PART II: AN EXPERIMENTAL STUDY INTO THE VISCOUS DAMPING RESPONSE OF PILE-CLAY INTERFACES

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Abstract

Using the laboratory device and the test procedures described in the accompanying paper (Part I), tests were carried out to at Monash University to study the viscous damping response of the pile-clay interface. This paper, which forms Part II of the discussion, reports on the post-test observations of the interface shear surfaces, the procedures for analysing the test results, and the dynamic friction behaviour.

Keywords: dynamic friction; pile-soil interface; viscous damping; dynamic pile testing

1. Introduction

As part of the experimental programme carried out at Monash University, the interface shear surfaces subjected to dynamic shearing are observed. The implications of the post-test observations on the analysis of the test data are discussed and a procedure for analysing the data is proposed. Finally, the dynamic friction behaviour is briefly discussed.

2. Pile-clay interface failure modes

The clay sample was separated from the pile after each series of quasi-static and dynamic tests in order to observe the shear failure mode, the location of the shear failure plane, the shear surface and the fabric of the clay, and the surface condition of the pile (i.e. whether it was clean or covered with clay).

2.1 Quasi-static and dynamic failure modes

The observations of interfaces subjected to quasi-static and dynamic shearing are summarised in Table 1.

For a particular pile-clay interface, the shear mode and the physical characteristics of an interface subjected to the dynamic test were different from those of the equivalent interface subjected to the quasi-static test.

Essentially three modes of dynamic shear failure could be identified. Mode 1 occurred when the interface involved a smooth pile surface and a low or medium plasticity clay. Mode 2 occurred when the interface involved a rough pile surface and medium plasticity clay. Mode 3 shear occurred when the interface involved a smooth surface and high plasticity clay. It is possible that for a clay with plasticity intermediate between the "medium" (I_p=20%) and the "high" (I_p =37%) sheared against a smooth pile, mixed mode of Modes 1 and 3 would result.

Table 1 Comparison of static & dynamic shear failure modes

Interface	Description of quasi-static shear surface	Description of dynamic shear surfaces	
Low and medium plasticity clay-Smooth pile surface	• Shearing occurred between the pile surface and the clay specimen • Clay fabric was homogeneous – smooth and polished in appearance, with minute striations orientated in the direction of shear and without sign of remoulding	Failure mode 1	• Shearing occurred between the pile surface and the clay specimen • Clay fabric was inhomogeneous: varied from sections with discontinuous residual shear surfaces with rough appearance and sections with striations disrupted by very small shear surfaces to sections were smooth in appearance
Medium plasticity clay-Rough pile surface	• Shearing failure occurred between the pile surface and the clay specimen • Clay shear surface was rough and imprinted by the large asperities of the rough surface – clay surface deformed according to the shapes of the asperities	Failure mode 2	• Shearing occurred between the smeared rough pile and the clay specimen • Clay shear surface was imprinted by the large asperities and had deep striations created by the ploughing action of the asperities
High plasticity clay-Smooth pile surface	• Shearing occurred partially within the clay and partially between the pile and the clay specimen • Clay fabric was inhomogeneous: varied from sections where clay adhered to the pile surface and sections where clay flowed in the direction of shear to sections where the surface was smooth and polished	Failure mode 3	• Shearing occurred between the intact clay specimen and a thin layer of clay that adhered to the pile • Clay fabric inhomogeneous: varied from sections where clay adhered to the pile surface to sections where shear surface of intact clay was rough

2.2 Implications for the normalisation of dynamic friction

The quasi-static friction is required to normalise the dynamic friction to obtain the strength ratio, which is used as a measure of the degree of strength increase due to viscous damping. However, because of the physical differences in the clay and the pile surfaces during the quasi-static test and the dynamic test, the quasi-static friction measured from the quasi-static test could not be used to normalise the dynamic friction measured from the dynamic test. The possible exception is for the very first cycle of each dynamic test sequence because the physical characteristics of the interface at this stage might be closest to the characteristics of the interface during the quasi-static test because the pore water pressure, remoulding, pile-smearing would be expected to be least at the end of the first dynamic test cycle, and because the change in fabric of the shear surface of the clay is not likely to vary the interface friction.

