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CLAY SOIL - A HISTORY OF THEORETICAL APPROACHES TO STRENGTH AND THE WAY FORWARD

Photo by Stefan Els

CLAY SOIL – A HISTORY OF THEORETICAL APPROACHES TO STRENGTH AND THE WAY FORWARD

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AGENDA

- Introduction
- Tailings Storage Facilities
- Clay Properties and Technical Definitions
- Historical Advances in terms of Clay Strength
- Clay Strength Formulae and Empirical Correlations
- Case Study
- Conclusions
- References

CLAY SOIL – A HISTORY OF THEORETICAL APPROACHES TO STRENGTH AND THE WAY FORWARD

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INTRODUCTION

- Structural failures on clay soils date back to antiquity.
- TSFs being particularly vulnerable due to their frequent foundation on clay.
- Clay's shrink-swell behaviour, low strength, high compressibility, and settlement issues pose significant challenges.
- Site-specific geotechnical data is essential for TSF designs.
- Early design phases, limited funding for detailed geotechnical investigations.
- Empirical correlations based on clay consistency limits are often implemented.
- Empirical correlations are generally clay soil specific.
- Strength (ϕ' and s_u) variations observed for different empirical correlations.

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TAILINGS STORAGE FACILITIES

- TSFs rank among the largest engineered structures globally.
- TSF implementation often spans more than 50 years.
- *Global Tailings Portal* (2025) lists 2144 TSFs worldwide, including 233 in South Africa.
- TSFs are founded on diverse soil types, including clay soil.
- Limited site selection often necessitates foundations on clay soils.
- Numerous TSF failures have resulted in catastrophic consequences, including fatalities, environmental damage, and long-term soil and water contamination.

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TAILINGS STORAGE FACILITIES (CONTINUE)

- Cumulative fatality rates are estimated at six deaths per failure as of 2020.
- Lyu *et al*., (2019) attribute over 300 failures (1910–2018) to five root causes, being 1) earthquake (17.0%), 2) foundation failure (17.3%), 3) overtopping (20.6%), 4) seepage (21.6%), and 5) others (23.5%).
- These figures confirm foundation failure as a significant contributor to TSF instability.

Alonso, 2021

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CLAY PROPERTIES AND TECHNICAL DEFINITIONS

- Skempton (1985a) refers to Hubert Gautier who in 1717 stated that earth fills can be divided into three classes: sand, ordinary earth and clay.
- The old US Bureau of Soils (later part of the USDA) formally, specifically around 1899–1900, defined clay as particles smaller than 0.005 mm (5 μm) in diameter.
- USCS and BSCS indicate that clay soil consists of mineral particles smaller than 0.002 mm (2 μm).
- Clay's Atterberg (consistency) limits cause it to adhere when wet, become brittle when dry, and undergo substantial swelling and shrinking with moisture variations.
- Hogentogler (1937) describes clay as a fine-textured soil forming hard lumps or clods when dry.

Soil properties, after Gautier 1717

Fill material	Specific weight lb/cu.ft.	Natural slope	Permeability
Clean dry sand	115	31°	pervious
Ordinary earth	85	45°	pervious
Compacted clay			impervious

Skempton, 1985a

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CLAY PROPERTIES AND TECHNICAL DEFINITIONS (CONTINUE)

- Al-Ani and Sarapää (2008) define 'clay minerals' as phyllosilicates and minerals that impart plasticity to clay. They occur mainly in shales, the most common sedimentary rock.
- Common clay minerals include kaolinite, smectite, montmorillonite, illite, chlorite, vermiculite, and palygorskite, each with distinct structures and compositions.
- In geotechnical engineering, clay strength refers to a soil's ability to resist failure, including penetration and load-bearing capacity.
- Resistance to shear failure is defined by drained shear strength (c' and ϕ') for long-term loading and undrained shear strength (s_u or c_u) for short-term loading.
- Understanding both drained and undrained behaviour is essential for safe and effective geotechnical design.

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HISTORICAL ADVANCES IN TERMS OF CLAY STRENGTH

- Skempton (1985a) divides the period 1700–1927 into four major phases of geotechnical study, each providing foundational insights into clay behaviour.
- Pre-Classical period (1700–1776) - Focused on natural slopes, soil unit weights, and semi-empirical earth pressure theories.
- Classical soil mechanics Phase I period (1776–1856) - Saw major French contributions (Coulomb, Poncelet).
- Classical soil mechanics Phase II period (1856–1910) - Marked the start of experimental soil mechanics.
- Modern soil mechanics period (1910–1927) - Saw a shift towards clay soils, research identified clay properties, etc.

