

# Lateritic Soils for Dam Foundations and Dam Cores -Two Case Studies and Their Typical Properties

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## Abstract

The present paper discusses both the principal properties of lateritic clay soils as foundation and construction materials, and the derived conclusions for the pore water pressure development in a rockfill dam with clay core on a residual soil foundation. Special attention is given to the consolidation behavior of a typical rockfill dam with a lateritic clay core founded on lateritic clay foundation. The data basis for this paper was obtained both from literature review, and from site data collected for hydropower projects in Laos and Uganda.

The aim of this paper is to provide a rough overview of some important engineering aspects of lateritic clays, and to present a simple method for the estimation of pore water pressure dissipation if lateritic clays are used as dam core material and/or foundation.

## Introduction

Lateritic soils, or more precisely Ferralsols (FR) are usually the product of an in-situ (lateritic) weathering process of a basement rock, under tropical climate conditions. The genesis results in typical lateritic weathering profiles, often having a considerable clay layer on top. Lateritic soils are located in tropical regions, where they are used as construction material for embankment dams, roads, etc. In some cases the clay can remain in the foundation, whereas in other cases the dam engineer will require its removal prior to constructing the dam.

In this paper, the typical geotechnical and engineering soil properties of lateritic soils are described, based on literature data and confirmed by soil investigation results from two case studies.

## The Occurrence and Genesis of Lateritic Soils

### Definition & Classification

Typical for the genesis of lateritic soils are the hot and wet climatic conditions of the tropical and subtropical regions. Lateritic soils are products of a three-stage in-situ weathering and decomposition process [1], [24]. Their color is generally reddish to yellowish, dependant on the water regime during

genesis, and on the mineralogical composition of the parent rocks [2]. Their name is derived from “Ferrum” and “Alumen” that are Latin for iron and aluminum. Usually the in-situ weathered lateritic soil does not show any distinctive stratification [3].

Another definition is given in [20]. “Lateritic soil” is the traditional expression for soils defined and named as Ferralsols [2], Ferrallitic soils [3] or Ferralites [5] according to different soil classification systems and approaches [10]. Referring to the color, “Red Earth” or “Tropical Red Clays” have also been used for the superficial soil that results from the weathering of typical basement rocks, e.g. Granites or Ultrabasites. Regionally, also the terms “Latosol”, “Latossolo”, “Kaolisols” are still in use [2].

A uniform soil or rock nomenclature/classification system for tropical residual soils does not exist. As stated in [6] “It is unfortunate that the terms ‘lateritic clays’ and even ‘laterite’ are still used by some engineers to describe any reddish tropical soil”. Fortunately for engineering purposes it does not matter whether the classification is correct, but that the geological and engineering properties as predicted or derived from testing are reliable.

In the present paper the term “Lateritic Soil” is consistently used, as it is commonly known and does not contradict any of the various existing classification approaches. International engineering practice treats lateritic soils under the topic “Residual Soils” [3]. More precisely this paper addresses particularly red clays, although lateritic tropical clays may also exhibit a yellowish color which have similar properties to the addressed red clays [11]. According to [6] “Red Tropical Clays” may be Ferrallitic Andosols, Ferruginous soils, Ferrisols and Ferralitic Soils classified corresponding to the soil and rock classification system of the Geological Society Working Party from the year 1990.

### Occurrence & Genesis

In [2], [3] and [6] maps are given which show the worldwide distribution of different soil types, particularly residual soils including Ferralsols. Due to the climatic conditions which are necessary for the typical genesis of recent lateritic soils, the occurrence is concentrated close to the equator, ranging from the southern part of South America to the mid of the United States. In Africa the lateritic soils are mainly located from the equator southwards. Asia, India and major parts of South-

East Asia, including Vietnam, Laos and Malaysia, are places where residual and especially recent lateritic soils are dominant [3].

In contrast to transported soils, the genesis of in-situ soils is crucially affected by the climatic site conditions and the topography, and by the nature of the parent rock itself. The chemical (decomposition) and physical (disintegration) weathering process is mainly summarized by the term “lateritization” [3], [5], [6], [24].

### Typical Weathering Profile

According to international practice in rock engineering a classification by six grades is usually applied for soil-rock-profiles subject to lateritization (see Figure 1).

