Federation of Piling Specialists' casing extraction review

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Abstract

During construction of rotary bored piles it is necessary to install a temporary casing to prevent the collapse of material into the open bore and provide edge protection. The preferred method of removal for some contractors is by means of the handling crane. The Federation of Piling Specialists (2010) released guidance to predict the load developed in the removal of casings. This paper investigated whether the recommended constants applied to the overburden and clay terms were reasonable for various casing diameters, embedment and depth of overburden. A series of five centrifuge tests were conducted where loads were recorded as casings were extracted. Results showed that the FPS method over predicted the pull-out force and indicated that the adhesion factor, α, and angle of dilation between the casing and soil, tanδ, are not constant. This paper proposes a new method of predicting extraction forces which was found to predict forces to within ±10% of those measured in centrifuge tests.

Keywords chosen from ICE Publishing list
Models (physical), piles & piling, safety & hazards.

List of notation

A_b	area of pile base
A_s	area of pile shaft
EA_o	external area of casing in contact with overburden
EA_c	external area of casing in contact with clay
F_{ext}	casing extraction force
FPS	Federation of Piling Specialists
g	Gravitational acceleration
h	height of concrete in contact with casing
HSE	Health and Safety Executive
IA	internal area of casing
K_s	coefficient of earth pressure
LBS	Leighton Buzzard Sand
N_q	bearing capacity factor
OD	outer diameter of casing
Q_{int}	internal force acting along casing
Q_{ext}	external force acting along casing

S_u	average undrained shear strength
SW	casing self-weight
α	adhesion factor
δ	angle of dilation between casing and soil
γ_{conc}	bulk unit weight of concrete
μ	coefficient of friction between concrete pile and casing
ϕ'	critical state angle of friction
σ'_v	average vertical effective stress
σ'_{vb}	vertical effective stress at base of pile

Introduction

Steel casings are often used in the construction of rotary bored pile foundations as a means of supporting the overlying granular material and provide edge protection. Tubular casings are too expensive to use as permanent sacrificial casings so they are typically removed shortly after the pile has been cast. Using their judgement, experienced piling contractors assess whether their plant is capable of extracting casings using the site crane as this eliminate the added cost of hiring specialist casing extractors, which can clutter constrained sites. However, following some catastrophic crane boom failures the FPS highlighted the risks associated with attempting to pull casings without suitable hand calculations to validate the judgement of experienced personnel (FPS, 2010). Consequently, the HSE discouraged the practice of pulling casings by crane unless it was completed in conjunction with specialist equipment.

Contractors are under increasing pressure to use specialist equipment, such as hydraulic jacks or oscillators to facilitate the removal of temporary casings. A more common approach is to use the piling rig to rotate the casing out of the ground, however this delays piling activities, increases plant tracking across the site, consequently increasing project costs and the risk of accidents on site. Although this mitigates the risk of exceeding the safe lifting capacity of the crane, it is considerably more time consuming and expensive than using the site crane. To date, a limited number of parametric physical modelling studies have been conducted (Gorasia *et al.*, 2012; Panchal *et al*., 2016) to model pull-out forces for a range of scenarios. Unfortunately, there are few published case histories available to aid in the validation of the conclusions made in those studies.

Following the report published by the FPS (2010), Balfour Beatty Ground Engineering and Cementation Skanska Ltd. commissioned a series of centrifuge tests at City, University of London in 2014. These tests were designed to model the effects of changes in casing diameter, overburden height and embedment depth on peak forces. Gorasia (2014) concluded that doubling the casing embedment depth influenced peak extraction forces greater than doubling the overburden height but stated that the FPS (2010 theoretical calculations “reasonably predict the peak extraction forces”. The results showed that the FPS method either over predicted or underestimated the extraction force by up to 20% and suggested that the force was heavily influenced by the frictional resistance from the overburden material.

This paper will rigorously explore the FPS method of predicting the extraction force and analyse the assumption that the adhesion factor and critical state angle of friction reduction factor are constant, regardless of variations of casing diameter, embedment and overburden depth. The paper draws on data collected in a series of four centrifuge tests reported by Gorasia *et al*. (2014) and Panchal *et al*. (2016) and is supplemented by a further centrifuge test.

2. Experimental design

The centrifuge experiments were designed to test up to four pile casings simultaneously on a geotechnical centrifuge. The apparatus arrangement allowed for a 5kN miniature load cell to be attached to each casing to enable independent measurement of extraction forces from each casing. This facilitated the investigation of the impact of embedment, overburden and diameter on extraction forces. The three casing diameters used across the tests comprised 17.5mmOD (*d*), 25mmOD (≈1.5*d*) and 35mmOD (2*d*), to observe the relationship between casing diameter and extraction force.

The casings were extracted at a constant rate until they had been completely removed from the clay layer. Consistency between tests was achieved by ensuring that there were no variations in the soil type, pre-consolidation pressure, depth of clay or model making procedure.

3. Model geometry

Plane strain tests were conducted in a centrifuge strongbox with 200 x 550mm internal plan dimensions; which was large enough for four test sites. A shallow sample of clay overlain by sand was necessary to provide sufficient range for extracting the casings in-flight using a lead screw actuator, which ensured that strain control was achieved during the experiments. A study conducted by Song (2008) demonstrated that soil movements arising from continuous plate anchor pull-out tests ranged between *d* and 1.5*d* for deep and shallow embedded anchors respectively. The casings used in this series of tests were installed along the strongbox centreline at 110mm centres, hence pile spacing ranged from 3.1*d* to 6.3*d*. In view of the findings of Song (2008), this was deemed sufficient to avoid interaction between casings and also sufficient distance from the edge of the box to prevent boundary effects.

The casings were embedded up to 25mm in the 100mm thick layer of clay, in a bore extending to the base of the strongbox. Craig (1995) suggested that the distance between the bottom of the sample and piles should be greater than 5*d* to avoid end bearing effects. This however was not a concern as the casings were extracted in these experiments, not loaded.

4. Soil sample

The soil model was prepared from over-consolidated kaolin overlain by crushed limestone sand. The soil samples were prepared using Speswhite kaolin clay slurry mixed in an industrial ribbon mixer to a water content of 120%; which is approximately twice its liquid limit. Preparation of the centrifuge strongbox comprised lubricating the walls with waterpump grease before placing a sheet of porous plastic and filter paper on top of the herringbone drainage channelled strongbox base. Slurry was carefully placed in the strongbox using a scoop and palette knife to a depth of approximately 220mm, whilst attention was paid to avoiding the entrapment of air bubbles. Another layer of filter paper and porous plastic sandwiched the clay slurry to allow water to drain from the top of the sample in addition to the bottom, thus accelerating the consolidation process.

The strongbox was then transferred to the hydraulic press where a platen was lowered onto the slurry. Water was drained from the sample around the sides of the platen and the drainage channels at the base of the strongbox. The pressure on the sample was gradually increased to 800kPa and left to consolidate for a minimum period of 5 days, before being swelled back to 400kPa the day prior to testing. Depending on the overburden surcharge in the test, this produced a clay sample with an OCR ranging from 4 to 5.8 at 50*g*.

In consideration of the centrifuge scaling laws, Devonian limestone was crushed to a fiftieth of prototype scale to provide model scale 6F2 grading and was used for the materials overlying the clay. 6F2 is the standard fill for earthworks in the UK (Volume 1 of the Manual of Contract

Documents for Highway Works, 2009) and was sourced from a UK quarry in Ashburton, Newton Abbot. This was washed and sieved prior to use in the tests. The grading curve is illustrated in Figure 1 and the material lay within the upper and lower bounds specified in the manual. Particle sizes ranged from 3.35mm to dust with a critical state angle of friction of 45°, determined from shearbox tests.

5. Model making and apparatus development

The clay sample was removed from the hydraulic press and the front face of the strongbox unbolted. The sample was then trimmed to a height of 100mm and sealed with a thin layer of silicone oil to prevent the clay from drying out. Several elements were designed by Gorasia *et al*. (2014) including cutters, guides, the actuator and casing connectors; these are described below. The model making process outlined below was developed by Gorasia *et al*. (2014) and the consistency between the previous and the current tests allow comparisons to be drawn between the results.

