Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering

doi:10.3233/978-1-61499-656-9-1857

Failure of peat dikes in The Netherlands

Rupture de digues en tourbe aux Pays Bas

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ABSTRACT

A peat dike in The Netherlands unexpectedly failed at the end of the dry summer of 2003. The failure mode was not a Bishop type circular failure used in routine dike stability analyses in The Netherlands. The failed dike segment was displaced horizontally over 6 m The failure plane was found to lie at the boundary between peat and the underlying sand. It was concluded that failure was caused by a chain of events in which weight loss and shrinkage of the peat, due to the dry weather conditions, are considered important factors. Analyses of the behaviour of the peat made clear that several processes, controlled by hydrological conditions in the unsaturated and saturated zones in the embankment, resulted in fracturing of the peat. The fracturing along with a very high strength anisotropy of the peat resulted in a connection between the water in the canal and the water in the sand, raising the piezometric head in the sand by several metres, allowing the dike to simply 'float' away for over 5 m, pushed by the water in the canal.

RÉSUMÉ

Une digue en tourbe a rompu de manière inattendue aux Pays-Bas suite à la sécheresse de l'été 2003. Le mode de rupture, de type non circulaire (Bishop), n'est intègre pas dans les procédures d'analyses de stabilité effectuées en routine aux Pays-Bas. La rupture associe un déplacement horizontal de 6 m et une surface de glissement à l'interface tourbe - sable sous-jacent. Une chaîne d'événements, incluant le retrait et le déjaugeage de la tourbe comme facteurs de déclenchement, a causé cette rupture. L'analyse du comportement hydro-mécanique de la tourbe indique que plusieurs processus, contrôlés par les conditions hydrologiques dans les zones non saturée et saturée de la digue, ont fracturé le matériau. Cette fracturation de la tourbe ainsi qu'une anisotropie de résistance très marquée ont conduit à mettre en connexion l'eau du canal et l'eau de la nappe phréatique dans le sable, résultant en une élévation du niveau piézométrique de plusieurs mètres, permetent la digue de « flotter » sur une distance de 5 m poussée par l'eau du canal.

1 INTRODUCTION

At the end of the very dry summer of 2003 in The Netherlands 2 containment dikes of polder canals failed; both dikes consisted of peat. The peat in the saturated zone has a gravimetric water content of over 800%, making the water defense to be composed of mainly water. The failures made clear that there were flaws in the safety of the land below the sea, see Figure 1. The Netherlands has about 3000 km of such peat dikes securing canals that drain well over 1000 km^2 of polder land. Moreover, the type of failure was not foreseen, although near failures in the past had indicated that the stability of peat dikes can be endangered in dry summers. The damage resulting from the water mass spilling from both canals was limited to a shallow sheet flood temporarily inundating the dike hinterland, and carrying mud and sand, which in one case, at Wilnis, was deposited in a housing area. Further damage resulted from bank collapse along the emptied canal and dramatic groundwater lowering, resulting in surface settlement and damage to foundations. Timely damming of the canals limited the extent of the damage due to groundwater lowering.

The polder canals are part of the polder water management system with a main function in drainage of the land below sea level. Water level in these canals is raised several meters above the surrounding terrain. The canals form a network discharging in the North Sea mostly by pumping stations. The canals and dikes are a main element of the historical, man made, landscape of the western Netherlands and have further functions in transportation, recreation, and in the ecological infrastructure.

The failed dike sections are remnants of a former regional peat accumulation initially at or above mean sea level, but lowered to well below sea level by continued drainage for agricultural land use, oxidation, and peat mining. Only the immediate surrounding of canals were left intact and shaped in the form of dikes containing these canals. These dikes therefore consist of predominantly the original peat.

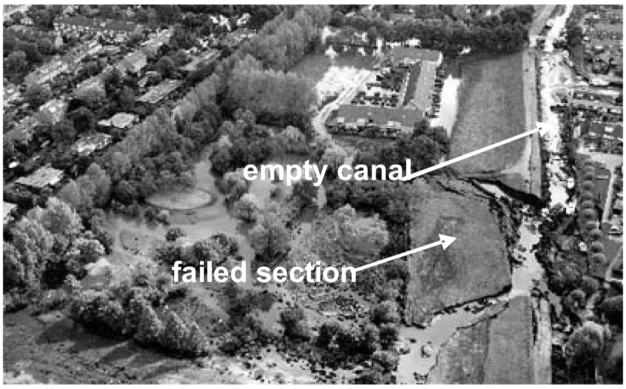

Figure 1: Failed canal dike at Wilnis, August 2004.

