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Residual friction angles of piles in clayey soils and soft rocks

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ABSTRACT: Soil-soil and pile-soil interface friction angles are important design parameters for driven or drilled and grouted pile foundations in clayed soils and fine-grained soft rocks. Peak and ultimate/ residual friction angles are routinely determined by direct shear box or ring shear tests and correlations are often explored by linking the angles to soils' index properties. However, significant variabilities are commonly observed with experimental data, and the exact reasons are not always clear. Deviations seen with empirical correlations often lead to stark choices of representative design values, which can impact foundation requirements substantially. This paper reviews first how clay mineralogy and activity affect the residual friction angle (φ_{res}) of pure minerals and soils. A database of φ_{res} values from high-quality published experiments is then assembled and presented. Factors contributing to the variations in φ_{res} are clarified. Trends for φ_{res} against clay size fraction, clay mineral content, liquid limit and plasticity index are identified. Further insights are provided into the interface residual friction angles (δ_{res}) for piles driven into fine-grained soft rocks, noting that the driving operations may break down large aggregates into clay particles and lead to potentially low δ_{res}, especially when they contain high activity platy clay minerals, such as montmorillonite. Recommendations are given of project-specific laboratory interface shear testing to determine representative δ_{res} and reduce design uncertainties. The findings of this work help to (1) facilitate the estimation of φ_{res} and δ_{res} based on minerology, clay content and other index properties, when project-specific testing is not available, and (2) provide guidance for developing tailored laboratory testing programme for acquiring φ_{res} and δ_{res} values.

Keywords: Residual friction angle; soil; soft rock; driven pile; interface friction angle

1 INTRODUCTION

Pile-soil interface shearing resistance is fundamental to the analysis and design of pile foundations in soils and soft rocks. Interface friction angle (δ) is routinely determined with Ring Shear (RS) or Interface Shear Box (ISB) tests with representative soil and interface surface conditions at suitable effective stress levels. Pre-conditioning or curing stages may be applied to cater for in-situ pile installation processes. Empirical trends or correlations have been proposed to link δ values with soil index properties, including for examples plasticity index (I_p) for clays (Jardine et al., 2005) and median particle size (D_{50}) for sands (Liu et al., 2019). However, significant variabilities are often observed with these correlations, especially for soils or fine-grained soft rocks containing clay minerals, see for example Jardine et al. (2005) and Cripps & Taylor (1981). Where possible, project- and soil-specific interface shear testing is recommended for determining representative friction angle angles. Vinck et al. (2023) and Westgate et al. (2023) report respectively specialised Bishop RS testing on low-to-medium density chalk and glauconite sands that are widely recognised as challenging geomaterials in wind farm projects in Europe and North America.

This paper starts with a review of factors that affect the residual soil-soil friction angle (φ_{res}). The development of a database of φ_{res} is followed for various clayey soils and soft rocks, noting that φ_{res} is inherently linked to residual soil-pile interface friction angle (δ_{res}) particularly in cases where soil-pile shearing migrates to the sorrounding soil mass. Empirical trends for φ_{res} (or δ_{res}) against index properties are identified and detailed considerations for employing the correlations for preliminary parameter selection in fine-grained soft rocks are provided. Further discussion is provided on how representative laboratory tests may be designed and undertaken to firm up the design values of φ_{res} (or δ_{res}).

2 DATABASE AND CORRELATIONS

Research into residual soil-soil shearing resistance commenced from the investigations into landslides in clays and shales, as highlighted in the Fourth Rankine Lecture by Skempton (1964) and the Third Terzaghi Lecture by Bjerrum (1967). To date, a wealth of experimental data typically from RS and direct shear testing is available in the public domain. Various empirical correlations have been proposed between φ_{res} and soil index properties, such as Clay-Size Fraction (CSF, < 2 μm), liquid limit (w_L) and plasticity index (I_p), to enable preliminary parameter choice.