5.1 Cutters and guides

The lengths of casings used in these experiments ranged from 150mm to 170mm which allowed for up to 120mm overburden with sufficient length of casing left protruding to which the lifting accessories were attached. The casings were fabricated from 316L stainless steel and had been sand blasted to produce a consistent textured surface.

To accurately position the casings, a Perspex template was manufactured with 40mm diameter holes drilled at 110mm centres which corresponded to the casing centres. Interchangeable small Perspex squares were fabricated to screw onto the main Perspex template, each with a bore to suit the variety of casing diameters, as illustrated in Figure 2(a).

Maintaining verticality of piles and casings was essential, hence jubilee clips clamped to short steel tubes provided the correct casing embedment, shown in Figure 2(b). The short tubes were twisted into the clay layer to cut a shelf to the correct depth. These tubes were also used to guide thin-walled cutters to form a vertical pile bore. Upon removing the template, a clearly visible cutting shelf was left in the clay (Figure 2c), which ensured that the correct casing embedment was achieved in each test.

To simulate the wet concrete piles, a series of flexible latex bags were sprayed with glue and dipped in Fraction B Leighton Buzzard Sand (LBS). This provided a sufficiently rough surface to simulate the friction from concrete aggregate. These latex bags were filled with Fraction E LBS and saturated with water to model the hydrostatic effects of wet concrete before being placed in the bore.

A small drainage channel was cut into the clay leading to a drainage port at the back of the strongbox. This was connected to a solenoid valve that was controlled remotely to allow standing water to be drained following the saturation of the overburden in-flight.

A plywood former was placed on the clay, which would later contain the overburden material, upon which the Perspex template rested. This served the purpose of guiding the casings into the clay layer, supporting the top of the casings during the placement of the 6F2 and maintaining verticality, as shown in Figure 2(a). This was essential as the shallow clay embedment would not have provided sufficient support to the casings.

5.2 Actuators, casing connectors and load cells

A 10kN lead screw actuator mounted to the top of the strongbox was remotely controlled to simultaneously pull all four casings in-flight. To fulfil the requirement to measure the force of each casing independently, an M5 stud was screwed into the actuator which was connected to a universal joint. A miniature load cell was sandwiched between universal joints and was secured to a cap that loosely fitted within the casing. M5 lifting eyes had been drilled into the casing and were aligned with the holes in the casing cap before being secured with a bolt. Universal joints either side of the load cell allowed the correction of any misalignment of the casing; consequently axial loads only were recorded. Figure 3 depicts the experiment set up used in Test 5 immediately prior testing.

6. Testing procedure

The Acutronic 661 beam centrifuge at City, University of London was used to conduct these experiments, details are described in Schofield and Taylor (1988).

The strongbox was bolted together, transferred to the centrifuge and was supplied with two water feeds. An overflow standpipe established a water table at the top of the clay layer, whilst water was fed directly to the top of the model to saturate the overburden material after the model was accelerated to 50*g*. On-board cameras provided visuals of the sample and once it was confirmed that the overburden had been fully saturated a solenoid valve was actuated to rapidly drain the water from the model. This process served the purpose of compacting the material and achieved a consistent relative density through the depth of the overburden.

Owing to the shallow clay depth and the nominal casing embedment, the sample was consolidated in-flight for a period of 5h to allow the dissipation of excess pore pressures and allow the clay to reconsolidate against the casing before testing. The test involved simultaneously pulling all four casings at a constant rate of 10mm/min until they had been completely removed from the clay layer. The sudden pulling force was comparable with the force experienced on site by a crane.

7. Test series

A total of five centrifuge tests at 50*g* were conducted to investigate the influence of casing diameter, embedment depth and overburden height on peak extraction forces. In each test, four casings were modelled providing 20 sets of data. The variables for each of the five centrifuge tests and the corresponding peak forces are reported in Table 1, whilst the experiment and apparatus set up is shown in Figure 4(a). The centrifuge tests included in this paper are illustrated in Figures 4(b) – (f) and detailed below.

Test 1 was conducted to establish the effect of doubling the casing diameter and embedment depths on peak forces (Gorasia *et al.*, 2014). Two 17.5mmOD and two 35mmOD casings were each embedded 10mm or 20mm in a 120mm deep layer of 6F2. Test 2 comprised a similar experimental set up however a shallower overburden depth of 60mm was used.

Having established the relationship between doubling the casing diameter, embedment and overburden, the effects of intermediate embedment depths were explored in Test 3 (Panchal *et al.*, 2016). Large and small diameter casings were used in a 120mm deep layer of 6F2. These casings were embedded to depths of 15mm and 25mm.

Test 4 (Panchal *et al.*, 2016) was conducted to determine the influence of consolidation time on peak extraction forces. Four 25mmOD casings were installed in a 120mm deep layer of 6F2 and were embedded to depths of 5mm, 10mm, 20mm and 25mmm. As with the other tests, the casings were initially left to reach hydrostatic equilibrium for 5h before being extracted at a rate of 10mm/min for 30s. This consolidation and extraction process was repeated for the following consolidation periods; 6s, 206s, 24s and 165s. At prototype scale, these translate to consolidation periods of 4h, 6days, 17h and 5days respectively.

7.1 Test 5 experiment set up

The tests outlined above were analysed using the FPS (2010) method to predict the extraction force. However, back analyses identified that over predictions or underestimations of extraction forces computed using the FPS method did not follow a trend. The FPS method will later be discussed in detail and further work was recommended to determine its reliability.

Owing to the complex interaction of forces between the casing, overburden, clay and concrete pile and the large number of unknown constants arising within each term, it was difficult to confirm whether the adhesion factor (α) and tanδ factor recommended by the FPS were suitable values. There was also a lack of clarity of whether these factors remain constant for all casing diameters. In view of this, Test 5 was conducted to reduce the number of variables acting on each casing. All casings were subjected to internal friction from a concrete pile, however the external forces applied were limited to either clay embedment or overburden friction.

In order to segregate the frictional forces arising from the 6F2, the centres of Teflon rods were bored out to produce two 3mm thick Teflon sleeves which were marginally larger than the 35mmOD and 17.5mmOD steel casings. This enabled the casings to be withdrawn with minimal interaction from the sleeve. The low coefficient of friction of Teflon (μ = 0.05) and high rigidity of the sleeve served the purpose of both reducing the magnitude of friction and the horizontal stresses applied by the overburden. The steel casings that were housed within a Teflon sleeve were embedded to a depth of 20mm to measure forces directly attributed to clay embedment, as previously shown in Figure 3.

The frictional forces associated with the overburden were determined using one 17.5mmOD and one 35mmOD casing seated on top of the clay layer with no embedment established.

8. Centrifuge test results

To date, five centrifuge tests have been performed at 50*g* and the peak extraction forces recorded in each of these experiments are presented in Table 1. A water table had been established at the surface of the clay layer and once the excess pore pressures had dissipated, the casings were extracted at a rate of 10mm/min. For the purposes of this paper all measurements will be presented at model scale, however Table 2 gives these at prototype scale.

9. The FPS guidelines for predicting extraction forces (2010)

The FPS (2010) released simple and clear guidance for predicting casing extraction forces. It was defined as a summation of the self-weight (*SW*) of the casing and frictional forces acting along its shaft, as illustrated in Figure 5. These comprise wet concrete (Q_{int}) along the internal diameter and external frictional forces (Q_{ext}) from the overburden material and adhesion from the clay. Each component is defined in Equations 1 to 3.

$$F_{ext} = Q_{ext} + Q_{int} + SW$$

1.

$$Q_{ext} = EA_o \sigma'_v \tan\delta + EA_c \alpha S_u$$

2.

$$Q_{int} = IA\gamma_c \frac{h}{2}\mu$$

3.

Equation 2 accounts for the frictional forces at the casing and overburden interface and the average vertical effective stress is considered here. δ is defined as the angle of dilation owing to wall friction and is dependent on the casing material and the critical state angle of friction of soil. The FPS (2010) recommend δ = 0.75ϕ'. The second term in Equation 2 relates to the shearing resistance between the casing and clay.

Consideration was also given to the frictional forces acting along the internal face of the casing (Equation 3). The average vertical stress acting along the inner diameter of the casing was used in this calculation. The FPS suggest that the coefficient of friction between the concrete and casing, μ, is taken as 0.1, as this value is recommended by Pallett *et al.* (2002) for the interaction between steel and cast concrete.

