Literature review Achilles-grant work relevancy for Dutch levees

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Summary

A review of the U.K. Achilles publications led to insights in clay deterioration process which are also relevant to Dutch clay slopes, including levees. These insights include deterioration in soil water retention curves, shear strength and an increase in hydraulic conductivity, which are all because of dry-wet cycles and subsequent cracking and micro-cracking. The influence on erosion of the slope surface was not covered by the Achilles program.

Instabilities during severe precipitation events as experienced in the UK with railroad and road embankments and cuttings are not expected for Dutch levees, because they were built differently. The process described by the Achilles publications are however relevant for Dutch levee circumstances because clay deterioration can reduce the safety margin in geotechnical stability which might be necessary for flood protection. The negative effects on clay strength will increase if more severe drought occur in the future.

The topic of clay deterioration will be addressed in the upcoming EU Bonsai project. This review is intended to provide input for the Bonsai program.

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1 Introduction

The Achilles program (https://www.achilles-grant.org.uk/programme/the-research-challenge/) has led to knowledge development on deteriorating effects of clay in embankments and cuttings, which increase the slope failure probability over the years from construction. Deterioration of the clay is attributed to dry/ wet cycles. The knowledge will support decisions on maintenance of LLA (Long Linear geotechnical Assets), railroads, roads and levees, optimizing life cycle costs and safety. The program has led to publications listed on the Achilles internet site (Publications – ACHILLES (achilles-grant.org.uk).

Deterioration of clay soils over time due to drying and wetting cycles, as covered by the Achilles program, but also frost, and other mechanisms as caused by flora and fauna, is a known phenomenon. The process is also known as in Dutch ‘vorming bodemstructuur’ or in English (not certain of the term) establishment of soil structure. The increase in permeability, cracking of clay and decrease in soil shear strength and water retention capabilities in certain cases is also a concern for the performance of Dutch clay levees and clay covered sand levees. Certainly, considering the expected increase in severity of drought and precipitation events in decades to come. The topic of clay deterioration will be addressed in the upcoming EU Bonsai project.

Preliminary to the Bonsai program and as possible input for research programs for Dutch levee safety assessment and design, The Achilles publications were scanned for relevant information for use for Dutch levees and as input for the Bonsai project.

2 Publications review

The total Achilles publications list contains approximately 140 publications. The list starts with 65-70 publications labelled Achilles. The list ends with about 70 references from Achilles predecessors and important references to Achilles publications. A selection of the Achilles publications was scanned. These are the most recent publications and presumed state of the art.

The Achilles program was induced by experiences of instabilities in railway and road embankments and cuttings. Embankments were made some 100 years ago, without much/ any compaction of the used clay soil. Besides the embankments elevated from the planes, cuttings were made through hills, creating slopes in untouched soils. The slopes of both cuttings and embankments seem to become instable over time (Briggs K.M. 2017) and (Briggs 2019). The processes driving the instabilities were investigated, mainly deterioration of soils due to wet/ dry cycles.

The key topics and findings of the scanned publications are given below. For some topics a reflection is given for Dutch levee circumstances. This is indicated by using *italic font*.

2.1 Guidance and support, asset performance curves, asset management

The publications by Armstrong (2021), Armstrong (2022) and Briggs (2017) are about providing guidance and decision support minimizing whole life cost at asset up to network levels, maintain serviceability and operational safety. The physics of deterioration, increasing failure probability, modelling and monitoring are input for providing guidance. These are covered by other, more technical, publications as described in the following paragraphs.

Asset performance curves are introduced giving the performance (low-high, with a certain threshold) against lifetime. Due to soil deterioration the asset performance drops, on the other hand maintenance actions increase the asset performance.

