Selection of undrained shear strength parameters of residual soils and their application in stability analysis

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ABSTRACT

Recent updates on tailings dam design guidelines require analysis of undrained (short-term) stability with the application of the SHANSEP model. The SHANSEP model, which was originally developed for alluvial soils, predicates that the Undrained Shear Strength (Su) increases with increasing effective stress. Residual soils by their nature do not necessarily follow this relationship. This paper examines an alternate method to define Su over a range of effective stress conditions for residual soils.

Residual soils, formed by weathering of their parent rocks, are generally micro-structured in nature. The microstructural features, such as interparticle bonding, play a fundamental role in stress-strain behaviour of the residual soils. As interparticle bonding is independent of effective stress and void ratio, the undrained shear strength of residual soils is expected to be less dependent on effective stress than alluvial soils, especially at low stress levels. A series of triaxial tests conducted on residual soils, however, indicated that the undrained shear strength and the undrained shear strength ratio (Su/σv') are to a degree dependant on effective stress. It was found that the undrained shear strength ratio is significantly higher under low stress levels and progressively reduces with increasing effective stress. Based on the laboratory testing data, a strength function with varying undrained shear strength ratios can be developed for the residual soils under the stress range anticipated for a design of a tailings dam. This includes capping the input undrained strength at lower effective stresses based on the drained (effective) and minimum undrained strength. The Factor of Safety (FOS) calculated for the embankment utilising the traditional limit equilibrium (LE) method indicated the application of undrained strength function for the residual soils can provide a significant optimisation for the embankment design compared to adopting a constant undrained shear strength ratio or constant undrained shear strength in the design.

Keywords: Undrained Shear Strength, Residual Soils, SHANSEP Model, Residual Soil Model, Tailings Dam Stability

INTRODUCTION

The rate of tailings dam failures is approximately 120% higher than the failure rate of conventional water dams, where on average, three of 3500 tailings dams fail every year (Lyu et al., 2019). Post-breach investigations of the recent devastating tailings dam failures highlighted that a lack of understanding of foundation and embankment materials is one of the root causes. Subsequently, industry bodies, such as Australian National Committee on Large Dams (ANCOLD) and Canadian Dam Association (CDA), revised their tailings dam guidelines to ensure safe and sustainable tailings dam development by mandating the requirement to consider the undrained behaviour of embankment and their foundation materials which contain contractive materials as a part of the design process.

ANCOLD 2019 recommends adoption of the Undrained Strength Analysis (USA) approach of Ladd (1991) for all materials that are contractive and generate pore pressures on shearing. The USA approach is commonly named as S_u/σ_v' approach, where the crux of the approach is that the undrained strength of the materials is a function of effective overburden stress. The original concept of USA approach: Stress History and Normalized Soil Engineering Property (SHANSEP), was defined by Ladd and Foote (1974) for sedimentary soils. The SHANSEP equation, was developed taking into account stress history and stress path of the contractive materials. This can be determined from a series of consolidated undrained (CU) triaxial tests under different effective confining pressures and oedometer tests to determine the over-consolidation ratio (OCR).

However, unlike sedimentary soils, where the behaviour of the soil is dependent on the OCR, the stress history of residual soils appears to be less critical (Blight & Leong, 2012). Vaughan (1985) argued that the classical concepts of soil mechanics such as index properties, plasticity, and stress history are almost universally non-applicable to the behaviour of the residual soils and that the concept of an OCR being defined for residual soils is flawed as there is no virgin consolidation line for a residual soils as there is in the sedimentary soils (Wesley, 2010).

Following a series of laboratory tests conducted on large block undisturbed soil samples, Meng and Chu (2011) showed that the undrained strength of intact residual soils is highly anisotropic in term of normalised undrained strength (S_u/σ_v'). It is, therefore, hypothesised that the strength of residual soil, especially at low effective overburden stress, is more closely related to the soil structure, which is a function of the parent rock and its weathering history. The effects of soil structure on engineering properties and soil compressibility of the residual soils are discussed in Viana da Fonseca (2003), Zang et al. (2007), Nagaraj et al. (1998), and Huat et al. (2008).

