LOUISIANA TRANSPORTATION RESEARCH CENTER

Technical Summary

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Internal Friction Angle of Sands with High Fines Content

Introduction

The internal friction angle (Φ) of soils is an important parameter used in the design of infrastructures. It can be determined either by conducting laboratory tests on retrieved soil samples, such as direct shear tests (DST) and triaxial tests, or from correlations with in-situ test results. Unfortunately, it is very difficult to obtain undisturbed sandy soil samples. As a result, the Φ for sandy soils cannot be accurately estimated directly from laboratory tests. Therefore, correlations are necessary to estimate the values of Φ for sandy soils from in-situ tests, such as the standard penetration test (SPT) or the cone penetration test (CPT).

Several correlation equations and charts were developed in the literature for clean sand using SPT or CPT data. However, sand soil mixtures (with fines content), such as silty sands and clayey sands, are more frequently encountered on project sites than clean sand soils. The shortcoming of available Φ-SPT and Φ-CPT correlations is that the effect of fines content on the Φ is not properly considered. The Louisiana Department of Transportation and Development (DOTD) uses the correlation recommended by the Federal Highway Administration (FHWA) to obtain the Φ for sandy soils, which are only developed for clean sand with fines content <5%. This shortcoming creates many problems in DOTD geotechnical engineering design for sand with fines content. Several projects featuring piles driven in sandy soils with a high percentage of silt or fine sand that were tested in the field have lower resistance than the anticipated design values, which led to the underestimation of pile lengths. This is primarily due to higher Φ values estimated from the current Φ-SPT correlations.

Therefore, there is a need to evaluate the effect of fines content and fine sand content on the Φ value for the silty/clayey sand or fine sand typically encountered in Louisiana soils. The effect of fines content and fine sand content on the interface friction angle (Φ) between the sandy soils with fines content and concrete piles need to be investigated as well. Furthermore, there is a need to investigate the threshold of fines content beyond which the sand soils mixed with fines (silt and clay) behave differently than clean sand (i.e., cohesive soil behavior).

Objective

The primary objectives of this study were to:

- Evaluate the effect of fines content and fine sand content on the internal friction angle (Φ) of sand soils mixed with fines typically encountered in Louisiana.
- Evaluate the effect of fines content and fine sand content on the interface friction angle (δ) between sand soils mixed with fines and concrete interface.
- Determine the threshold of fines content beyond which sand soils mixed with fines (silt and clay) will behave differently than cohesionless soils.

Scope

In this study, the small direct shear test was performed to evaluate the internal friction angle (Φ) for sand soils mixed with fines, while the large direct shear test was conducted to evaluate the interface friction angle (Φ) between sand soils mixed with fines and the concrete pile surface. Different fines contents (silt/clay), relative densities, moisture contents, soil particle shapes, gradations, and confining stresses were considered to determine the effect of these parameters on the values of the Φ and δ. The results of these tests were used to develop regression relationships between relative density, fines content, moisture content, and the Φ (or δ). These relationships were used to modify the correlation equations and charts used to evaluate the Φ of sand using the standard penetration tests (SPT) to consider the contribution of the fine contents. A statistical regression analysis and artificial neural network (ANN) were used to develop equations and models to estimate the Φ considering the fines content and other parameters.

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Methodology

To achieve the objectives of this study, a comprehensive laboratory testing program, including both small-size and large-size direct shear tests, was performed on sand soil mixed with different fines contents. The small direct shear tests were performed to evaluate the internal friction angle (Φ) for sand soils mixed with different fines contents (10% to 70%), different relative densities, and different moisture contents, while the large direct shear tests were conducted to evaluate the interface friction angle (δ) between sand soil mixed with fines and the concrete pile surface. Four different soils (Soil 2 to Soil 5) with high fines contents were mixed with the original sand soil (Soil 1) at different fines contents and different water contents. The SPT(N_{60}) values for the different soil mixtures were obtained at three normal stresses (10 psi, 16 psi, and 22 psi) using the original Schmertmann chart based on relative density. The values of SPT(N_{60}) versus the Φ for the different soil mixtures were used to modify the Schmertmann chart to incorporate the effect of fines contents (see Figure 1).

