Free Falling Penetrometers : A Laboratory Investigation in Clay

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ABSTRACT

This paper presents the results of a series of laboratory model free falling penetrometer (FFP) tests in kaolin clay. A thin-shafted FFP has been allowed to free-fall and has also been pushed at a relatively slow constant-rate into claybeds. Different configurations are used to examine the influences of various properties (FFP mass, tip diameter, tip shape, impact velocity and claybed strength) on the rate effects in FFP tests. The rate effects are determined by comparing the dynamic and static penetration resistances measured from the free-fall and constant-rate-of-penetration tests. The rate effects are found to be independent of the FFP mass, tip shape and tip diameter, but are influenced by the claybed strength and FFP velocity.

Keywords: clays, free falling penetrometer tests, laboratory model tests, offshore engineering, rate effects

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1 **Introduction**

2 Free falling penetrometers (FFP) are expendable or retrievable probes that are most
3 commonly launched from small vessels and free-fall into the seabed. FFPs have been
4 developed for many military and civilian applications, which include deep sea radioactive
5 waste disposal carrier feasibility studies (Freeman et al. 1984), naval mine countermeasure
6 research (Lott and Poeckert 1996), seabed characterization (Dayal 1974), deepwater
7 anchoring systems (Lieng et al. 1999) and paleo-limonology applications (Spooner et al.
8 2004). The application of FFPs in seabed characterisation is especially attractive, considering
9 their relatively simple test equipment and procedure, which enables rapid testing with wider
10 test area coverage than conventional full-flow or cone penetrometer tests. As a result of these
11 advantages and some promising results in full scale field trials, many FFP systems have been
12 developed such as the Marine Impact Penetrometer (Dayal 1974); Expendable Doppler
13 Penetrometer, XDP (Beard 1977); Expendable Bottom Probe, XBP (Akal and Stoll 1995);
14 Seabed Terminal Impact Naval Gauge, STING (Mulhearn 2003); Free Fall Cone
15 Penetrometer, FFCPT (www.brooke-ocean.com); CPT lance (Stegmann et al. 2006); and
16 Nimrod (Stark et al. 2009). However, despite successful field trials for the many FFP systems,
17 their applications are still not wide spread mainly due to uncertainties in data interpretation.

18 The uncertainties in FFP data interpretation are mainly owing to “rate effects”, which
19 herein refers to the increase in resistance due to the rapid rate of penetration and high strain
20 rate in FFP tests. The effects of rate of penetration in cohesive soils during conventional cone
21 penetration and full-flow penetrometer tests have been widely reported (Lunne et al. 1997;
22 Lehane et al. 2009) and are often attributed to soil viscosity. In FFP tests the penetration
23 resistance in cohesive soils is much greater than measured by conventional penetration tests,

but there is little consensus on how to account for the high rates and obtain reliable estimates of undrained strength. The determination of this rate effect is further complicated by its possible dependencies on soil properties (e.g. strength, stress history), FFP properties (e.g. geometry, density) and external effects (e.g. FFP impact velocity). One way to provide better FFP interpretation is to investigate the influences of these variables using well-controlled laboratory tests on model FFPs (Dayal 1974; Levacher 1985; Hurst and Murdoch 1991; Akal and Stoll 1995; Stoll et al. 2007). These studies have used different FFP systems, with most investigating full-shafted FFPs with identical shaft and tip diameters (Dayal 1974; Levacher 1985; Akal and Stoll 1995; Stoll et al. 2007); and one investigating a thin-shafted FFP with much smaller shaft diameter (Hurst and Murdoch 1991).

Full-shafted FFPs have been better investigated, with the influences of soil strength (Dayal 1974; Levacher 1985; Akal and Stoll 1995), FFP mass (Dayal 1974), tip shape (Dayal 1974; Levacher 1985) and impact velocity (Dayal 1974; Levacher 1985; Stoll et al. 2007) examined. On the other hand, the sole investigation into thin-shafted FFPs has been limited to studying the influences of tip shape and impact velocity (Hurst and Murdoch 1991). The studies on full-shafted FFPs have revealed that rate effects (or the increase in penetration resistance) increase as undrained shear strength, s_u reduces from 80 to 3 kPa, and as impact velocity, v_o increases for tests involving v_o values of up to 6.1 m/s (Dayal 1974). However, at higher v_o (> 6 m/s) the rate effects appear to reach a limit (Levacher 1985). Dayal's study has also indicated negligible influence of FFP mass and an influence of tip shape on the dynamic resistance for the full-shafted FFP. On the other hand, the sole study using the thin-shafted FFP has suggested negligible tip shape effect and a similar increase in rate effects with increasing v_o (Hurst and Murdoch 1991).