It was therefore necessary to develop a reasonable and independent method of estimating the quasi-static friction associated with the dynamic friction for all the dynamic tests at various test cycles and various applied normal stresses.

2.3 Procedure for obtaining quasi-static interface friction associated with dynamic test

Based on a particular dynamic test record, the quasi-static friction can be defined as the friction corresponding to near-zero pile velocity towards the end of the dynamic event; this definition of the quasi-static friction is illustrated in Figure 1. The appropriate point to be selected on the interface dynamic friction curve is the point immediately before the pile became stationary (namely when the interface shear force was still mobilised). Since the dynamic load cell works on the basis that voltage is only registered when there is an applied differential force, the load cell starts to discharge voltage when the carriage is stationary. In all cases, the occurrence of zero carriage velocity coincides with a characteristic plateau followed by erratic oscillation in the dynamic load response, as shown in Figure 1. This characteristic of the dynamic load cell helps in identifying the aforementioned point.

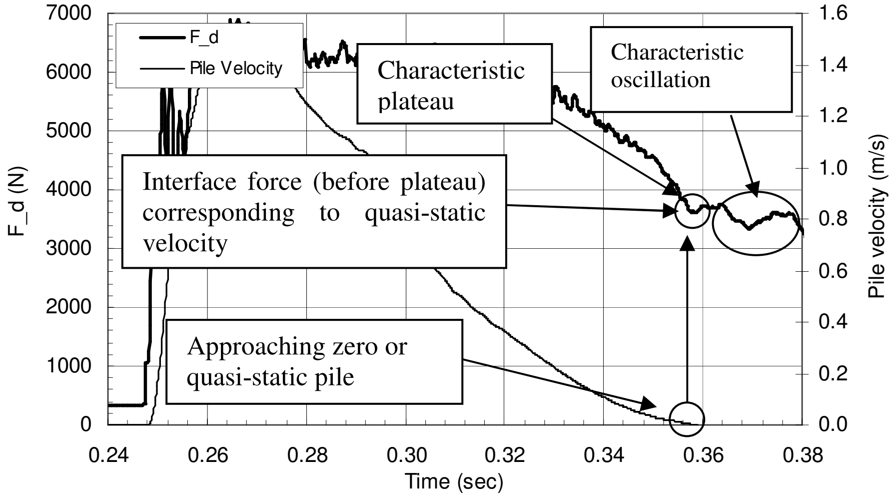


Figure 1 The definition of the quasi-static friction from a dynamic test

Given the consistent characteristic of the dynamic load cell response, a procedure can be developed to determine the quasi-static friction. The start of the characteristic plateau (which is followed by the characteristic oscillation) in the dynamic force curve (labeled F_d) can be identified and the quasi-static friction corresponding to the time immediately before the pile became stationary can be defined. Whilst it would be desirable to compare the velocity corresponding to the quasi-static friction obtained using the procedure with the quasi-static shear rate, the velocity could not be reliably determined because of its minute value and the limited accuracy of the velocity deduced from the measured acceleration.

It has been discussed in Section 2.2 that the development of shear-induced pore pressures, the remoulding, and for Modes 2 and 3, the pile-smearing after the first test cycle in the dynamic test sequence are likely to be insignificant. Therefore, it could be expected that the deduced quasi-static friction associated with the first test cycle in the dynamic test sequence is comparable to that measured in the quasi-static test. The two values for the various interfaces tested were found to be comparable and the maximum percentage difference in the strength ratio was less than 10%. The comparison indicates that the procedure for deducing the quasi-static friction is reasonable.

The reasonableness of the estimated quasi-static value was further evaluated by observing the strength ratio (which was based on the estimated quasi-static value) *vs*. pile velocity plot. It was tentatively accepted based on the previous research that the dynamic friction increases with increasing velocity; therefore, the strength ratio must increase from a value of 1.0 to a higher value as the velocity increases. Indeed, this was found to be the case for all the strength ratio *vs*. velocity plots which will be later presented.