It is the view of the authors, based on several geotechnical testing programs, that the SHANSEP model poorly represents the actual behaviour of residual soils; therefore, this paper evaluates the validity of using the classic SHANSEP method along with modifications to the method (the Residual Soil Model) to better define the undrained strength of residual soils and its applications in stability assessments for the tailings dams.

SHANSEP MODEL & RESIDUAL SOIL MODEL THEORY

Ladd and Foote (1974) proposed that S_u/σ_v' nonlinearly increases with increasing OCR of the saturated fine-grained sedimentary soils and the relationship of the SHANSEP concept proposed by Ladd et al. (1977) is illustrated in Eqn. 1.

$$S_u/\sigma_v' = S * (OCR)^m \qquad Eqn.1 \text{ (Ladd et al., 1977)}$$

$Where$:

$S = S_u/\sigma_v'$ of the normally consolidated soils,

$OCR = o\text{ver} - \text{consolidation ratio},$

$\text{m} = \text{constant (typically ranges between 0.75 and 1)}.$

Holtz et al. (2011) proposed 0.23 ± 0.04 as the typical range of ‘S’ for normally consolidated, saturated, and fine-grained soils with this relationship demonstrated for sedimentary soils in numerous studies (e.g. Moses et al., 2003, Zhang et al., 2007). The OCR for the sedimentary soils is defined by Eqn. 2 and is estimated from the pre-consolidation stress obtained by graphing the data obtained from odometer testing on undisturbed samples of sedimentary soils with an example of the typical behaviour of the sedimentary soil is shown on Figure 1(a).

$$OCR = \frac{\sigma_v'}{\sigma_c'} \qquad Eqn.2\ (Casagrande, 1936)$$

$Where$:

$\sigma_v' = \text{Effective overburden pressure (kPa)},$

$\sigma_c' = \text{Preconsolidation stress (kPa)}.$

Wesley, 2010 argued that the relationship between void ratio/compression and pressure/stress in log scale mistakenly interprets the compressibility behaviour of residual soils and therefore, suggested to adopt linear scale for presenting the results of oedometer tests of the residual soils. For many residual soils, such as residual red clays of Java illustrated in Figure 1(b), there is an almost linear relationship between pressure and compression in linear scale. These materials do not display an inflection point, when data is graphed, which would typically be used to determine the pre-consolidation stress. It is noted that some residual soils do show an inflection point in odometer consolidation curves, however, this should be considered to be the yield pressure or vertical yield pressure and should not to be confused with the pre-consolidation pressure defined for sedimentary soils (Wesley, 2010).

Based on the fact that it is not possible to define the pre-consolidation stress and OCR for residual soils, the SHANSEP method defined in Eqn. 1 cannot be directly applied to the residual soils.

This study, therefore, proposes the Residual Soil Model (RS Model), which displays a nonlinear decrease in normalised undrained strength with increasing overburden stress with the relationship related to the strength associated inherent parent structure controlling S_u at low stress levels, which is overcome at higher stresses above the vertical yield pressure. To describe the RS Model the original SHANSEP equation (Eqn. 1) was restructured in this study as illustrated in Eqn.3,

$$S_u / \sigma_v' = A * (\sigma_v')^B \qquad Eqn. 3$$

$Where: A \& B = Material\ specific\ constants$

This paper examines the applicability of the RS Model (Eqn. 3) to residual soils and extremely weathered rocks derived from igneous and sedimentary parent lithologies.

