Proceedings of ISFOG 2025
5TH INTERNATIONAL SYMPOSIUM ON
FRONTIERS IN OFFSHORE GEOTECHNICS
Nantes, France | June 9-13 2025

ISBN 978-2-85782-758-0

Estimating fines content directly from CPTU data in saturated natural soils using the I_{pzo} parameter

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ABSTRACT: The I_{pzo} parameter (Ramsey and Tho, 2024) enables Plasticity Index to be estimated directly from Piezocone Penetration Test (CPTU) data - and the potential of the I_{pzo} parameter for improving the reliability of other soil parameter estimates was noted by the authors. This paper utilizes the I_{pzo} parameter – and empiricism - to estimate Fines Content (FC) directly from CPTU data. The reliability of the method has been assessed using a geographically and geologically diverse database extending over three continents, eleven marine sites, and more than fifty soil layers. The results suggest that FC estimates made using the new method are reasonably reliable and particularly useful for assessing layer changes. However, given its empirical nature, a "2-Step" method is employed. In Step-1 (Estimation), FC is estimated directly from CPTU data. In Step-2 (Validation), measured FC values are compared with their complementary estimated values to assess the reliability of the estimates, and whether layer-specific or geotechnical unit-specific corrections factors are needed.

Keywords: Fines Content; I_{pzo}; CPTU; Correlation; Validation

1 INTRODUCTION

1.1 General

This paper presents a proposed new method for estimating Fines Content (FC) from CPTU data. A key component of the new method is the I_{pzo} parameter (Ramsey and Tho, 2024). The new method assumes typical Activity values for offshore soils and typical ratios of Fines Content to Clay Content, for a variety of soil types. However, as soils can vary considerably from what might be considered "typical", the new method comprises two steps. In Step-1 (Estimation), FC is estimated directly from CPTU data. In Step-2 (Validation), measured FC values are statistically compared with their complementary estimated values to assess the reliability of the estimates, and whether layer-specific or geotechnical unit-specific corrections factors are needed.

1.2 Database and Validation Details

The database used for the validation was intentionally geographically and geologically diverse, comprising 114 Fines Content (FC) measurements, with complementary CPTU measurements from more than 50 geotechnical layers/units at 11 marine sites distributed across the Americas, Europe, and Asia. The soils in the database range from coarse sand with gravel, with FC <1%, to highly plastic clays, with FC >99%.

Measured Activity values, defined as the ratio of Plasticity Index to Clay Content (2 μm), were in the range 0.5 to 2.

The horizontal distance between corresponding CPTU and borehole locations was, in all cases, between three and ten metres, which is a typical range for offshore site investigations.

The authors consider that a statistically reliable number of relatively high-confidence validation points offers the best opportunity of assessing the quality of CPTU correlations, and this is best achieved by choosing validation points over depth intervals where the CPTU data indicate relatively uniform soil condition. In this paper, the general conditions for choosing whether laboratory FC measurements should be considered for validation were:

- complementary cone resistance, cone sleeve friction, and pore pressure profiles covering ± 0.35m of the depth of the measured FC value. The primary objective for choosing a validation depth range of ± 0.35m was to have sufficient data points for reliable assessment of soil uniformity (more than 30 points would be collected at a standard penetration rate of 20mm/s) whilst avoiding choosing validation points that were close to layer boundaries or significant changes in soil conditions. A validation depth range of ± 0.35m also provided some flexibility for small lateral variation in soil layering between the borehole and CPTU locations. Additionally, 0.35m is equivalent to 8 to 10 cone diameters for standard 10cm^2 and 15cm^2 piezocones, which is in good agreement with the maximum expected influence, of a change in soil conditions below the cone tip, on the measured cone resistance (Lee, 1989).

- After some experimentation, it was concluded that it was only necessary to exclude a measured Fines Content value from the validation process, when either the cone resistance or the sleeve friction values over the validation depth range varied be more than 80% over the validation depth range. In other words, to be excluded from validation, either the maximum cone resistance or the maximum sleeve friction needed to be more than 80% higher than the corresponding minimum value.

