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

A. Ronald Haselsteiner[1], B. Hans-Georg Schuetz[1], C. Cristian Osan[1] and D. Björn Somdalen[1]

[1] Fichtner GmbH & Co. KG, Renewable Energies & Environment, Sarweystraße 3, 70191 Stuttgart

E-mail: ronald.haselsteiner@fichtner.de

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. For example, rockfill dams will often require to be founded on relatively strong rock. Usually, the lateritic clay is a favorable core material for embankment dams. If a concrete dam type, e.g. an RCC dam, is chosen, the clayey overburden layers will usually have to be removed in order to provide suitable foundation conditions. The excavation should then, ideally reach unweathered rock formations.

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. One of the case studies is for a hydropower project in Uganda, where embankment dams are partly placed on residual lateritic soils, and where the lateritic soil in the form of clay, is also used for the core material. The other case study is a project in Laos, where a soil investigation program was carried out as part of a feasibility study for a hydropower project. In the latter case the abutments were covered by lateritic clays of considerable thickness.

The particular in-situ conditions complicate the task of deriving comprehensive data from laboratory testing. Both relevant site experience and an extensive (critical) analysis of test results have to be combined, in order to find applicable soil parameters.

According to [20], in the case of lateritic soil several aspects need to be questioned and discussed regarding the probability of existing sink holes, the fabric and texture of the in-situ weathered lateritic soil, the suitability as clay core fill material and the in-situ permeabilities.

The Occurrence and Genesis of Lateritic Soils

Definition and 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. Consequently, in

literature, and particularly in engineering practice, different classifications and nomenclature will be found. Even a mix-up with similar soil types, e. g. Acrisols or Andosols, cannot be excluded. 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”. This supports the thesis that not all “laterite” soils in literature were, in fact, what they were assumed to be. The transition to other soil types is gradual. 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. Ferralsols have several subclasses, e. g. plinthic, red or yellow ferrallitic Latosols [5]. Some sources propose “combined charts of Casagrande's plasticity and Skempton's activity chart for identification of fine-grained tropical soils” [18].
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]. Andosols and Vertisols are also residual soils which may have similar properties to red clays and are discussed in [3]. The transition from a Ferralsol (red clay) to an Andosol is smooth regarding their engineering properties, their composition and their occurrence. According to [6] “Red Tropical Clays” may be Ferciallitic 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.
Ref [3] proposes a classification of residual soils based on a consideration of their mineralogical influence. The problems of using classical, existing classification systems are complex and may be summarized as follows [3]:

1. Laboratory tests may be misleading due to the particular importance of the in-situ structure of lateritic soils.
2. Existing classification systems were not established for tropical in-situ formed residual soils but mainly for transported and remolded soils.
3. Existing correlations and empirical relationships describing engineering parameters may not be valid for residual soils.

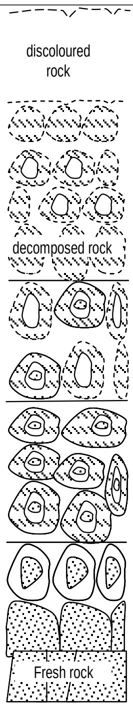
In order to gain representative soil and rock samples the method of sampling, the treatment of the samples and, of course, the number and the origin of samples play an important role in providing a reliable data basis for the engineering properties [3] [6]. With increasing depth the samples are less representative due to larger heterogeneity as result of the in-situ weathering process [3].

Occurrence
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]. Generally 20% of the recent tropical soils are Ferralsols [4]. On old terrestric land masses, relic soils are most likely to occur as Ferralsols which are considered to be typical for perpetual wet climates. In Europe lateritic soils are originated from the palaeozoic era and occur e.g. at the Vogelsberg in Germany.

Genesis
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”. In addition, biological weathering processes can also have an effect on the soil genesis [3].
Particularly, the chemical reactions that are supported by all types of weathering processes are responsible for the removal of silica and bases, and for the concentration of iron and aluminum oxides. These elements are responsible for the soil color. The lateritic clays are most likely consisting of Kaolonite or Halloysites, Smectites and Allophane at an earlier weathering stage [5] [6]. Under humid climate conditions a Kaolonite may undergo alteration to a Gibbsite.
The presence of cracks, fissures and joints in the parent rock results in infiltration of water and transportation of dissolved parts caused by chemical weathering. Local inhomogeneity will also result in a corresponding weathering pattern.
Lateritic soils result from all types of rocks, either igneous, metamorphic, or sedimentary rocks [24]. “Sandstones and granites are the most common rocks subject to lateritization” [3]. In literature this process is also called “ferralization”.