1 This brief review has illustrated that work is still needed to investigate test variables such
2 as FFP mass and soil strength for thin-shafted FFPs that have not been previously
3 investigated. In addition, more studies are required to confirm the negligible influence of tip
4 shape, which differs from that observed for full-shafted FFPs, and to cover a higher range of
5 impact velocity to investigate the limiting rate effects observed by Levacher (1985). Because
6 the diameter of the shaft is much smaller than the tip, thin-shafted FFPs such as the STING
7 have the advantage of attracting minimal dynamic shaft resistance as has been observed in
8 field tests (Mulhearn 2003). Even though the mechanism responsible for the absence of any
9 shaft resistance is unclear, the minimisation of the shaft resistance has the potential to greatly
10 simplify FFP interpretation because experience with full-shafted FFPs suggests that the shaft
11 experiences greater rate effects than the tip (Dayal 1974). In addition, the thin-shafted FFP
12 has similar geometry to the increasingly popular quasi-static full-flow penetrometers (Stewart
13 and Randolph 1994), enabling well-established bearing capacity solutions to be adopted for
14 interpreting the thin-shafted FFP. However, the thin-shafted FFP has exhibited a dependency
15 on tip diameter, with an increase in the interpreted undrained shear strength with decreasing
16 tip diameter observed in field tests (Mulhearn 2003; Abelev et al. 2009a). Therefore, more
17 studies are needed to demonstrate whether thin-shafted FFPs such as the STING can provide
18 reliable soil characterisation.

19 In this study the influences of the penetrometer mass, tip diameter and geometry, impact
20 velocity and soil strength on a FFP similar to the STING are investigated using multiple
21 series of well-controlled laboratory tests on model FFP in kaolin clay. These tests are
22 intended to provide a complete set of data to evaluate rate effects and provide greater
23 confidence in the interpretation of a thin-shafted FFP. In addition to free falling tests,
24 relatively slow constant-rate-of-penetration (CRP) tests have also been conducted to provide
25 comparison between the static and dynamic penetration resistances, and to determine the rate

effects in FFP tests. The test setup and procedure for both CRP and FFP tests are first described briefly, followed by an examination of the influences of the different test variables.

Test Materials and Setup

Soil Properties and Claybed Preparation

Kaolin clay with the properties obtained from laboratory index property tests, as summarised in Table 1, has been used to prepare claybeds for the model FFP tests. The claybeds were produced with undrained shear strength, s_u profiles that varied linearly with depth with a gradient, k . Claybeds with two different strength profiles were prepared: (a) uniform strength ($k = 0$); and (b) non-homogeneous with strength gradients of $k = 35, 50$ and 95 kPa/m. The non-homogeneous claybeds were prepared using the hydraulic gradient similarity method (Zelikson 1969). The apparatus used to prepare the claybeds for the FFP tests is shown in Fig. 1. To prepare the claybed, kaolin powder was mixed at a moisture content of 1.1 times the liquid limit and placed into the tank. The claybed was then consolidated under uniform stress applied by hydraulic pressure via a rubber membrane on the top of the clay. Depending on the claybed dimensions and final vertical effective consolidation stress, it was left to consolidate for 3 to 6 weeks to reach equilibrium with negligible ongoing change in settlement. Further details of the claybed preparation are given in Chow and Airey (2013).

Model FFP

The model FFP, shown in Fig. 2 has a similar geometry to the STING and consists of a thin steel shaft with exchangeable tips of different shapes and sizes. Four different tip shapes were fabricated, namely 5 mm thick circular plates of various diameters, 20 mm diameter ball, 20 mm diameter cone with 60° apex angle and 20 mm diameter cone with 90° apex angle. The 5

mm thick circular plate tip was used in most of the tests and was fabricated in five different diameters (10, 20, 30, 40 and 60 mm). The top of the shaft was fitted with four plastic fins to improve its aerodynamic stability in addition to a magnetic fixture that provided an automatic release mechanism from an overhead mount. Brass weights in multiples of 50 g and 100 g could be attached to the top or bottom of the shaft as required to increase the FFP mass (see the weight placed on the top of shaft in Fig. 2).

Constant-Rate-Of-Penetration (CRP) Test Apparatus and Setup

To obtain the static penetration resistances of the claybeds, CRP tests with the apparatus and setup shown in Fig. 3 were conducted. The CRP test has a similar geometry to the FFP but different instrumentation and operation. The CRP consists of a thin steel shaft, 9.5 mm in diameter, which can be connected to the same exchangeable tips used with the FFP. In addition, a cylindrical T-bar tip of diameter, $d = 12.5$ mm and length, $L = 50$ mm could be attached to perform T-bar penetrometer tests (Stewart and Randolph 1994). At the top of the shaft the CRP device is connected to a load cell and a linear actuator with a maximum travel of 450 mm. To ensure the measured force is solely end-bearing, an outer sleeve was fitted over the shaft to exclude the sleeve frictional resistance from the load cell measurement.

For most claybeds, CRP tests, using the same tip geometry as for the FFP tests, were conducted to provide direct comparison between the CRP and FFP tests. In addition, T-bar penetrometer tests were conducted as standard tests to enable comparison between claybeds and provide an estimate of the undrained strengths. Details of the CRP tests conducted can be found in Table 2. All the CRP tests were conducted at a constant penetration rate, v of 0.011 m/s, to provide a normalised velocity, V (equivalent to vd/c_v , where c_v is the soil coefficient of consolidation), high enough to ensure undrained conditions (Lehane et al. 2009).

