EFFECT OF LOADING RATE ON THE UNDRAINED LIMITING PRESSURE OF DEEPLY-EMBEDDED PILE

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KEYWORDS

Bearing capacity of clay, loading rate, finite element analysis

ABSTRACT

The soil behaviour is rate-dependent as observed in the laboratory and field tests. The foundations can be loaded at various rates in practice, which will cause (i) a wide range of strain rates, and (ii) inhomogeneous strain rate distribution in the surrounding soil. This may cause difficulties to calculate the undrained bearing capacity of clay using the undrained shear strength from standard laboratory and insitu tests at a reference strain rate. This paper investigates the effect of loading rate on the undrained limiting pressure of the deeply-embedded rigid pile section in homogeneous clay using a rate-dependent constitutive model, the MIT-SR. Results suggest that the bearing capacity is strongly affected by the loading rate, which is consistent with observed data.

1. INTRODUCTION

The soil behaviour is time and rate dependent as observed in the lab tests such as drained creep or secondary compression in 1-D consolidation tests, and the strain-rate effect on the shear resistance in shear tests. In addition, the shear strength interpreted from insitu tests is also affected by the strain rate which can be significantly higher than that in standard lab tests. These rate effects are related to the viscous resistance of soils which is a nonlinear function of strain, strain-rate, stress, and electrochemical reaction. The time and rate dependent soil behaviour has significant impacts on the foundations that are subjected to the long-term dead loads from the structure and to the rapid loading of the environmental factors such as wind and wave. Since the shear strength of soil is rate-dependent, the bearing capacity will also be affected by the loading rate.

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This paper investigates the effect of loading rate on the undrained limiting pressure of the deeply-embedded rigid pile section in clay using finite element analysis and the MIT-SR model. The computed results clearly demonstrate that the loading rate has significant effect on the undrained bearing capacity on the clay, which is consistent with the observed test data.

2. DESCRIPTION OF THE MIT-SR MODEL

Model description

The MIT-SR model (Yuan and Whittle 2021a) is a generalised elasto-visco-plastic model to describe the time and rate dependent behaviour of saturated clays in shearing, creep and relaxation, and can explain the controversial hypothesis A and B in a unified framework. The model extends the incrementally linearized elastoplastic framework used by the MIT-S1 model, but introduces a generalized hysteretic formulation and a physically-based evolution law that attributes the macroscopic viscoplastic strain to an internal strain rate (occurring within mesoscale soil structure) related to the prior strain rate history.

The MIT-SR model was implemented into Abaqus^{TM} through a user-specified subroutine (UMAT), using the explicit substepping algorithm with error control as described in Dong (2023).

Plane-strain compression tests in the bedding plane

Yuan and Whittle (2021b) evaluated the model performance on the resedimented Boston Blue Clay (BBC) in K_0-consolidated triaxial compression and extension tests, at four different constant strain rates ($\dot{\varepsilon}_a = 0.05\%/hour, 0.5\%/hour, 5.0\%/hour, 50.0\%/hour$). Fig. 1 shows the computed K_0-normally consolidated plain strain compression tests on BBC in the horizontal bedding plane (PSK$_0$UC-H) at the same four strain rates.

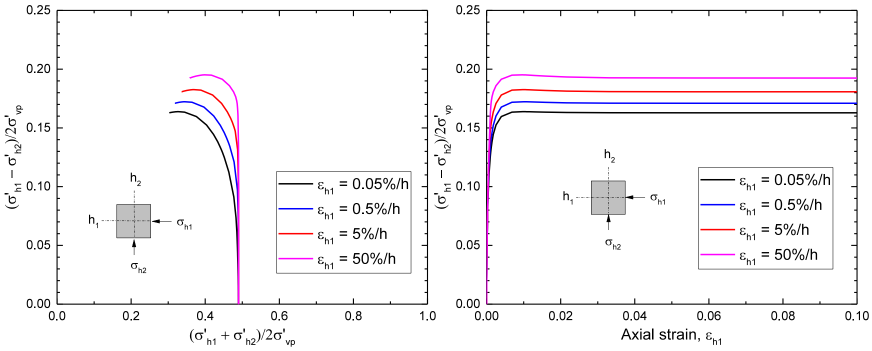

Figure 1 Computed behavior of K_0-normally consolidated plane-strain compression tests of BBC in the isotropic bedding plane at different constant strain rates