Das, 2013

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HISTORICAL ADVANCES IN TERMS OF CLAY STRENGTH (CONTINUE)

- The Post-1927 period - Marked significant advances in geotechnical engineering, transitioning from empirical to analytical approaches (Das, 2013).
- Karl von Terzaghi's, widely recognised as the 'father of geotechnical engineering' and 'father of soil mechanics', pioneering research on soil behaviour, clay settlement, and piping failure in sand beneath dams laid the foundation for modern geotechnical analysis.
- Skempton (1948) further addressed the $\phi = 0$ analysis of stability for saturated clays.
- Two further milestones between 1948 and 1960 were the Skempton (1954) A and B pore pressure parameters, enabling practical effective stress calculations, and the Bishop and Henkel (1957) influential book 'The Measurement of Soil Properties in the Triaxial Test'.
- Bishop *et al.*, (1960) also provided early guidance on factors controlling the strength of partially saturated cohesive soils, paving the way for unsaturated soil mechanics.
- Collectively, these developments refined understanding of drained shear strength (effective stress) and undrained shear strength (total stress), forming the analytical basis for safe and efficient geotechnical design.

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CLAY STRENGTH FORMULAE AND EMPIRICAL CORRELATIONS - DRAINED

- Empirical correlations are widely used in geotechnical engineering in conjunction with back-analyses to estimate soil/rock parameters, verify laboratory data, and validate slope failure analyses.
- They provide cost-effective initial estimates (e.g., using plasticity or SPT-N values) that are refined by back-calculating from observed performance.
- Early clay strength formulae, developed in the late 18th century, addressed *drained* shear strength only.
- In terms of drained shear strength, Coulomb (1776) established that shear strength (τ) is depended on normal stress (σ) and friction, proposing $\tau = \sigma \tan(\phi)$, where ϕ is the angle of internal friction.

Portrait by Hippolyte Lecomte (1894 copy)

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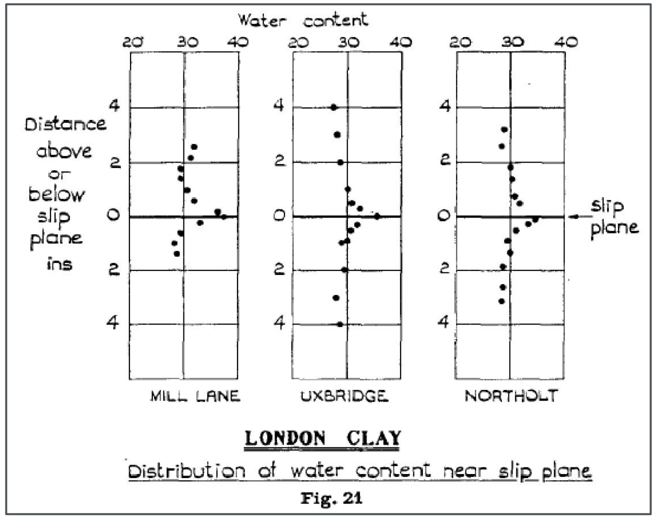
CLAY STRENGTH FORMULAE AND EMPIRICAL CORRELATIONS - DRAINED

- Mohr (1882) combined Coulomb's equation with the concept of cohesion (c), a material's inherent stickiness, to create the combined Mohr-Coulomb equation $\tau = c + \sigma \tan(\phi)$.
- Hvorslev (1937) shows that the strength (τ_f) could be expressed by equation $\tau_f = c_e + \sigma'_n \tan \phi_e$, where the 'true' cohesion (c_e) and 'true' angle of internal friction (ϕ_e), were parameters characterising the soil.
- Skempton (1964), fourth Rankine lecture, indicates that the shear strength (s) of a clay may be represented by the Coulomb-Terzaghi equation $s = c' + (\sigma - u) \tan \phi'$, where c' is the 'cohesion intercept' and ϕ' is the 'angle of shearing resistance', both parameters being expressed in terms of the effective stress $\sigma' = (\sigma - u)$ acting normal to the slip surface. As the clay is strained, so it builds up an increasing resistance.



Skempton, 1964

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CLAY STRENGTH FORMULAE AND EMPIRICAL CORRELATIONS - DRAINED

- Skempton (1985b) states that for slopes with pre-existing shear surfaces, residual drained strength should be used in stability analyses. In over-consolidated clays, post-peak strength reduction occurs in two stages: 1) at small displacements, strength falls to the 'fully softened' or 'critical state' value due to increased water content (dilatancy), and 2) at large displacements, strength drops to the residual value as clay minerals reorient parallel to the shear direction. In normally consolidated clays, strength reduction is solely due to particle reorientation.
- Stark and Eid (1997) confirm that the fully softened shear strength (ϕ_{fs}) is the appropriate strength to use for designing first-time slides in stiff fissured clays, and that this strength can be accurately predicted using empirical correlations based on the liquid limit (LL) and clay-size fraction (CF).