This section discusses first φ_{res} values of pure minerals, providing important basis and fundamental explanations for the wide range of φ_{res} values often observed with clayey soils and soft rocks. A high-quality database is collated and presented in Section 2.2 from which correlations between φ_{res} and index properties are identified. Section 2.3 discusses further the effects of cementation in soft rocks, a factor that introduces additional uncercertainties and necessitates special considerations.

2.1 φ_{res} of pure minerals

Common types of clay minerals encountered in practice include chlorite, kaolinite, smectite, mica and halloysite, while quartz, calcite and feldspar are often categorised as 'massive' minerals. Kenney (1967) and Yamasaki et al. (2000) reported values of residual friction ratio, μ_{res} (= tan(φ_{res})), for some pure minerals measured on samples consolidated from slurries. Their results are plotted against effective normal stress (σ'_n) as shown in Figure 1.

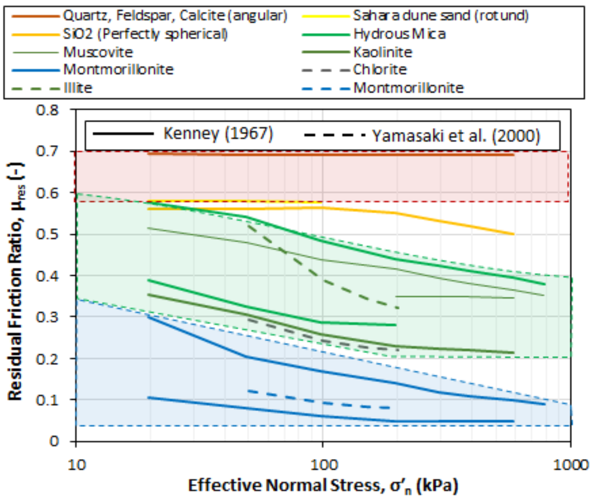

Figure 1. Residual friction angles of pure minerals

As indicated in the shaded areas in Figure 1, the mineralogical composition can be broadly divided into three groups in relation to drained residual strength, as represented by μ_{res} or φ_{res}:

(1) Massive minerals, such as feldspar, calcite and quartz, with $0.58 < \mu_{res} < 0.7$ ($30° < \varphi_{res} < 35°$) if excluding rotund particles. Particle size effect appears to be negligible as no difference can be noticed between samples with particle size < 60 μm and < 2 μm. However, aggregates with angular particles exhibit higher μ_{res} than those with rotund particles, such as dune sands and pure SiO_2 of perfectly spherical particles (Kenney, 1967). The dependency of μ_{res} on stress level appears to be less significant for the massive minerals, in comparison with clay minerals.

(2) Low activity clay minerals such as kaolinite, chlorite, muscovite and hydrous micas (including illite, glauconite, and brammallite), with $0.21 < \mu_{res} < 0.60$ ($12° < \varphi_{res} < 31°$). The variations observed with hydrous mica can be primarily attributed to differences in pore fluid composition and the nature of lattice cation. For a given mineral, the dependency of μ_{res} on stress level is also significant.

(3) High activity clay minerals such as those in the smectite group (e.g. montmorillonite), or mixed-layered minerals containing smectite, with $0.047 < \mu_{res} < 0.35$ ($2.7° < \varphi_{res} < 19.5°$). As found with hydrous mica, the shear strength of montmorillonite depends critically on the type of cation in the system and the concentration of ions in the pore fluid.

Lupini et al. (1981) elaborated the reasons behind the marked differences observed in the φ_{res} values between different soils. Aided by optical and electron microscope imaging (e.g., Mitchell, 1956), two distinct residual shearing modes may be identified:

(1) turbulent shear involving particle rolling and translation. This typically occurs in soils consisting of massive minerals and the shearing mode is similar to that occurring at critical state (constant volume) where particles are orientated randomly.