10. Analysis of results

The centrifuge results from Test 5 were used in the back analysis of α and tanδ for each test. The frictional force resulting from the concrete pile was calculated using the factor μ = 0.1. The results are presented in Table 3 and 4 respectively.

10.1 Adhesion factor

To determine the adhesion factor, α, 35mmOD and 17.5mmOD casings were embedded to a depth of 20mm in the clay layer and a Teflon sleeve, seated on the clay, prevented any interaction with the overburden. Hence, the extraction force was a combination of the concrete pile friction, casing self-weight and clay adhesion.

The casing self-weight was easily quantifiable by scaling the weight of the casing and connectors. However, the magnitude of the concrete pile friction was calculated by following the FPS (2010) guidelines and using a coefficient of friction value of 0.1.

Equations 4 and 5 were used to obtain the adhesion coefficient. An assumption was made that the increase in undrained shear strength with depth for shallow casing embedment was negligible, thus a constant Su value was used in each of the following analyses.

$$Q_{ext(clay)} = F_{peak} - (SW + Q_{int})$$

4.

$$\alpha = \frac{Q_{ext(clay)}}{S_u \times EA_{clay}}$$

5.

The results presented in Table 3 indicate that casing size has some influence over the magnitude of α. It may therefore not be advisable therefore to assume that a constant value of α can be used in predicting casing extraction forces.

Linear interpolation showed that $\alpha = 0.64$ for 25mmOD casings. Although this is within the range of α values for London Clay (Bell & Robinson, 2012), these results illustrate that the magnitude of α is not solely dependent on the undrained shear strength of the soil and that casing diameter plays an important role in extraction forces.

10.2 Overburden tanδ factor

A similar analysis was conducted to establish whether the reduction factor applied to the critical state angle of friction was constant across all tests. The three α values presented in Table 3 were used to back analyse centrifuge tests 1 – 5 and the results are presented in Table 4.

Owing to the consistent manner in which the clay samples had been prepared, it was reasonable to assume that the adhesion factors obtained from Test 5 would apply to casings of similar diameter in other pull out tests.

The FPS (2010) recommend that the critical state angle of friction is reduced by 25% to account for the friction between the casing and soil. In this series of experiments $\tan\delta = \tan(0.75*45^{o})$ which equates to 0.668. However, this analysis revealed that the factor applied to the angle of friction was significantly lower and is a function of casing diameter, embedment and overburden depth.

To investigate the sensitivity of $\tan\delta$ to changes in embedment, the results from all tests were plotted on Figure 6. The trend suggests that for an embedment up to 10mm, $\tan\delta$ is relatively constant at approximately 0.25. However, increasing the embedment depth results in a larger value of $\tan\delta$ where an embedment of 30mm, equivalent to 1.5m at prototype scale, can be as large as 0.6, which is closer to the value recommended by the FPS (2010). These values generally lie within ±25% of the trendline.

The scatter of the 17.5mmOD data plots either side of the trendline suggest that there is a lack of reliability for small diameter casings compared with large diameters. The 35mmOD and 25mmOD data points are consistently on one side of the trendline.

This analysis suggests that the FPS (2010) recommendations to reduce the critical state angle of friction to 75% may only be reasonable for significant embedment depths. However, on site the embedment of a casing is dependent on its total length, the depth of the overburden and the requirement that approximately 1m of the casing protrudes above ground level. As embedment depths can range anywhere between 0.5m and a couple of metres at prototype scale, it is important to be aware that tanδ is not only dependent on soil properties.

10.3 Modified FPS method

The tanδ chart, illustrated in Figure 6, and the α constants defined in Table 3 were used to predict casing pull-out forces for each casing scenario modelled in the centrifuge experiments. For the purpose of this paper this procedure will be referred to as the “modified FPS method”.

Comparisons between the predicted forces and the centrifuge measurements are ilustrated in Figure 7(a) – (e). The modified FPS method closely predicted the pull-out force in Tests 1, 2, 4, and 5. Although this method generally overestimated the extraction force, Test 3 was underpredicted by an average of 12%. This may be owing to the effects of consolidation time on the magnitude of α and tanδ.

Figure 8 highlights the improved reliability of the modified FPS method over the FPS (2010) method. Although the FPS (2010) method overpredicted the extraction force in almost all cases, it calculated values up to three times greater than those measured in the centrifuge tests and on average overestimated forces by 65%. The modified FPS method provided better agreement with an average overprediction of 4%. Predictions made with the modified FPS method typically lie within ±10% of the recorded extraction force.

11. Discussion

11.1 Casing self-weight discrepancy

The loads, recorded in the centrifuge tests, used in the analyses were not zeroed at the point at which the test started. During model making there was some degree of slack between the bolt, the lifting eye and the casing cap. Hence, when the model was accelerated one of a number of situations may have arisen. It is possible that the casing was fully supported by the clay, hence did not slip or hang from the load cell. It is equally possible that the casing was not supported by the soil at all and the load measured accounted for the entire self-weight of the casing and cap. Alternatively, it can be argued that the load measured during the acceleration was only a proportion of the casing self-weight, however it is difficult to quantify what proportion was supported.

This is illustrated in Figure 7d, Test 4 for 35mmOD (15mm embedment) and 17.5mmOD (25mm embedment) casings. There was an initial spike in force measured by the load cell before levelling out. This was caused by the casing cap (Figure 3) becoming suspended but before the bolt engaged with the lifting eye in the casing. The subsequent rise in force is therefore attributable to the extraction of the casing. However, as the casing self-weight also includes the weights of the universal joint, casing cap and bolt, any potential errors accrued are minimal.

11.2 Horizontal stresses

Terzaghi's (1943) method of calculating the bearing capacity of a pile is defined in Equation 6. Arguably this could determine the extraction force of a casing, with the omission of the base capacity term, which gives Equation 7. It is comparable with the FPS guidelines with the exception of K_s, which is the coefficient of earth pressure and can be calculated using Equation 8. As the critical angle of friction of the 6F2 overburden material is 45º, this gives a K_s value of 0.293. If this were applied to the predicted force it would reduce the magnitude of the overall extraction force. This is also the case for the internal interaction from the concrete pile. Although, as the calculated concrete pile force was less than 1N, any reduction would have a negligible effect on the total extraction force.

$$Q_f = \Sigma(K_s \sigma'_v \tan\delta \, A_s) + A_b \sigma'_{vb} N_q$$

6.

$$Q_{ext} = \Sigma(K_s \sigma'_v \tan\delta \, A_s) + SW$$

7.

$$K_s = 1 - \sin\phi'$$

8.

12. Implications of research

This study highlighted inaccuracies with the original method proposed by the FPS (2010) for estimating casing pull-out forces. The new modified FPS method offers improved accuracy in assessing pull out forces. The original FPS method was generally shown to overestimate the extraction force in the majority of instances. Although it was more conservative in predicting forces, the FPS method (2010) could result in unnecessary use of costly specialist pile extraction equipment. Bearing in mind that the modified FPS method predicts extraction forces within ±10% of the measured force it is suggested than a factor of safety of 10% is applied to the computed force to determine whether the load will exceed the capacity of the site handling crane. In addition to the phenomena reported in this paper it should be noted that there are also implications for delays in extraction of casings as reported by Panchal *et al*. (2016).

This method would provide contractors with more certainty and confidence in their calculations and therefore ensure improved safety during casing removal. Moreover, the simplicity of this method relies solely on information obtained from a SI report and the tanδ design chart (Figure 6) to reliably predict the expected extraction force. Calculations are simple to perform by hand to determine the extraction force. This increases the likelihood of contractors completing safety checks on site and can contribute to safer working practices.

13. Conclusions

This research investigated the reliability of the FPS (2010) proposed method for predicting pull out forces of temporary steel casings. This paper incorporated data from a series of four centrifuge tests including those conducted by Gorasia *et al.* (2014) and Panchal *et al.* (2016); an additional test was carried out for this study and formed the basis of this paper. Therefore, to date a total of five centrifuge tests at 50*g* have been conducted, modelling the extraction forces for varying casing diameters when pulled from a layer of clay and through a prescribed depth of overburden.