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CLAY STRENGTH FORMULAE AND EMPIRICAL CORRELATIONS - UNDRAINED

- Formulae for *undrained* strength emerged in the early 20th century, followed by empirical correlations based on Atterberg (consistency) limits.
- The undrained strength of a fine-grained soil is not an intrinsic material property but dependents on the state of the soil (as defined by *w*) and the stress level.
- Skempton and Golder (1948) address the 'ϕ = 0 analysis' for saturated clays under undrained conditions, where water content remains constant. This approach treats soil as purely cohesive, with zero friction angle, and evaluates stability using undrained shear strength (c_u or s_u) and was originally proposed by Fellenius (1927).
- Skempton (1954) introduced pore-pressure coefficients (A and B parameters) to predict changes in pore pressure under undrained conditions, a key factor in analysing undrained shear strength, particularly in clays. This work is fundamental for understanding soil behaviour when water cannot drain, critical for stability in earth dams and similar structures.

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CLAY STRENGTH FORMULAE AND EMPIRICAL CORRELATIONS – UNDRAINED

- Skempton (1957) examined c_u during the Hong Kong Airport geotechnical investigation, vane shear tests (VST) for soft clays. In normally consolidated clays, c_u at any depth is proportional to effective overburden pressure (p'), the ratio c_u/p' closely correlates with PI. Refer equation c_u / p' = 0.11 + 0.0037 (PI).
- Wroth (1984) explored interpreted pressure meter tests (PMT). He stressed the importance of selecting appropriate properties for correlations and proposed the undrained strength ratio (s_u / σ'_{v0}) as a function of friction angle and OCR, or s_u / σ'_{v0} = f (ϕ, OCR). σ'_{v0} denotes the in-situ vertical effective stress.
- Knappett and Craig (2012) address c_u and sensitivity (S_t). S_t is a measure of the loss of shear strength of a clays. It describes how brittle a clay is. Sensitivity is also correlated to LI ($S_t \approx 100^{(0.43\ \mathrm{LI})}$).
- Mohammed (2024) investigates s_u in high-plasticity clays (CH), exploring its correlation with index properties, moisture content, and dry density. $s_u = 26.3 * (\mathrm{LL})^{0.5} * (\mathrm{PI})^{-0.3} * (\mathrm{MC})^{-0.2} * (\gamma_d)^{1.9}$.

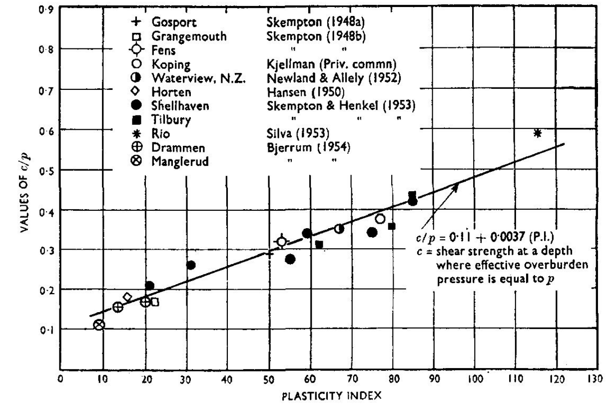

FIG. 21

Skempton, 1957

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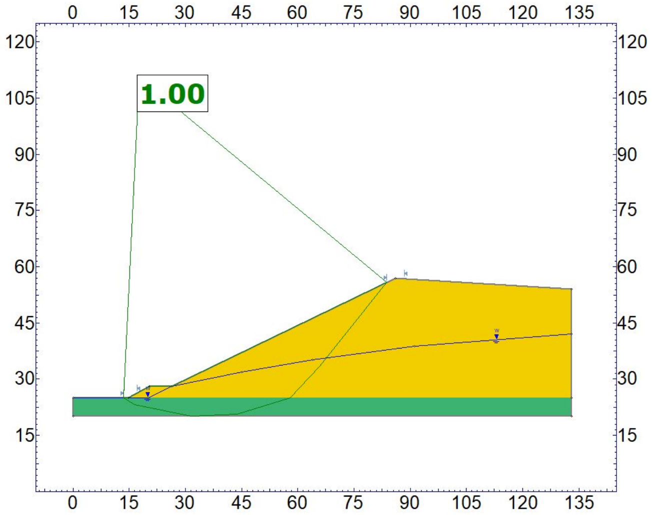
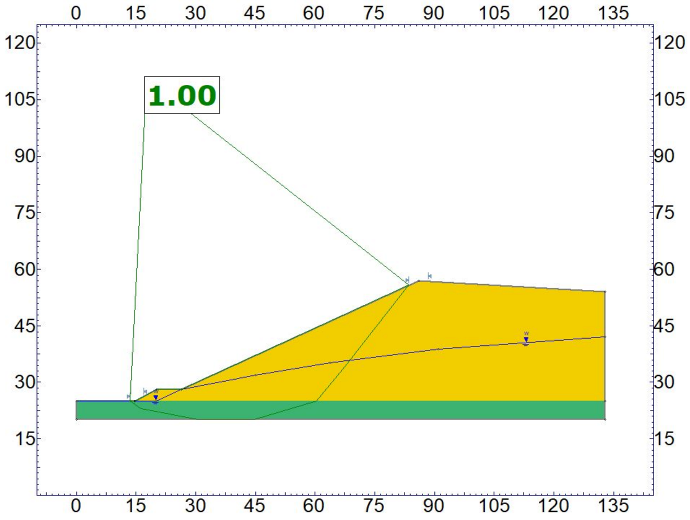
CASE STUDY