(2) sliding shear involving direct sliding between platy clay particles in a concentrated shearing zone which is strongly orientated to the direction of shearing. This is not recognised in critical state soil mechanics and requires relatively large displacements to develop fully (i.e., to orientate the platy clay minerals to shearing direction). As observed by Skempton (1964), the corresponding φ_{res} values could be directly comparable to the friction angles between mineral particles, φ_μ, as measured by Horn and Deere (1962).

The occurrence of the sliding shear mode is governed by particle shape rather than mineral type. For example, needle-shaped clay minerals such as halloysite (often found in soils formed from vocanic ash), behave as rotund particles and develop high φ_{res} values as shearing is dominated by turbulent mode (Lupini et al., 1981), as discussed further. Although not all clay minerals are plate shaped, the most common types found in clays and fine-grained rocks are platy, for examples illite, chlorite, kaolinite, montmorillonite, among which montmorillonite particles exhibit greatest aspect ratio and lowest φ_{res}.

2.2 φ_{res} of natural soils and soft rocks with mixed minerals

The φ_{res} values of soils with mixed massive and clay minerals could vary considerably, depending primarily on soil constituents and to a lesser extent on pore-water chemistry and effective stress level. Intensive research has been reported on the development of empirical correlations between φ_{res} and soil index properties, such as CSF, clay mineral content (CMC, determined by X-ray diffraction, XRD), liquid limit (w_L) and plasticity index (I_p). Both CSF and CMC indexes are considered in this study, although CMC is believed to be a more reliable parameter than CSF, especially for soft rocks, as discussed later.

2.2.1 φ_{res}-CSF and φ_{res}-CMC correlations

Figure 2 presents variations of φ_{res} against CSF from an assembled database comprising natural clayey soils and indurated fine-grained soils, such as shales, mudstones, claystones and siltstones. Note that Figure 2 differentiates indurated soils and soils containing halloysite and/ or allophane with open square and circle symbols respectively, as also applied in the later figures.

Excluding the data points of the soils containing halloysite and/or allophane and those from Tiwari & Marui (2005) which are dominated by mudstones with smectite >10% dry weight, the results are broadly consistent with the observations by Skempton (1985). Clays with CSF < 25% resemble sandy or silty soils with relatively high values of φ_{res} that are largely comparable to critical state fricion angles (φ_{cs}). Conversely, shearing of clays with CSF of >50% is controlled predominantly by sliding friction of the clay minerals, developing relatively low φ_{res} values that are affected only marginally by any further increase in CSF. A transitional shear mode between turbulent and sliding is likely for clays with 25% < CSF < 50% (Lupini et al., 1981). The φ_{res} value is dependent on the percentage of clay minerals and their mineralogical nature.