Classes <sup>A)</sup>	W weathering Profile <sup>A)</sup>	Description <sup>A)</sup>	Fichtner (Uganda) – Classification <sup>C)</sup>		Classes <sup>B)</sup>
			Description (Rock: Amphibolite)	Project Classes	
Top soil		Influenced also by bioturbation and climate (changes).			
VI Residual Soil	discoloured rock	All rock material converted to soilstructure and fabric destroyed	Reddish Brown Clay variable lateritization stage, typical depth 0-4m	WVI	IA
V Compl. Weathered	decomposed rock	All rock material decomposed and/or disintegrated to soil. Original mass structure still largely intact	Pale pink clay/silt, ferruginous, relic minerals and structures, typical depth 4-20m	WV	IB
			Pale greenish yellow silt/clay with fine sand, relic miner. and struct., typical depth 20-30m		IC
IV Highly weathered		>50% rock material decomposed and/or disintegrated. Fresh/dicoloured rock present as discontinuous framework or corestones	Brownish grey, coarse grained, weak strength	WIV/III	II A
III Moderat. Weathered		<50% rock material decomposed and/or disintegrated to soil. Fresh/dicoloured rock present, discontinuous framework or corestones	Grey, coarse grained, moderately strong/strong		
II Slightly weathered		Discoloration due to weathering of rock and discontinuity may weaker than fresh rock.	Dark grey, coarse grained, very strong, joint surfaces iron stained	WI/II	IIB
IB Faintly weath.		Discoloration on major discontinuity surfaces	Dark grey, coarse grained, very strong, joint surfaces fresh.		III
IA Fresh	Fresh rock	No visible spot of rock material weathering			

Notes:

<sup>A)</sup> Classification proposed by the Geological Society of London (Fookes, 1997)

<sup>B)</sup> Typical Weathering grades for Igneous and Metamorphic Rocks (Deere & Patton, 1971)

<sup>C)</sup> Highly weathered and moderately weathered are treated equally in terms of engineering properties; this was also done for WI/II.

Figure 1: Typical Lateritic Weathering Profile including Soil and Rock Classification corresponding to [12] [13] [20] and the applied Uganda Project Classification

This paper focuses on the residual soils, as a result of the lateritization process, which comprise zones IA and IB. Below the residual soil, horizons IC, IIA and IIB are composed of Saprolites and weathered rock formations. The transition takes place gradually, which leads to an inhomogeneous and indistinct stratification. Unweathered rock forms horizon III and is simultaneously the parent rock

material for the genesis of the lateritic clay [3]. The parent rock type is also important for the later engineering properties of the soils.

Lateritic soil profiles with a considerable depth (more than 20m) result from terrestrial weathering over long periods, even millions of years. The classified horizons for “IA, IB, IC” or “V/VI” (Figure 1, [12], [13]) may reach a few meters, whereas the whole weathering profile frequently results in a thickness exceeding 20m. Below the lateritic clay horizon further layers of moderately weathered and decomposed rock layers (Saprolites) are of varying thickness. The thickness can be similar to that of the soil horizon [4] or can exceed even depths of 100m as reported for Saprolite thicknesses in [5].

## Properties and Engineering Parameters

### General

Due to the variability of lateritic soils, laboratory and field tests can only provide a general “average” of the real in-situ properties. The determined values are generally more representative for the remolded and compacted soils used as construction material, than for the specific local situation of the residual soil. The description and definition of the engineering parameters and properties, are as difficult as the definition, nomination and classification of lateritic soils [6].

“The main difficulty in dealing with these soils for engineering purpose is that their characteristics are very different from those of transported soils” [3]. This is also based on the particular structure and fabric that differs from those of transported and/or remolded, compacted soils.

In [6] it is explicitly stated that the color does not need to be a proper criterion for engineering classification since soils with different colors may have the same engineering properties. Although, the different soils may be correctly classified according to soil and rock classification systems. Examples are Ferralsols (red, yellow) and Andosols (brown, yellowish brown). The latter can also exhibit a reddish color. Due to difficulties in engineering classification and a wide variety of engineering parameters and properties, geotechnical and civil engineers frequently still consider the “red lateritic clays” as “problem soils” and “troublesome” when encountered on site [6]. However, an early awareness may help to avoid mistakes and misinterpretation and may lead to a correct and cautious handling of this “Red Earth”.

### Case Studies: Laos and Uganda

In Laos, Fichtner was contracted to evaluate the technical and economical feasibility of a 120MW hydropower plant located at a tributary to the Mekong River, close to the borders with Myanmar and China, in the Northern part of the country. For this study, a geotechnical field investigation campaign was performed by a local contractor. Different dam types, e.g. 140m high rockfill and RCC dams, were considered at different locations. All along the corresponding section of the

river, the potential abutments were covered by residual soils with 40m to 60m thickness in the upper slope regions. The soil could generally be identified as tropical lateritic clay. The color typically changed from reddish to yellowish. At the riverbed itself fresh rock was encountered. The parent rock is an Andesite.

