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Determination of shear wave velocity of Yangtze Delta sediments using seismic piezocone tests

L.Y. Tong *, H.B. Che, M.F. Zhang, H.S. Pan

Institution of Geotechnical Engineering, Southeast University, Nanjing, PR China

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ABSTRACT

Shear wave velocity is one of the most important parameters in the evaluation of soil dynamic behavior and seismic design of geotechnical structures. In this study, a comprehensive geotechnical in situ and laboratory investigation into the predominantly intermediate soils deposited in the upper Quaternary basin of the Yangtze Delta (YD) was carried out. It is indicated that uncertainty may be introduced when applying existing empirical shear wave velocity correlations from the literatures due to the heterogeneous and highly stratified nature of such sediments, and the issue of change of drained, partially drained and undrained conditions during penetration. The applicability of six existing CPT-V_s correlations for YD mixed soils, relied on direct CPT measured data or other indirect parameters incorporated, has been first compared and evaluated. The results show that all the selected correlations tend to be biased to varying degrees, demonstrating the need for a YD-specific V_s prediction correlation. Hence, new prediction models are proposed through multiple linear regression based on the YD SCPTU database, which relies on CPT-based variables (q_t, f_s, B_q, I_c, z) and additional laboratory data. The performance of these models is evaluated through comparisons of predicted and measured V_s values. Moreover, several significant influencing factors are analyzed including the initial effective stress, void ratio and pore pressure ratio. It is found that the coefficients of determination are generally larger when cone resistance, overburden stress, void ratio or pore pressure ratio are considered in the regression equations rather than cone resistance solely. Additionally, an appropriate CPT-V_s model is suggested from a practical standpoint, which depends on terms directly measured by the CPT (q_t or q_c, f_s and z). Although situated in the Chinese context, the proposed correlations can be helpful in preliminary estimate of the stiffness at small strain of similar deltaic deposits encountered in other countries.

Introduction

In geotechnical practice, the evaluation of shear wave velocity V_s is primarily important in defining the small-strain stiffness characteristics of soils, commonly expressed in terms of the low-amplitude shear modulus G_0. Shear wave velocity is also useful in earthquake site response analyses as well as in the evaluation of liquefaction potential, site classification, soil unit weight, soil stratigraphy and foundation settlements (e.g., [22,12,39,23].

There are numerous techniques available for obtaining in-situ measurements of V_s, including cross-hole, down-hole, spectral analysis of surface waves and also advanced piezoelectric sensor-based devices (e.g. [39,23]. In the context of hybrid in-situ geotechnical tests [16,30], the seismic cone penetration (SCPTU) test has grown more popular worldwide since it provides an optimization of data collection by combining down-hole shear wave velocity profiles with either conventional penetration measurements.

Although direct measurements of V_s are preferred over estimates, in-situ seismic measurements may not be economically feasible due to the requirements of specialized equipment and technical expertise. Empirical correlations between V_s and cone penetration test (CPT/CPTU) data turn out to be potentially useful for low-risk projects or preliminary design. As a result, many such correlations have been established to determine shear wave velocity from CPT data. Most of them have been developed for sands (drained behavior) or clays (undrained behavior) [32,23].

However, evaluating properties of intermediate soils (e.g., Vs and G_0), such as silty sands, clayey sands, sandy silts, sandy clays, and low-plasticity silts, remains one of the most pervasive and uncertain challenges in geotechnical and geological engineering. Additionally, it is important to underline that V_s correlations based on CPT/CPTU data depend not only on the soil type but also the geological age, cementation, and effective stress state. Empirical interpolation of existing correlations is not always satisfactory.

* Corresponding author.
E-mail address: 101010519@seu.edu.cn (L.Y. Tong).

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The main objective of this paper is to evaluate the applicability of the existing interpretation methods to reasonably estimate shear wave velocity of predominantly intermediate sediments in Yangtze Delta, whose mechanical behavior has been generally found not to fit easily into published frameworks and widely used CPT/CPTU-based correlations, utilizing seismic piezocone testing (SCPTU) data. For this purpose, two anchorage sites of Nanjing Fourth Bridge, which is a suspended bridge crossing over the Yangtze River, were selected in this study. In each site, extensive in-situ SCPTUs were conducted, and DHTs were also complemented to calculate the reference V_s parameters. The predicted V_s from SCPTU tests using different methods was compared with the reference soil parameters obtained from DHT tests. New correlations for such deltaic soils were also developed to estimate G_0 based on the collected SCPTU data.

Test sites and geology

The soil deposits of the Yangtze Delta, which reach depths of approximately 50–60 m, were formed throughout the Quaternary. They are composed of a complex system of interbedded sands, silts, silty clay and gravel sediments. Due to the varying depositional mechanisms and environments, which influenced the evolution of the lower reaches of the Yangtze Delta, the stratigraphy is always complex with silt mixtures and sand mixtures widespread. Such intermediate sediments exhibit significant non-homogeneity, with variation of particle size distribution even in samples only a few centimeters long.