Large parts of the densely populated Netherlands, including some highly industrialized zones and build up areas, rely on proper functioning of the canal drainage system for which the dikes are a prerequisite. This condition, together with the ancillary functions of the dikes, demand that evaluation of safety and optimization in various aspects of land use, can avail of suitable instruments. This contribution communicates part of the analyses necessary for the development of such instruments. It provides an overview of the build up and the failure of the Wilnis canal dike, and presents findings of an analysis pinpointing mechanisms in the chain of events resulting in the failure. The findings are corroborated by the conditions encountered at the second location. The findings are discussed and conclusions regarding failure mechanisms and consequences for extending safety evaluation of dikes in the polder land are given.

Throughout this contribution extensive use is made of the information in the reports GeoDelft (2003a, 2003b).

2 PEAT DIKES IN THE NETHERLANDS

The failed dikes are located in the western part of the Netherlands, a beach barriers enclosed coastal plain of the delta of the Rhine and Meuse rivers in the southern North Sea Basin (Beets and Spek 2000). The young coastal plain deposits consist of mainly clays and peat. These mostly somewhat impervious deposits are underlain by predominantly permeable sands of Pleistocene age. Peat accumulation used to dominate in large areas, and continued to levels well above the contemporaneous sea level. In the riverine stretches of the peat accumulation zone, such as at the Rotterdam location, clay and occasional sand inclusions are common in the peat. The widespread peat lands in the highly developed western Netherlands pose geotechnical challenges, among which peat dikes were slumbering up till the summer of 2003.

From Roman time onwards, increasingly large areas of the peat swamp were cultivated (see De Bont 1999). Initially natural, gravity, drainage of the high peat land, using ditches, created agricultural land. Small dikes along natural creeks, that drained the peat areas, helped to keep occasional floods out. Ever larger natural waters were embanked with dikes and ever larger terrains were drained. The lowering of the groundwater table resulted in oxidation and shrinkage of peat at and above groundwater level, and compaction of the underlying peat and clay. The peat terrains subsided and higher dams were maintained or erected along the open water to prevent flooding of the land. Artificial drainage of the land had to be employed. Peat mining for fuel became widespread and systematic from the 17th century onward, and it was excavated in large areas up to sometimes over 5 m below present sea level. Most of the systematically mined out areas were reclaimed by making polders (permanently artificially drained land). Drainage canals, also acting as transportation routes for the peat, were left standing between the mined out areas, shaped into stable embankments with their crest at approximately the original terrain level. These embankments therefore consist of predominantly original in situ peat. The failures in August 2003 did concern 2 of such dikes.

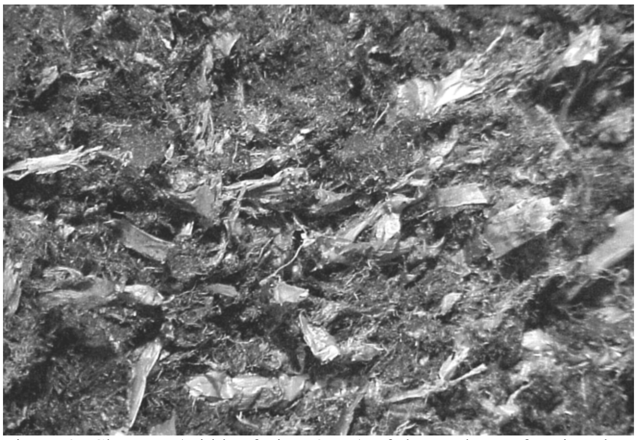

Figure 2: Close up (width of view 3 cm) of the reed peat forming the larger part of the failed dike sections.