FFP Test Setup and Procedure

Fig. 4 shows the FFP test setup. The model FFP was attached onto a magnetic mount above the claybed, and could be released at different fall heights using the cable and winch mechanism. Multiple FFP drops and at least one CRP test were conducted in each claybed, with a minimum spacing of 5 tip diameters between adjacent FFP drops to minimise interference and any boundary effects. This separation is believed to be sufficient as repeat tests conducted in the centre and at 2.5 tip diameters from the confining vessel side gave essentially identical results, and numerical simulations of a STING penetrating into clay (Abelev et al. 2009b) showed that most of the radial deformation was concentrated within 2 tip diameters. For FFP tests with fall heights below 1.2 m, the FFP was instrumented with an accelerometer mounted at the upper end of its shaft. For greater fall heights the accelerometer could not be used and high speed photography coupled with PIV (particle image velocimetry) image analysis was used to detect the displacement of the FFP and hence its velocity and acceleration. A digital black and white high speed camera was used to capture the FFP penetration event at a frame rate of 2000 frames per second. To track the FFP displacement between the photos, GeoPIV, a MATLAB module employing the PIV technique developed by White et al. (2003) was used. GeoPIV employs cross-correlation to determine the displacement vectors between patches in successive photos. More details about the validation of the combined high speed photography and GeoPIV technique can be found in Chow et al. (2010).

Test Program

Fifteen test series involving 45 CRP tests and 56 FFP tests were conducted as detailed in Table 2. The test program lists the test series number, TS., the undrained shear strength estimated from CRP tests, $s_{u(CRP)}$, the FFP total mass, m (including additional weights added),

the FFP tip diameter, d , the FFP tip shape, the FFP impact velocity, v_o and details of the CRP tests conducted. The test program has investigated the influence of five test variables as follows:

- FFP mass, m (262.0, 353.2, 446.6, 539.2, 631.7, 724.4 g)
- FFP tip diameter, d (0.01, 0.02, 0.03, 0.04, 0.06 m)
- FFP tip shape (circular plate tip, ball, 60° cone, 90° cone)
- FFP impact velocity, v_o (1.4 to 12.2 m/s)
- Claybed undrained shear strength, $s_{u(CRP)}$ (4.4 to 32.2 kPa for uniform claybeds and strength gradients, k of 35 to 95 kPa/m for non-homogeneous claybeds)

Most test series in the test program involved uniform claybeds except TS. 6, 9 and 15 which had non-homogeneous claybeds. The non-homogeneous tests were included in order to investigate the response in more realistic non-uniform strength profiles. However, it should be noted that the stress levels and strength gradients investigated here cannot be related directly to conditions on the seabed. For instance, the k values are much greater than are typically found in the field. This was due to experimental constraints, primarily the limited tank depth, which required higher s_u and higher k to ensure penetrations greater than the tank depth did not result. However, the dependency of the FFP rate effects on penetrometer geometry, impact velocity and soil strength can be expected to be similar in field conditions.

Test Analysis and Results

Analysis Approach

The analysis of the results requires determination of the static penetration resistance, q_s and undrained shear strength, $s_{u(CRP)}$ from the CRP tests, and the estimation of dynamic tip

penetration resistance, q_d , rate factor, R_f and final embedment depth, H from the FFP tests. The static penetration resistance, q_s established from CRP tests using various tips can be obtained from Eq. (1).

$$q_s = \frac{F}{A} \quad (1)$$

where F is the load measured by the load cell on the penetrometer, A is the penetrometer tip area taken as $(L \times d)$ for a T-bar with length, L and diameter, d and $\pi d^2/4$ for a plate/ball/cone with diameter, d . The undrained shear strength, $s_{u(CRP)}$ can then be estimated using Eq. (2).

$$s_{u(CRP)} = \frac{q_s}{N} \quad (2)$$

where N is a resistance factor that is believed to depend on tip shape, with some typical reported values summarized in Table 3. The T-bar resistance factor, N_{T-bar} is well-established, with a range of values reported from analytical and numerical studies that depend on T-bar roughness, strain softening, rate effects, buoyancy and surface effects (e.g. Martin and Randolph 2006; Zhou and Randolph 2009; White et al. 2010). N_{T-bar} has also been determined from numerous laboratory and field T-bar tests, with a mean value of N_{T-bar} of 10.5 typically recommended for use in practice (e.g. Stewart and Randolph 1994; Low 2009). Comparisons between CRP tests with the T-bar tip and the ball, circular plate and cone tips have been used to examine the influence of tip shape on N . For most claybeds, between 1 and 3 q_s profiles have been obtained to determine the strength, static resistance and any non-uniformity across the depth and cross-section of the claybed.

The dynamic tip penetration resistance, q_d can be estimated from the acceleration measured either from the accelerometer or from analysis of the high speed photography based on Newton's second law of motion. Taking the FFP as a rigid body, the various forces

(penetrating and resisting) acting on the FFP being considered are shown in Fig. 5. Equilibrating the forces, the soil tip force, F_t and hence the dynamic tip penetration resistance, q_d can be obtained as shown in Eqs. (3) and (4).

$$F_t = W - F_r \quad (3)$$

$$q_d = F_t/A \quad (4)$$

where W is the FFP total self weight taken as mg where m is the FFP mass and g is the free fall acceleration, 9.81 m/s^2 , F_r is the reaction force taken as ma where a is the acceleration obtained from the accelerometer or PIV technique, A is the FFP tip area taken as $\pi d^2/4$ with tip diameter, d . The q_d can be compared with q_s measured from CRP tests to obtain a rate factor, R_f as shown in Eq. (5).

$$R_f = \frac{q_d}{q_s} \quad (5)$$

In addition to q_d and R_f , another parameter that can be obtained from a FFP test is the final embedment depth, H . The H can be obtained through analysis of the accelerometer data, or physical measurement at the end of a FFP drop using a ruler to an accuracy of 1 mm. Typically the differences in H between the methods of estimation are less than 5%. Using the above analysis approach, q_s , q_d , R_f and H for all test series have been determined and the influences of the five test variables on them are examined below.