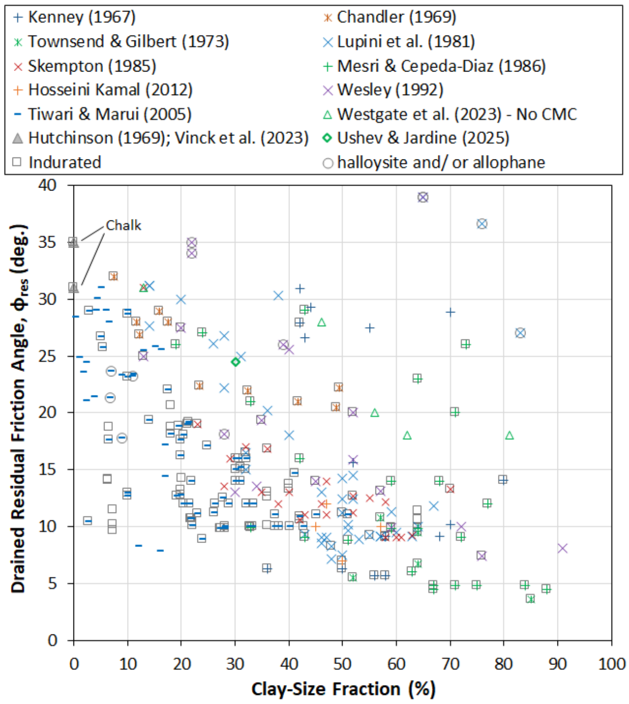

Figure 2. Residual friction angles vs. clay-size fraction

Although a general decreasing trend for φ_{res} against CSF may be identified in Figure 2, significant scatter is evident. One possible reason is inaccurate determination of CSF due to for examples flocculation during grain size testing or insufficient break-down of aggregates during sample preparation, as discussed by Kenney (1967), Mesri and Cepeda-Diaz (1986) among others. In addition, it is not necessarily true that particle with size < 2 μm can be treated as clay minerals (e.g. rock flour).

Therefore, the dataset is re-plotted in Figure 3 in correlation with CMC. Where detailed CMC measurements were unavailable, CMC values were assumed to be identical to CSF, as indicated in the figure legend. Comparison between Figures 2 and 3 appear to indicate that φ_{res} correlates more strongly with CMC than CSF, particularly for indurated soils, for which CSF measurements may not be reliable since clay particles could aggregate to form larger sized aggregates that are not broken down completely for precise CSF measurements. However, the φ_{res}-CMC correlations could also be subject to considerable uncertainties, which may be ascribed partly to cementation effects, as discussed further in Section 2.3.

Also plotted in Figure 3 as dashed lines are relationships derived from artificial mixtures of various clay and massive minerals. The trends highlight the fundamental reasons for the reduction of φ_{res} with increasing CMC in natural soils: the decreasing rates and φ_{res} minima are governed by the relative quantity and nature of the clay minerals. In mixtures with high activity clay minerals (e.g., smectite and bentonite), the reduction rate of φ_{res} against CMC is greater and the φ_{res} minima are lower, in comparsion with mixtures with clay minerals of low activity (e.g., kaolinite and mica). As annotated in Figure 3, mixtures with high mica content exhibit higher φ_{res} than those with other clay minerals. Glauconite sands tested by Westgate et al. (2023) also developed relatively high φ_{res}.

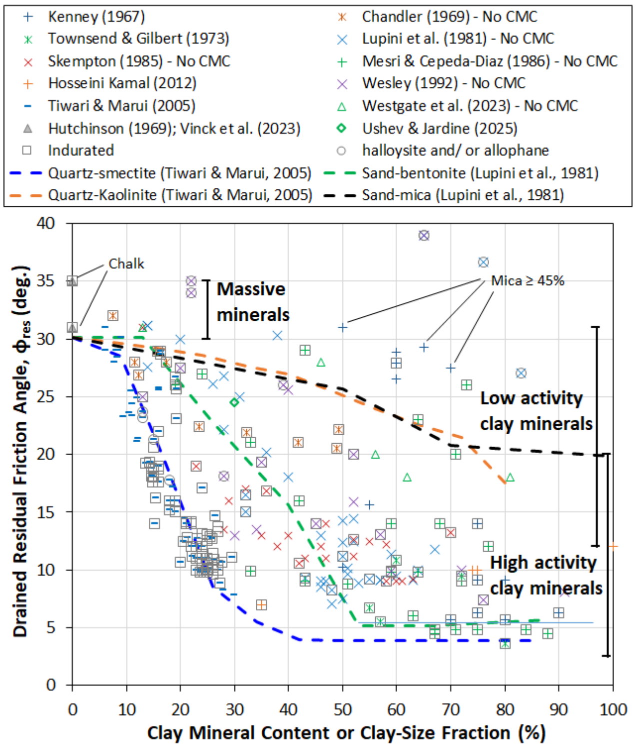

Figure 3. Residual friction angles vs. clay mineral content

As noted previously, soils containing halloysite and/or allophane (for examples those formed from volcanic ash) develop significantly higher φ_{res} than other clayey soils, confirming that particle shape plays a more dominant role than particle size.