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).
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.
Corresponding to the lateritization process, the fabric and structure is usually dominated by the weathering process and genesis. For example, the laterite weathering profile in Uganda exhibited steeply inclined, almost vertical joints and fissures.
The soil and rock classification tends to be difficult to apply in practice, due to the gradual transition. Zones (I) and (VI) are relatively easy to identify, but classification of the intermediate zones is more problematic. The correct classification of upper zones III to V is often important for the determination of an appropriate foundation depth. For these strata, the assumed engineering design parameters will have to be guaranteed which can only be assured by a competent and experienced site supervision.

Classes A)	Weathering Profile A)	Description A)	Fichtner (Uganda) – Classification C)		Classes B)
			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/discolored 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/discolored 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.	Fresh rock	Discoloration on major discontinuity surfaces	Dark grey, coarse grained, very strong, joint surfaces fresh.		III
IA Fresh		No visible spot of rock material weathering			

Notes:
A) Classification proposed by the Geological Society of London (Fookes, 1997)
B) Typical Weathering grades for Igneous and Metamorphic Rocks (Deere & Patton, 1971)
C) 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

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.
Due to the weak texture lateritic soils are subject to superficial erosion after topsoil stripping like other unprotected soils. In this context, it is noted that Plinthosols, a subclass of Ferralsols, have hydromorphic properties and therefore have to be treated with appropriate care if used for foundation or for fill material.
In [5] the occurrence of "slickensides" in tropical residual soils is also mentioned. "Slickenside" surfaces are sliding surfaces that generate from processes where high stresses caused a rectification of the clay minerals. This results in predefined slip surfaces within the soil, having effective shear strength values significantly lower than the corresponding average shear strength of the soil complex.
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. From the project experience it can be stated that the problems related to classification of the soils and their engineering properties can be considered to be typical for lateritic soils. 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. However, the involved engineering parties representing the Owner, the Design Engineer, the Contractor, the Check Consultants and the Dam Safety Panel reached an agreement on the engineering parameters after an extensive evaluation and specific additional laboratory tests carried out in Europe. The design parameters both allow a technically safe and economical design. The parent rocks of the lateritic soil were dominantly Amphibolites but also some schist (see also Figure 1).

Index Properties and Consistency

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 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. The same is valid for clays consisting of Halloysites. However, the given Casagrande diagram also shows that a considerable number of soils with LL < 60% are located above the A-line. The Andosols may plot in this area, too..

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 = 50kPa. The index properties show that this lateritic clay could be classified as CL to OL according to USCS.

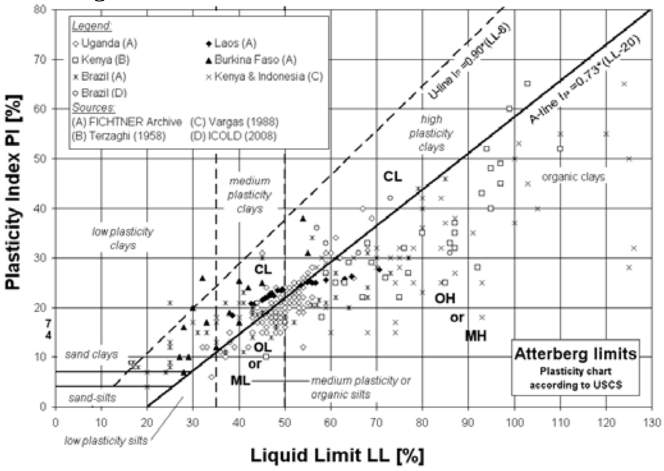


Figure 2: Casagrande diagram for various lateritic soils (according to [3], [18] and [22])

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.

A detailed discussion of the soil indices of residual soils is given in [3]. A-line plots for red clays are also given in [6], differentiated by their parent rock types. Younger quaternary parent rock types seem to generate rather plastic silts. However, the parent rock type is only one aspect that influences the genesis of lateritic soils, particularly of its clay minerals.

Composition of Lateritic Soils

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. The grading diagram clearly shows two ranges. However, 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. Evidently a significant number of boulders may provoke difficulties with regard to the subsoil treatment. Attention has to be paid to this aspect since special construction methods and/or the combination of different techniques, e.g. jet grouting, cutoff walls and conventional grouting, may be necessary to reach a successful result.