Data from the most recent centrifuge test was used to ascertain the adhesion factor, α, and the angle of dilation between the casing and soil, tanδ. It was confirmed that α varied with casing diameter even when the undrained shear strength of the clay was constant. Analysis of tanδ showed that this value was sensitive to variations in embedment and casing diameter. The proposed calculation was applied to the scenarios tested by Gorasia *et al*. (2014) and Panchal *et al*. (2016) and proved to accurately predict extraction forces to within 10% of those measured in the centrifuge tests.

14. Further work

To confirm the validity of the proposed modified FPS prediction method it is proposed that field studies are carried out in a range of ground conditions and time frames. This would provide some context and comparison for this study and illustrate whether this method is appropriate for use in the field. Another centrifuge test could be conducted to establish the relationship between consolidation time and the magnitude of tanδ and α. Owing to the relatively shallow embedment depths used in this series of tests it is advisable to back analyse the factors for an embedment up to 3m at prototype scale.

Acknowledgement

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Figures

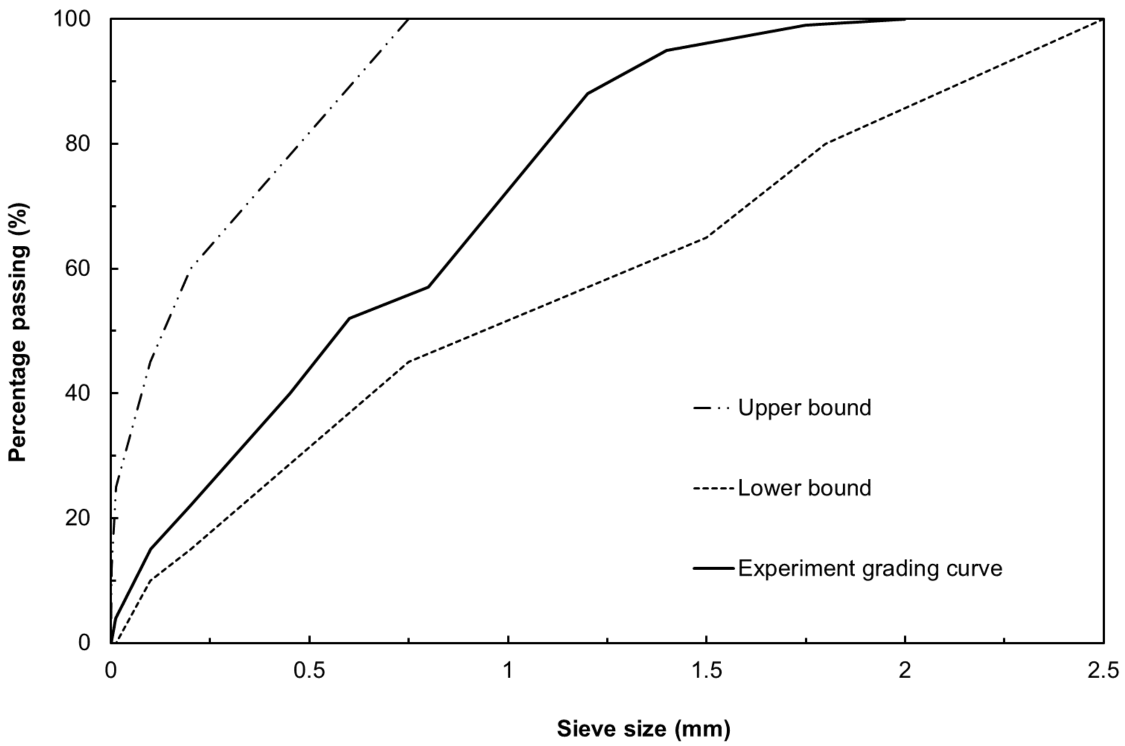


Figure 1. Grading curve of 6F2 overburden material used in centrifuge tests

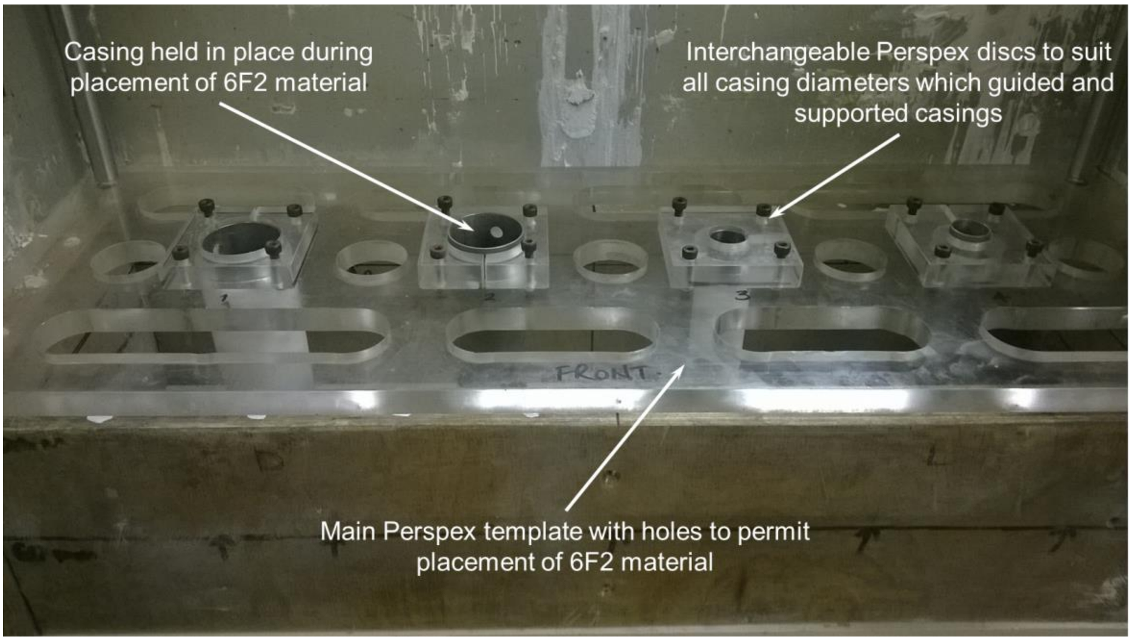


Figure 2(a). Perspex template and interchangeable casing squares supporting casings prior placement of overburden

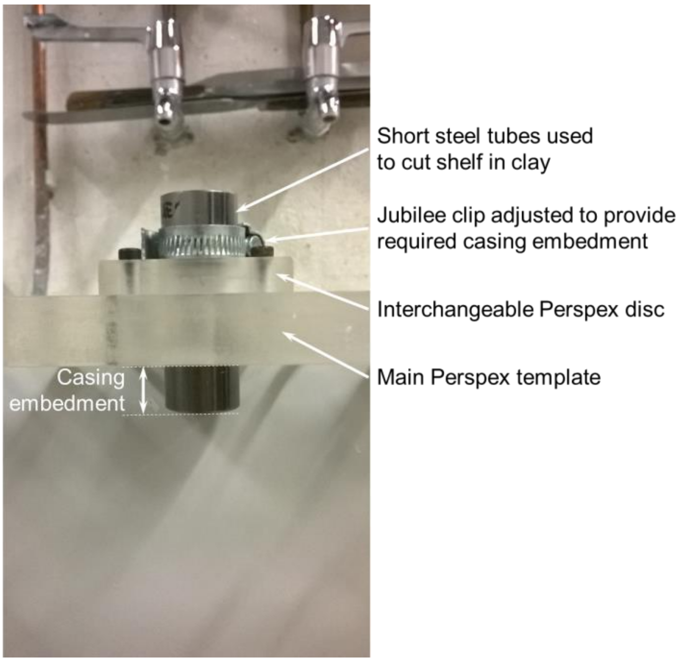


Figure 2(b). Elevation of Perspex template showing short lengths of steel tube with jubilee clips to provide required embedment