2.2.2 Correlations between φ_{res} and w_L, and between φ_{res} and I_p

Noting Atterberg limits can reflect to a large extent the relative amounts of soil constituents and mineral types, correlations of φ_{res} with w_L and I_p were also explored, as shown in Figure 4 and Figure 5, respectively. The data are grouped according to CMC levels, noting the data points for soils containing halloysite and/or allophane minerals are removed for clarity. Similar decreasing trends can be identified for φ_{res} with w_L and I_p. The overall trends indicate that CMC does not necessarily correlate well with w_L or I_p, which depends on clay particles' mineralogical nature, rather than their quantity. The w_L and I_p maxima for low activity clay minerals are rarely greater than 100 % and 70 % respectively. In contrast, much higher w_L and I_p maxima of 350 % and 320 % respectively can be observed with higher activity clay minerals which develop markedly low φ_{res} values with a minimum of 3.6°. Low φ_{res} values reflect soil characteristics of large quantities of high activity clay minerals such as montmorillonite or mixed-layer minerals containing montmorillonite. Conversely, soils of high φ_{res} typically contain large quantities of massive or micaceous minerals. Similar to CMC, the overall φ_{res}-w_L and φ_{res}-I_p trends are subject to considerable variabilities that can be partly attributed to cementation effects, as discussed subsequently.

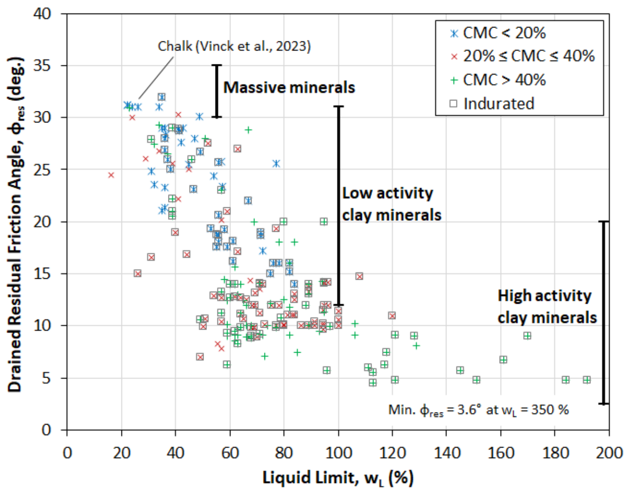

Figure 4. Residual friction angles vs. liquid limit

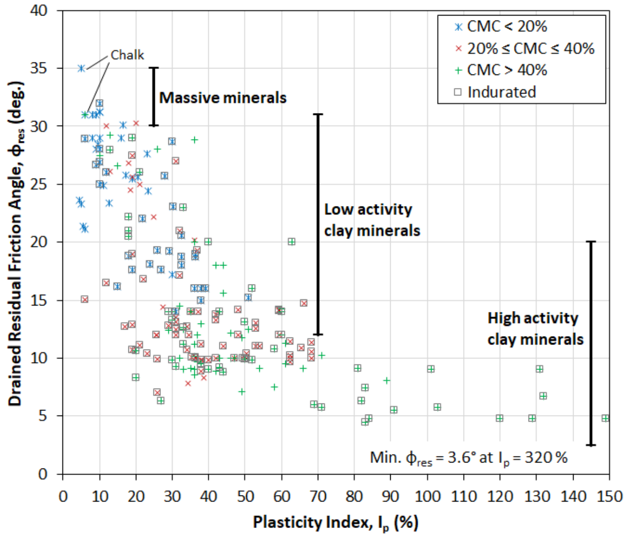

Figure 5. Residual friction angles vs. plasticity index

2.3 Variations due to cementation

The trends indicated in the above Figures 3-5 are subject to greater uncertainties for fine-grained soft rocks such as shales and mudstones that typically possess highly aggregated fabrics in which clay particles are bonded diagenetically to form sand- and silt-sized particles. Depending on the strength of the bonds, which could be affected by weathering and treatment procedures, rock aggregates may not be broken down fully into clay-sized particles during sample preparation (Mesri & Cepeda-Diaz, 1986), introducing uncertainties in the determination of index properties and φ_{res}.