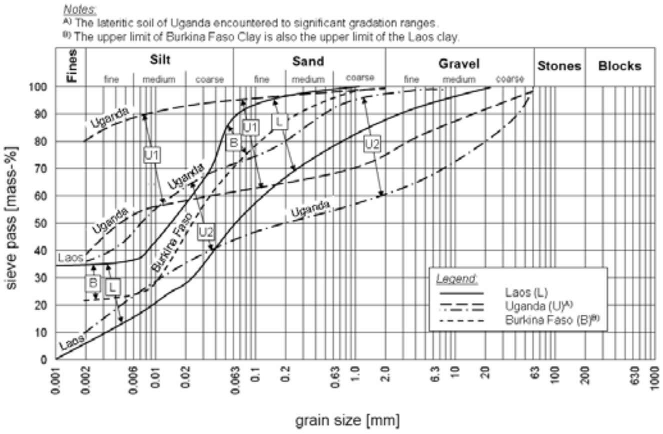


Figure 3: Sieve curves for lateritic soils

Other Geotechnical Parameters and Behaviour

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.

TABLE 1: SELECTED SOIL AND ENGINEERING PARAMETERS OF LATERITIC SOILS

Parameter	Unit	General Range	Laos	Uganda
Permeability k_{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 γ	kN/m³	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

For the design of embankment dams, the stress-deformation behavior, seepage conditions, and slope stability are particularly important considerations. The shear strength parameters will be discussed in the next paragraph.

As expected, the actual site data from the two case studies, fall within limits typically found for lateritic soils.

The permeability of lateritic soils is dependant 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 $k = 10^{-4}$m/s to 10^{-11}m/s whereas [20] also mentions maximum permeabilities of $k = 10^{-2}$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}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 Oedemeter 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 [8], a Brazilian Oxisol was investigated considering its collapsibility. The collapse potential of tropical residual soils is also discussed in [3]. 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]. An interpretation of the findings in [17] leads to the conclusion that soils with a bulk density of more than 14kN/m³ and a percentage of at least 70% fines can be considered as not collapsible. The collapsibility can be classified by its collapse potential according to [9]. The impact of collapse processes should be assessed in terms of their impact on the stability and durability of the structures. For embankment dam structures, collapsibility in the foundation may cause sink holes and/or considerable settlements with subsequent cracking. In addition, a corresponding piping process may be initiated.

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). In many cases, however, the tropical dry climate and high precipitation will result in variable in-situ moisture contents, and continual adjustment of the work process will be necessary, in order to achieve the required moisture content. This is clearly of importance during construction, as a smooth and efficient construction process is necessary in order to achieve the required fill quantities, the required rate of construction, and the required quality. Investigations presented in [24] confirm that compaction on the wet side of OMC will most likely result in the lowest permeabilities, whereas compaction dry of optimum can result in permeabilities of one magnitude higher.

Shear Strength Parameters

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.

TABLE 2: SHEAR STRENGTH PARAMETERS OF LATERITIC SOILS

Soil Characteristic	Cohesion [kN/m²]		Friction Angle [°]	
General Range				
Peak	c’	0-25	φ’	5-37
Uganda[C)]				
Peak	c’	15	φ’	25
Undrained	c_U	50[B)]	φ_U	0[A)]
Residual	c_R	0[A)]	φ_R	23
Laos				
Peak	c’	24	φ’	17
Undrained	c_U	30[B)]	φ_U	(18)[A)B)]

Notes:

A) Set to “Zero” due to safety aspects.

B) Applying full excess pore water pressures, the undrained cohesion c_u and the undrained friction angle $\varphi_u = 0°$ is one conservative method to evaluate the stability during consolidation phase.

C) 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.

The strength behavior of compacted lateritic soils for unsaturated conditions is discussed in [25]. Usually, shear strength parameters increase in unsaturated soils due to matric suction which is usually neglected providing a conservative design approach.

The choice and determination of the shear strength parameters of lateritic soils, especially of impervious soils, may be a scientific work since laboratory and in-situ testing are susceptible to be misleading and a time wasting process [3]. Therefore, simple and reliable methods should prevail hand in hand with an appropriate design in order to cover all possible uncertainties. Thus, the given shear strength values of lateritic clay soils are only shown to provide a general indication.

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. That means that at least 2/3 or 1/2 of the test result plots should be plotted above a selected design curve or values.

