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

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Abstract

Dynamic methods for forecasting the drivability of piles and for verifying the capacity of installed piles are premised on accurate modelling of the dynamic friction due to viscous damping at the pile-soil interface. Whilst various dynamic friction models for the pile shaft-soil interface have been proposed, these models are either not based on experimental data, or based on experimental studies with perceived limitations. In order to develop an improved and physically based viscous damping model, an experimental study has been undertaken at Monash University on the viscous damping response of the pile-clay interface. This paper, which forms Part I of the discussion, reports on the development of a novel test device for simulating the dynamic response of the pile-clay interface in the laboratory and the test programme.

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

1. Introduction

During a dynamic event, the pile head is loaded, forcing the pile shaft downward. In the initial stage, the strain in the soil adjacent to the pile wall is very small, and the pile shaft and the soil move in concert. As the pile moves downward to a critical displacement, the plastic strength of the pile-soil interface is exceeded, resulting in a localized band of high shear strain in the soil at the interface and the pile shaft slips past the soil. During the phase of relative movement between the pile and the soil, the pile-soil interface friction is found to be rate-dependent due to viscous damping.

The rate dependent friction, τ_t, measured during dynamic shearing can be defined as the sum of the viscous damping friction, τ_d, and the static friction, τ_s, and can be expressed as follows:

$$\tau_t = \tau_d + \tau_s \tag{1}$$

The static friction is the friction measured at a reference low shear rate and as such is really a quasi-static friction.

In order to normalize the total friction and to quantify the degree of the viscous damping effect, the total friction is normalised by the static resistance as follows:

$$\frac{\tau_t}{\tau_s} = \frac{\tau_d + \tau_s}{\tau_s} = \frac{\tau_d}{\tau_s} + 1.0 \tag{2}$$

For the sake of convenience, the ratio of the total friction to the quasi-static static strength is referred to as the strength ratio from hereon. The numerical value of the strength ratio quantifies the proportion (or potentially the percentage) of the strength increase. It is significant to note that the dynamic interface strength associated with the pile-driving event relates to the high displacement or the residual strength; as such, the quasi-static interface strength for normalizing the dynamic strength should correspondingly be the high displacement strength.

2. Review of previous research

Based on his experience, Smith (1960) proposed the following model:

$$\tau_t = \tau_s(1 + J_{Smith}v) \tag{3}$$

where

τ_t = total friction [kPa]
τ_s = *instantaneous* static friction [kPa]
v = pile velocity [m/s]
J_{Smith} = Smith damping parameter [s/m]

A modified version of this model is used in CAPWAP® and GRLWEAP® where the instantaneous static friction is replaced with the ultimate static friction. It is noted that the Smith model is not based on experimental studies.

All researchers who have measured the dynamic friction have unanimously found that it is dependent on the pile velocity (v). Dayal and Allen (1975), and Litkouhi and Poskitt (1980) performed penetrometers tests whilst Heerema (1979) performed direct shear tests. They proposed models that are generally in the form of:

$$\tau_t = \tau_s(1 + Jv^N) \tag{4}$$

where

τ_s = *ultimate* static friction [kPa]
J = damping constant [$(\mathrm{s/m})^N$]
N = index [-] with a value of about 0.2

Heerema (1979) suggested that the damping factor increases with decreasing shear strength of the clay. The remaining researchers did not evaluate the dependence of the factor on soil parameters because of insufficient data in the individual studies.

The models which are based on experimental studies appear to have some significant limitations. The studies by Litkouhi and Poskitt (1980) and Dayal and Allen (1975) were based on penetrometer tests performed at constant or near-constant velocity. Based on data presented in Litkouhi and Poskitt (1980), the interface dynamic friction continued to increase with depth such that it was not possible to associate a unique friction value to the particular velocity, and data for tests performed under the same boundary condition were highly variable. The data from Dayal and Allen (1975) showed that a “critical velocity” existed below and above which the strength ratio increased at drastically different rates. The likely causes of these anomalies are hypothesised. The interface behaviour of the trailing pile shaft was apparently dependent on the way the leading tip deformed the soil. Also, the penetration behaviour of the pile tip might have subjected the interface to different normal stresses depending on the rate of penetration, in which case, the strength ratio would be a function of not only the penetration rate, but also of consequent normal stress variations. Thus the interface component of the penetrometer test would appear to be unsuitable for studying the interface-only behaviour.

The data obtained by Heerema (1979) showed that the dynamic friction varied significantly even when the velocity was almost constant, and showed excessive increase in friction (up to nine times the static friction at a pile velocity of 1.0m/s) that has not been encountered in practice. As a particular sample was used in many tests, including the quasi-static tests that took considerable time to complete, the sample could have lost significant moisture as the tests were carried out. If so, this effect would have been additional to the rate effects and would have been reflected in the friction-velocity relationship proposed by Heerema.