Variations in measured pore pressure were not considered when choosing validation points, because of the greater sensitivity of pore pressure to local variations in soil fabric.

In a few cases, to produce a reasonably uniform distribution of fines content measurements covering a wide range of soil types, the typical validation criteria were slightly relaxed, on a "whole profile" basis – either to enable more validation points to be collected at sites with more variable soil conditions, or to reduce the number of validation points at sites with relatively uniform soil conditions. This process had no impact on the derived formula of the new method.

2 THE NEW METHOD

The new formula for estimating Fines Content (defined as the percentage, by weight, of soil passing a 0.063 mm sieve) is presented in Equation (1):

$$FC\ (\%) = \alpha_{FC} * I_{pzo} * \frac{\left[9.2 - \frac{I_{pzo}}{2}, 3.2\right]_{max}}{\left[log_{10}\frac{Q_t}{2.7}, 1\right]_{max}} \qquad (1)$$

where:

FC is limited to 100%

α_{FC} is a correction factor (default value =1)

The I_{pzo} parameter (Ramsey and Tho, 2024) is calculated using Equation (2):

$$I_{pzo}(\%) = \frac{12 * F_{rt} * \left(1 + B_q\right)^{1.2}}{\left(\frac{Q_t}{3}\right)^{0.3}} \qquad (2)$$

The Q_t and I_{pzo} values are calculated using total and effective vertical stress profiles based on unit weights estimated using Equation (3) proposed by Robertson and Cabal (2010):

$$\frac{\gamma}{\gamma_w} = 0.27.log\left(R_f\right) + 0.36.log\left(\frac{q_t}{p_a}\right) + 1.236 \qquad (3)$$

Symbols used in Equations (1) to (3) are defined in the “Symbols and Terms” section of this paper.

As noted in the introduction, the new method comprises two steps. In Step 1 (Estimation), an FC profile is estimated directly from the CPTU data. In Step 2 (Validation), measured FC values - derived via ISO 17892-4 (2016) - are statistically compared with corresponding FC estimates, and - if considered necessary - layer-specific and/or geotechnical unit-specific correction factors, α_{FC} are developed to assess a statistical best estimate correction. Note that additional FC measurements may be required.

The new method has been validated using CPTU data obtained using only 10cm^2 and 15cm^2 piezocones conforming with ISO (2012) Application Classes 1 or 2. As other cone types and sizes can record different sleeve friction and pore pressure values in the same soils – see for example Ramsey (2021) - the new method is not intended for use with these other cones.

3 RESULTS

3.1 Overall results

Figure 1 presents estimated FC values versus FC measurements, for the 114 data points, highlighting where Δ exceeds ±15%. In this paper, Δ is defined as the percentage difference (Δ%) between an estimated and a complementary measured value and ±15% is the target maximum Δ.

Although there is significant scatter, a clear trend is apparent in Figure 1, with the inset Δ% histogram indicating that the mode of the estimated FC values is within ±5% of the measured FC. Figure 2 presents a Δ% box chart, which indicates that median and mean Δ values are less than 1%, and more than 80% of the estimated FC values are within the target maximum Δ of ±15%.

3.2 Comparison profiles

Figures 1 and 2 are useful for illustrating general trends and errors, but the operational performance of the method is better illustrated on comparison profiles at individual sites. Consequently, Figures 3 and 4 present comparison profiles from four globally distributed sites. At each site the following information is presented:

- An estimated FC profile, together with measured FC values.
- An adjacent Δ% profile illustrating the difference between complementary measured and estimated values at validation elevations.
- A Δ% box chart, with tabulated summary statistics, to enable quantitative evaluation of the overall reliability of the FC estimations at each site.

