained tropical peatlands frequently drop below 0.5 metres, occasionally below 1 metre, but very rarely below 1.5 m.

Nearly all remaining forested peatland in Sumatra and Borneo has been drained to some extent by logging activities, either at the large scale or illegally at the small scale, and often both (Miettinen et al., 2012a).. A dense network of logging tracks and ditches ('tatas') exists in most peat domes. The effect that this has on water levels is highly variable, depending on water level in the ditch/track, surface gradients and hydraulic conductivity of the peat. However it is notable that even for forested peatlands that are characterized as relatively (but not completely) undrained, an average water table depth of 0.11 m below the peat surface is reported for Sebangau National Park in Central Kalimantan (Hirano et al., 2012). For natural forest around Acacia plantations in Riau, Hooijer et al. (2012) report an average water table depth of 0.33 m over a 2 km zone, and suggest that the effects on water tables of plantation drainage may extend well beyond that 2 km zone. In drained and degraded areas close to oil palm plantations in Jambi, water table depths around 0.5 metres are reported. It should be noted that these water table depths of 0.11 m to 0.5 m reflect conditions many years after drainage for logging occurred; all three areas are known to have been logged at a large scale in the 1980s and 1990s. Therefore, it must be assumed that substantial subsidence had already taken place at the time of first water depth measurement, and that initial water table depths must have been greater.

We conclude that the water table regime in peatlands that are about to be converted to plantations would often be hydrologically disturbed already, because i) logging and limited drainage usually preceded plantation establishment by decades; ii) there usually is a further increase in logging and drainage intensity (legal and/or illegal) over a period of 5 to 10 years prior to plantation establishment (Miettinen et al. 2012b) and iii) the plantation boundary itself tends to be 'moving' as cleared and drained areas are expanded stepwise. Therefore, we may assume that the average water table depth in the 10 years prior to plantation development has been about 0.25 m.

For consolidation calculations, we apply the following pre-plantation water table regime:

- For at least **3000 years**, since peat development began: average water table depth is 0 m, but a water table depth of 0.5 m applied for <u>one month</u> towards the end of every annual dry season and of 1 m 10 years during extreme dry seasons. An additional weight is generated by the intact forest, which we estimate at 500 t ha^{-1} including both dry biomass and water content.
- For the **last 10 years before drainage**: average water table depth is 0.25 m, but a water table depth of 0.5 m is applied for <u>two months</u> towards the end of every annual

dry season and of 1 m once during an extremely dry season. The additional weight of remaining forest is reduced to 250 t ha^{-1}.

It should be noted that the above numbers represent an average for a large region. As major differences in rainfall regime exist (Vernimmen et al., 2012), no single water table depth regime applies to all SE Asian peatlands. The regime now applied to the consolidation model is representative of conditions in the central parts of Sumatra and Kalimantan where the subsidence/BD method has been applied.

A.2 Water table depths after plantation development

Agricultural and silvicultural crops require severe lowering of the water table through intensive drainage. In Acacia and oil palm plantations the distance between canals (including mid-field drains) is usually 400 m or less. With existing hydraulic conductivities, which are generally between 1 and 100 m d^{-1} (Ritzema, 2007) and above 50 m d^{-1} in the Acacia plantations studied by Hooijer et al. (2012) as reported by Hooijer et al (2009), this is sufficient to lower groundwater to quite uniform levels, with the average groundwater table usually being less than 0.2 metres above the average canal water level (Hooijer et al. 2009).

When plantations are established, the peatland is drained and cleared almost simultaneously, usually well within a year for individual sections of thousands if hectares, as canals serve not only to lower water tables but also to remove timber and allow access for staff and resources. Planting of crops (Acacia or oil palm) often follows within two years after drainage, after the top peat is sufficiently solidified and stable for access and planting. In the initial period immediately after drainage, the peat surface is widely reported to drop rapidly, by about one metre, through a combination of consolidation, oxidation and compaction, after which subsidence stabilizes at lower rates (Andriesse, 1988; Wösten et al., 1997; DID Sarawak, 2001; Hooijer et al., 2012).