For Dutch primary levees in principle a similar approach is in operation, with a periodic safety assessment of the slope stability. Each time, the true state (e.g. not the design state) of the levee must be assessed. This assessment gives the performance for the coming period, whether it is above or below the threshold or in other words if the failure probability is sufficiently low. Otherwise, an intervention is required. There are a few key differences, however:
1) In practice, deterioration of clay is not addressed explicitly. The clay shear strength both in the saturated and unsaturated zone are in practice presumed constant in time. Recently research has started to investigate the shear strength of the clay in the unsaturated zone in more detail.
2) In practice many of the Dutch levees are already of age. Deterioration has had its effect. Cracking and aggregate formation has taken place. Hydraulic conductivity is already presumed relatively high, orders of magnitude higher than naturally deposited undisturbed soils, as described by Dixon (2019). Increased deterioration due to more severe droughts and precipitation events are however not explicitly considered in current practice.
3) Levee embankments have a high level of safety, e.g. are relatively mild sloped, due the high level of required safety. Normative conditions are high water levels of sea, lake or rivers, not extremes in precipitation.

2.2 Mechanisms slope instability due to soil deterioration and modelling

Experiences of failures in road and railroad embankments are described. There are differences between the two embankment types (Briggs K.M. 2017).

- Railway: over the top clay dumping. This results in clod-matrix structure. Deterioration of clods leads to deformation. No compaction was applied. Steep slopes 1:1,5-1:2, up to 16 m high. No removal of soft top soil prior to construction. Vegetation includes mature trees. *These embankments are very different from almost all Dutch Levees, which are in general compacted at construction, have more gentle slopes and have a smaller height. Mature trees on primary levees are rare, more common on local, secondary, levees.*
- Roads were constructed later in time, following major rail works, the base of soil mechanics was available. Compaction of fill material, gentler slopes. Vegetation kept short. *Road embankments compare better with Dutch levees.*

Three types of failure are considered (Briggs K.M. 2017):

1. Failures due to pore water pressure increase.
2. seasonal shrink/swell deformation.
3. progressive failure.

The failure types are inter-related and may act together in combination or sequentially (e.g. shrink-swell deformation may lead to progressive failure of the embankment, with the final rupture triggered by an increase in pore water pressure).

Ad 1) Pore water pressure failure. Rain infiltration induced slip failure. Embankment were built with the idea of having surface run off in case of severe precipitation, however cracks from dry summers facilitate fast infiltration. The slip surface is generally shallow. Piezometer measurements (113) showed an increase in water pressure up to hydrostatic in the winter 2001-2002 (wettest since 1766), 100 slip failure of railroad embankments and 60 of road embankments occurred. Noticeable differences between fills on draining deposits and non-draining deposits (clay). *Remarkable: Permeability is very low compared to Dutch levee clays (‘low’ <1x10*$^{-8}$ *m/s and ‘high’ >0.5x10*$^{-7}$ *m/s for rail and road embankments). In Dutch clay dikes low is smaller than order 10*$^{-6}$ *m/s and high is order 10*$^{-4}$ *m/s or higher.*

Ad 2) Deformation failure. Railway problem (uncompacted clod matrix soil), hardly road (compacted at construction). Deformation problems occur in embankments in high plasticity soils and hardly in low plasticity soils. Shrink -swell is also dependent on vegetation (trees = a lot of shrink/ well; grass less). Shrinkage seems to have the overhand. In time compaction of the fill volume occurs. *Not that relevant for Dutch levees which are in general well compacted. Dutch ‘klink’ in the few years after construction is accounted for by profiling above design dimensions, accounting for approximately 5% volume change.*

Ad 3) Numerical calculations with summer/ winter conditions on vegetated slopes with the model Vadose/w give insight in the slope behavior during multiple years. Climate change scenarios can be simulated by increasing precipitation and/ or evaporation rates. The model does not yet have prediction value. Boundary conditions are back calculated from LUL (London Underground Ltd) railway embankment measurements. The model predicts failure within a certain number of year cycles. Accumulation of shear stresses occurs because of the drought/ wetting cycles eventually ‘ratcheting’ the slope to failure. Ratcheting to slope failure can be stopped if there is a remaining suction stress from summer drought which holds through wet winter conditions.

This ratcheting process is investigated and numerically modelled by Posthill (2020), Morsy (2023), Woodman (2020) and Rouainia (2020).

They provide methods to determine slope stability of over-consolidated plastic clays under the influence of seasonal wetting and drying cycles. This gives way to taking climate changes into account when considering slope stability under influence of ‘ratcheting’: progressive deformations and shear stress accumulation due to wetting and drying cycles over years.