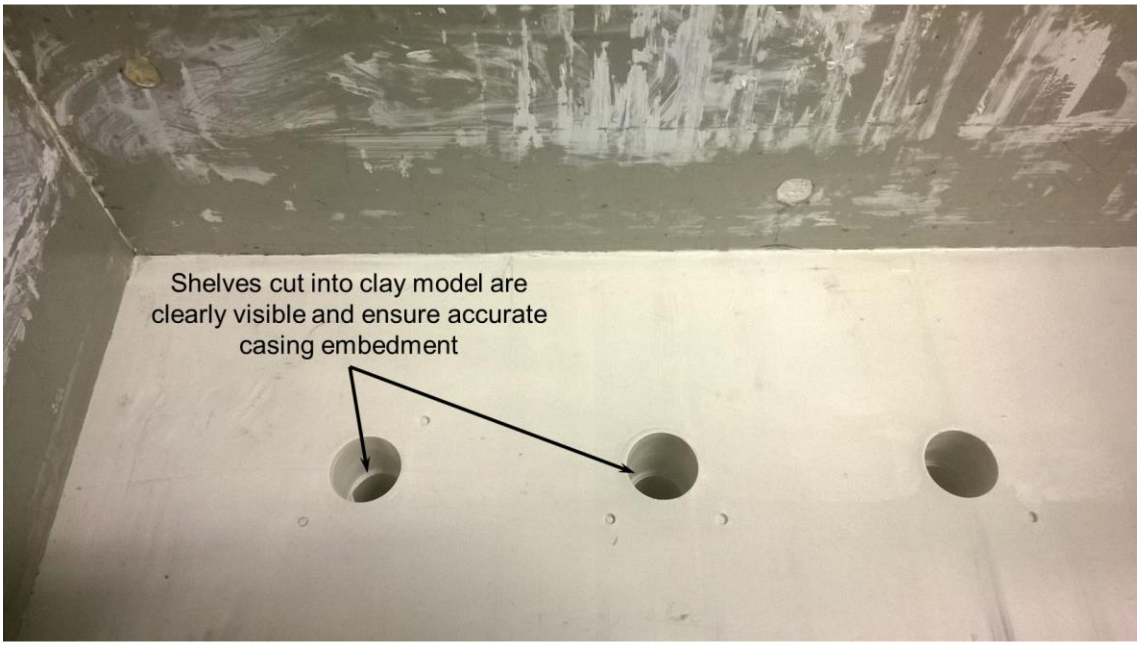


Figure 2(c). Shelf cut into clay layer to ensure accurate embedment

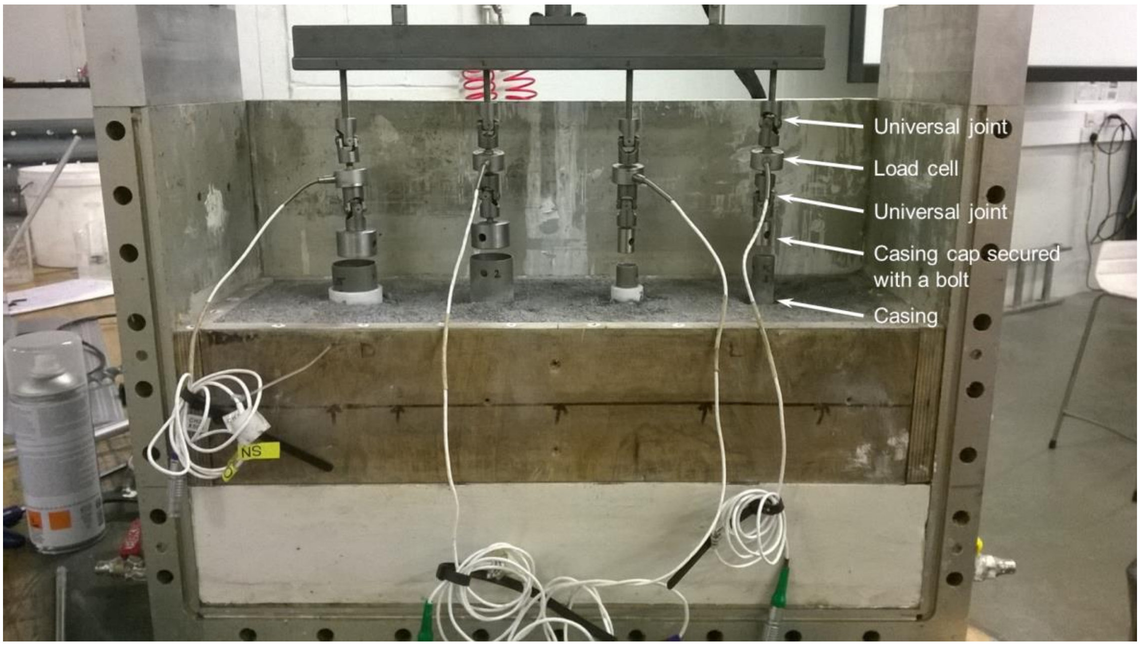


Figure 3. Casing and connector components set up used in Test 5

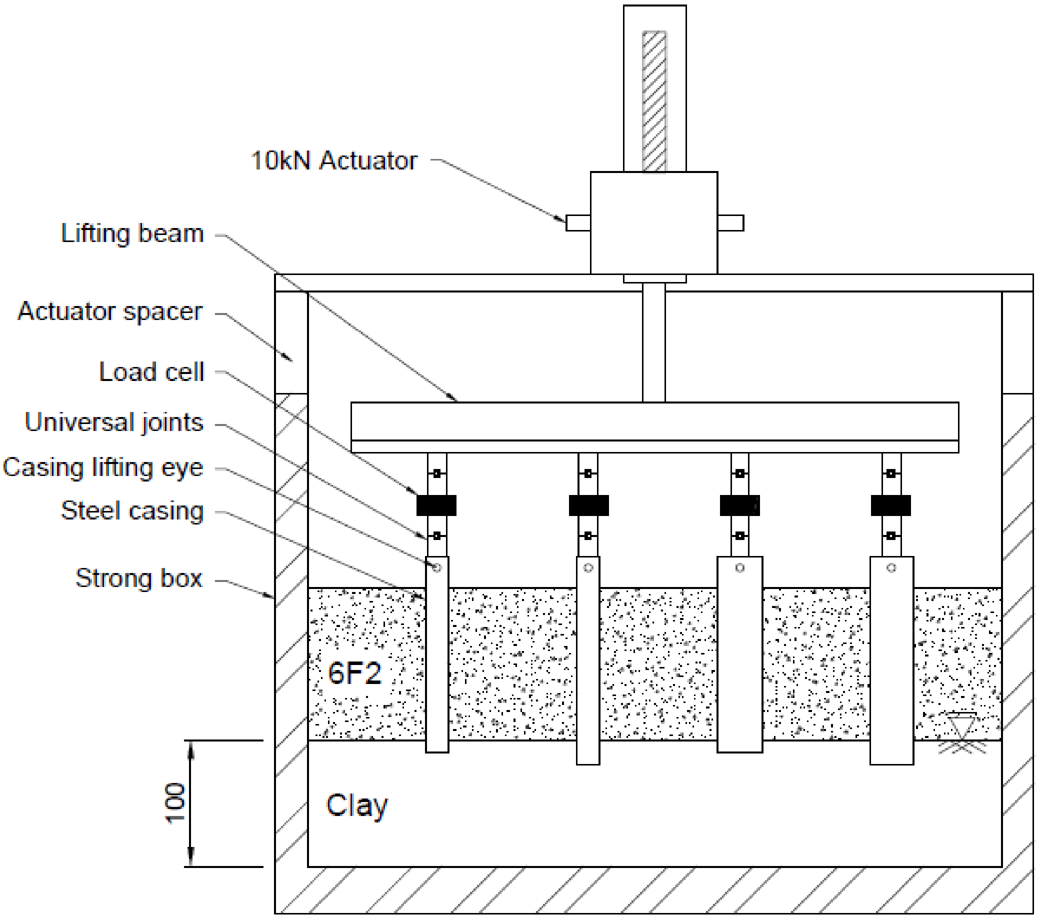


Figure 4(a). Generic apparatus arrangement for experiments

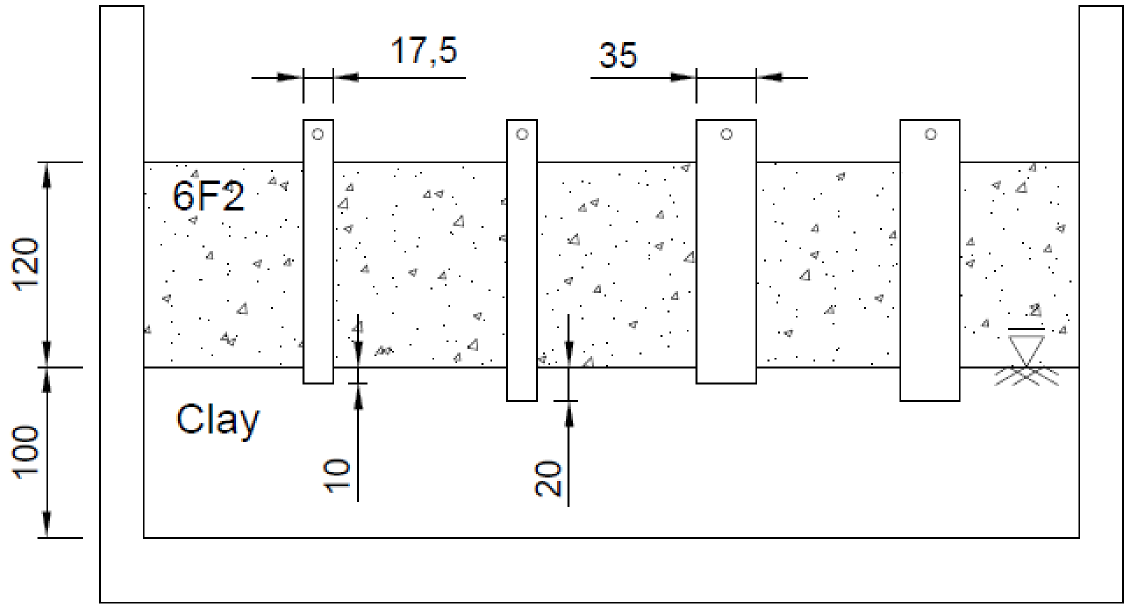


Figure 4(b) Test 1; 120mm overburden, 17.5mmOD and 35mmOD casings of 10mm and 20mm embedment