The following observations relate to Figure 3:

- The FC estimates at both locations (Site A and Site B) seem visually reasonable.
- The complementary adjacent Δ % profiles do not indicate any layers with obvious systematic differences between estimated and measured FC values.
- The quantitative Δ box charts, at the base of each profile indicate that the median and mean Δ values are less than ±2% and that more than 80% of the estimated values are within ±12% of the measured values.

The following observations relate to Figure 4:

- The FC estimates at Site C and Site D seem generally reasonable. However, there are some zones of consistently lower reliability.
- At Site C, the box chart indicates that the median Δ is +9.1% and P90 is 22.9%, which suggest that a correction factor, α_{FC}, may be needed in one or more soil layers. Examination of the Δ% profile suggests 3-8m, and below 30m, might need correction factors (subject to a review of the measured data).
- At Site D, the box chart indicates that the median Δ is -4.5% and P10 is -18.5%. Examination of the profile indicates some potentially spurious values, but no obvious layers with a systematic bias of Δ. Therefore, it may be impractical to apply a correction factor to improve estimations at this site.

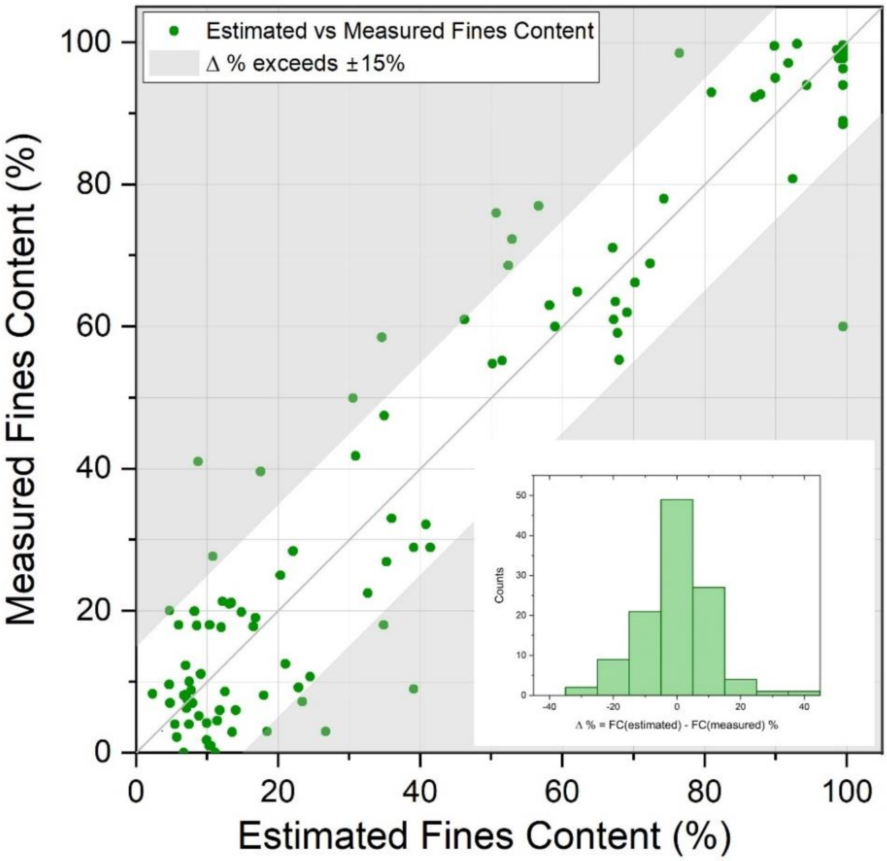

Figure 1 – Estimated versus Measured Fines Content (114 validation points – more than 50 soil layers-3 continents)