Influence of FFP Mass

The effect of FFP mass is investigated using tests with the 20 mm circular plate tip and six different masses, m (262, 353, 447, 539, 632 and 724 g) in TS. 1. The mass of the FFP is increased by adding different configurations of weights to the top and bottom of shaft. The effect of FFP mass on q_d and H in TS. 1 are illustrated in Fig. 6a. The corresponding velocity

profiles for all drops in TS. 1 are also included in Fig. 6b. Increasing the FFP mass is found to increase H , and to have negligible influence on q_d . There is some variability in q_d , especially evident for the test with mass of 447 g, which is believed to be a consequence of the slight non-uniformity of strength across the depth and cross-section of claybed as shown in the three q_s profiles obtained from the T-bar tests (Fig. 6a). Similar effects of FFP mass on q_d and H were also reported by Dayal (1974) in model FFP tests with masses between 16.2 to 25.7 kg. This negligible effect of FFP mass on q_d suggests that heavier FFP can be used to increase penetration depth and obtain deeper soil strength profiles.

Influence of FFP Tip Diameter

The effect of tip diameter, d is investigated in both CRP and FFP tests using circular plate tips with d of 10, 20, 30, 40 and 60 mm (TS. 2 to 6 in Table 2). Figs. 7a, b and e show q_s profiles obtained from three series of CRP tests involving the different diameters. Also included in these figures are q_s profiles obtained from CRP tests using the T-bar tip. The q_s profiles show no systematic influence of d with similar profiles observed in tests with different diameters, and as shown below with different undrained strengths. These profiles, which show a response with depth that is independent of diameter, are not consistent with many static bearing capacity and penetration solutions that depend on embedment ratio, h/d , and strength ratio, $s_u/\gamma'd$, where h is the penetration depth and γ' is the soil submerged unit weight (e.g. Skempton 1951; White et al. 2010). However, these observations, based on tests with $10 < d < 60$ mm and normally consolidated clay with $3 < s_u < 32$ kPa, should be relevant to many FFP systems which typically have diameters less than 200 mm and penetrate soft seafloor sediments, and in particular to the STING (the prototype FFP modelled in this research) for which tip diameters from 25 to 70 mm have been used in field trials (e.g. Abelev et al. 2009a).

The effect of d on q_d and H is examined in FFP tests as shown in Figs. 7c, d and e. Increasing d is found to decrease the final embedment depth H , as expected because of the increased resistance with increased area. Similar results have also been reported from field studies using the STING penetrometer (Mulhearn 2003; Abelev et al. 2009a). The data also suggest that the dynamic resistance q_d is independent of d . Fig. 7c shows negligible difference in q_d between d of 40 and 60 mm in TS. 4, but the 30 mm tipped FFP produces higher q_d . This difference is believed to be a consequence of the strength variability indicated in the three q_s profiles in Fig. 7c, because negligible differences in q_d with d are also observed for d of 30 and 60 mm in TS. 5 (Fig. 7d) and for d of 20 and 30 mm in TS. 6 (Fig. 7e).

The negligible tip diameter effect in both q_s and q_d indicates that the rate factor, $R_f(q_d/q_s)$ is independent of the FFP tip diameter. This observation of R_f independent of diameter helps to explain the apparent diameter effect reported in field trials using the STING (Mulhearn 2003; Abelev et al. 2009a), for which the interpretation algorithm uses $R_f = (v/d)^{0.15}$, and thus introduces an incorrect diameter dependence. It was also shown by Abelev et al. (2009a) that removal of the diameter dependency led to a more consistent interpretation of the field trial data.

Influence of FFP Tip Shape

CRP and FFP tests with four tip shapes (circular plate, ball, 60° cone and 90° cone) all having a diameter of 20 mm have been conducted in this study (TS. 7 to 10 in Table 2). In addition to these four test series, additional CRP tests using the four tips and the T-bar have been conducted on the soil retained in the top collar after it had been trimmed off from the tank base in TS. 7. The q_s profiles obtained from these additional CRP tests are illustrated in Fig. 8a. Some variation in q_s ($\pm 10\%$) is observed between the different tip shapes, with the ball tip appearing to produce the highest q_s . Similar variations in q_s are observed in TS. 7, 8 and 9

(Figs. 8b, c and 9a). However, there is no systematic difference in q_s between the different tip shapes of similar tip diameter in the three test series. Therefore, the variation in q_s profiles is believed to be a consequence of the slight non-uniformity in strength across the depth and cross-section of the claybeds, rather than a genuine tip shape effect.

Similar negligible tip shape effects in CRP tests have been reported in centrifuge and field studies involving T-bar, ball and plate penetrometers of similar projected tip areas (Chung and Randolph 2004). In addition, CRP calibration chamber tests involving miniature full-shafted penetrometers with cone and flat tips have also shown negligible tip shape effects in clayey sand (Kim et al, 2008). A recently compiled and extensive field database, summarized in Table 3 (Low 2009), also indicates similar ranges for the resistance factors for the ball, N_{ball} and T-bar, N_{T-bar} , but slightly higher resistance factors for the plate, N_{plate} . However, the theoretical and numerical factors for N_{ball} and N_{plate} (e.g. Randolph et al. 2000; Lu et al. 2001; Martin and Randolph 2001; Martin and Randolph 2006) shown in Table 3, are higher than the experimental and field data. The higher numerical N_{ball} has been attributed to strength anisotropy (Randolph et al. 2000), and the higher numerical N_{plate} is possibly caused by the difference in the assumed failure mechanism. The assumed mechanism of soil flow-back for the plate tip at deep penetration in the theoretical and numerical solutions (Lu et al. 2001; Martin and Randolph 2001) has not been observed in this study.