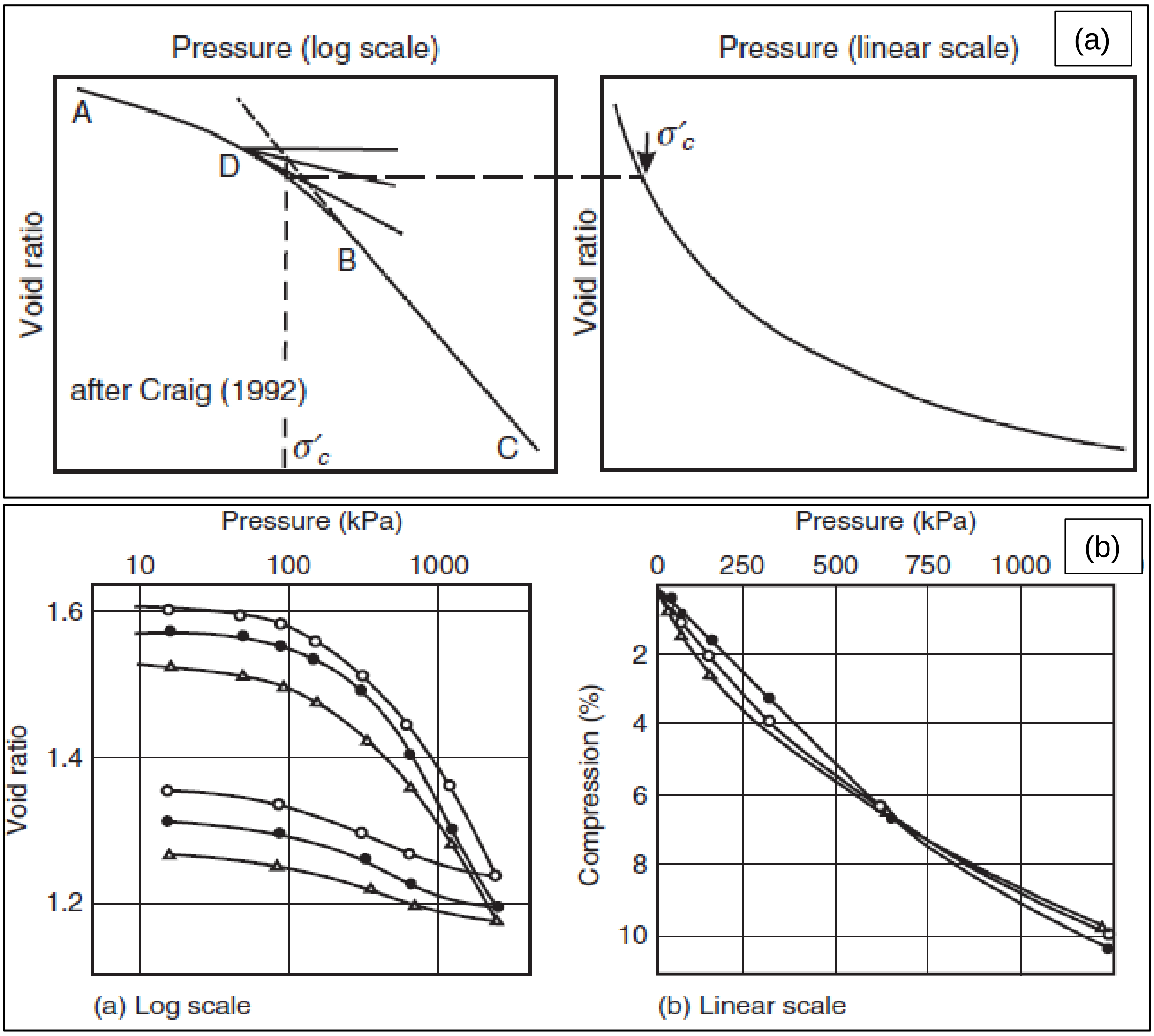

FIG 1 – Typical Odometer Data Interpretation: (a) Sedimentary Soils and (b) Residual Red Clays (After Wesley, 2010)

DERIVATION OF RESIDUAL SOIL MODEL (RS MODEL) INPUT PARAMETERS

The RS Model utilises a curve developed by combining the normalised undrained strength, the minimum strength and the effective strength to produce a single undrained strength curve which can be employed to model the undrained strength of the residual soils over a large range of effective overburden stresses. The general method is demonstrated in the flow chart provided in Figure 2.