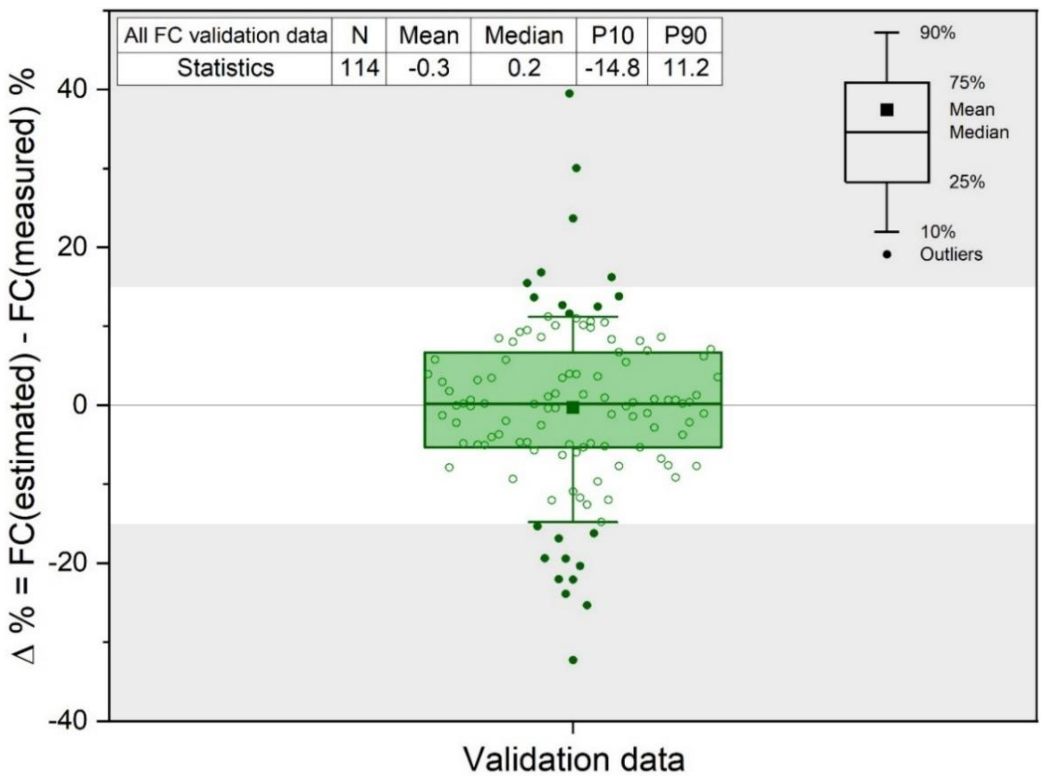

Figure 2 – Δ % Box Chart and key statistics (114 validation points – more than 50 soil layers-3 continents)

4 DISCUSSION

The profiles presented on Figures 3 and 4 suggest that FC estimates made using the new method follow the trends of the measured FC values, and can be used to help identify layer or unit changes. However, in some cases, layer-specific or unit-specific correction factors (α_{FC}) might be required.

Where there are clear discrepancies between the estimated and predicted values, the soil descriptions and/or borehole log sometimes provide an explanation. For example, in "Zone 1" at Site A on Figure 3, the measured FC values suggest transitional soils, whereas the estimated FC is 100%. However, it is notable that the corresponding Site A borehole log (not shown) indicated a thin clay layer at similar depth, so the discrepancy is considered likely to be due to lateral soil variability.

Lateral and vertical soil variability can make it difficult to validate the reliability of FC estimations. For example, in "Zone 2" at Site A on Figure 3, the estimated FC profile is very variable, and this was supported by a description of interbedded sands and clays on the corresponding borehole log. So, although the "Zone 2" FC estimates appear to be qualitatively reasonable, quantitative validation would be challenging. Another potential explanation, for an unreliable estimate is that the measured FC value may not be from a laterally continuous soil layer. Possible examples of this issue may be seen on Figure 4 (in "Zone 3" at Site C, and in Zone 4 at Site D). Consequently, additional laboratory testing is recommended, before deciding whether a correction factor is justified.

The Robertson and Cabal (2010) formula for estimating unit weight is another potential cause of error, but is considered unlikely to be significant. Furthermore, if needed, these errors could be removed by substituting a characteristic unit weight profile derived from laboratory measurements.