The tests by Dayal and Allen (1975), Heerema (1979) and Litkouhi and Poskitt (1980) were performed at constant or near-constant velocity. For each test, the measured dynamic friction was interpreted to correspond to the constant or near-constant velocity such that one test yielded only one data point in the friction-velocity plot. Hence, the data from a collection of these tests each performed at a different constant velocity form the friction-velocity plot. In theory, the tests would give the actual friction-velocity response if and only if the instantaneous friction could be associated with its corresponding instantaneous velocity. However, there is indication that the interpretation of the dynamic friction in the work of Litkouhi and Poskitt, Dayal and Allen, and Heerema was not unique and was therefore questionable. A detailed discussion of their interpretation can be found in Chin (2003). Also, since the friction-velocity relationship was obtained by combining data points from individual constant velocity tests, there is typically significant scatter in the friction-velocity plot, which introduces some uncertainty to the actual response. In addition, such tests do not simulate a typical pile driving event which involves transient velocities and varying accelerations, and therefore, did not allow any effect of acceleration on the dynamic friction to be investigated.

Benamar et al. (1991, 1992) and Benamar (1999) investigated the dynamic response of pile-clay interfaces by driving a miniature pile through the specimen contained in a triaxial cell. Whilst they were able to continuously record the instantaneous dynamic friction and the corresponding instantaneous pile velocity during one single driving event, the friction-velocity response obtained by Benamar et al. applies to the loading phase of a single driving event. At the beginning of their force-velocity curve, which is based on the initial loading stage of the event, two effects occur concurrently. The first effect is the dynamic or viscous effect. The second effect is the incomplete mobilization of the quasi-static resistance (that will only be fully mobilised after sufficient shear displacement known as the quake has been reached). Therefore, it is not possible to simultaneously determine the instantaneous static resistance and viscous damping resistance for the data at the beginning of the force-velocity curve. This has the implication that the dynamic friction cannot be normalized by the quasi-static friction, and that the force-velocity curve from Benamar et al. cannot be applied generally to other situations.

Therefore, a laboratory set-up that overcomes the major limitations of these previous studies must be developed, and based on the data obtained using this set-up, the actual strength ratio-velocity relationship for the pile-clay interface must be obtained.

3. Development of laboratory set-up

In an attempt to overcome some of the limitations of the previous laboratory set-ups, a novel test device was developed at Monash University to perform quasi-static and dynamic pile-soil interface tests. Key requirements were isolation of the pile tip response from the pile shaft-soil interface response; one-to-one modeling of the interface; facility for the testing of different pile materials and piles of different roughness; transient motions for determining the effect of velocity and acceleration on the dynamic friction; facility for controlling and measuring the stress acting normal to the interface in order to replicate various stress conditions; minimization of radiation damping by minimising the thickness of the soil specimen; repetitive testing of a particular pile-soil interface so that the clay would be remoulded as is the case for both driven and drilled piles.

Also, the friction-velocity relationship was to be obtained by continuously logging the dynamic friction and the velocity during a single driving event. It is the author's belief that this is the most reliable approach to obtaining the dynamic response of the interface in a driving event where the velocity of a particular segment of the pile increases to a maximum, then decreases to smaller values before becoming negative during rebound. The friction-velocity response obtained in this way would directly give the functional relationship between velocity and dynamic friction throughout the driving event. This approach requires no interpretation of the appropriate interface friction, and enables direct association of interface friction with the corresponding velocity. From the practical point of view, this approach has the advantage of only needing to perform a single test to obtain multiple data points (that form the friction-velocity relationship) for a particular interface tested under a particular set of boundary conditions.

To fulfil the requirements, a scheme based on the direct shear device was adopted. A schematic of the device (for the dynamic test configuration) is shown in Figure 1. Constant normal load is applied to the interface using a loading platen in the vertical direction, and shear load is applied to the interface in the horizontal direction. The pile section is locked onto a carriage. The carriage is coupled to an actuator so that it is pushed rather than impacted.

The shear box accommodates a clay specimen measuring 555mm x 160mm in plane and 40mm thick. As shown in Figure 1, the shear box is topless and bottomless so that the loading platen can come in contact with the top of the sample and the pile surface with the bottom of the sample.

In the quasi-static tests, the shear load is applied using an Instron® actuator. For the dynamic tests, the shear load is applied by a specially designed high-speed actuator, and the carriage and the actuator are stopped mechanically. Further details of the device can be found in Chin (2003). During the dynamic test, the following are recorded using high-speed data acquisition: the acceleration of the pile, the displacement of the pile, the normal load on the interface, the vertical displacement of the sample, and the force delivered by the high-speed ram to the carriage. The acceleration of the pile is integrated to give the velocity. The product of the acceleration and the mass of the body moved by the ram (i.e. the pile and the carriage) gives the inertial force. The interface friction is obtained by deducting the inertial force from the force delivered by the ram to the carriage.