In Uganda, a 250MW hydropower project is under construction on the Nile River. Fichtner is the Design Engineer of the EPC contractor. The HEPP is a combined structure consisting of three embankment dams, a gravity dam, two different concrete spillway structures and a powerhouse. All three embankment dams are zoned rockfill dams with a total length of more than 500m and a maximum height of approximately 35m. The rockfill dams are all designed with a clay core. Both abutments and parts of the foundation are covered by lateritic soils (clay) under which Saprolite of more than 10m thickness is

found. Although a comprehensive field and laboratory investigation program was carried out starting in the mid-1980s, the engineering properties and design parameters of the rock foundation, of the residual soil, and of the core fill material (residual clay soil) left considerable room for interpretation. The parent rocks of the lateritic soil were dominantly Amphibolites but also some schist.

### Index Properties

Corresponding to statements in literature, e.g. [6], [24], [25], lateritic or residual soils have a wide spread

variability regarding their engineering properties. This is also documented by the liquid limit (LL) and the plasticity index (PI). In Figure 2, several residual soils, mainly lateritic clays, are presented referring to literature, applying literature data, project archive data and data of the two recent case studies in Laos and Uganda. According to [7] clays consisting mainly

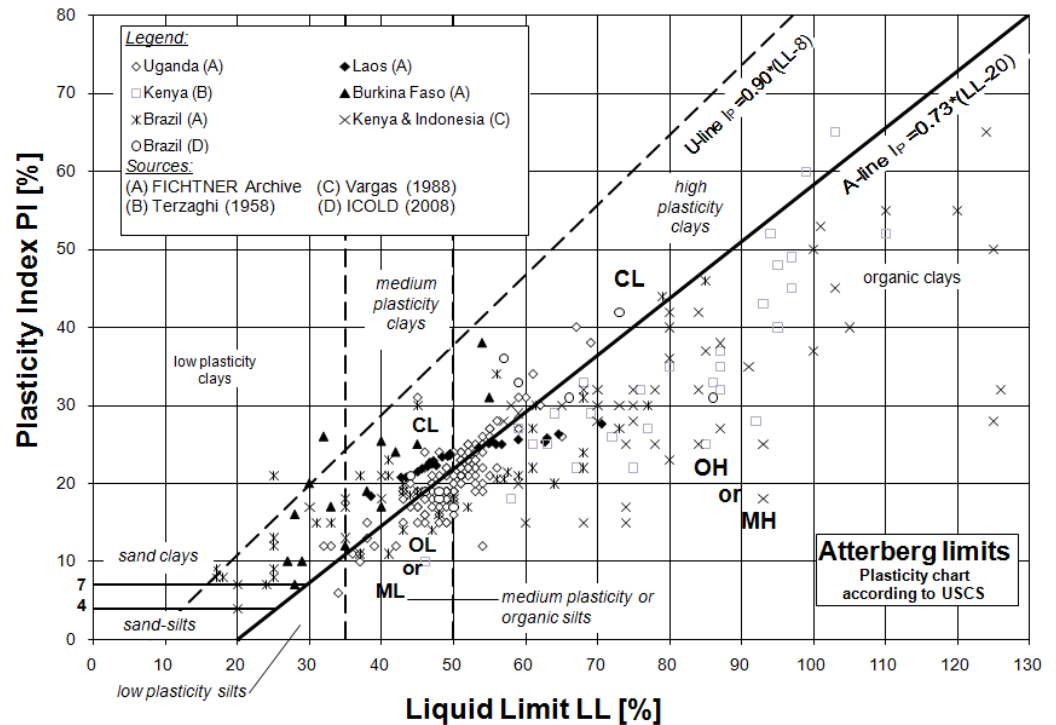


Figure 2: Casagrande diagram for various lateritic soils (according to [3], [18] and [22])

### Notes:

- A) The lateritic soil of Uganda encountered to significant gradation ranges.
- B) The upper limit of Burkina Faso Clay is also the upper limit of the Laos clay.