3. DEEPLY EMBEDDED PILE SECTION

Finite element model

The undrained resistance of deeply-embedded pile section in homogeneous clay (Randolph and Houlsby 1984), is conducted to investigate the effect of loading rate on the undrained bearing capacity of clay. The plane strain finite element model is shown in Fig. 2, considering that the pile is long. A normalised displacement ($s/D = 0.05$) is applied on the pile/pipe section in six different durations ($0.001hour, 0.01hour, 0.1hour, 1hour, 10hour, 100hour$) from seconds to a few days, representing a wide range of loading rate.

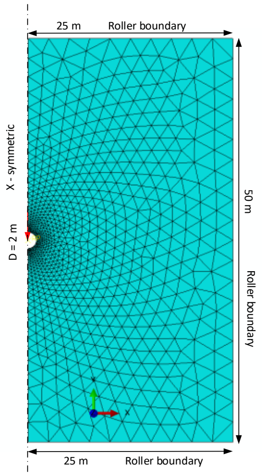

Figure 2 Finite element model of the deeply embedded rigid pile section

Computed results

Fig. 3 shows the variation of the normalised load ($N_p = P/Ds_{u,ref}$) with the normalised displacement (s/D) for the rigid pile section at various loading rates, in the isotropic bedding plane with smooth and rough interface. The undrained shear strength $s_{u,ref}/\sigma'_{v0} = 0.1722$ is selected as the value derived from the plain strain compression test at a reference strain rate $\dot{\varepsilon}_{h,ref} = 0.5\% / hour$ in Fig. 1. For the slow loading case ($0.05\% / hour$) with smooth interface in Fig. 3 (a), the peak resistance factor N_p is slightly below the lower bound solution (Ukritchon 1998). However, the peak resistance factor N_p increases with the loading rate and can be significantly larger than the analytical solutions from the limit analysis. Similar rate-dependent observation can be seen in Fig. 3 (b) for the rough interface case.

The computed results in Fig. 3 has strong practical implication in the design of laterally loaded vertical piles (such as monopiles for offshore wind foundations) that can be loaded in a wide range of rates.

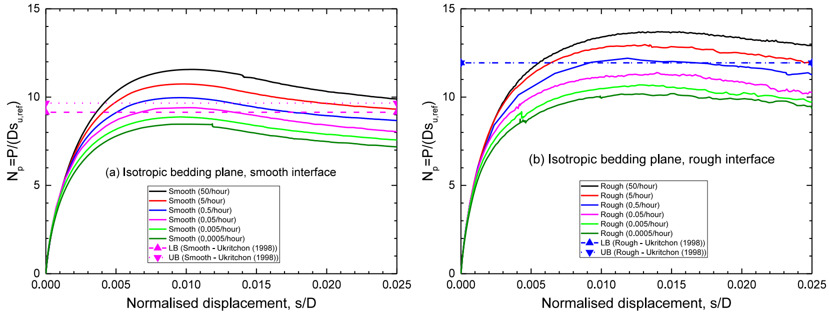

Figure 3 Normalised load-displacement response of rigid pile section in deeply embedded clay at constant loading rates in isotropic bedding plane

4. CONCLUSIONS

The undrained bearing capacity is closely related to the undrained shear strength of clay that is rate-dependent. Using the shear strength obtained from the lab at a reference strain rate may cause uncertainties in calculating the bearing capacity of foundations. Finite element analyses with advanced rate-dependent constitutive models are useful to predict the undrained bearing capacity of foundations at various loading rate conditions.

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