Given the reasonableness of the procedure, the quasi-static friction associated with each dynamic test cycles was estimated using the proposed procedure.

3. Dynamic pile-clay interface friction

In order to determine the dynamic response of the pile-clay interface, the dynamic records are analysed for dynamic effects.

3.1 Velocity-dependence

Analyses of the dynamic test records showed that the dynamic friction for the pile-clay interface is greater than the quasi-static friction and is velocity-dependent. This is consistent with the findings from previous studies (e.g. Dayal and Allen, 1975; Heerema, 1979; Litkouhi and Poskitt, 1980; Benamar, 1999).

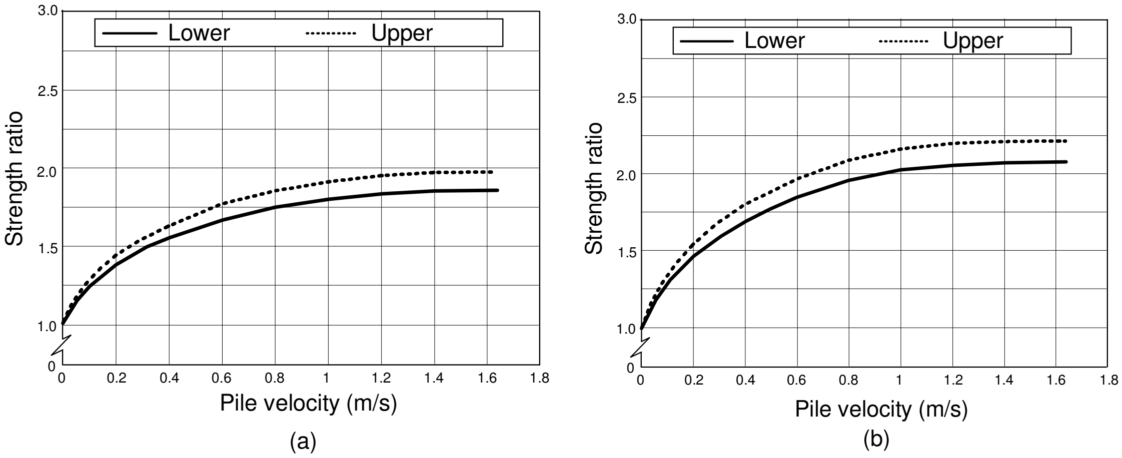
3.2 Strength ratio-velocity responses

Given that the dynamic interface friction is dependent on the shear rate or the pile velocity, the dynamic response is best presented using a plot of the normalised dynamic friction or the strength ratio vs. the pile velocity. The plots, which contain experimental scatter, have been drafted for the sake of presentation. The strength ratio-velocity responses for a pile-clay interface with Mode 1 failure shown in Figure 2. (The responses for interfaces with Modes 2 and 3 failure have the same functional form.)

As mentioned in the accompanying paper (Part I), three consecutive tests were performed for a particular boundary condition; the “lower” and “upper” labels relate to the lower bound and the upper bound of the responses for the consecutive tests. As indicated by the upper and lower bounds, the strength ratio-velocity responses associated with the three consecutive tests vary from each other in the magnitude of the strength ratio. It was found that the strength ratio-velocity response obtained in this study could be best-fitted with the exponential function of the form, $\alpha(1\text{-}e^{-\beta v})$. It is noted that the parameter α is unitless, whilst β has the unit [s/m]. The α values were between 0.51 and 1.70, whilst the β values ranged between 2.5s/m and 3.5s/m.