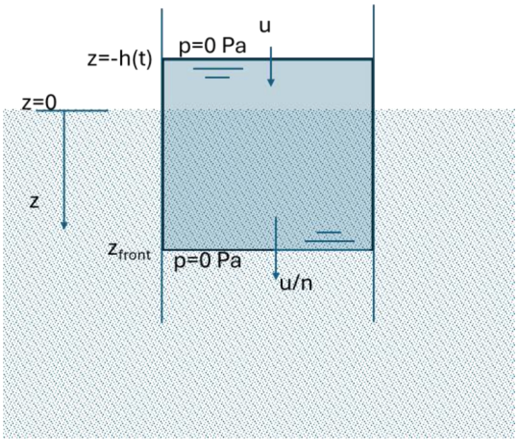
Essential in the reported methods is being able to model hydrology in the unsaturated zone, under influence of precipitation and evaporation, influenced by vegetation, and considering strain softening soil behavior. Both hydraulic conductivity of the soil and stiffness are reported to be important for ratcheting or progressive failure. The studies consider slopes of over-consolidated plastic clay. The desiccation of the shallow soil layer (<1 m) during drought causes cracking and increases the hydraulic conductivity. This is not yet incorporated into the given methods but could according to the studies have a significant impact on the slope stability. As reported by Stirling (2021) the SWRC (Soil Water Retention Curves), which play a part in the hydrology of the unsaturated zone, are not constant but are influenced by drying and wetting cycles, especially drought extremes. *Given this SWRC behavior a SWRC state parameter would be required to model hydrology in the unsaturated zone accurately in the time scale of years, e.g. long term (climate) trends. This is not part of Dutch practice, as is modelling the hydrology in the unsaturated zone in levees, which is done occasionally, certainly not standard.*

To investigate the relevance of (climate influenced) progressive slope failure for Dutch clay dikes, the circumstances between UK embankments and Dutch levees could be compared. Probably the most comparable Dutch levees will be clay dikes, consisting of plastic clay with relatively steep slopes. This might be the case in parts of the lower river area. Plastic clay dikes with relatively steep slopes are however also prone to creep deformation. It might be a challenge to separate the distinct mechanisms 1) progressive deformation by creep and 2) ratcheting by seasonal wetting and drying cycles.

2.3 Hydrology and conductivity

Dixon (Dixon 2019) describes laboratory and in situ tests to determine the hydraulic conductivity of near surface (up to 1 or 2 m) fine soils in embankment slopes and cut slopes. The publication summarizes the findings from measurements on different scales and locations. Due to wetting drying cycles and various other process the cap of an embankment or cut has a higher conductivity. Measuring the conductivity of weathered soil in saturated or near saturated conditions is addressed in this paper. Distinction is made between laboratory and in situ tests. Laboratory tests 70-100 mm are often too small to capture the bulk conductivity. Bore hole and double ring infiltrometer tests are described as in situ tests.
The conductivity calculated from the double ring test is based on a gradient of 0,2 (-) based on pore pressure measurements.

In Dutch practice we usually assume a gradient of 1 (-) and using Darcy’s law to estimate the saturated hydraulic conductivity of fine soils with macro-pores from an infiltrometer test. Using Darcy’s law simplifies the complex process, much more than for instance the Green Ampt method. It does not take into account parameters soil suction head, porosity and time (https://en.wikipedia.org/wiki/Infiltration_(hydrology).



Gradient i (-)

$$i = \frac{z_{front} - (-h)}{z_{front}} = \frac{z_{front} + h}{z_{front}}$$

If the water layer above the soil surface is small relative to z_{front} *the gradient will be near 1 (-).*

Using a gradient of 0.2 (-) instead of 1 results in a 5 times higher conductivity from the double ring infiltrometer test. Using for instance the Green Ampt method will require more parameters, to be estimated or determined by laboratory tests in addition to the ring infiltrometer test. The simplification could be justified by being able to neglect the suction head (flow through macro pores) and the observation in Dutch practice that the water level drop becomes linear after a short time. The parameters obtained from the Darcy simplification seems to perform well, when back calculation full slope infiltration tests. It could be worth investigating if the bulk conductivity can be estimated more accurately by applying a more accurate model, although this will require additional parameters (estimated or determined by laboratory tests).