The archetypal build up of the subsurface at the sites of the 2 failed dike sections is given in Table 1. Figure 2 shows details of the typical structure of reed peat forming a larger part of the failed sections. Most larger fragments are oriented horizontally, resulting in a marked anisotropy. Vertical stem and root elements, however, can extent over several decimeters thickness, which, with the hollow stem and root structure, results in the omnipresence of vertical shortcuts for gas and water transport in the peat. The horizontal anisotropy in the structure of the peat is enhanced by horizontal fracture planes, so-called splits. The splits are common in the coastal plain peats in The Netherlands, and are thought to result from, probably repeated, uplift of free methane containing peat in response to a water table rise during riverine or marine floods (Streif 1990). The production of free methane is significant in the organic subsurface. Free methane gas induced uplift of peat has been witnessed to occur also nowadays.

The organic material of peat is used by a variety of microorganisms, creating methane in anoxic conditions and carbon dioxide in the aerated zone at and above the groundwater table. In grassland on peat almost 0.5 m thickness of peat soil per 100 year is oxidized (Beuving and Akker 1996). For the peat dikes, with a somewhat thicker aerated zone, the mass and thickness of peat disappearing in the atmosphere will be higher than this figure. A peat dike carved 200 years ago, will therefore have been lowered by about 1 m, in an irreversible process that continues at the present day which not only affects the height of the dike, but also conditions concerning stability.

Table 1: Schematic build up of the original subsurface at the locations of the 2 failed dike sections

Wilnis	Rotterdam
0.5-1 m Peat weathered	0.5-1 m Peat weathered
4 m Peat, mainly reed peat	1 - 3 m Peat, reed peat
1-2 m Peat with clay intercalations	1 - 5 m riverine sand intercalation
1 - 2 m Peat, various peat types	0 - 4 m Peat or clay and sand
Sand, Pleistocene accumulation 9 m below original ground surface	Sand, thick Pleistocene accumulation

3 SOIL INVESTIGATIONS AND DESCRIPTION OF THE FAILURES

The sudden enigmatic failures of a very common type of dike in The Netherlands warranted an extensive soil investigation programme to be carried out as part of the investigation of the failures, even when the direct material damage was limited. The piezometric heads at various levels in and surrounding the failures were being monitored within 10 hours after the failures, and surface movements were followed in detail. The soil investigation included coring and CPT's in the failed dike sections as well as in sections representative for the conditions existing before the failure. In view of the coarse structure and very low stiffness of the reed peat, undisturbed sampling of 0.4 m diameter and 0.5 - 1.2 m high samples from sample pits was included. The large samples were used for large triaxial tests, determination of saturated permeability, and drying shrinkage tests. Vertical profiles of soil temperature and gas content were measured. Soil water retention and unsaturated permeability of relevant depth zones were determined in detail at selected locations as well as soil moisture content and degree of saturation over the entire depth of the failed section.

In spite of the rapid response, hydraulic heads in the permeable sand and in the deeply fractured peat of the failed dike were already to a large extent influenced by the events. Most hydraulic head conditions at the dike, preceding the failure, were reconstructed in the analyses.

The illustration in Figure 3 provides an overview of the piezometric levels, build up and geometry of the dike, canal and terrain at Wilnis before failure. Here, some characteristics of the 2 locations are given, which influence the hydrology of the dike, notably the unsaturated zone and piezometric head development at the base of the peat, and which may cause strength and stiffness anomalies.

The dike of the Wilnis location has a grassland cover. A sheet pile wall with board lengths up to 4.5 m, had been placed along the canal about a decade ago for bank protection. Maintenance dredging of the canal to a water depth of about 2 m was carried out 1 year before the failure. A wide ditch drained the toe of the dike and was lined with shrubs and some tall poplar trees. Transverse breaks in build up of the dike did could be recognized on 19th century topographic maps in the vicinity of the failed dike section. The clay layers in the subsurface increase in thickness towards the west along the dike, and decrease in thickness eastwards from the failed section.

The dike of the Rotterdam location was used for recreational gardening and supported some semi permanent sheds with scattered patches of shrubs and small trees on the failed dike section. The canal had an a few decimeters deep mud line, and an only very shallow bank protection. Detailed historic maps of the area show that the dike at the location was in use as shipyard terrain when the mined out area was still a lake; notably small harbour inlets did occur at the site. The dike crosses a riverine shoestring sand, locally about 1.5 m below the surface at the toe of the dike.