Taking account of the discussion above, the authors consider that, if an estimated FC profile had been used to identify "appropriate depths" for complementary FC measurements then, at almost all the sites in the database, the reliability of the validation could have been improved. In this context, "appropriate depths" would preferably be at least 1.5 metres from any soil boundary, with less than 10% variation in FC estimates over ±0.5 metres.

If, after allowing for the error sources above, there is still a significant and obvious systematic bias of Δ % - for example in "Zone 5" on Figure 4 - then a statistical approach is recommended for assessing a best estimate correction factor, α_{FC}. For this task, at least six FC measurements are recommended per geotechnical unit, with more measurements likely to be required in variable soil conditions.

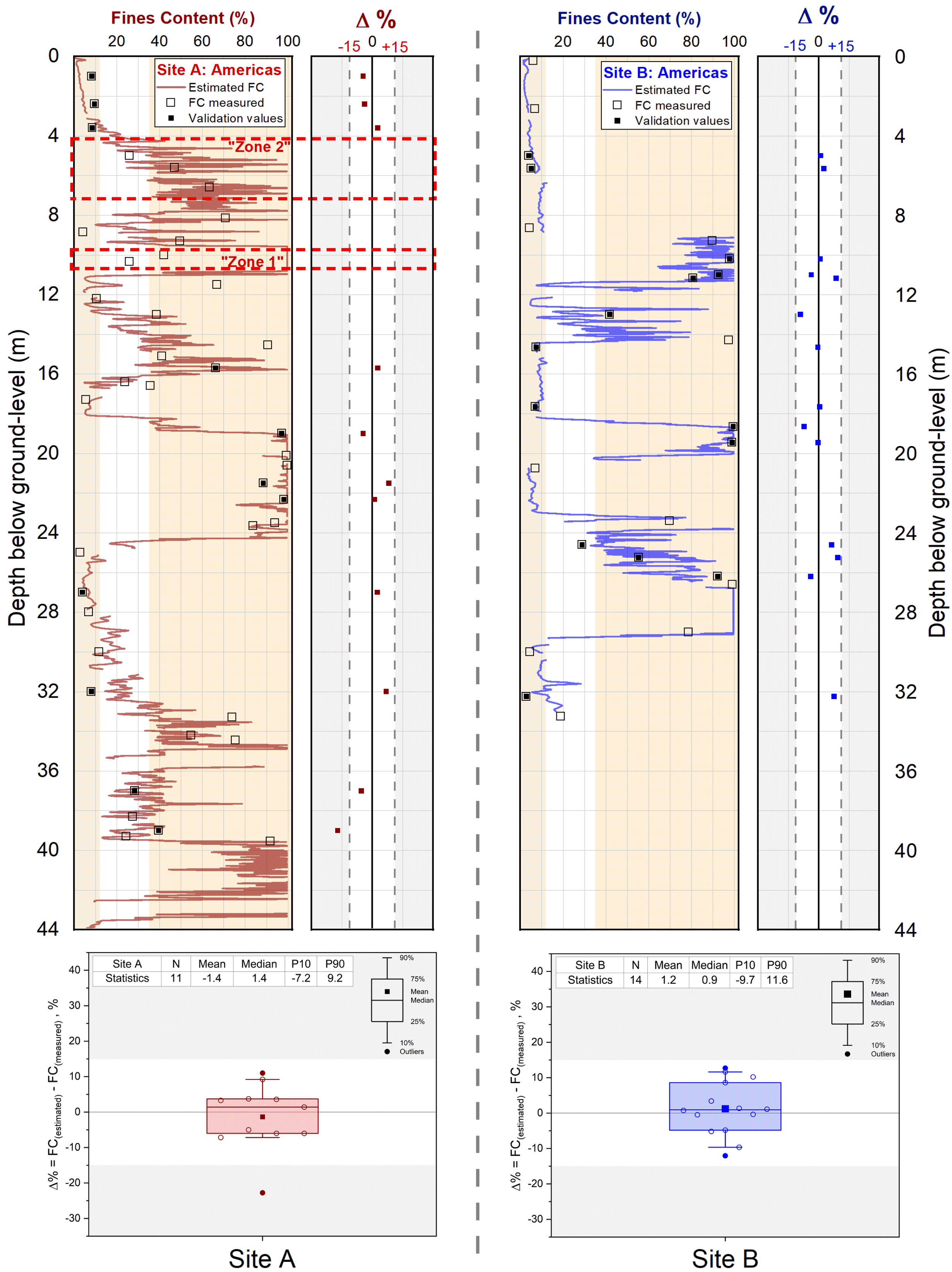

Figure 3 – Two example profiles at sites with variable soil condition – both sites offshore Americas