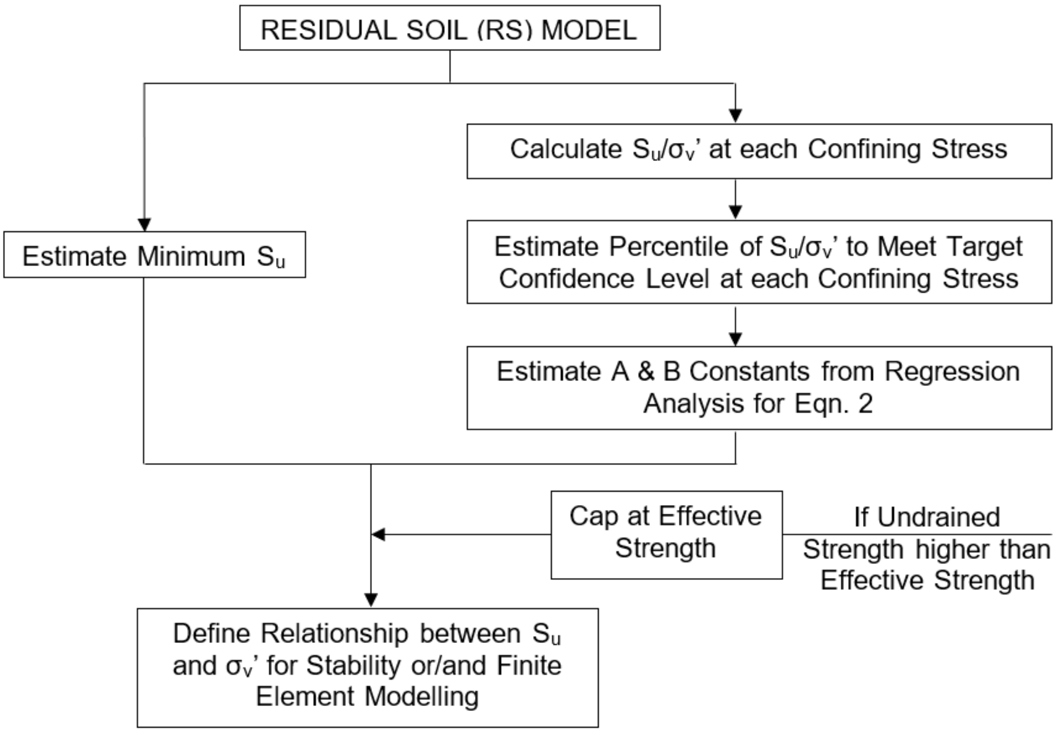

FIG 2 – Methodology to Estimate Residual Soil (RS) Model Parameters

The first step in developing the RS Model curve is to determine the S_u/σ_v' over a range of confining stresses (i.e. effective overburden stress). The S_u/σ_v' can be determined by single stage CU triaxial or multi-stage CU triaxial. Multiple tests are needed at each confining stress such that a statistical analysis of the S_u/σ_v' can be conducted. The statistical confidence level adopted can be adjusted based on the amount of data, quality of data, stage of design or criticality of the design as shown in Figure 3.

This study has adopted 85% of confidence for all calculations presented which is consistent with recommendations by Hawley and Cunning (2017) and Read and Stacey (2009). As such the 15th Percentile value (approximately equal to the mean minus one standard deviation) was calculated at each of confining stress ranges. After evaluating the regression parameters of ‘A’ and ‘B’ as illustrated in Figure 3(a), The relationship between S_u and confining stress (Figure 3(b)) can be developed as the second step, which shall be capped at both minimum and effective strengths.

Unlike normally consolidated fine-grained sedimentary soils, the minimum strength of residual soils is generally higher than zero. Therefore, the relationship between S_u and confining stress is to be capped at the minimum strength as illustrated in Figure 3(b). Laboratory testing, such as CU triaxial, vane shear, and Unconsolidated Undrained (UU) triaxial and field testing such as SPT, insitu vane shear, CPT, pocket penetrometer, and visual logging of consistency, can be used to define minimum undrained strength of the residual soil.

Furthermore, if the estimated undrained strength is higher than the effective strength at any stress level, the undrained strength shall be capped at the effective strength to avoid the reliance on the negative pore pressure (ANCOLD, 2019) as shown in Figure 3(b).

Note that since the minimum strength at low stress levels is higher than the effective stress, the minimum strength is also capped by the effective stress in the example presented in Figure 3.