The influence of tip shape on H in FFP tests (TS. 7, 8 and 9) is summarised in Table 4. Also included in Table 4 are the H observed in Dayal (1974) involving four different tip shapes. H appears to increase with the tip nose sharpness in the ascending order of circular flat plate, ball, 90° cone and lastly 60° cone for most of the tests. In TS. 8 and 9, lower H are observed for the 60° cone than the 90° cone. However, this is believed to have been a consequence of the FFP leaning over as it came to rest and hence to unreliable measurement.

1 A similar dependency on H is also observed for Dayal's data covering cone tip with nose
2 shapes of blunt, 30°, 60° and 90° apex angles. Nevertheless, the influence of tip shape on H
3 remains insignificant with the largest difference in H between the different tip shapes ranging
4 from 11 to 37 mm in this study and Dayal (1974).

5 The influences of the tip shapes on q_d in the FFP tests are illustrated in Figs. 8b, c and 9a.
6 Similarly to the CRP tests, negligible tip shape effect is observed in q_d in both uniform and
7 non-homogenous claybeds. However, the circular plate tip is able to capture higher q_d from
8 the moment of impact, compared to other tips that only pick up the full resistance with full tip
9 embedment at deeper penetration. The negligible tip shape effect in both q_s and q_d indicates
10 that the rate effects ($R_f = q_d/q_s$) are independent of FFP tip shape as well as the diameter as
11 discussed previously. This is clearly illustrated in Fig. 9b where identical R_f profiles are
12 obtained in TS. 8 involving both CRP and FFP tests using three different tip shapes (circular
13 flat plate, ball and 60° cone) in the same claybed. Similar negligible tip shape effects in FFP
14 tests have also been reported by Hurst and Murdoch (1991) using a FFP with square, 45°
15 pyramid and horizontal cylinder tips and Mulhearn (2003) using the STING with flat plate,
16 hemisphere and 60° cone tips. On the contrary, Dayal (1974) reported a tip shape effect in
17 both the tip and shaft resistances with the tip resistance decreasing in the sequence of blunt
18 tip, cone tip with 90°, 30° and 60° apex angles, and the shaft resistance decreasing in the
19 order of cone tip with 30°, 60°, 90° apex angles and lastly the blunt tip. This contradictory
20 finding is believed to be caused by the differences in the FFP shaft geometry, and hence the
21 different failure mechanisms associated with the cone penetrometer design with identical tip
22 and shaft diameter used by Dayal (1974) and the thin shafted design adopted by Hurst and
23 Murdoch (1991), Mulhearn (2003) and used in this study.

The independence of the rate factor to tip shape and diameter suggests that any tip shape will suffice; however, certain tip shapes have advantages over others in field application. For instance, the thin circular plate enables sharp detection of the impact which is an advantage in detecting the mudline in very soft seabed. However, the thin circular plate tip might be subject to bending upon deeper penetration as the soil accumulates beneath it or upon hitting a hard layer, and its geometry deters inclusion of additional instrumentation at the tip such as a pore pressure transducer. Cone tips are likely to be advantageous in harder materials, but will have difficulty in detecting the seabed. Alternatively, the ball tip is an attractive option as it can detect the soft seafloor, its geometry allows inclusion of a pore pressure element at its mid-height (Kelleher and Randolph 2005) and it is growing in popularity as a CRP test with published theoretical, numerical and experimental works (Randolph et al. 2000; Kelleher and Randolph 2005; Zhou and Randolph 2009). As the circular plate tip is the default tip shape adopted in STING, most FFP test series here have used the circular plate tip. However, considering its potential an additional test series using the ball tip (TS. 10) has been included in the investigation into the effects of impact velocity.

Influence of FFP Impact Velocity

The influence of impact velocity, v_o on FFP tests is investigated in TS. 10 using the ball tip and TS. 11 to 15 using the circular plate tip. These test series have a similar FFP configuration (20 mm tip diameter and similar mass), but the penetrometer has been allowed to free fall with different v_o into claybeds of different s_u . The influence of v_o on H for TS. 11 to 14 involving the circular plate tip and uniform claybed are illustrated in Fig. 10. As expected, H increases with increasing v_o . The influences of v_o on q_d for TS. 10 to 14 involving uniform claybeds are illustrated in Fig. 11. Also included in Fig. 11 are the q_s profiles obtained from CRP tests using similar tips (ball or plate) and/or the T-bar. For TS. 10