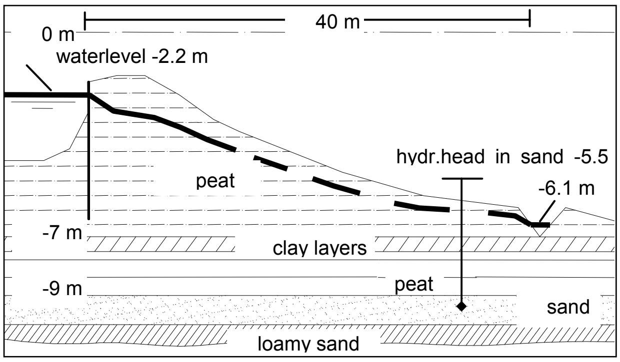

Figure 3: Cross section with relevant geometry specifics for the Wilnis location

At both locations water was heard or seen running from cracks in the dike's landward surface 0.5 - 1 hours preceding the main failure event. The main failure event at both locations was a lateral translation of several meters of a section of the dike, taking less than 15 minutes. The canal emptied through the wide opened lateral cracks resulting in a sheet flood. At Wilnis the flow in the failure's main bounding cracks eroded peat and a significant amount of sand from the Pleistocene below the peat and clay.

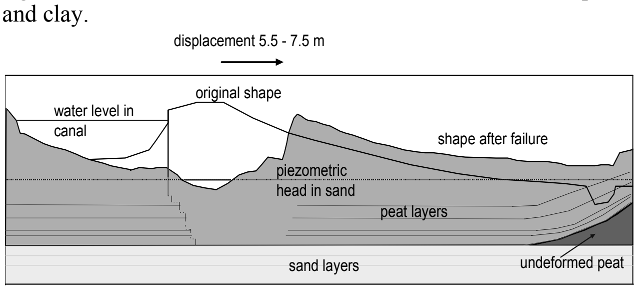

Figure 4: Embankment geometry before and after the failure at Wilnis. The various layer boundaries in the subsurface are indicated after failure, as well as the original water level in the canal and the piezometric head in the sand.

The failures consisted of coherent horizontal translation of about 6 m over a 60 m stretch at Wilnis, and a few meters at Rotterdam over a width of tens of meters. Vertical displacement was less than a few decimeters. At Wilnis, a planar horizontal basal sliding plane was reconstructed from borehole and excavation data and located to have been at the base of the peat, i.e. at the top of the sand. The failed slices at both locations were bound laterally by major linear fractures oriented outward at angles smaller than 45^0, indicating the wedge to have been pushed by a force from the canal. Displacement of the slice was accommodated in part by filling a ditch and, mainly, in a subsequent upthrust over the existing terrain surface. The movement of the toe and part of the failed slice at the Rotterdam location was accommodated by surficial folding without significant thrusts. Only a small part of the lateral bounds of the failure was found to have been influenced by terrain features. At the Rotterdam location shrubs and small trees had moved with the sliding mass. At Wilnis a tall poplar tree at the toe of the slide had remained in place with its roots firmly anchored in the underlying sand, cutting the about 4 m thick sliding peat and clay mass.

4 ANALYSES OF THE FAILURES

The summer preceding the failure had been exceptionally dry in The Netherlands, such as occurring only appr.1/25 year^{-1} on average. The 2 failures within a period of 2 weeks at the end of the dry summer, together with the condition that both dikes consisted of peat, suggested that effects of decreasing moisture content, i.e. weight loss and shrinkage, had to be considered in the analysis.

The analysis discussed here focuses on the Wilnis site and makes mention of the findings for the Rotterdam site only.

The geometry of the failure, a 60 m long flat slab with only lateral displacement and with lateral bounding fractures oriented as an active wedge angle to the canal, made it clear that the water level in the canal provided the driving force for the displacement. The hydraulic heads in and below the dike were calculated for the locations as they would have been prior to the failure, based upon the known heads in the canal, the polder behind the dike, and the underlying sand in the far field. Data from tests on large samples of peat and various approximations for in situ permeability of the underlying sand, including that of a less permeable silty sand layer about 1m below the top of the sand, were used for the determination of the hydraulic heads. The not well known bulk permeability of the deep wooden sheet pile bank protection at Wilnis did have a notable influence on the calculated heads, as anticipated. In undisturbed condition, the high hydraulic heads in the canal were hardly communicated to the sand below the peat due to, amongst others, clay layers in the peat.