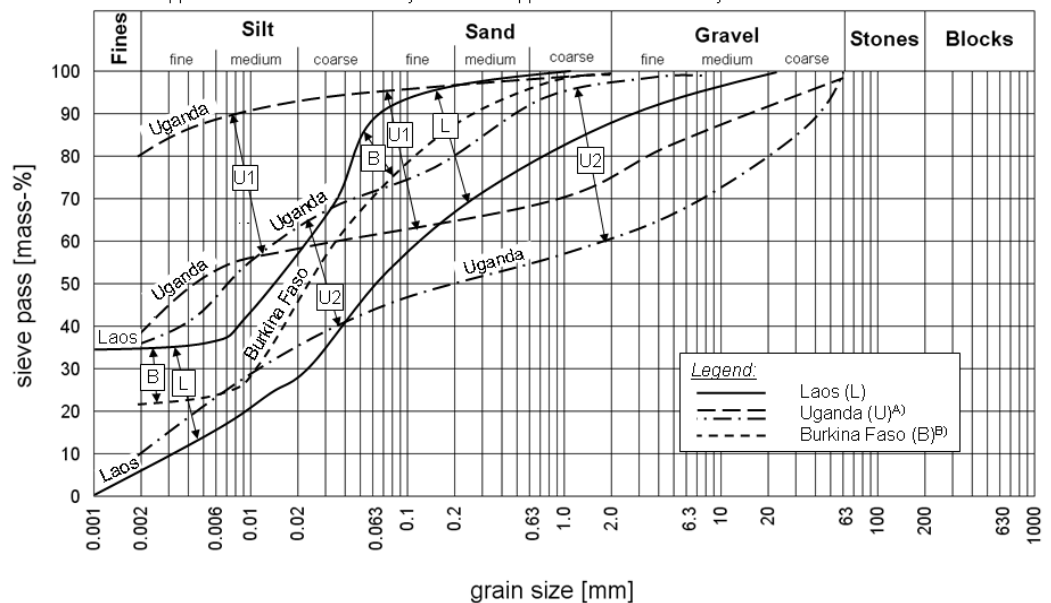


Figure 3: Sieve curves for lateritic soils

of Kaolinites are generally located below the A-line in Figure 2. Also [20] states that lateritic soils are clays, sandy clays and gravelly sandy clays which usually plot below the A-line. It should be noted that the accuracy of laboratory tests depends crucially on the pretreatment of the specimen, and on the testing procedure [3], [6]. Soil index test results are typical and stand for the general variability of engineering properties of lateritic clay soils. The lateritic clay as found at the Uganda site is rather stiff having a  $c_u$ -value (undrained, unconsolidated) of  $c_u = 50\text{kPa}$ . The index properties show that this lateritic clay could be classified as CL to OL according to USCS.

In Laos, the investigated soil samples were limited to 24 tests of remolded and undisturbed samples which indicate a possible classification as CL according to USCS.

### Composition & Geotechnical Parameters

This paper contributes to a discussion of lateritic clay/silt soils as one type of residual soil derived from different parent rocks. Only the highly clayey strata of the lateritic profile are included. Therefore, the soils for which the grading was studied will always have a percentage of fines above 40% as shown in Figure 3. In literature the range of investigated lateritic soils varies from lateritic coarse gravel size, to high plasticity clay as indicated by the data in Figure 2.

The soils encountered in Uganda and Laos had different gradings as shown in Figure 3. In Laos a clayey-silty soil was found, whereas in Uganda the lateritic soil has a relatively wider grading. A definite separation of the ranges was not possible regarding both strata depth and sample site.

The occurrence of hard residual boulders [24] embedded in a relatively weak soil and rock matrix is also encountered in lateritic profiles.

In Table 1 selected engineering parameters for lateritic soils are listed, together with a general range of values typically found. The range of values found in the two case studies are also presented.

The permeability of lateritic soils is dependent on several factors. However, it is clearly related to the weathering process and its products. Under specific conditions pseudo-sands may occur. These will naturally result in high permeabilities, even if a corresponding clay fraction is present. The lateritic soil genesis tends to form layers of high permeability below the surface clay layer. This was observed on-site in Uganda, where high water losses were seen both during drilling and during in-situ water pressure tests. High permeability layers, mostly located within the Saprolitic subsoil area, have also been documented in [3] and [20]. In general, the permeability of lateritic soils lies within a range of  $k = 10^{-4}\text{m/s}$  to  $10^{-11}\text{m/s}$  whereas [20] also mentions maximum permeabilities of  $k = 10^{-2}\text{m/s}$  in the Saprolite zones where a vertical joint system usually prevails. Laboratory tests of clays may also lead to lower values than encountered in Uganda, also referring to [16] for laboratory tests for a clay core in Indonesia. In Laos the range of values was found

to vary from  $k = 10^{-4}$  to  $10^{-7}\text{m/s}$ . If lateritic clay is used as core material, the final in-situ permeabilities are one to three orders of magnitude higher than indicated by laboratory testing. However, "typical values of permeability can be problematic and misleading" [3] since local fabric may be completely different from laboratory conditions. In [3] it is also warned to give attention to the IC and IIA horizons in respect to eventual piping development due to high permeability and low stability in these strata.