A difference is made between embankments and cuttings (Relevant for Dutch levees are embankments). *Hydraulic conductivity has a high variation, as experienced in Dutch levees, however the variation reported by* (Dixon 2019) *is even higher.* It is concluded that apart from scale of the sample, spatial and temporal variation dominate the high variation.

Reported spatial variation of the conductivity over an entire slope ‘plan’ at depth of 0,3 m is 5 orders of magnitude! (*much more than Dutch dike experience*). The conductivity decreases by 4 orders of magnitude from 0,3 m to 1,2 m depth. *Decrease is in line with Dutch levee experience, however, 4 orders of magnitude is much more than for Dutch levees in construction soils (worked/ anthropogenic). When considering the naturally deposited unworked soil layers, these can be 4 orders of magnitude lower in conductivity.*

Dixon (Dixon 2019) reports a variation coefficient in measured conductivity of 2-4 for fill material embankments. Based on comparing test results it is concluded that spatial variation of the material properties, e.g. macro pores, is dominant in this large variation coefficient. Next is variation in season, or moisture content at the test time. *The spatial variation will probably become less when the test scale increases. For example, imagine testing on cm-dm scale (worm hole present or not) and slope scale (1000 worm holes present).*
Conclusions from (Dixon 2019) based on 143 conductivity tests show:

- In the top 0,5 m there is a variation of 5 orders of magnitude. *Note: test scale up to ring infiltrometer; not full slope tests.*
- Decreasing conductivity and decreasing variability with increasing depth.
- Greatest source of variability in test results is spatial variability of conductivity, mainly caused by variation in macro pores. Seasonal effects, moisture content during test performance (dry summer/ wet winter) causes some variability.
- Variability is to some extent influenced by the test method, primarily by the tested zone, where larger zones result in larger conductivity.

2.4 Measuring and monitoring, site investigations

Blake (2022) and Brooks (2022) give an overview of long-term monitoring of weather, soil moisture, (suction)pressure and slope deformations for three sites.

1) BIONICS: An embankment which was specifically build to conduct research, 6 m high, 1:2 slopes, boulder clay Ip=18,5%, several sections with different compactions, 0,3 m topsoil with grass. Since 2007.
2) Newbury, highway cutting. Since 2003.
3) Warden, 600 m flood defense embankment. 3 m high, sloped 1:2,5 to 1:3, construction 2009 from stony clay after failure in 2005. Monitoring since 2021.

Goal is understanding of deterioration process in earth embankments and its effect on slope performance. Investigations and studies were performed considering cracking and conductivity (Dixon 2019). Soil water retention curves (SWRC's) define the relationship between soil suction, soil water content and provide a proxy for mechanical and hydraulic properties. SWRC's were shown to change over time due to wetting drying cycles. Volume and fabric were shown to change over time, including formation of micro cracks.

In (Ball 2022) the electrical resistivity tomography (ERT) technique is investigated in an embankment near the Thames estuary. The many anomalies found in 2D surveys were allocated to 3D effects. Time lapse use of ERT in embankments along rivers revealed seepage paths. Electrical resistivity tomography (ERT) used for slope stability proxies are described by Boyd (2021). The measurements were linked to spatial saturation profiles. These were linked to (suction) pore pressure and to shear strength parameters via correlations or calibration to bore hole mechanical tests or laboratory tests on samples. Periodic surveys or permanent installation are suggested to determine the slope's response to precipitation and give input for stability models. The profile information can be preferred to point measurements by (traditional) pore pressure transducers. (J. C. Holmes 2022) takes ERT monitoring to 4D giving insight in the influence of vegetation (e.g. grass, trees) on the hydrology of slopes. Making use of petrophysical relationships with electrical resistivity models (J. C. Holmes 2022) couples ERT measurements to suction profiles and hence insight in slope stability.
In Dutch levee practice ERT techniques are sometimes tried but have never come to massive use. In theory very useful, in practice not so much, because of difficulties in interpretation of the results. Lots of anomalies are found, which are not always important. Many parameters influence the measurements, more than just the moisture content and stratification, making interpretation too much of a challenge up till now for widespread application for Dutch levees.