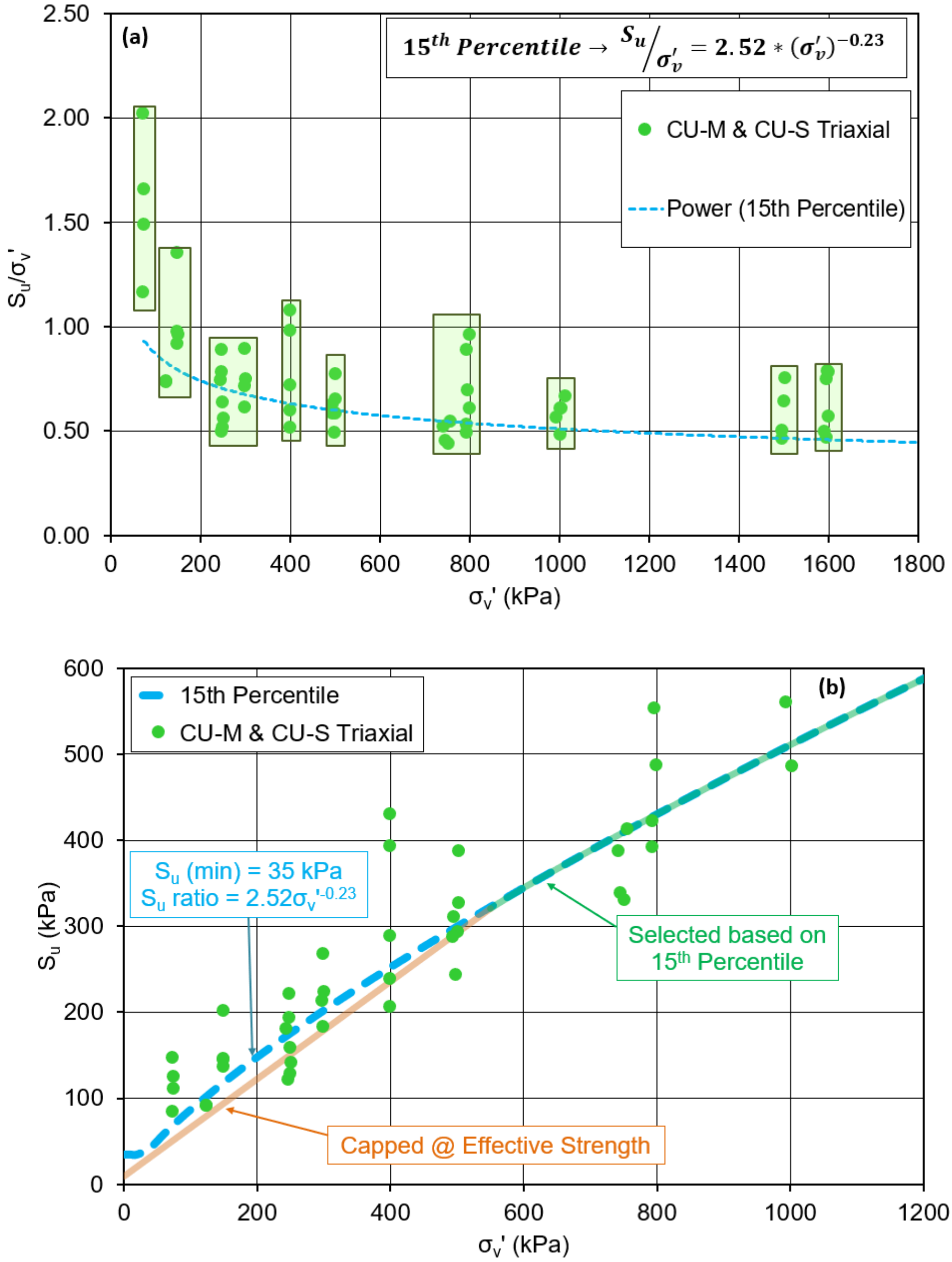

FIG 3 – Parameter Estimation: (a) A & B regressions and (b) Relationship between Su & σ_v'

CASE STUDIES

Three types of residual soils, which were weathered from different parent rock types were used in this study as summarised in Table 1. Residual soil / extremely weathered rock originated from two different sedimentary rocks; Siltstone and Greywacke (alternately named Lithic Arenite) and one igneous rock; Monzonite were studied in this paper. The sedimentary soils were from separate TSF sites in Laos PDR with the monzonite samples from a TSF site in western New South Wales. The weathering process of the sedimentary rocks is normally quite different to weathering of igneous rocks. Igneous rocks are typically broken up and converted chemically into clay minerals, while the sedimentary rocks in which cementing agents are dissolved by percolating water (Wesley, 2010). All basic index tests, triaxial testing, and field testing were conducted and classified according to the Australian Standards. Averages of the basic testing results are presented in Table 1.