A few results of consolidation tests on the Uganda soils indicated a possibility of collapsibility when saturated. Collapsible soils are usually found among deposit soils or in residual soils resulting from specific dry weathering processes. Generally, for in-situ weathered soils a "lack of information on the collapse mechanism" has to be stated [8]. In general, a low bulk density and a low percentage of fines (percentage of particles retained by No. 200 sieve) are crucial parameters for the collapsibility of soils [9], [17].

TABLE 1: SELECTED SOIL AND ENGINEERING PARAMETERS OF LATERITIC SOILS

Parameter	Unit	General Range	Laos	Uganda
Permeability $k_{\text{Sat}}$	m/s	$10^{-2}$ - $10^{-11}$	$10^{-4}$ - $10^{-7}$	$10^{-4}$ - $10^{-9}$
Permeability Lugeon	Lu	>2	4-30	2-30
Unit Weight $\gamma$	kN/m <sup>3</sup>	14-22	15-18	16-22
Porosity n	%	25-60	45-54	26-46
Liquid Limit LL	%	>25	38-50	32-69
Plasticity Index PI	%	5-65	20-26	6-40
Fines Content	%	10-100	50-90	13-98
OWC	%	10-35	20-32	14-32
Depth of Bed. Rock (WIII-IV)	[m]	~6-50	~50	~30

Experience has shown that the residual moisture content of lateritic clays can be relatively high and may reach the optimum moisture content (OMC), as determined in the Proctor test. Therefore, the soil can often be used as fill material with minimal requirement for moisture conditioning (drying or watering). Investigations presented in [24] confirm that compaction on the wet side of OMC will most likely result in the lowest permeabilities.

The determination of reliable design shear strength parameters has to consider the calculation tools, programs and methods applied for the stability analysis as well as the characteristics and properties of construction materials and

foundation layers, whilst paying attention to the predicted stress range, stress-deformation behavior and the foreseen degree of protection of the dam structure. Some values for shear strength parameters are given in Table 2 [3], [25].

TABLE 2: SHEAR STRENGTH PARAMETERS OF LATERITIC SOILS

Soil Characteristic	Cohesion [kN/m <sup>2</sup> ]		Friction Angle [°]	
General Range				
Peak	c'	0-25	φ'	5-37
Uganda <sup>C)</sup>				
Peak	c'	15	φ'	25
Undrained	c <sub>U</sub>	50 <sup>B)</sup>	φ <sub>U</sub>	0 <sup>A)</sup>
Residual	c <sub>R</sub>	0 <sup>A)</sup>	φ <sub>R</sub>	23
Laos				
Peak	c'	24	φ'	17
Undrained	c <sub>U</sub>	30 <sup>B)</sup>	φ <sub>U</sub>	(18) <sup>A)B)</sup>

**Notes:**

- <sup>A)</sup> Set to “Zero” due to safety aspects.
- <sup>B)</sup> Applying full excess pore water pressures, the undrained cohesion c<sub>u</sub> and the undrained friction angle φ<sub>u</sub> = 0° is one conservative method to evaluate the stability during consolidation phase.
- <sup>C)</sup> Due to safety aspects the same shear strength parameters were applied both for the clay core and the residual soil, although higher values would have been justified for the clay core.

Usually, the 2/3-rule or the 1/2-rule are applicable methods for the determination of reliable shear strength parameters [23] in terms of preparing a safe and economical design.

### Consolidation of Lateritic Soils Used for a Zoned Rockfill Dam and Its Foundation

**General**

The stability of embankment dams and related structures that are founded on residual soils is affected by the development of excess pore water pressures since lateritic clays may exhibit impermeable, highly compressible properties. Although, the typical fabric of in-situ weathered soils support a fast and smooth pore water pressure dissipation by their joint system, excess pore water pressure will be encountered in both compacted clay cores or in clay foundation layers. The excess pore water pressure behavior is particularly important for the End of Construction (EoC), eventually also for the First Impoundment (FI), if impoundment takes place more or less immediately after EoC and the consolidation process is still going on, as well as for Rapid Reservoir Drawdown.