Monitoring of ground movement with optical fiber techniques was tested on the Hollin Hill landslide location, which was also monitored by GPS trackers and point measurements of soil moisture as described in Clarkson (2021). Also, low frequency acoustics were measured, which are associated with ground movement. Only the abstract was available. Other monitoring techniques for man-made and natural slopes were installed, tested and coupled to automated data processing and modelling (Chambers J. 2021a), (Chambers J 2021b), (Chambers 2021c). Monitoring of slope movement using satellite data is described by Grebby (Grebby 2021).

2.5 Physics of deterioration process clay due to dry/wet and freeze/thaw cycles

Weather driven deterioration processes in clay are described by Stirling (2021). Due to dry/wetting cycles a system of large and small cracks occurs in 'freshly' compacted soil. This is similar to near surface soils in a recently constructed and compacted embankment going through dry summer and wet winter conditions. The system of cracks in clay influences 1) the Soil Water Retention Curves (SWRC's), 2) the shear strength of the unsaturated clay and 3) the tensile strength.

All three effects were simulated and tested on laboratory produced clay samples subjected to cycles of wetting and drying. Dry/wet cycles cause the soil to lose to some extent its ability to retain water at a certain suction level. After only a few cycles of the same magnitude, the SWRC will converge to a lower level. However, if the sample is subjected to a more severe dry cycle the SWRC again adjusts to an even lower level. The lower water retention capacity decreases the soil shear strength of the unsaturated soil, as was shown by performing triaxial tests on samples exposed to several dry/wet cycles. The shear strength reduction seems to be a consequence of the loss of suction due to micro cracks in the clay. The tensile strength also deteriorated, which means that there is less resistance against cracking. Larger and deeper cracks, in turn, expose deeper soil layers to effects of drying and wetting, further increasing the clay deterioration zone and decreasing the slope stability.

The process converges; however, more extreme events deepen the deterioration front. For the effects of the hydraulic conductivity (Stirling 2021) refers to (Dixon 2019). Similar results for low plasticity soils were found by (Liu G 2020). The shrinkage and swelling of samples, together with measurements of suction and sample weight were followed during multiple cycles. An irreversible shrinkage and lowering of the SWRC was measured with more cycles, converging after 3 cycles or more. The effect of compaction conditions on SWRC in dry-wet cycles of glacial till was also tested in the laboratory by (Toll DG 2019).

The described processes in (Stirling 2021) *are also occurring in Dutch clay levees. The consequences of these processes are likely to become more pronounced if extremes in drought and precipitation events become more severe. Up till now, however, we seldomly have collapsing levee slopes due to precipitation events as is the case with road and railway embankments and cuttings in the UK. Dutch dikes are almost all already of age and have endured severe drought and precipitation events. They are constructed in layers where a dike improvement, a berm and some height is added to an already existing dike body. This is done with well compacted materials. Because of the high required safety levels required for flood protection, slopes are relatively gentle. Extreme precipitation events are generally not normative above events with high river or sea water levels. It is therefore explainable we do not, or hardly, experience slope collapses due to extreme precipitation events. A few cases are known e.g. Zuiderlingedijk and Maasdijk. More severe effects of deterioration (deeper cracks, deeper deterioration front, behind which: higher conductivity, lower shear strength.*

The emphasis in Achilles research is on the effect of dry/wet cycles. Hughes (2019) describes laboratory research on freeze/ thaw cycles (FTC) on sandy clay (glacial till). The same deterioration effects are found as for dry wet cycles: micro-cracking, loss of water retention capacity (lowering of SWRC) and a deceasing shear strength and stiffness. Suction reductions were the dominant factor behind FTCs’ influence over soil strength for investigated soils.