and 11 covering a higher v_o range of 4.6 to 12.2 m/s, q_d appears to be unaffected by v_o with identical q_d profiles observed between tests with different v_o , agreeing with Levacher (1985). For TS. 12 to 14 covering a lower and wider range of v_o (1.4 to 12.2 m/s), similar negligible difference in q_d is observed for the whole range of v_o , and not the expected decrease in q_d at lower v_o as reported by Dayal (1974), Hurst and Murdoch (1991) and Stoll et al. (2007). However, the observation of the negligible effect of v_o at low impact velocities might not be reliable as q_d has yet to be fully mobilised for these tests ($v_o < 4.6$ m/s) with only very shallow penetrations (< 0.03 m) were achieved. To further inspect the influence of lower v_o values, TS. 15, involving v_o between 1.2 and 6.4 m/s, was conducted using a non-homogeneous claybed to enable deeper penetration. Fig. 12a shows q_d increases with increasing v_o , a pattern which was not observed in the uniform claybeds. It is believed that the increase in q_d will cease at higher v_o as observed for uniform claybeds when v_o was greater than 5 m/s. This could not be confirmed because higher drops with deeper penetration were not possible due to the limited claybed depth. Nevertheless, combining observations from TS. 10 to 15, it is believed that q_d increases with increasing v_o until reaching a critical value, v_c at approximately 5 m/s. However, the determination of v_c remains uncertain, as it might depend on soil or FFP properties and requires more investigation.

The q_d and q_s profiles in Fig. 11 enable R_f (q_d/q_s) profiles to be evaluated as shown in Figs. 12c and 13 and as shown previously in Fig. 9b. R_f appears to be approximately constant for most of the penetration. However, at shallow penetration, R_f tends to be higher as mobilisation of q_d occurs more rapidly than q_s . This spike in R_f is typically observed at penetration depths less than 0.02 m ($h/d < 1$). Excluding R_f for penetrations of less than 0.02 m, R_f is found to remain approximately constant for all tests involving uniform claybeds (TS. 10 to 14) until q_d and R_f drop off towards at rest when $v < v_c$. However, the constant R_f is not observed in the non-homogeneous claybed (TS. 15), which shows R_f decreasing with

1 increasing depth. This decrease in R_f is related to the increase in $s_{u(CRP)}$ with depth, as will be
2 shown later.

3 In summary it has been shown that R_f tends to increase with increasing v_o until a limiting
4 rate factor, R_{fl} is reached above a critical velocity, v_c (approximately 5 m/s). The relationship
5 between R_f and v for $v_o < v_c$ is hard to establish due to either shallow penetration or the
6 dependency of R_f on $s_{u(CRP)}$, but it has been suggested that the relationship could be semi-
7 logarithmic (Dayal 1974) or power-law (Hurst and Murdoch 1991) in form. For $v_o > v_c$, the
8 limiting R_{fl} can be determined for all FFP drops with $v_o \geq 4.6$ m/s in TS. 10 to 14 as shown in
9 Fig. 13 and Table 5. As shown in Table 5, no systematic difference in R_{fl} can be observed
10 between tests with different v_o within the same test series, which indicates the independent
11 relationship between R_{fl} and v_o for $v_o \geq 4.6$ m/s. Therefore, a mean limiting $R_{fl(mean)}$ can be
12 determined for each test series as summarised in Table 5. Similar limiting rate effects have
13 also been observed in an impact type triaxial rate study conducted by Gibson and Coyle
14 (1968), and also in the FFP studies by Levacher (1985). However, confirmation of a limiting
15 rate factor from field FFP studies (e.g. Beard 1977; Mulhearn 2003) is unfortunately not
16 possible due to the narrow impact velocity ranges investigated.

17 In view of the potential of the ball tip, the effect of v_o on the ball tipped FFP is also
18 investigated in TS. 10 as illustrated in Fig. 11a. Similar to the circular plate tip, constant and
19 limiting q_d and R_f profiles are observed between tests with different v_o , indicating a similar
20 negligible effect of v_o for the ball tipped FFP for $v_o > v_c$. R_{fl} are also determined for all FFP
21 drops in TS. 10 with an overall $R_{fl(mean)}$ of 1.88 as summarised in Table 5.

Influence of Soil Undrained Shear Strength

The influences of soil strength on q_d , H and R_f are examined in TS. 11 to 14 from tests using the circular plate tip and uniform claybeds with $s_{u(CRP)}$ of 7.2, 10.2, 15.8 and 32.2 kPa respectively. Higher q_d and lower H are observed with increasing claybed strength, a pattern which has been reported in other FFP studies (Dayal 1974; Abelev et al. 2009a). However, the higher q_d does not necessarily equate to higher rate effects with increasing s_u . For tests with $v_o \geq 4.6$ m/s in TS. 11 to 14, the relationship between $R_{fl(mean)}$ and $s_{u(CRP)}$ is shown in Fig. 14. Lower $R_{fl(mean)}$ is observed with increasing $s_{u(CRP)}$ and the relationship can be expressed in Eq. (6).

$$R_{fl(mean)} = 2.945 - 0.029 s_{u(CRP)} \quad \text{for } v_o \geq v_c \text{ and } s_{u(CRP)} \text{ in kPa} \quad (6)$$

This s_u dependency is consistent with the observations from the non-homogeneous claybed shown in Fig. 12c, which indicate R_f decreasing with increasing $s_{u(CRP)}$ with depth. Similar s_u dependency on R_f has also been reported in the model FFP tests conducted by Dayal (1974) with their semi-logarithmic rate parameter found to increase with decreasing strength. Combining the relationships observed between R_f , v_o and $s_{u(CRP)}$, an exponential rate equation has been formulated to address the rate effects in FFP tests in this study. More details about the formulation of the rate equation can be obtained from Chow and Airey (2013).