Compacted clay cores usually exhibit stronger shear behavior than residual in-situ soils. Residual lateritic soils in which the structure of fracture planes still remains have in several cases shown an agglomeration of certain minerals, e.g. Hematite, at the upper part of former vertical joints. For existing planes very low values for the friction angles φ’ = 5-7° (with c’ = 0kN/m^2) has been encountered also due to predefined slip surfaces with Hematite agglomeration or from planes reported as “slickensides”.

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 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. Liquefaction during seismic events due to high pore water pressures usually plays a subordinate role since lateritic clays have a considerable percentage of fines which withstand also critical pore water pressures, e.g. caused by dynamic loads.

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, both the additional soil testing and dam monitoring in order to determine the real embankment behavior for the later verification of the numerical model, do not seem appropriate, eventually wasting both planning resources and time. For small rockfill dams the deformation behavior usually plays a subordinate role. 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.

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

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 $\Delta\sigma_1$ [kPa]. The B-value reflects the pore water pressure change Δu with regard to the change of the minor principal stress $\Delta\sigma_3$ [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].

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 the performed estimation of the pore water pressure dissipation Curve No. 1 (see [15]) was considered to be representative for a zoned rockfill dam with a central clay core (Figure 4).

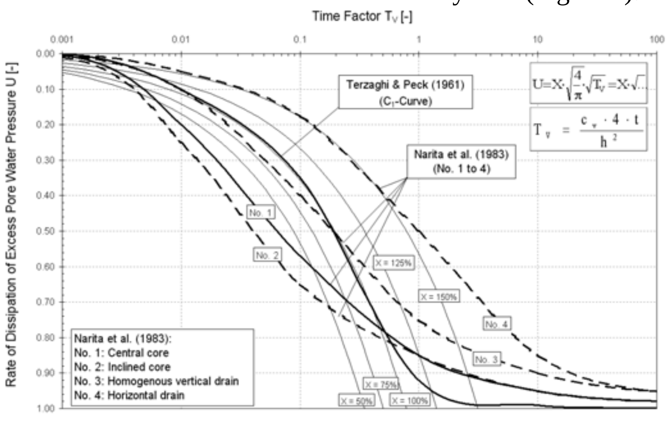


Figure 4: Pore water pressure dissipation/consolidation curves (according to [14] and [15])

For this approach, it is necessary to know the consolidation coefficient c_V, 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).

The rates of construction for the Uganda rockfill dams were assumed to be between 0.15m/d and 0.30m/d as given in the construction schedule. The consolidation coefficient values ranged from $c_v = 10^{-7}$ to 10^{-9}m²/s according to laboratory tests. The thickness of the residual soil at the considered critical sections varied from 5m to 20m, the core height was assumed to reach a maximum of 35m and the core width a maximum of 25m at the foundation.

Results

The results are shown in Figure 5 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.

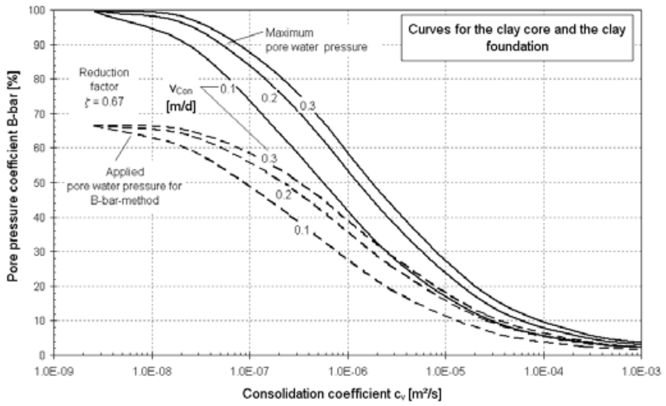


Figure 5: Calculation example for the pore water pressure coefficient (B-bar) versus the consolidation coefficient for different rates of construction

The excess pore water pressures were implemented in the stability analysis by constant B-bar-values for each modeled soil zone. Since this is also a rough approximation of the real pore water pressure conditions and this approach tends to overestimate the real conditions, curves were multiplied by 2/3 assuming a parabolic pore water pressure distribution along the slip surface.

The curves shown in Figure 5 were analyzed for EoC. The applied model also enabled an estimation for further dissipation after EoC and for the continuing consolidation process. In this case, the pore water pressures in the relatively thin foundation layer are likely to dissipate faster than in the core. 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.

Figure 5 shows also that almost full pore water pressures are reached for consolidation coefficients $c_V < 10^{-7}$m²/s. Otherwise, for $c_V > 10^{-4}$m²/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.