Crack dimensions and distribution along the BIONICS embankments were reported by Yu (2021). The volume of cracks was estimated using an empirically derived equation. Wind, relative humidity, precipitation and potential evapotranspiration govern the near surface soil hydrological conditions and hence the forming, expansion, contraction and closing of cracks. In field conditions linearly discrete cracks form as opposed to polygonal crack patterns under laboratory conditions. Crack length growth stops before the maximum crack volume is reached.

A large outdoor lysimeter test was conducted (McConnell E 2022). The tested slope was heavily instrumented. Scale in the order of 2 m by 1 m by 4 m. The test scale holds between full scale field slopes and laboratory scale. Cracking patterns and suction stresses were measured. The test set up allows to monitor the hydrological regime under simulated weather events.

2.6 Soil improvement

Soil improvement using biopolymers is described in (Maguda Vishwanath 2021). Unconfined compression tests, tensile stress tests (Figure 2.1) and erosion tests were performed on treated soils, showing the positive effect of different biopolymer treatments.

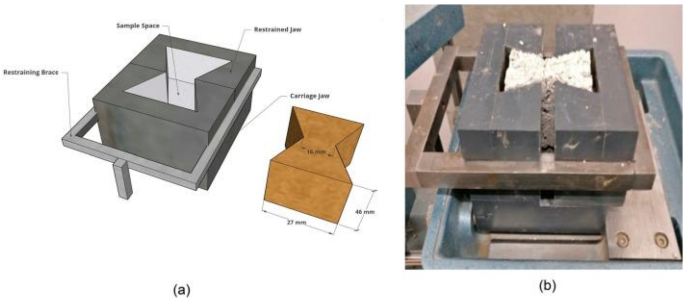


Figure 2.1 Tensile stress test in bow-tie sample set up (Maguda Vishwanath 2021).

Fiber additions (plastic) will increase the tensile strength of soils and reduce cracking (Wang 2022).Tests were performed high plasticity London clay. The used fibers are 12 mm long and used at a ratio of 0.9%.

The positive effect of using a (sand) topsoil in the order of 0.1 m to reduce crack formation of clays is described in McConnell (2022). The study was about crack formation patterns as a result of desiccation. It was found that the evaporation potential, the driving factor in crack formation, could be significantly reduced by applying a topsoil. The experiments did not include vegetation.

3 Discussion and reflection for Dutch levees

The Achilles research is very relevant for both high and low plasticity clay slopes in The Netherlands and elsewhere in Europe. The same processes in clay due to wet/ dry cycles and frost/ thaw cycles occur. Under the assumption of more severe drought and precipitation events in the future, the margin between stable and unstable slopes will become smaller. The formation of cracks (micro/ macro) and the effect on the hydraulic conductivity, the shear strength and the water retention capacity were investigated and lead to practical results.

For Dutch levees, this will much less likely result in instability caused by ‘ratcheting’ or a severe precipitation event after deterioration of the soil structure, because the levees were and are built sturdier than the railway and road constructions from the UK some 100 years ago, with milder slopes and proper compaction of the used materials. Nevertheless, the deterioration process will cause an unknown reduction in safety margin in case of high-water loading, especially in case of overtopping or overflow.

Deterioration of the clay is to some extent accounted for in Dutch dike design. The top approximately 1 m of clay is known to have a high conductivity due to development of soil structure, cracks. The conductivity has the same order of magnitude as sand. This is the top end of the conductivity found by Achilles. The interpretation of double ring infiltrometer results needs to be addressed. The Achilles approach leads to a factor of 5 difference to Dutch practice interpretation. A less simplified method than Darcy’s law could possibly result in more accurate estimates of the conductivity.

The reduction in water retention capability is not incorporated in common Dutch levee design and assessment practice. It is not known if this effect has a substantial influence on levee hydrology in high-water situations, this could be topic of further investigation. This could also be important for the wellbeing of vegetation, which is important for erosion resistance.

The shear strength of clay with developed soil structure is topic of a current investigation (Dutch: SIOZ; Sterkte Initieel Onverzadigde Zone). The strength of clay covers in overtopping conditions is topic of research (Dutch: Stabiliteit bij Golfoverslag).

The Achilles program was aimed at geotechnical instability of slopes, not at erosion of the slope surface.

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