Conclusions

The influences of five test variables (FFP mass, tip diameter, tip shape, FFP impact velocity and soil strength) on the rate effects in FFP tests have been investigated using extensive laboratory tests on model FFPs in clay. The FFP mass, tip diameter and tip shape are found to have negligible influence on the rate effects in FFP tests. Increasing the impact velocity tends

to increase the rate effects until a critical velocity is reached around 5 m/s. The limiting rate effects observed beyond the critical velocity have not been widely reported and further tests on other soils to determine soil parameters on which the critical velocity depends are desirable. The limiting rate effects are found to decrease linearly with increasing soil undrained shear strength, within the range investigated ($v_o \geq 4.6$ m/s and $s_{u(CRP)}$ up to 32.2 kPa). More tests are desirable to further explore the influences of more test variables, such as the influence of soil type or plasticity, soil stress history and the inclusion of water above claybed to truly represent field conditions.

Acknowledgements

The work described in this paper is supported under the Australian Research Council. The first author was supported by an Endeavour International Postgraduate Research Scholarship (EIPRS) and an International Postgraduate Award (IPA) scholarship. These supports are gratefully acknowledged.

Notation

A	penetrometer tip area
a	acceleration
C_c	compression index
CK _o UC	K _o consolidated undrained compression triaxial test
C_r	recompression index
CRP	constant rate of penetration
c_v	coefficient of consolidation
d	penetrometer diameter
F	load measured on a CRP penetrometer

1	FFCPT	Free Fall Cone Penetrometer
2	FFP	free falling penetrometer
3	F_r	reaction force
4	F_t	tip force
5	G_{max}	maximum shear modulus
6	G_s	soil specific gravity
7	g	free fall acceleration, 9.81m/s^2
8	H	final embedment depth
9	h	penetration depth
10	h/d	embedment ratio
11	k	strength gradient of claybed
12	L	length of a T-bar
13	LL	Liquid limit
14	m	penetrometer mass
15	N	resistance factor in CRP tests
16	N_{ball}	resistance factor for ball penetrometers
17	N_{plate}	resistance factor for circular plate penetrometer
18	N_{T-bar}	resistance factor for T-bar penetrometer
19	P_a	atmospheric pressure
20	PIV	particle image velocimetry
21	PL	Plastic limit
22	p'	mean effective stress
23	q_d	dynamic penetration resistance
24	q_s	static penetration resistance
25	$R_f, R_{fl}, R_{fl(mean)}$	rate factor, limiting rate factor, mean limiting rate factor
26	STING	Seabed Terminal Impact Naval Gauge

1	s_u	undrained shear strength
2	$s_u / \gamma' d$	strength ratio
3	$s_{u(CRP)}$	undrained shear strength estimated from CRP tests
4	TS.	Test Series
5	V	normalised velocity equivalent to vd/c_v
6	v	penetration rate in CRP tests or instantaneous velocity in FFP tests
7	v_c	critical velocity
8	v_o	impact velocity
9	W	penetrometer total self weight
10	XBP	Expendable Bottom Probe
11	XDP	Expendable Doppler Penetrometer
12	γ'	soil submerged unit weight
13	M, Γ, λ	critical state parameters
14	σ'_v	vertical effective stress

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21 dependent and strain-softening clay." *Geotechnique*, 59(2), 79-86.

Table 1. Properties of kaolin clay obtained from index property tests

Specific gravity tests <ul style="list-style-type: none"> Specific gravity, G_s 	<ul style="list-style-type: none"> 2.636
Atterberg Limit tests <ul style="list-style-type: none"> Plastic limit, PL Liquid limit, LL 	<ul style="list-style-type: none"> 27% 44%
Oedometer tests <ul style="list-style-type: none"> Coefficient of consolidation, c_v Compression Index, C_c Recompression Index, C_r 	<ul style="list-style-type: none"> 8.0 to 10.8 m²/yr (for $\sigma'_v \sim 18$ to 288 kPa) 0.205 0.073
Triaxial tests <ul style="list-style-type: none"> Critical state parameters Stiffness parameters 	<ul style="list-style-type: none"> $M = 0.986, \Gamma = 2.238, \lambda = 0.083$ $\frac{G_{\max}}{P_a} = 432.9 \left(\frac{p'}{P_a} \right)^{0.709}$ where p' is the mean effective stress and P_a is the atmospheric pressure

1

Table 2. Model test program

2

TS.	$s_{u(CRP)}$ (kPa)	FFP tests				CRP tests
		m (g)	d (m)	Tip shape	v_o (m/s)	
(I) Influence of FFP Mass						
1	4.98	262.0, 353.2, 446.6, 539.2, 631.7, 724.4	0.02	plate	4.8	3 x T-bars
(II)Influence of FFP Tip Diameter						
2	17.11	Only CRP tests with 2 x T-bars, 4 x plates ($d = 0.01, 0.02, 0.03, 0.04$)				
3	15.19	Only CRP tests with 3 x T-bars, 3 x plates ($d = 0.01, 0.02, 0.06$)				
4	6.48	736.9	0.03, 0.04, 0.06	plate	4.8	3 x T-bars
5	4.37	736.9	0.03, 0.06	plate	4.8	3 x T-bars
6	$k = 95$ kPa/m	361.0 to 388.0	0.02, 0.03	plate	4.8	See next row
		CRP tests with 3 x plates (d = 0.01, 0.02, 0.03 m)				
(III) Influence of FFP Tip Shape						
7	15.33	344.5 to 371.6	0.02	plate, ball, 60° cone, 90° cone	4.7	1 x T-bar 1 x ball 1 x plate
8	14.40	347.9 to 371.6	0.02	plate, ball, 60° cone	4.7	See next row
		CRP tests with 3 x T-bars,1 x ball, 1 x plate,1 x 60° cone				
9	$k = 50$ kPa/m	344.5 to 371.6	0.02	plate, ball, 60° cone, 90° cone	4.4	2 x T-bars 1 x plate
10	15.47	368.7	0.02	ball	4.7, 7.8, 9.5, 11.4	1 x ball
(IV) Influence of Soil Strength and Impact Velocity						
11	15.75	332.7	0.02	plate	4.7, 7.8, 9.7, 11.1, 12.2	3 x T-bars 1 x plate
12	7.22	347.8	0.02	plate	1.4, 2.2, 2.8, 4.7, 7.8, 9.5	1 x plate
13	10.16	347.8	0.02	plate	1.4, 2.8, 4.8, 7.9, 9.5, 11.9	1 x plate
14	32.18	347.8	0.02	plate	2.2, 2.8, 4.7, 7.7, 9.2, 12.0	1 x plate
15	$k = 35$ kPa/m	349.4	0.02	plate	1.4, 2.2, 2.8, 4.6, 6.4	1 x plate