Variations also arise from sample preparation methods for measuring φ_{res}, depending on the extent to which rock aggregates are broken down. The level of particle disaggregation may also partly attribute to the data scattering observed with the indurated soils included in Figures 4-5. As discussed by Cripps & Taylor (1981), for a given CMC, φ_{res} values could increase with increasing degree of induration (or decrease with increasing degree of weathering), since aggregation by diagenetic bonds could lead to increases in particle size and decreases in platyness. The resulting φ_{res} values are also expected to vary with particle shapes, as discussed in Section 2.1.

Although the correlations identfied above are subject to uncertainties, they still represent a useful starting point for preliminary choice of parameters before detailed laboratory testing becomes available. The correlation with CMC may be least uncertain than with the other indexes, as CMC is less affected by sample preparation methods. The degree of induration (or weathering), which governs the amount of 'effective' clay minerals, may be introduced and adequately characterised to enhance the correlation.

3 PILE-SOIL INTERFACE FRICTION ANGLE & INSTALLATION EFFECTS

Interface shear strengths of drilled and grouted, bored or rock socketed piles are often governed by the roughness conditions along the borehole walls and the properties of surrounding rocks. Such pile-soil interfaces can be typically assumed as fully rough and the interface fricion angles (δ) are directly relevant to φ_{res} as interface shearing commonly migrates into the surrounding rock mass, rather than along interface surface.

In comparison, interface shear mechanism involved in driven piles is more complicated as it varies between soils and soft rocks and depends also on particle size distribution and mineralogy. Earlier studies on soils often express interface efficiency, which is defined as $\tan(\delta_{res})/\tan(\varphi_{res})$ ratio, as a function of interface roughness (R_a) (Rabie, 2016) or nomalised roughness R_a/D_{50} (Uesugi and Kishida, 1986). However, the latter is less applicable for fine-grained soils. When particles are relatively small, particle shape and mineralogical compositions play more significant roles.

Estimation of δ_{res} for coarse-grained soft rocks, such as sandstone, may be more straighforward than for fine-grained soft rocks. Coarse-grained rocks are expected to be shattered when pile tip advances and δ_{res} values are expected to vary as a function of normalised pile surface roughness. The interface friction ratio of a fully rough surface may be expected to resemble the soil-soil μ_{res} value of massive minerals, as shown in Figure 1.

When piles are driven into fine-grained soft rocks, the resulting δ_{res} value is typically less certain. George et al. (1976) highlighted the difficulty in predicting the behaviour of H-section piles in slaty mudstone of moderate strength. A 'skin' of clay from weathered rock can form on pile's surface which might be cleaned off subsequently when pile advances to greater depths or enters stronger rocks. If a clayey 'skin' is formed along pile surface, the φ_{res} (hence δ_{res}) values can change significantly depending on the clay composition, which in turn is governed by the minerology of the fine-grained soft rocks, and on how easily the aggregates can be de-aggregated during pile driving.

The pile-driving process may also influence the δ_{res} values, due to the aggregrated fabric of the rocks, as discussed in Section 2.3. For example, driving induced shearing cycles may release more clay particles along the pile-soil interface and hence lead to lower δ_{res} values, which depend also on the nature of the clay minerals. As observed by Chandler (1969) and Tiwari and Marui (2005), large strain shearing may break down aggregates and release clay particles.

As such, rock interface shear tests and index property tests (particularly XRD analysis) are recommended to address these uncertainties. Note that XRD test can determine specimen's mineralogical composition and crystalline structure, which were found to have major impact on the φ_{res} values of fine-grained soft rocks, as discussed earlier.