Test Type	Residual Soil Greywacke	Extremely Weathered Siltstone	Extremely Weathered Monzonite
Clay Percentage (%)	14.6	28.2	52.0
Silt Percentage (%)	35.1	41.8	33.9
Sand Percentage (%)	48.9	30.0	13.1
Liquid Limit, LL (%)	36.0	50.0	62.4
Plastic Index, PI (%)	17.0	21.0	40.3
Soil Classification	Low Plasticity Clay (CL)	Intermediate Plasticity Clay (CL-CH)	High Plasticity Clay (CH)
Linear Shrinkage, LS (%)	3.0	7.0	16.6
Specific Gravity, G_s	2.65	2.69	2.58
In-situ Void Ratio, e_0	0.70	0.63	0.68
In-situ Dry Unit Weight, Υ_d (kN/m^3)	15.3	16.2	15.2
In-situ Moisture Content (%)	24.7	24.3	24.2
SPT Range	4.0 – 26.0	6.0 – 80.0	13.0 – 66.0
15^{th} Percentile of SPT	7.0	12.0	18.0

TABLE 1 – Soil Index and In-situ Testing Results

RESULTS AND DISCUSSIONS

Figure 4 summarises the relationships between S_u/σ_v' and effective overburden stress of greywacke residual soil, extremely weathered siltstone, and extremely weathered monzonite. The results indicated a tendency of S_u/σ_v' reduction with increasing effective overburden stress irrespective to the parent rock type. At lower stress levels, the S_u/σ_v' highly variable, however, the variability gradually diminished with increase in effective overburden stress.

This supports the initial hypothesis adopted in this study, where the strength associated inherent parent structure controls the S_u at lower stress levels; however, it may be overcome at higher stresses. Furthermore, compared to the extremely weathered rock, the scattered behaviour of S_u/σ_v' diminishes at lower stress levels in the residual soil weathered from greywacke, as shown in Figure 4. This indicated that soils with microstructure, such as residual soils, require less energy to break the interparticle bonding compared to the soils with macrostructure, such as extremely weathered rocks. Blight & Leong (2012) confirm this observation by citing that the soils with even weak bonding shall be delicately handled to avoid destroying the structure, which can have a significant influence on the engineering behaviour, especially at shallow depths or low stress levels.

Common approaches for modelling of residual soils are to adopt a constant S_u/σ_v' or employ a constant undrained shear strength. However, as illustrated in Figure 4, neither approach appropriately accounts for the strength behaviour of the residual soil as:

- Adoption of a constant S_u/σ_v' results in underestimation of the shear strength of soils at low stress levels and overestimation of the strength at higher stress levels.
- Adoption of a constant S_u overestimates the soil strength at low stress levels, while underestimate at higher stress levels.
- The RS Model appear to address these deficiencies and maintain the estimated strength at or close to the adopted confidence level across the full range of stress levels considered.