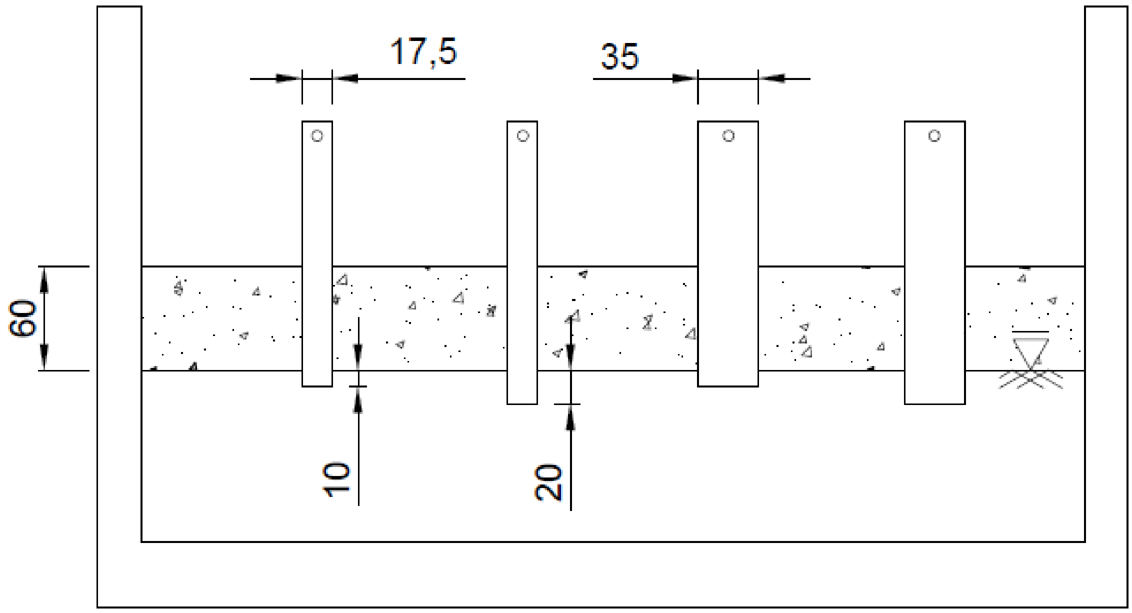


Figure 4(c) Test 2; 60mm overburden, 17.5mmOD and 35mmOD casings of 10mm and 20mm embedment

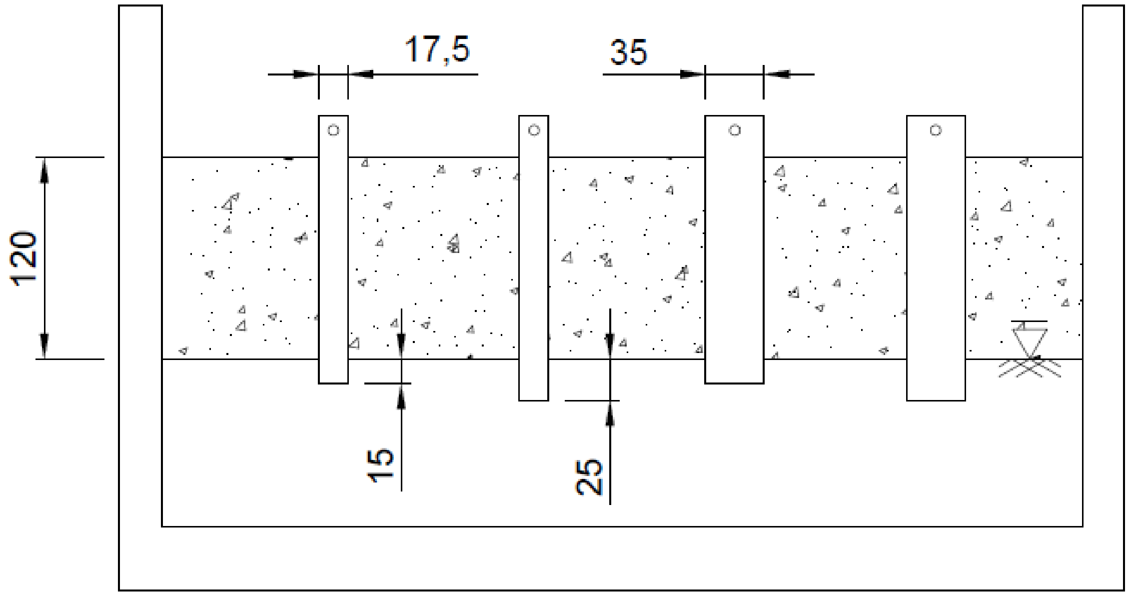


Figure 4(d) Test 3; 120mm overburden, 17.5mmOD and 35mmOD casings of 15mm and 25mm embedment

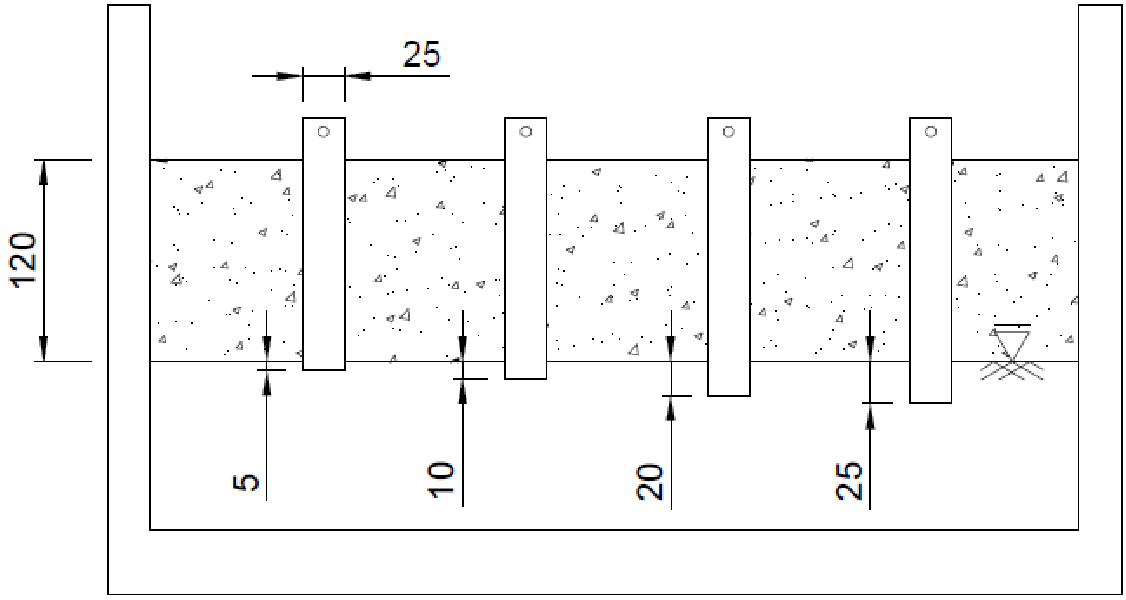


Figure 4(e) Test 4; 120mm overburden, 25mmOD casings of 5mm, 10mm, 20mm and 25mm embedment