Note:

- Unless specified, all CRP tests involve tips with 0.02 m diameter (excluding T-bar).
- Repeat FFP tests have been conducted randomly to check test repeatability and consistency, but not specified in the table.
- $s_{u(CRP)}$ are average undrained shear strengths at mid-height of claybed estimated using Eq. (2) with $N = 10.5$

Table 3. Selected reported resistance factors, N for CRP penetrometers

	N_{T-bar}	N_{ball}	N_{plate}
Plasticity solutions	UB: 9.14 (smooth) to 11.94 (rough) LB: 9.20 (smooth) to 11.94 (rough) (Martin & Randolph 2006)	UB: 10.98 (smooth) to 15.10 (rough) LB: 11.60 (smooth) to 15.31 (rough) (Randolph et al. 2000)	Exact: 12.42 (smooth) to 13.11 (rough) (Martin & Randolph 2001)
Numerical solutions (Lu et al. 2001)	9.6 (smooth) to 12.1 (rough)	11.4 (smooth) to 15.1 (rough)	13.2 (smooth) to 13.9 (rough)
Field data <ul style="list-style-type: none"> • $s_{u,c}^1$ • $s_{u,ave}^2$ • $s_{u,vane}^3$ (Low 2009) ⁵	9.1 to 13.2 (10.8) ⁴ 8.8 to 13.3 (10.7) 11.6 to 14.1 (13.0)	10.1 to 13.2 (10.9) 9.4 to 13.6 (10.9) 11.7 to 14.1 (13.0)	10.3 to 15.0 (12.2) 10.9 to 14.8 (12.3) 12.6 to 15.8 (14.5)
<ul style="list-style-type: none"> • $s_{u,c}^1$ • $s_{u,ave}^2$ • $s_{u,vane}^3$ (Low 2009) ⁶	7.9 to 14.0 (10.3) ⁴ 9.8 to 14.7 (11.9) 10.1 to 14.1 (11.9)	8.2 to 10.7 (9.4) 10.8 to 11.5 (11.2) 12.0 to 12.4 (12.2)	-

Note:

¹ $s_{u,c}$ were obtained from triaxial compression tests

² $s_{u,ave}$ were obtained from the average of triaxial compression, triaxial extension and simple shear tests

³ $s_{u,vane}$ were obtained from vane shear tests

⁴ mean value indicated in bracket

⁵ field data obtained from CRP tests on Burswood Clay

⁶ covering 3 onshore and 11 offshore sites (Japan, Australia, Norway, West Africa, Timor Sea, Egypt, the Gulf of Mexico)

Table 4. Final embedment depths for FFPs with different tip shapes

Tip shapes	Final embedment depth, H (mm)			
	Dayal (1974)	TS. 7	TS. 8	TS. 9
circular plate	213.4	43.6	54.1	160.4
ball	-	45.9	53.5	171.5
90° cone	227.1	51.7	64.2	181.5
60° cone	244.8	54.3	56.2	172.7
30° cone	249.9	-	-	-

Table 5. Rate factors for TS. 10 to 14

TS.	$s_{u(CRP)}$ (kPa)	Limiting rate factor, R_{fl} ¹ for test with impact velocity, v_o of					
		4.8 m/s	7.8 m/s	9.6 m/s	11.2 m/s	12.2 m/s	$R_{fl(mean)}$
10 ²	15.47	1.65	1.92	1.97	2.01	-	1.88
11	15.75	2.44	2.75	2.57	2.40	2.88	2.61
12	7.22	2.62	2.60	2.46	-	-	2.56
13	10.16	2.91	2.67	2.77	-	2.64	2.75
14	32.18	2.02	1.90	2.02	-	1.84	1.94

Note:

¹ R_{fl} for tests with different v_o in the same TS. are estimated at the same instantaneous v . For instance, R_{fl} are taken at $v = 6.51$ m/s for all tests with $v_o > 4.8$ m/s in TS. 10.

² All test series involve 20 mm diameter circular plate tip except TS. 10 that involves 20 mm diameter ball tipped FFP

1 LIST OF FIGURE CAPTIONS

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- 3 Fig. 2. Model FFP with different tip geometries
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Figure 1
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Note : All dimensions in mm
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Figure 2

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