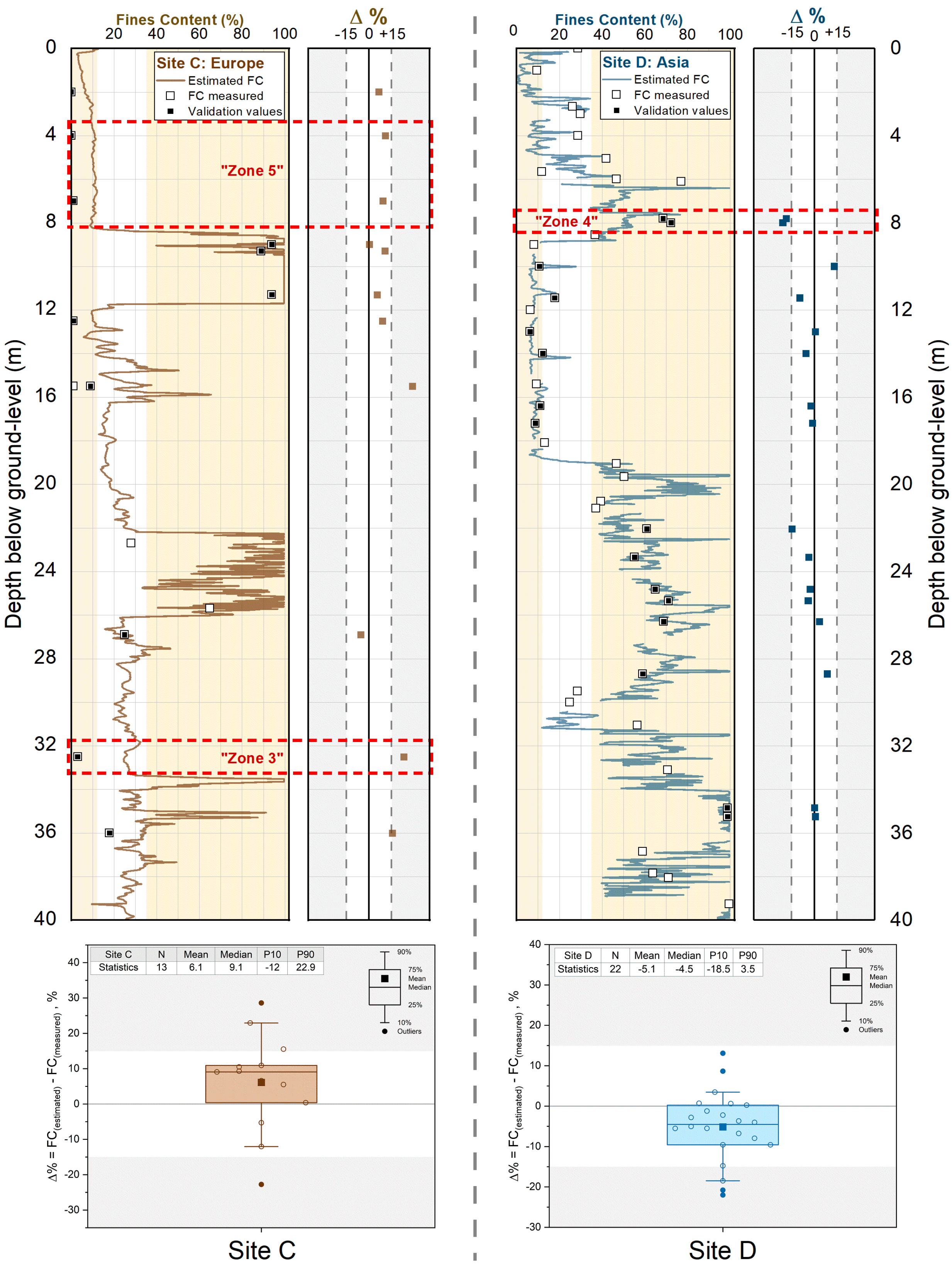

Figure 4 – Two example profiles at sites with variable soil conditions - offshore Europe and offshore Asia

5 CONCLUSIONS

This paper presents a new 2-Step method for estimating Fines Content from CPTU data. In Step 1 (Estimation), an FC profile is estimated directly from the CPTU data. In Step 2 (Validation), measured FC values are statistically compared with corresponding FC estimates, and - if considered necessary - layer-specific and/or geotechnical unit-specific correction factors, α_{FC}, are developed to assess a statistical best estimate correction. At least six Fines Content measurements are recommended per geotechnical unit, with more measurements likely to be required in variable soil conditions.

If comparisons of corresponding estimated and measured FC values indicate a significant systematic Δ, the following questions should be considered before deciding on whether a correction factor is needed:

- Can discrepancies between estimated and measured FC values, be explained via detailed scrutiny of the borehole log and/or soil descriptions?
- Will application of a correction factor lead to a measurable increase in foundation reliability and/or a measured decrease in foundation cost?

Poor reliability estimations may also be an indicator of particularly challenging soil conditions. Ramsey and Tho (2024) note the following examples:

- soils with Activity, A > 2
- soils with sensitivity > 16
- cemented soils
- structured soils, e.g. fissured, blocky
- gassy soils