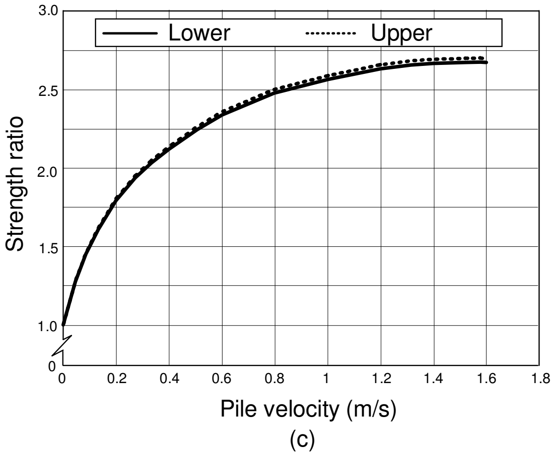
3.3 Magnitude of strength ratio

The values of the strength ratio from the current study are plotted together with those from the previous studies in Figure 3. For convenience, data from Dayal and Allen (1975) have been modelled using the power law with exponent 0.2 although they were originally modelled with two logarithm functions by the researchers. The data from Heerema (1979) were not included because of excessively high strength ratio values.



(a)

(b)



(c)

Figure 2 BallR(σ'_p=325kPa)-Steel: Strength ratio-velocity responses at normal stresses of (a) 250kPa (b) 150kPa (c) 60kPa

It should be noted that the values from previous studies may not be directly comparable to those obtained from this study because of significant differences in the experimental methods.

The reasonableness of the values of the strength ratios suggested by each of the studies can be better assessed by comparing them to those back-calculated from typical monitoring and conventional analysis of dynamic pile testing events. Thus, the upper and lower bounds of the strength ratio-velocity relationships from signal-matching experience, from the current study and from a number of previous studies are plotted in Figure 3. The upper bound value of the linear damping factor recommended in CAPWAP for piles installed in clay is 1.3s/m. Since the lower bound value recommended in CAPWAP is intended for piles installed in sand, a lower bound value of 0.5s/m based on experience in signal-matching analyses is adopted in this exercise.

The values of the strength ratio of Litkouhi and Poskitt (1980) and Dayal and Allen (1975) are generally higher than those encountered in practice. The values of strength ratio found by Heerema (1979) are excessively high compared with those encountered in practice. It is encouraging to note, however, that the values of the strength ratio found in the present study are comparable to those encountered in practice based on the linear model.

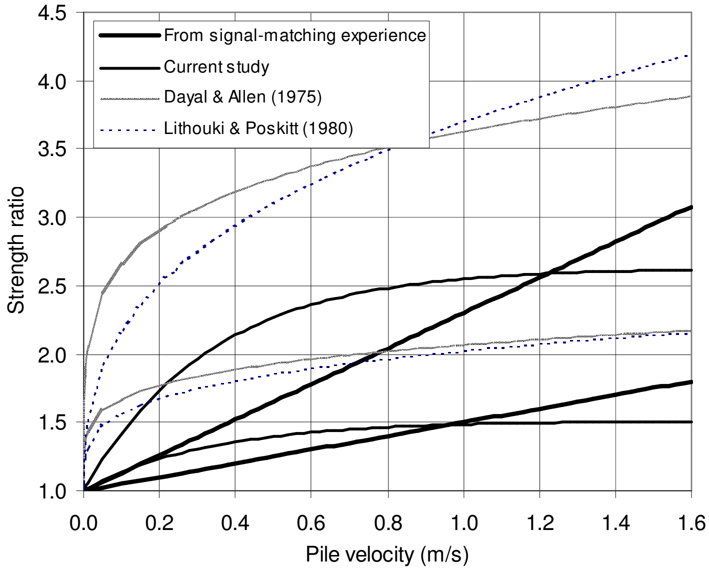


Figure 3 Upper and lower bounds of strength ratio-velocity relationships from current and past research

4. Conclusion

Based on dynamic pile-clay interface tests, it has been shown that the characteristics of shear surfaces subjected to quasi-static and dynamic shearing are significantly different and need to be taken into account in the normalisation of the dynamic friction with the quasi-static friction. For the pile-clay interface, the dynamic friction due to viscous damping has been demonstrated to be dependent on the shear rate, and it has been found that the functional form of the characteristic strength ratio-velocity response can be described by an exponential function.

Acknowledgement

The work described in this paper was funded by the Australian Research Council (ARC). The first author was supported by Monash University scholarships. The support of both ARC and Monash University is gratefully acknowledged.

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