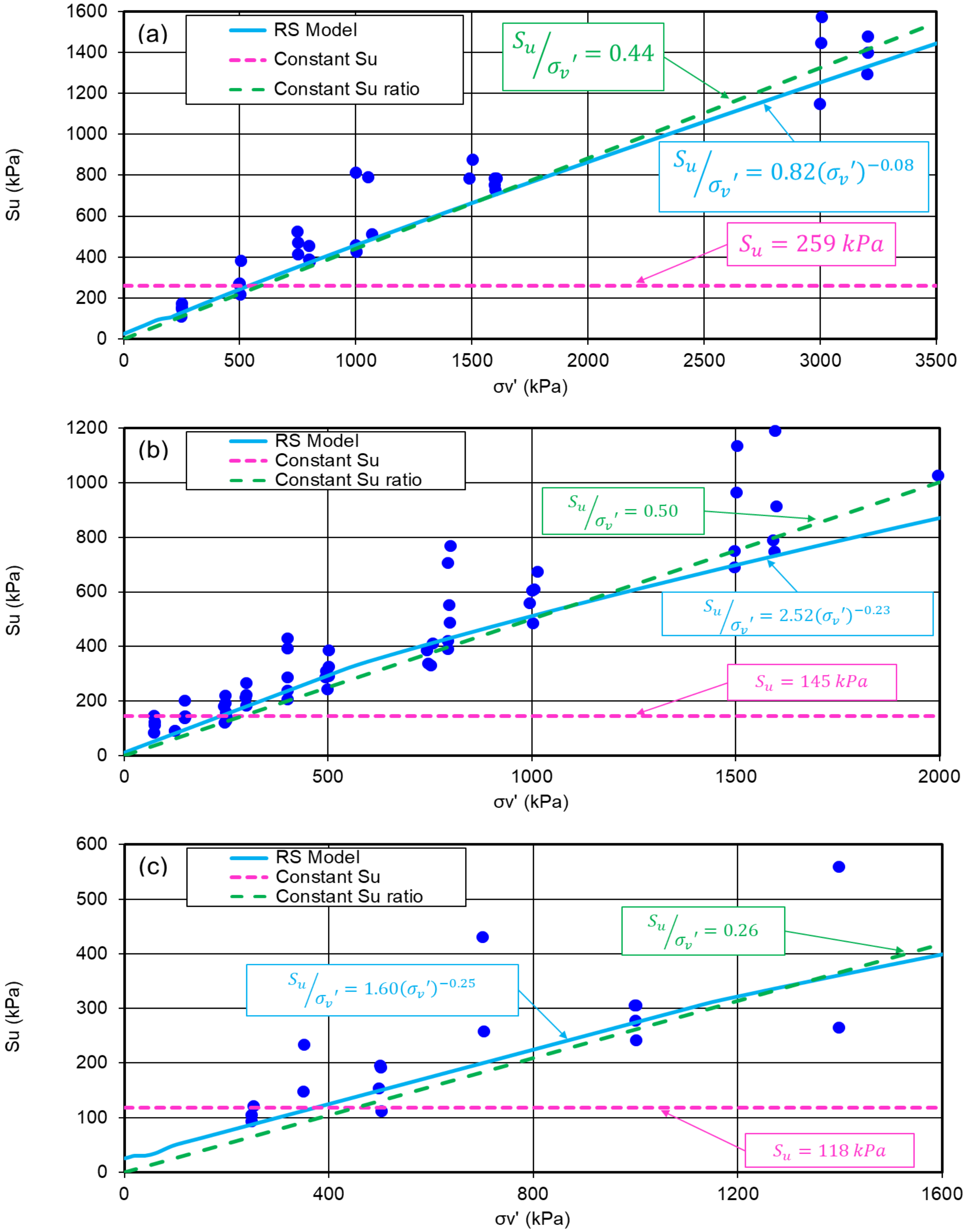

FIG 4 – Constant S_u/σ_v', Constant S_u and RS Model (a) Siltstone (b) Greywacke (c) Monzonite

The application of the proposed RS Model parameter interpretation for the residual soils in stability modelling are summarised in Table 2, the Tailing Storage Facility (TSF) embankment stability model is illustrated in Figure 5. Only residual soils weathered from greywacke were used in this stability assessment, which was assessed using SLOPE/W software, where the limit equilibrium stability analysis (i.e. Morgenstern-Price analysis method with optimised critical failure surfaces and suction removed) was adopted for the study under the short-term (undrained) loading conditions. The results indicate that the adoption of constant undrained shear strength significantly underestimate the FOS of the embankment compared to the other two options, requiring a large buttress to meet the minimum FOS requirements.

Adoption of constant S_u/σ_v' is conservative compared to the RS Model approach at low stress levels; however, at a higher stress the FOS of the TSF embankment is overestimated. Therefore, the adoption of RS Model approach with variable undrained strength ratios for the residual soils shall enhance the confidence level with increasing height of the TSF embankment, and may save significant construction cost at low stress levels and ensure the stability at higher stress levels.