4. Test Programme

For a particular pile-clay interface, quasi-static and dynamic tests were performed in order to establish the effect of shear rate on the interface friction.

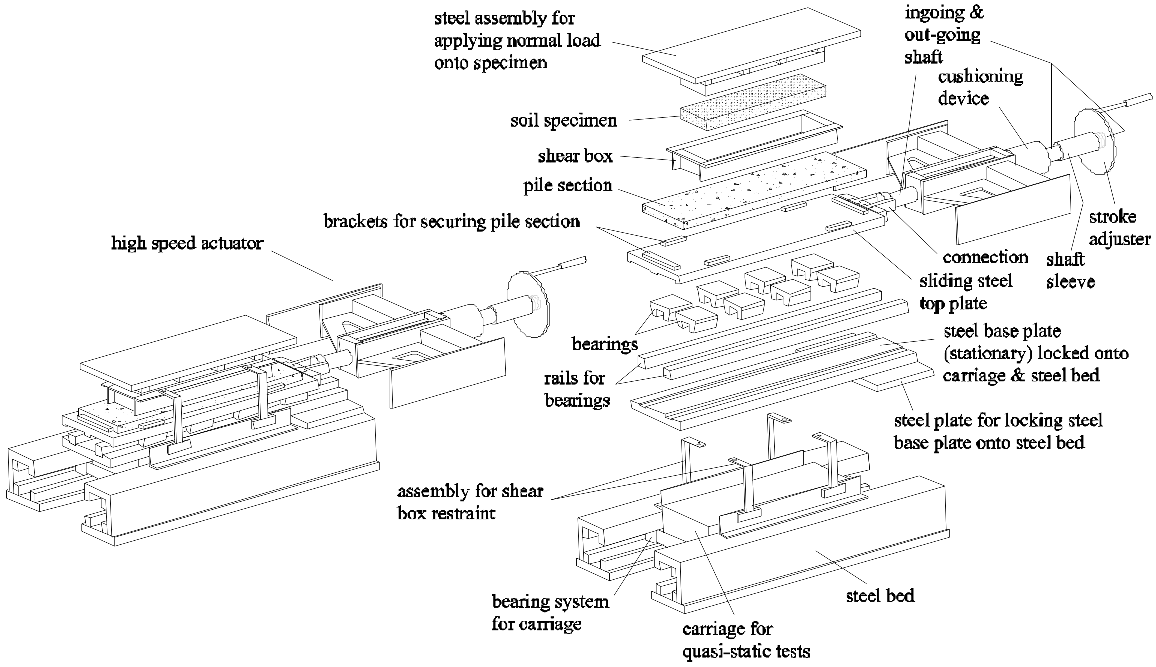

Figure 1 Configuration of the shear device for dynamic test

Three types of clay of low, medium and high plasticity (according to the plasticity chart) were tested. In order to investigate the effects of the preconsolidation stress, normal stress, *OC*R and hence the shear strength on the interface behaviour, these parameters were varied. For a particular type of clay, samples with two preconsolidation stresses at 325kPa and 500kPa were fabricated, and for a particular preconsolidated sample, normal stresses ranging from 60 to 250kPa were applied to the sample during the tests. Thus, the effective *OCR* of the sample and the shear strength of the sample (which depended on the normal stress and the *OCR*) were varied.

In order to determine the effect of the pile surface roughness on the interface behaviour, tests were conducted on a smooth concrete pile, rough concrete pile and a smooth steel pile.

5. Test procedures

In order to test clay specimens of known properties, procedures were developed to fabricate clay specimens with consistent properties in the laboratory. The clay was purchased from a pottery material supplier in the form of dry powder. The powder was mixed with water in a mixer to form a slurry. The slurry was placed in a purpose-built mould for consolidation to a target preconsolidation stress.

The dynamic tests were performed at transient velocities up to 1.6m/s. As the clay specimens took a considerable amount of time to fabricate, three-staged testing was performed on the same interface sample for the sake of efficiency. The multi-stage testing was based on the principle of multi-stage testing of soil in the standard direct shear device as outlined in Head (1994) but with slight variations.

The quasi-static tests were performed at a shear rate of 0.01mm/s. Water was poured onto the pile section and around the sample to prevent moisture loss at the interface. Under the applied normal stress, the pile-clay interface was sheared by moving the carriage using the actuator until the residual strength was reached.

6. Conclusion

In order to improve the reliability of the dynamic methods, research has been undertaken to better model and characterize the dynamic response of the pile-soil interface during pile-driving events. The approach adopted in the experimental program has been to simulate the field response as accurately as practically possible in the laboratory under controlled conditions, and in a way which overcomes the deficiencies perceived in previous research programs. The response of the pile-soil interface thus attained is discussed in an accompanying paper which forms Part II of the discussion.

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