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.

To underline the high variation of the pore water pressures occurring in the foundation, Figure 6 shows an evaluation of the pore water pressure coefficient for different lateritic clay foundation thicknesses. The figure also considers different embankment construction periods T_{Con} for the load case End of Construction. As expected, pore water pressures exhibit higher values for shorter construction periods. Also, thin subsoil layers < 2m encounter only maximum 30% of the overburden stress in terms of applied conditions, particularly the selected consolidation coefficient $c_V = 2.6\ 10^{-6}$m²/s. Although, Figure 6 reflects a rough estimation, the deduced curves should be universally valid for described boundary constraints of typical embankment dams founded on corresponding foundation soils.

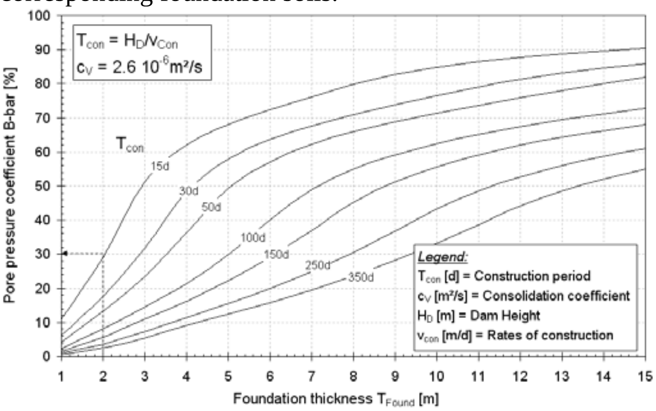


Figure 6: Calculated pore water pressure coefficient (B-bar-value) for residual soil layers of varying thicknesses beneath embankment dams at End of Construction

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. Although this paper provides a brief overview of typical engineering parameters and properties of lateritic clay soils, engineers have to refrain from a generalized application and from transferring results and interpretations from one to another project, also if only little differences are expected. 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 5 and Figure 6, 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.

In such cases, simple estimation methods generate satisfactory results since the precise prediction of excess pore water pressures is difficult and may be misleading due to the sensitivity of the influencing factors, soil parameters and local particularities. However, corresponding control measurements should be performed during construction.

Although more and more embankment dams are built with, and on, lateritic clays and the experience and knowledge has increased considerably over the last decades, the tasks, engineering aspects and requirements should not be underestimated. Uncertainties in predicting excess pore water pressures and effective shear strength values can have a serious impact on the progress of a project, even if major failure processes can be predicted and avoided during the design and construction phase. With regard to the rate of construction, the removal of impermeable foundation layers which may be causing concern, may be preferable to applying a sophisticated analysis and design, in order to avoid critical excess pore water pressures, even at the expense of slightly increased fill quantities. Lateritic clays can be ideal clay core materials, exhibiting satisfactory shear strength and low permeability characteristics. However, as with all earthfill placement, water content must be carefully controlled in order to ensure acceptable quality, whilst achieving the required rates of construction.

Acknowledgements

Fichtner would like to thank all its Employers for the permission to use the applied project data.

References

[1] Ganssen, R. (1965): *Grundsätze der Bodenbildung.* Hochschultaschenbücher, Bibliographisches Institut, Mannheim

[2] Glaser, B. (2005): *Böden und Landnutzung in den humiden Tropen – Ferralsole (FR).* Department of Soil Physics, University Bayreuth

[3] ICOLD (2008): *Tropical Residual Soils As Dam Foundation and Fill Material.* ICOLD Committee on Material for Fill Dams, International Commission On Large Dams (ICOLD), ICOLD-Bulletin (Draft)

[4] Scheffer, F.; Schachtschnabel, P. (2002): *Lehrbuch der Bodenkunde.* 15. Auflage, Spektrum Akademischer Verlag, Heidelberg

[5] Kuntze, H.; Roeschmann, G.; Schwerdtfeger, G. (1994): *Bodenkunde.* 5., neu bearbeitete und erweiterte Auflage, Verlag Eugen Ulmer, Stuttgart

[6] Northmore, K. J.; Culshaw, M. G.; Hobbs, P. R. N.; Hallam, J. R.; Entwisle, D. C. (1992): *Engineering Geology of Tropical Red Clay Soils – Summary Findings and Their Application for Engineering Purposes.* Technical Report WN/93/15, Overseas Development Administration (ODA) & British Geological Survey (BGS), Nottingham