Stage	Embank. Height (m)	FOS with Residual Soil – Greywacke		
		RS Model (15th percentile)	Constant S_u/σ_v': 0.5 (15th percentile)	Constant S_u: 145 kPa (15th percentile)
Stage 1	34.0	2.00	1.98	1.33
Stage 2	55.0	1.82	1.69	0.82
Stage 3	75.0	1.54	1.57	0.66

TABLE 2 – Estimated FOSs using Different Interpretation of Undrained Shear Strength of Residual Soil

Color	Name	Model	Unit Weight (kN/m³)	Strength Function	Minimum Strength (kPa)	Tau/Sigma Ratio	Cohesion' (kPa)	Phi' (°)	Phi-B (°)	Cohesion (kPa)	Constant Unit Wt. Above Water Table (kN/m³)	Undrained Shear Strength vs Vertical Effective Stress Function	Piezometric Line
	Residual Soil - Greywacke	Undrained (Phi=0)	19.3							145	18.9		1
	SWR	Mohr-Coulomb	22				40	35	0		21.5		1
	Tailings	SHANSEP	17.1		0	0.2					16.6		1
	Zone A	SHANSEP	20.4		50						20	Zone A Su ratio	1
	Zone B	Mohr-Coulomb	20				0	36	0		19.5		1
	Zone C2-(Rockfill)	Shear/Normal Fn.	22.5	Rockfill					0		22		1
	Zone F	Mohr-Coulomb	20				0	34	0		19.5		1

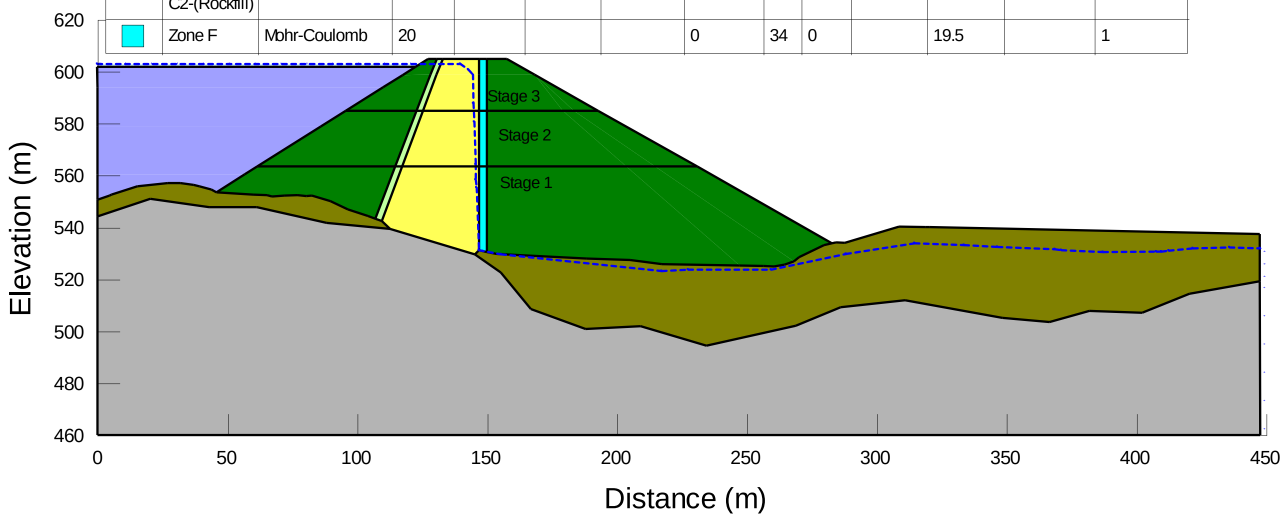

FIG 5 – TSF Embankment Adopted for Stability Assessment

CONCLUSIONS

The undrained shear strength of intact residual soils and extremely weathered rock originating from Greywacke, Siltstone, and Monzonite are presented with reference to CU multistage and single stage triaxial tests. The following conclusions can be made from the results of the testing and their interpretations:

1. Irrespective to the parent rock type, the S_u/σ_v' for residual soil/extremely weathered rock tends to nonlinearly decrease with increasing effective overburden stress. Therefore, S_u tends to nonlinearly increase with increasing effective overburden stress,
2. The undrained shear strength variation for residual soil/extremely weathered rock can be represented by the RS Model equation, irrespective to the parent rock type.
3. The proposed RS Model parameter interpretation method for residual soils can be directly used in SHANSEP material model in Limit Equilibrium program (SLOPE/W), UDSM-SHANSEP MC material model in finite element program (PLAXIS), and UBCHYST material model in finite differential program (FLAC).

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