Soil mechanical force equilibrium calculations for horizontal slip of the dike upon pressure from the canal, including the calculated initial hydraulic head distribution, were made. The results suggested that for undisturbed conditions, the relatively high hydraulic head in the sand would cause uplift of the peat at the toe of the dike, thus reducing friction there, but insufficient to cause failure. The calculations used the soil weights as determined on representative samples of the failed peat, but even assuming a decrease in moisture content to very conservative values had only limited effect on this outcome.

From trial pits at the Wilnis location, it became clear that there were no evident changes in the relative position of the predominantly saturated zone, both at the top and at the toe of the dike. The base of the intensely weathered peat coincided approximately with the top of the observed largely saturated zone. This observation does not include effects of any volume changes due to dewatering. Gley (discoloration) features in the soil, however, made clear that the water table in the dike at Wilnis was frequently raised for extended periods up to 0.5 - 0.7 m below the surface at the top of the dike, and up to 0.3 m below the surface at the toe of the dike.

The findings from this initial stability analysis and the observations made clear that the cause of the failure was more complex than mere weight loss, both at Wilnis and at Rotterdam. The location of the basal sliding plane at the top of the sand immediately below the peat prompted investigations after mechanisms that could result in higher hydraulic heads in the sand below the crest of the dike than assumed in the initial stability analysis.

The sheet pile bank protection along the canal at Wilnis, locally piercing clay layers in the peat, had a major influence as came out of the initial hydrological analyses. The results from hydrological calculations incorporating leaks from the piles in the peat and clay layers made clear that the leaks had effect on the head in the sand below the bulk of the dike. The leaks would have to extend deeper than the piles, however, and had to be wider than mere local millimeter cracks in order to cause the head in the sand to rise to a level causing loss of friction at the base of the peat. An investigation of the effects of water pressure in vertical cracks in peat showed the cracks to widen substantially upon pressure, due to the very low stiffness of the peat, and in spite of the peat not being very impervious (Figure 5). The resulting shear stresses at the tip of the water filled cracks in the peat were found sufficient to cause fracture expansion and growth. Thus penetration of the hydraulic head of the canal a few meters deep along the sheet piles in the peat would result in fracture propagation. Shrinkage of peat due to the dry weather conditions adversely affected stresses and deformation at the sheet pile wall. Increase in evaporation causes negative pore pressure, which induces shrinkage of peat below the already intensely fractured top layer, creating tensional stresses parallel to the dike surface over the depth of the zone experiencing negative pore pressure. The tensional stresses exert a pull on the peat at the sheet pile away from the canal (Figure 5), thus enhancing creation of space along the piles and adding some tensional stress at the tip of shallower cracks. It must be noted that horizontal fracture-like surfaces are widespread in the peat mass. The extent to which the sub horizontal stresses can be transferred across such rough planes was not investigated. These planes are known to be conduits for water in peat, however, enabling high water pressures to be transferred efficiently through the peat mass. Fracturing of the peat mass by water pressure is therefore not limited to the tip of the initial leak.

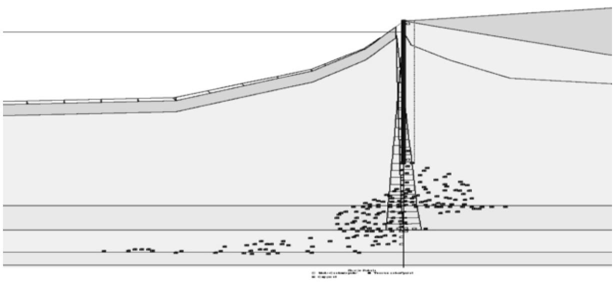

Figure 5: Cross section of the canal and dike with sheet pile. The dots at the base of the pile indicate occurrence of plastic behaviour in calculations using a Mohr Coulomb model.

At the Rotterdam location, initial soil mechanical stability analysis made clear that the relatively thin peat cover overlying somewhat over pressured sand, resulted in a less stable dike than at the Wilnis location. Already the presence of a hydraulic discontinuity along the canal, as detected on historical maps, was found a sufficient condition for weight loss causing uplift of the peat and failure of the dike.