In a typical vertical profile of the Quaternary sediments in this project region, a dual structure can be identified, the top of which is the fine-grained deposition (clay and clayey soils) and the lower part is the coarse-grained deposition (sands and gravel), except the top soil formed by arable land or back filling of only 0.5–1.5 m in thickness. Due to the complex geological history, a transitional zone often occurs, composed of interbedded sands and clays. From the top layer down, the deposit changes in sequence of silty clay, muddy silty clay (occasionally disappear), silt mixtures, sand mixtures and gravel. Of particular note is that a high number of thin layers and unclear soil interfaces, as well as presence of clay seams, lenses, and sand stringers, result in the difficulty to delineate the stratigraphy.

At both sites, the high quality samples of 76 mm diameter were taken at different depths using stainless steel fixed-piston tube samplers below ground level. Once the fixed-piston sampler was withdrawn from the borehole, the soil sample at the end of the tube was excavated for waxing sealing at the both ends.

Fig. 1 sketches a soil profile determined at the sites on the basis of the grain-size distribution, SPT, natural water content. Aterberg limits (W_L, W_P), in situ void ratio (e_0) and overconsolidated ratio (OCR) are also reported. OCR values determined from odometer tests show that the floodplain sediments are under normally-consolidated to slightly overconsolidated condition throughout the profiles. The overconsolidated state at shallow depths, at site A, where the OCR ranges from 3 to 7, is considered to be caused by man-made construction activities, including dewatering, land filling and compacting, etc. At great depths, it is likely that the slightly overconsolidated state results from a combination of aging and removal of overburden soils.

Typical values of void ratio e_0 for Yangtze Delta soils range from about 0.579 to 1.476. For fine-grained soils (silty clay, muddy silty clay), they range between 0.631 and 1.476; for coarse-grained soils (silty sand, fine sand), the majority of e_0 values are somewhat lower and fall in the range of 0.579–1.103.

Testing program and testing results

In this paper, series of SCPTU soundings was performed for site-specific mapping of V_s in conjunction with a conventional downhole series (DHT) in the Nanjing Fourth Bridge Project. The SCPTU tests were carried out adjacent to the boreholes in each site using a standard piezocone (60° apex angle, 10 cm^2 base area, and 150 cm^2 sleeve areas with filter just behind the shoulder) with geophones installed in the cone, to perform the downhole tests. All SCPTU tests were performed at a penetration rate of 2 cm/s, and

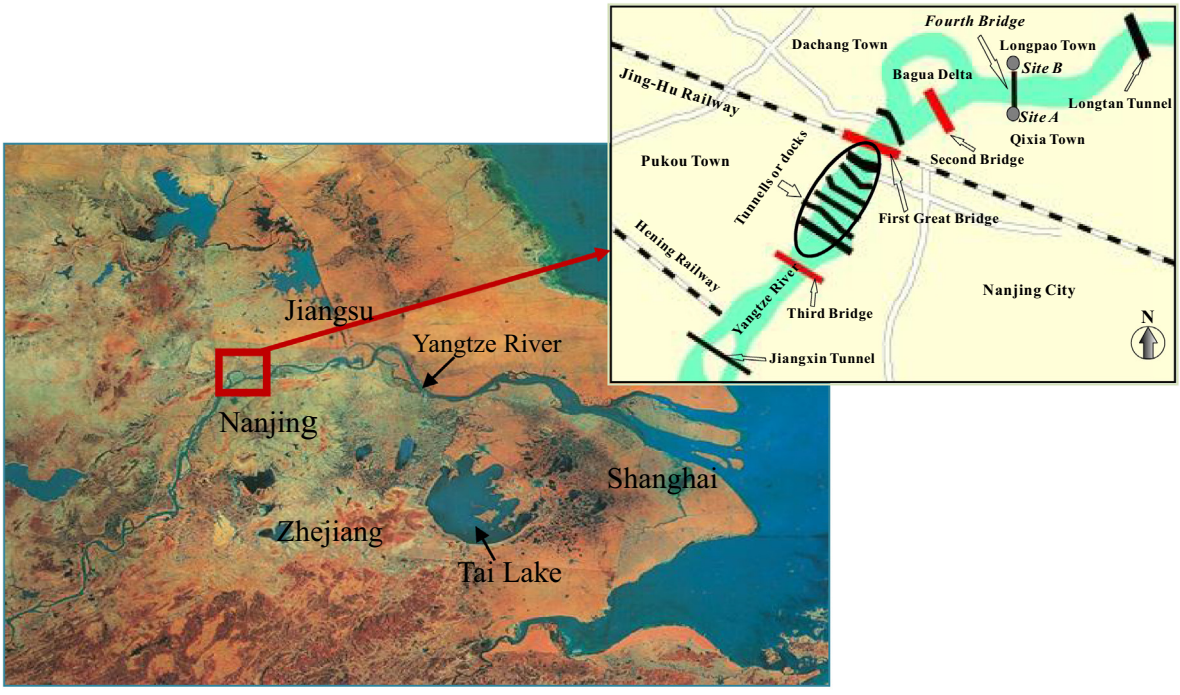

Fig. 1. Aerial map of Yangtze Delta area showing the SCPTU site locations (Nanjing, China).