To optimise the validation process, the authors recommend using an estimated FC profile to identify “appropriate depths” for complementary FC measurements. In this context, “appropriate depths” would preferably be at least 1.5 metres from any soil boundary, with relatively uniform FC estimates (±10% variation) over ±0.5m.

AUTHOR CONTRIBUTION STATEMENT

Nick Ramsey: Conceptualization, Methodology, Data curation, Formal analysis, Writing- Original draft.
Kee Kiat Tho: Formal analysis, Writing- Reviewing and Editing.

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SYMBOLS AND TERMS

α_{FC}	FC correction factor
α_{fs}	net area ratio of friction sleeve
Δu	pore pressure minus hydrostatic pressure
γ	total unit weight of soil
γ_w	unit weight of water
σ_{vo}	total vertical stress relative to ground-level
σ_{vo}'	effective vertical stress relative to ground-level
B_q	excess pore pressure ratio, $\Delta u / q_{net}$
f_s	measured sleeve friction
f_t	corrected sleeve friction = $f_s + \alpha_{fs} * u$
F_{rt}	normalised corrected friction ratio, f_t / q_{net}, %
I_p	Plasticity Index, %
I_{pzo}	Plasticity Index estimated directly from piezocone data, %
Mean	the arithmetic average of the validation values
Median	the middle value of the validation values (by linear interpolation, if necessary)
P10	10% percentile
P90	90% percentile
p_a	atmospheric pressure in the same units as q_t
q_t	total piezocone resistance relative to seafloor (ground-level) = $q_c + (1-\alpha) * u$
q_{net}	net piezocone resistance = $q_t - \sigma_{vo}$
Q_t	normalised cone resistance = q_{net} / σ_{vo}'
R_f	friction ratio, f_s / q_t, %
u	pore pressure at cone shoulder