The build up of a high hydraulic head in the sand below the peat at Wilnis was enhanced by the occurrence of an about 0.5 m thick loamy sand layer about 0.5 m in the sand below the base of the peat. The effect of the loamy layer was discernable on the pore pressures detected by piezocone CPT's. In the calculations, the loamy layer did allow even limited flow from the canal through the cracks to build up a sufficiently high water pressure below the crest of the dike.

The drought of the 2003 summer in The Netherlands gave rise to conditions that led to failure of peat dikes at 2 locations. The failure at both locations did occur due to combinations of circumstances, of which a major discontinuity along the bank of the canal, concerning bulk permeability, strength and stiffness, is common to both. The failures involved planar slides with a basal sliding plane on sand in which the high hydraulic head was relatively too high. The major discontinuities along the canal are features from present and past land use. Such features are common in much of the intensively used canal dikes of The Netherlands, and can therefore be expected to exist at other locations.

5 DISCUSSION AND CONCLUSIONS

The local drainage canals and their dikes are important elements of the historically developed, man made, landscape of the western Netherlands. The dikes retain water in the drainage canal system, and many have further important functions in transportation, recreation, and in the ecological infrastructure. The chain of events described above for the failure of such a dike can be well appreciated in hindsight, but was not foreseen in spite of an extensive safety evaluation programme in the 1970's and 1980's for these dikes. The failures discussed here did involve hitherto not diagnosed nor anticipated mechanisms in stability evaluations of the peat dikes. In part this is due to the material at hand. The failures involve peat which is a peculiar soil: Only 10 - 20% of the volume of the peat discussed here, is an actual solid. Changes in ambient conditions, notably weather, surface and ground water, and vegetation have significant and partly self explanatory effects for dikes of such soil. The influence of these changes on the stability of the dike is not immediately evident as follows from the analyses described above. However, in order to come to a systematic safety evaluation of the many thousands of kilometers of dikes the routine geotechnical analysis has to incorporate evaluation of the effects of changes in ambient conditions. These effects involve changes in weight with evident influences on stability, and changes in volume of the soil mass with largely indirect effects. The above described analysis of the failure suggests that mechanisms such as fracturing and unsaturated hydrology have played a significant role. The processes and parameters involved in these mechanisms are notoriously complex in real life settings, and are hard to measure and uncertain.

From the analysis it is clear however, that conditions affecting the hydrology of the saturated and not saturated zone of the dikes have to be taken into account to enable systematic safety evaluation of the dikes. Many of these conditions will be manmade, and may be very local. In many cases only a review of the development of the dike in an historical context will be able to provide information necessary for estimation of the likelihood of adverse conditions. Systematic evaluation of the safety of the dikes will need methods that deal with the uncertainties concerning the ambient conditions as well as their effect on soil properties, conditions, and behaviour; i.e. the effect of a possible drought on the weight of a peat dike in a variety of settings must be evaluated.

An effort in physical and other modeling studies, simulating a wide variety of conditions will therefore be necessary to come to a system for safety evaluation of the peat dikes that can be used in practice.

REFERENCES

Beets, D.J. and A.J.F. van der Spek 2000. The Holocene evolution of the barrier and back-barrier basins of Belgium and The Netherlands as a function of late Weichselien morphology, relative sea-level rise, and sediment supply. Netherlands Journal of Geosciences 79(1), 3-16.

Beuving, J. and J.J.H. van den Akker 1996: Maaiveldsdaling van veengrasland bij twee polderpeilen in de polder Zegvelderbroek; vijfentwintig jaar zakkingsmetingen op het ROC Zegveld, Wageningen , SC-DLO Rapport 377.

De Bont, C.H.M. 1999: Delft's water; two thousand years of habitation and water management in and around Delft, Delft: IHE / Zutphen, Walburg.

GeoDelft 2003a. Rapport CO-123456/123. GeoDelft report CO-123456/890 for AKG, Hilversum.

GeoDelft 2003b. Rapport CO-123456/123. GeoDelft report CO-123456/890 for Schieland, Delft.

Streif, H. 1990. Das ostfrieische Kuestengebiet, Nordsee, Inseln, Watten und Marschen, Sammlung Geologischer Fuehrer 57, Gebr. Borntraeger, Berlin, 180 pp.