As the longer-term plantation water management target is to have water tables around 0.7 m or 0.6 m below the peat surface on average (Hooijer et al. 2008; DID Sarawak, 2001), and 1 to 1.5 m of subsidence is to be expected in the first 5 years alone, and some ‘operational water management room’ must be created to allow upward adjustments with dams (0.5 to 1 m), initial water table depths need to be far below the eventual target. Indeed, canal water table depths below 2 and sometimes even 3 metres are often observed in the first months after drainage, which is sometimes called the ‘dewatering phase’ during which major discharge of displaced groundwater towards rivers is seen to take place. Even if such very low water tables would not be intended, they could not be prevented as i) the canals need to be open for timber removal and staff access, and ii) it takes time to establish a water level control system once canals have been dug. Even in a ‘best case’ scenario, where plantation managers would want to keep water levels as high as possible to reduce subsidence and emission in the initial period, and where substantial subsidence had already taken place prior to full plantation development, water tables would have to be at least 1.5 metres below the peat surface. In the following few years, water table depth will gradually decrease, though a combination of subsidence and the start of active water management i.e. building of control dams and spillways, before they can stabilize.

For consolidation calculations, we apply the following plantation water table regime:

- During the **initial year after drainage**, average water table depth is 1.5 m (‘best case’) to 2 m (‘common’) below the peat surface.
- During the **second and third year after drainage**, average water table depth is 1 m (‘best case’) to 1.5 m (‘common’) below the peat surface.

- **Beyond 3 years after drainage**, average water table depths is maintained at 0.7 m.

These water table depth scenarios should be considered conservative, as lower depths have been observed in the initial period (see above), and it usually takes more than 5 years before a somewhat uniform (in space) and stable (in time) water level can be maintained. In the 'best case' water management scenario that applied to the study by Hooijer et al. (2012), where major investments had been made to improve water management in Acacia plantations, the average water table depth after 5 years was in fact still estimated at 1.2 metres by the company (Hooijer, 2005, 2008).

Figure A Canal water depths at 3 to 6 months after canal construction (top left), one to 2 years after canal construction and clearing (top right), in an Acacia plantation more than 6 years after drainage (bottom left) and in an oil palm plantation 18 years after drainage (bottom right). (Photos Hooijer, 2006 -2010).

Figure B Water management in an Acacia plantation, more than 5 years after drainage. (Photo Hooijer, 2008).

Figure C Ground water table depths in Acacia plantations, around 3 to 5 years after drainage, in relatively dry (left) and wet (right) conditions. (Photo Jauhiainen, 2008).

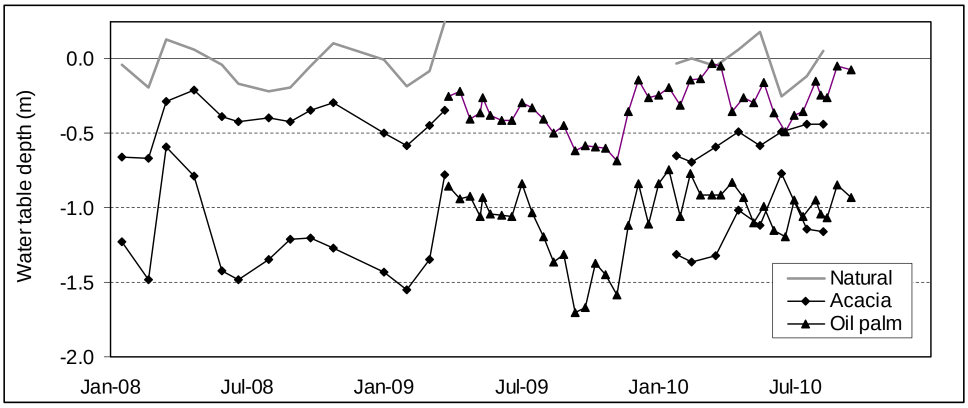

Figure D Time series of water table depth as measured at some selected individual locations in Acacia and oil palm plantations, and in nearby natural forest at 2 km from the Acacia plantation. In both plantation types, the records nearest the lower and upper 10-percentile average water levels are shown. (From Hooijer et al., 2012).