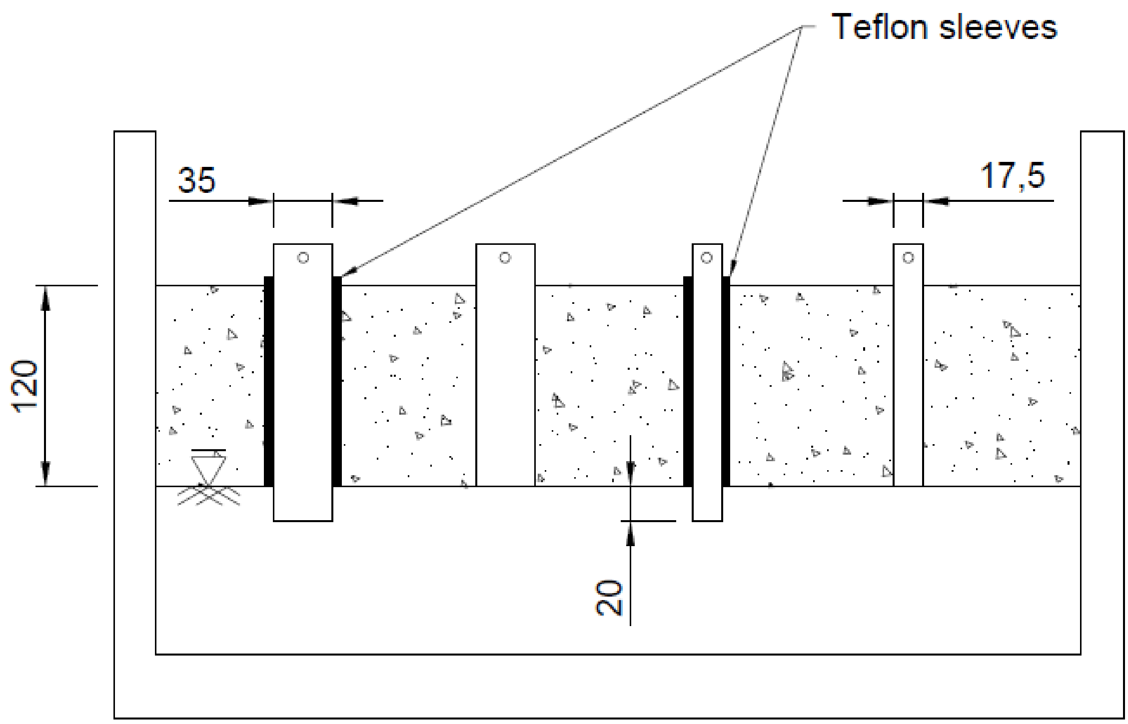


Figure 4(f) Test 5; 17.5mmOD and 35mmOD casings subjected to either 20mm embedment or 120mm overburden