Figure 6 compares the assembled φ_{res}-I_p database of clays and indurated fine-grained soft rocks with the δ_{res}-I_p database of clayey soils against (rough) steel by Jardine et al. (2005). Both datasets indicate similar trends for φ_{res} and δ_{res} against I_p, although apparently the clayey soils considered by Jardine et al. (2005) may be dominated by low activity clay minerals.

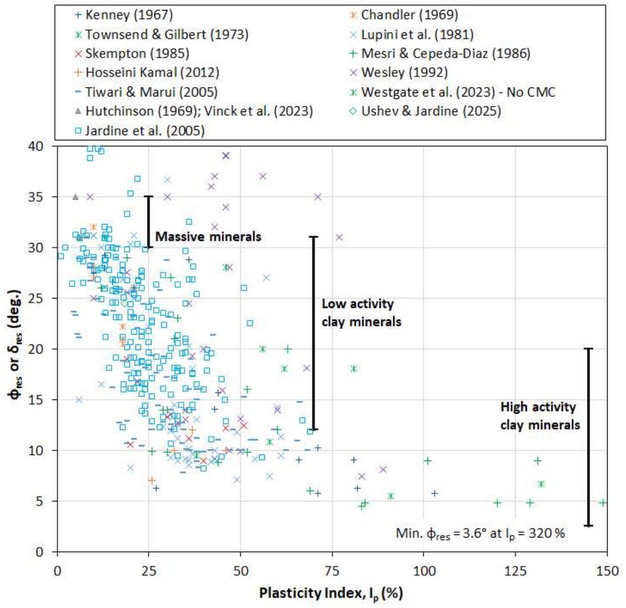

Figure 6. Minerology-based refinement of δ_{res} and φ_{res}

4 LABORATORY MEASUREMENTS OF FRICTION ANGLES OF SOFT ROCKS

Laboratory RS and ISB tests applying project-specific soil and stress conditions as well as pile installation methods are performed routinely to measure and refine φ_{res} and δ_{res} values. Jardine et al. (2005) set out Bishop RS testing procedures for measuring δ, in which large-displacement fast shearing stages are incorporated to reproduce pile driving effects.

Although horizontal displacements achieved in routine monotonic ISB tests are limited, the shearing can be applied in a cyclic manner to achieve large shear displacements. By this means, ISB testing can partly simulate the relatively large displacements experienced in pile driving process, and the periods of re-consolidation and subsequent cyclic loading conditions. This may offer a simpler alternative to the RS tests, which are especially challenging to perform for rock specimens. Furthermore, constant normal stiffness conditions can be applied in shear box tests (Johnston et al., 1987) to measure δ_{res} reliably and model pile-soil interaction mechanism particularly under axial cyclic loading conditions.

As can be inferred from the foregoing discussion, relatively more tests may be required for driven piles in fine-grained soft rocks than in coarse-grained rocks due to the uncertainties associated with pile installation effects in combination with variable degrees of weathering.

5 SUMMARY AND CONCLUSIONS

This paper reports a literature summary with an assembled database to enable the estimation of φ_{res} (and δ_{res}) of clayey soils and soft rocks from index properties. It clarifies that φ_{res} values depend primarily on soil constituents and to a lesser extent on pore-water chemistry and effective stress level. The occurrence of turbulent or sliding shear mechanism depends critically on particle shape and mineral type.

While empirical correlation trends for φ_{res} may be identified with clay size fraction, mineral content and Atterberg limits, significant scatter is evident and such correlations should be adopted with caution. Factors such as soil minerology, degree of cementation, and project-specific stress conditions and pile installation methods should be considered in the prelimiary choice of φ_{res} based on index properties.

The assembled database and the literature summary presented in this paper provide useful guidance for developing laboratory testing programmes to firm up and refine soil-soil and soil-interface friction angles for design practice.

AUTHOR CONTRIBUTION STATEMENT

H. Zhou: Data curation, Formal Analysis, Writing- Original draft. **T. Liu**: Investigation, Writing- Reviewing and Editing. **B. Noel and P. Carotenuto**: Writing- Reviewing and Editing,

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