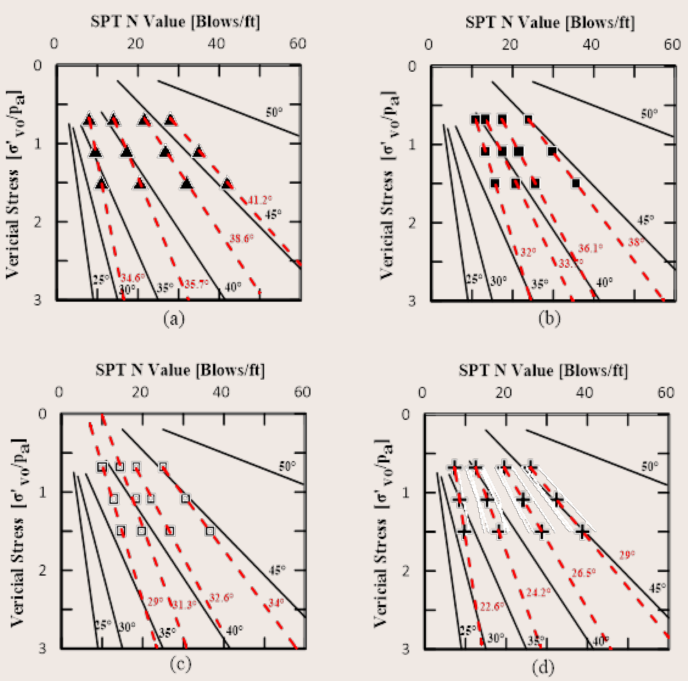

Figure 1. Modified Schmertmann chart for the combined Soil 1 and Soil 3 mixtures at different fines contents: (a) 10% fines, and (b) 30% fines

Non-linear regression analyses were performed to modify the Schmertmann and Japan Road Association (JRA) Φ-N_{60} models to estimate the internal friction angle (Φ) of sand-fines mixtures based on silt content, fine sand content, water content, and roundness. ANN models were also developed to estimate the Φ of sand-fines mixtures. Two problematic sites in Louisiana (Boeuf River Bridge and Tangipahoa River Bridge replacement sites) with a high percentage of fines (primarily silts) were used to verify the developed regression equations.

A reduction factor (Ψ) was introduced to account for the effect of silt and fine sand contents, which represent the ratio between the interface coefficient of friction [tan(δ)/tan(ϕ)] for clean coarse/medium sand and sand with fines content, and two equations were introduced for calculating Ψ.

Results from the literature and this study were explored to provide insight into factors governing the critical threshold of fines content and guidelines to evaluate the threshold of fines content (silt or clay) beyond which the sand soils mixed with fines will behave as silty or cohesive clayey soils.

Conclusions

- The values of the internal and interface angles (ϕ, δ) were found to decrease when increasing fines content (mainly silt content), increasing fine sand content, and increasing moisture content, and to decrease when decreasing the relative density.
- The ϕ corresponding to SPT(N_{60}) values for the different soil-fines mixtures are lower than those obtained from the original Schmertmann chart or JRA equation. The SPT-ϕ chart was modified to include the effect of fines contents on various sand-fines soil mixtures.
- Non-linear regression models were generated to modify the Schmertmann and JRA correlations for sand-fines mixtures based on silt content, fine sand content, water content, and roundness.
- Two equations were developed to calculate the reduction factor [Ψ = tan(δ)/tan(ϕ)] that accounts for the effect of silt and fine sand contents. The results suggested that a sand mixture with approximately 60% silt or approximately 20% fine sand will reduce the interface coefficient of friction by ~80% of the value for clean sand [$\Psi_{(Clean\ sand)}$].
- The modified Schmertmann and JRA ϕ-N_{60} models for the two problematic sites gave good estimates of the ϕ for sand-silt mixtures, with an error ≤5% for the Boeuf River Bridge replacement site and an error <±10% for the Tangipahoa River Bridge replacement site.
- The threshold of fines content (F_{thr}) beyond which the sand soils mixed with fines will properly behave as fine-grained (FC) soils is 35%. For sand soils with FC <25%, the sand-fines mixture will properly behave as sand soil. However, for sand soils with 25%<FC<35%, the sand soil will behave within a transitional shearing mode that contains both sliding and turbulent shearing simultaneously.

Recommendations

- It is recommended that DOTD geotechnical design engineers utilize the modified Schmertmann and JRA models of ϕ-N_{60} correlations and the ANN models developed in this study to estimate the ϕ for sand mixed with fines content for subsurface soil characterization, as well as for analysis and design of pile foundations.
- It is recommended that DOTD design engineers use the values of interface friction angles (δ) estimated using the modified Schmertmann model, modified JRA model, and ANN ϕ-N_{60} correlations and the Ψ reduction factor for the design of piles in problematic sites with high fines content, and that they compare the estimated pile capacities with the measured capacities from pile load tests.
- It is recommended to perform additional experimental work on sand-fines mixtures to more accurately evaluate the threshold of fines content (clay, silt, or both) beyond which the sand soils mixed with fines will behave differently than clean sand. This evaluation should include three criteria: sand mixed with clay fines, sand mixed with silty fines, and sand mixed with clay + silt fines.