[7] Day, R. W. (2000): Geotechnical *Engineer's Portable Handbook*. McGraw-Hill, New York

[8] Galvao, T. C. de Brito; Schulze, D. G. (1996): *Mineralogical Properties of a Collapsible Lateritic Soil from Mias Gerais, Brazil*. Soil Sci. Am. J., 60, pp. 1969–1978

[9] ASTM 5333-03: *Standard Test method for Measurement of Collapse Potential of Soils.* American Society for Testing and Materials, Annual Book of ASTM Standards 2007, Volume 04.08, Baltimore, USA

[10] Wesley, L. D.; Irfan, T. Y. (1997): *Classification of Residual Soils. Mechanics of Residual Soils.* Editor: G. E. Blight, A.A., pp. 17-30

[11] Dumbleton, M. J.; Newill, D. (1962): *A study of properties of 19 tropical clay soils and the relation of these properties with the mineralogical constitution of these soils*. British Road Research Laboratory, Note 44

[12] Fookes, P. G. (1997): *Tropical Residual Soils*. The Geological Society, London

[13] Deere, U.; Patton, F. D. (1971): *Slope Stability in Residual Soils.* Proceedings 4th Pan-Am Conference Soil Mechanics Found. Eng. (San Juan, Puerto Rico), vol. 1, pp. 87-170

[14] Terzaghi, K.; Peck, R. B. (1961): *Die Bodenmechanik in der Baupraxis.* Springer-Verlag, Berlin Göttingen Heidelberg

[15] Narita, K.; Okumura, T.; Murata, N.; Ohne, Y. (1983): *A simplified method of estimating construction pore pressures in earth dams.* Soils and Foundations, Japanese Society of Soil Mechanics and Foundation Engineering, vol. 23, no. 4, pp. 43-55

[16] Djarwadi, D.; Suhendro, D.; Hardiyatmo, H. C. (2004): *Engineering properties of kaolinitic clay as core as core of Batutegi dam*. New Developments in Dam Engineering. Editors: Wieland, Ren & Tan, Taylor & Francis Group, London

[17] Mock, R. G.; Pawlak, S. L. (1983): *Alluvial Fan Hazards at Glenwood Springs*. Geological Environment and Soil Properties, ASCE Conference Proceedings, Houston, Texas, October 17-21, 1983, pp. 221-233.

[18] Vargas, M. (1982): *Characterisation, identification and classification of tropical soils.* Proceedings of the 2nd International Conference on geomechanics in Tropical Soils, Singapore, A.A. Balkema, Rotterdam, vol. 2, pp. 469-487

[19] Skempton, A. W. (1954): *The pore pressure coefficients, A and B.* Geotechnique, Vol. 4, pp. 143-147.

[20] Fell, R.; MacGregor, P.; Stapledon, D.; Bell, G. (2005): *Geotechnical Engineering of Dams.* A. A. Balkema Publishers, Leiden London New York Philadelphia Singapore

[21] Hunter, G.; Fell, R.; Khalili, N. (2000): *The deformation Behaviour of Embankments on Soft Ground*. UNICIV Report No. R-391, University of New South Wales, Sydney 2052 Australia

[22] Terzaghi, K. (1958): *Design and performance of the Sasumua Dam*. Proceedings of the Institution of Civil Engineers, Harvard soil mechanics series, no. 55, pp. 369-394

[23] USSD (2007): *Strength of Materials for Embankment Dams*. White Paper, Committee on Materials for Embankment Dams, United States Society of Dams (USSD), Denver (USA)

[24] Nwaiwu, C. M. O.; Osinubi, K. J.; Afolayan, J. O. (2005): *Statistical Evaluation of the Hydraulic Conductivity of Compacted Lateritic Soil*. Geotechnical Testing Journal, Vol. 28, No. 6, pp. 586-595

[25] Mahalinga, U.; Williams, D. J. (1995): *Unsaturated strength behaviour of compacted lateritic soils*. Geotechnique, vol. 45, no. 2, pp. 317-320

[26] Li, C. Y. (1967): *Construction Pore Pressures in Three Earth Dams*. Journal of the Soil Mechanics and Foundations Division, Proceedings of the American Society of Civil Engineers (ASCE), March 1967

[27] Skempton, A. W.; Bjerrum, L. (1957): *A contribution to the settlement analysis of foundations on clay*. Geotechnique, vol. 7, no. 4, pp. 168-178