Failure of 32 m high platinum TSF (slope angle 1:2) on 'black turf' at RoR of 4-5 m/year

Tailings: c = 1 kPa ϕ' = 35°
Clay: ϕ' = 19.5°



Tailings: c = 1 kPa ϕ' = 40°
Clay: ϕ' = 17.5°



Simple back analysis suggests that the clay strength lies between 17.5° and 19.5°

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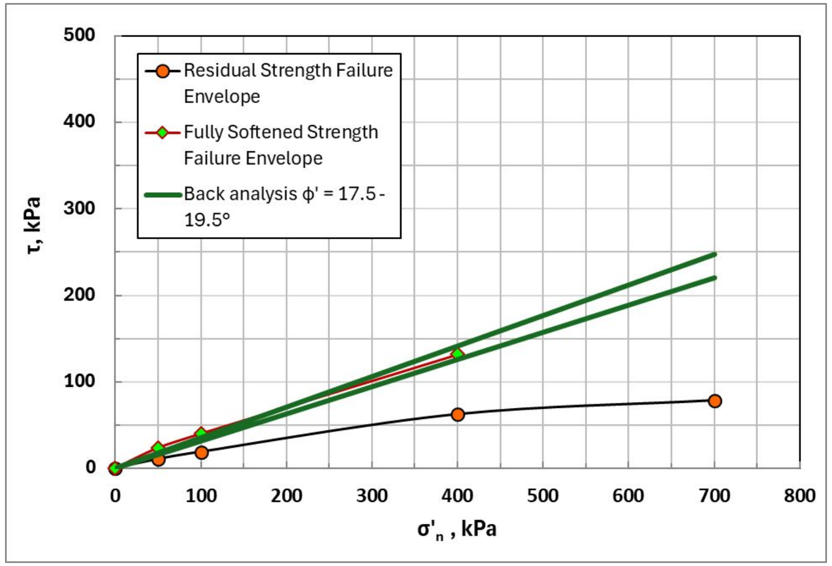
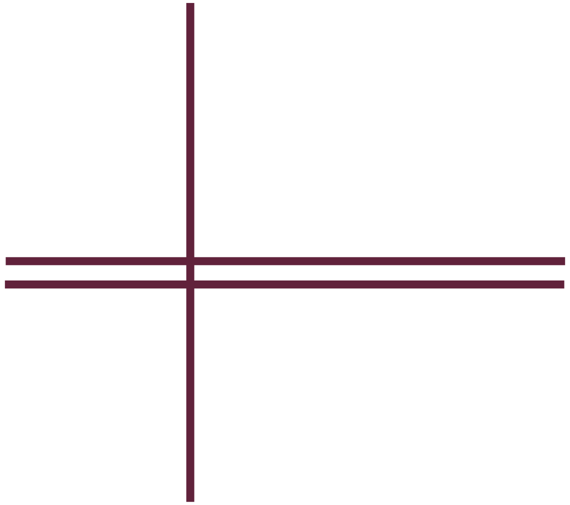
CASE STUDY (CONTINUES)

Indicators: Average LL = 90%, Average CF = 57%, Average PI = 50%



Stark and Hussain (2013)

PI = 50%



Knappet and Craig (2020)

Back analysed strengths match fully softened strength predicted by Stark and Hussain (2013) but are not well predicted by the correlation in Knappet and Craig (2020)

CONCLUSIONS

- Clay soil's unique geotechnical properties result in ongoing design and operational related challenges.
- TSF foundation failures to date resulted in numerous fatalities, environmental damage, etc.
- Understanding clay strength has evolved over three centuries (1700 to current).
- Post-1927 period, last century, marked significant advances in geotechnical engineering.
- Literature study indicates that some correlations have been shown to significantly over- or underestimate strength.
- To address these limitations, a reliability assessment of key empirical correlations estimating clay shear strength from index properties such as Atterberg limits and particle size distribution is recommended.
- These correlations should be evaluated against documented failure case studies of TSFs and embankments founded on clay soils to determine predictive accuracy.
- The outcome will guide appropriate use of empirical methods where laboratory data is limited, contributing to safer, more reliable TSF design and improved long-term performance.

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