A combined 2D FEM seepage and stress-deformation model can be applied for modeling. However, in many cases the efforts for the preparation of a corresponding model will not be justified since it does not generate better or more reliable results compared to simple analytical approaches because of

both the varying work conditions and the inhomogeneity of the material. Thus, the application of a simplified 1D pore water pressure model was considered to be justified for the Uganda project. Here, the calculated excess pore water pressure during EoC and during FI were input data for the stability analysis considering effective stresses. The predicted pore water pressures were considered by B-bar-values in the stability analysis according to [19]. In Equation (1) the B-bar is defined.

$$\bar{B} = \frac{\Delta u}{\Delta \sigma_1} = B \cdot \left[ \frac{\Delta \sigma_3}{\Delta \sigma_1} + A \cdot \left( 1 - \frac{\Delta \sigma_3}{\Delta \sigma_1} \right) \right] \quad (1)$$

The B-bar-value [-] is derived from the quotient of the pore water pressure changes Δu [kPa] and the changes of the major principal stress Δσ<sub>1</sub> [kPa]. The B-value reflects the pore water pressure change Δu with regard to the change of the minor principal stress Δσ<sub>3</sub> [kPa] during triaxial testing. For common saturated soils the B-value is usually equal to 1.0, consequently the B-bar-value is a function of the major and minor principal stresses and the parameter A [-] which considers the (over)consolidation condition according to [27]. Several authors investigated the pore water pressure behavior of soils and, therefore, gave hints for values of the parameters A and B [13], [19], [20], [27]. Generally, it has to be noted “that it is difficult to predict the pore pressure response with any degree of accuracy” [21] and the described method and results can only reflect a rough estimation of the actual in-situ conditions.

**Simplified 1D Approach**

The simplified consolidation/pore water dissipation 1D-model was applied in order to estimate potential excess pore water pressures in the lateritic core and the residual soil foundation. The applied approach is based on Terzaghi’s consolidation theory [14] and on simplifications made for typical rockfill dam designs as described in [15]. For this approach, it is necessary to know the consolidation coefficient c<sub>v</sub>, the rate of construction, and the thickness and number of compacted layers. Firstly, the drainage path length and, finally, the excess pore water pressures are determined. For this purpose the modeled layer thickness, the number of modeled layers, and the time steps must be defined. The approach of [15] postulates that the consolidation process reacts similarly to the pore water pressure dissipation behavior (Figure 4).

**Results**

The results are shown in Figure 4 where the pore water pressure coefficients are plotted versus the considered consolidation coefficients. The results were approximately similar for the core and for the foundation layer, consequently it is applicable to summarize the results in one plot. Curves were prepared for three different rates of construction. The curves reflect the average values for varying dam/core heights and foundation thicknesses.

The applied model also enabled an estimation for further dissipation after EoC and for the continuing consolidation process. For the load case FI the pore water pressures in the foundation are predicted to be already reduced to 10% of maximum at EoC, whereas in the core still 40-80% of the maximum calculated excess pore water pressures are still effective.

Almost full pore water pressures are reached for consolidation coefficients  $c_v < 10^{-7} \text{m}^2/\text{s}$ . Otherwise, for  $c_v > 10^{-4} \text{m}^2/\text{s}$  no remarkable excess pore water pressures have to be expected. Therefore, the consolidation coefficient derived from soil tests, may be one applicable indicator as to whether significant excess pore water pressure may occur within a dam structure under consideration.

## Conclusion

Lateritic clay soils do have a wide range of engineering parameters and accordingly show also a wide range regarding their geotechnical behavior due to their specific composition and genesis. Due to the observed and documented variation of parameters and properties, a comprehensive investigation campaign consisting of both field and laboratory tests must be carried out in order to determine reliable design soil properties and parameters.

Regarding the specific boundary constraints of the Uganda project, average pore water pressure coefficients (B-bar-values) were deduced from a simple analytical 1D approach. B-bar-values of 40% to 65% for both the core and the foundation layer were applied in terms of load cases regarding unconsolidated states, e.g. End of Construction. Although, site specific data was considered the deduced results, particularly the curves in Figure 4, would seem to be universally applicable for approximate estimations of pore water pressure development for similar projects. Comparison with documented case studies [21] [26] confirm this statement since the final results would seem to be sufficiently accurate, and not “excessively” conservative. Nevertheless, a project specific evaluation of the pore water pressure development should be performed when the detailed design and construction phases start.

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