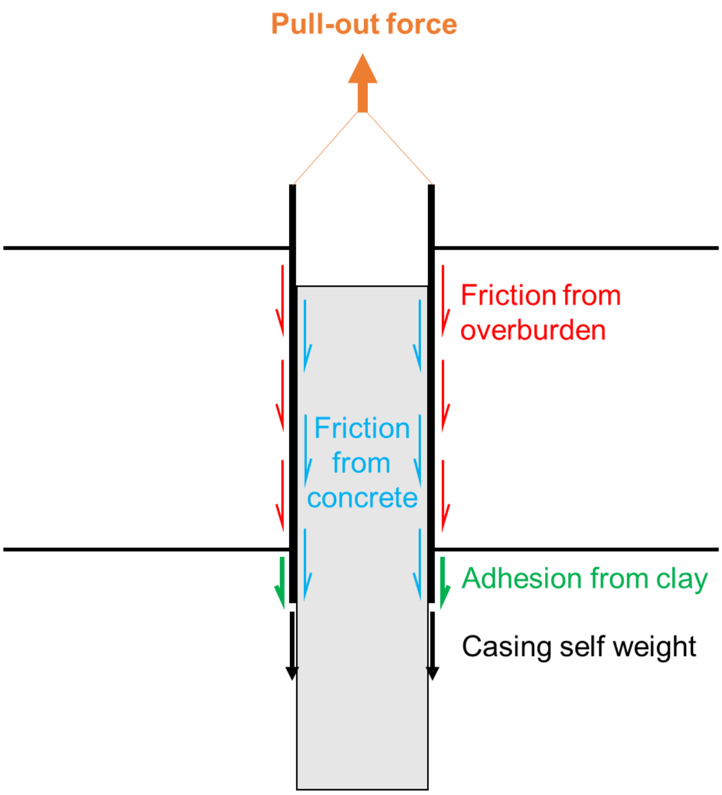


Figure 5. Forces acting along casing shaft

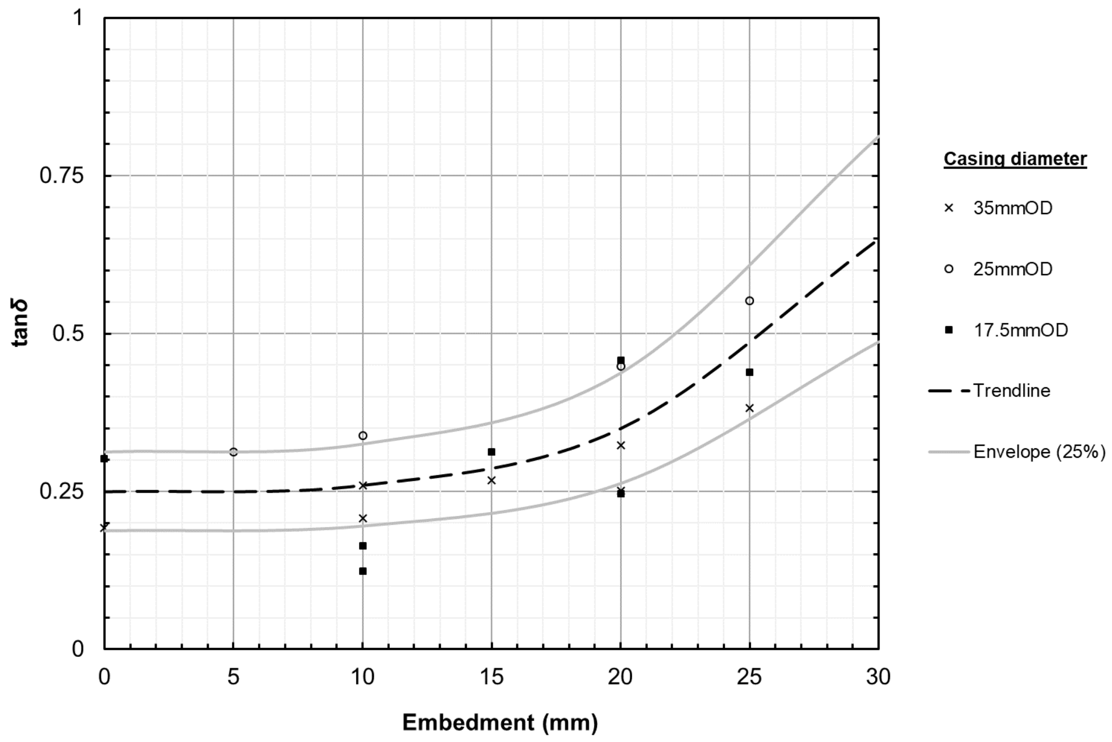
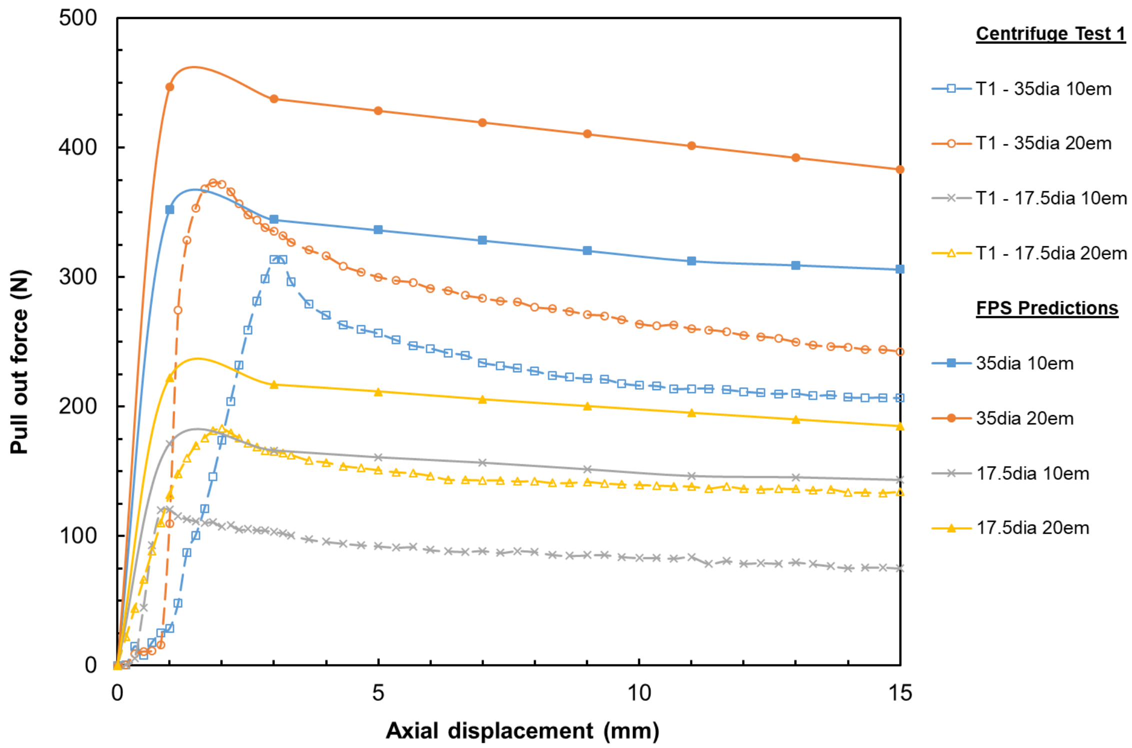
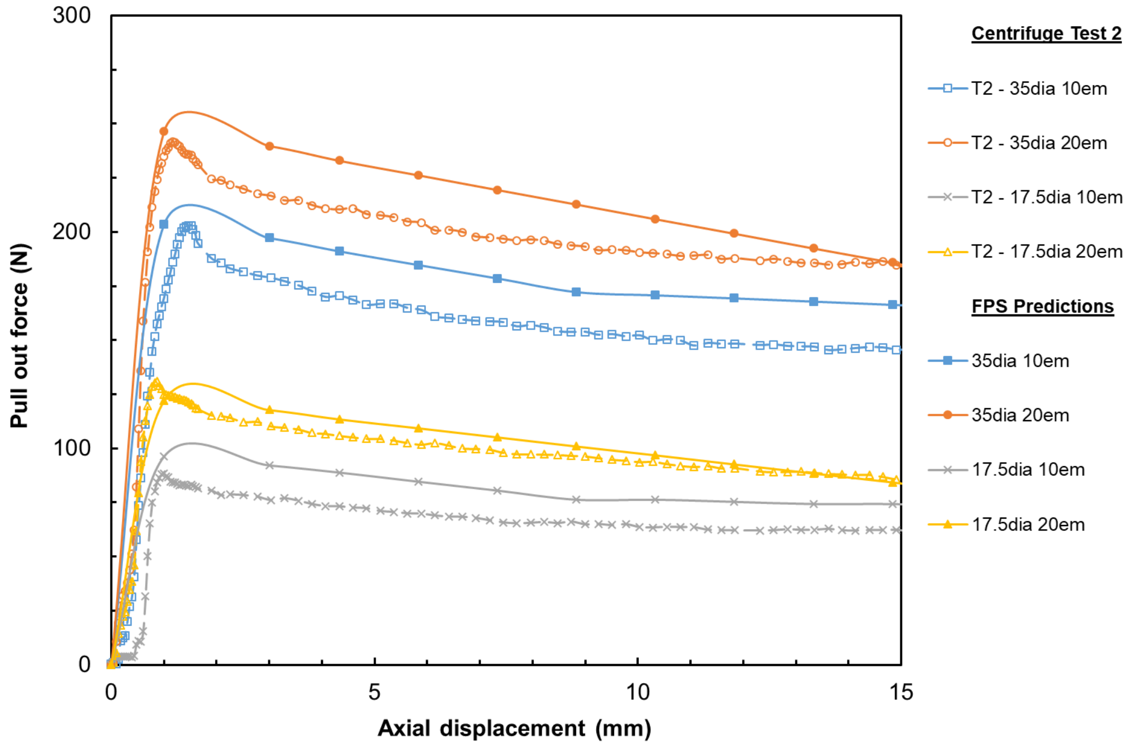


Figure 6. tanδ design chart for varying casing embedment depths

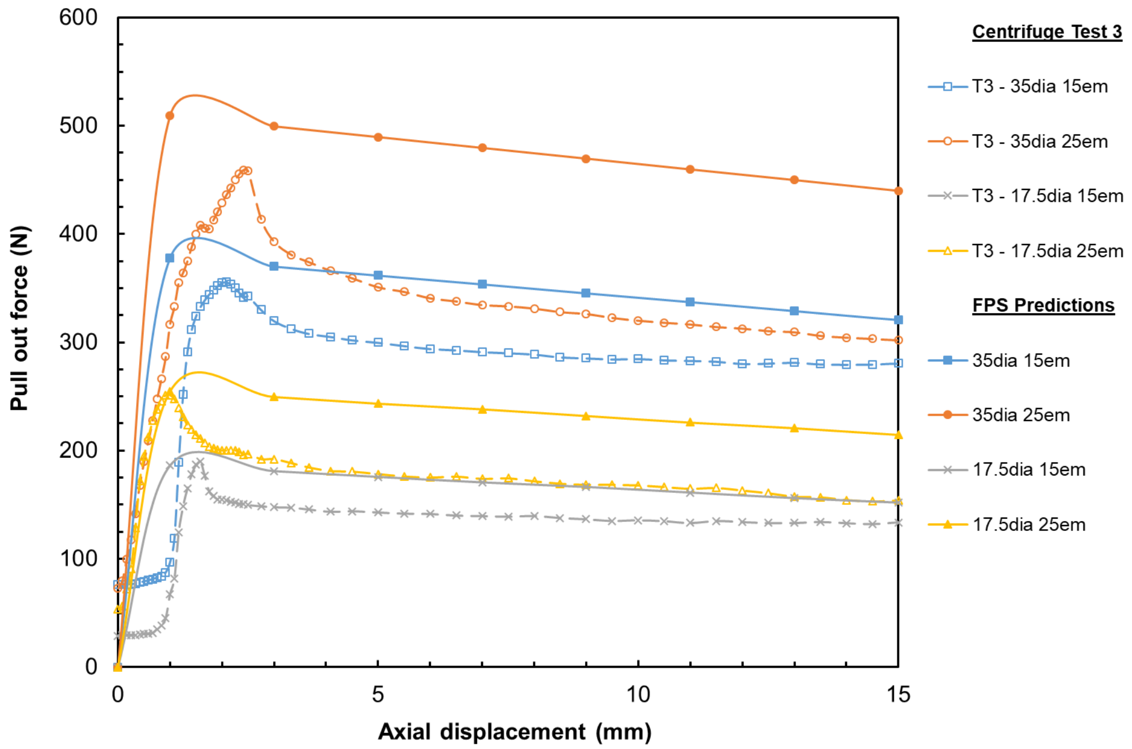
Figure 7 Modified FPS method predictions against centrifuge results:



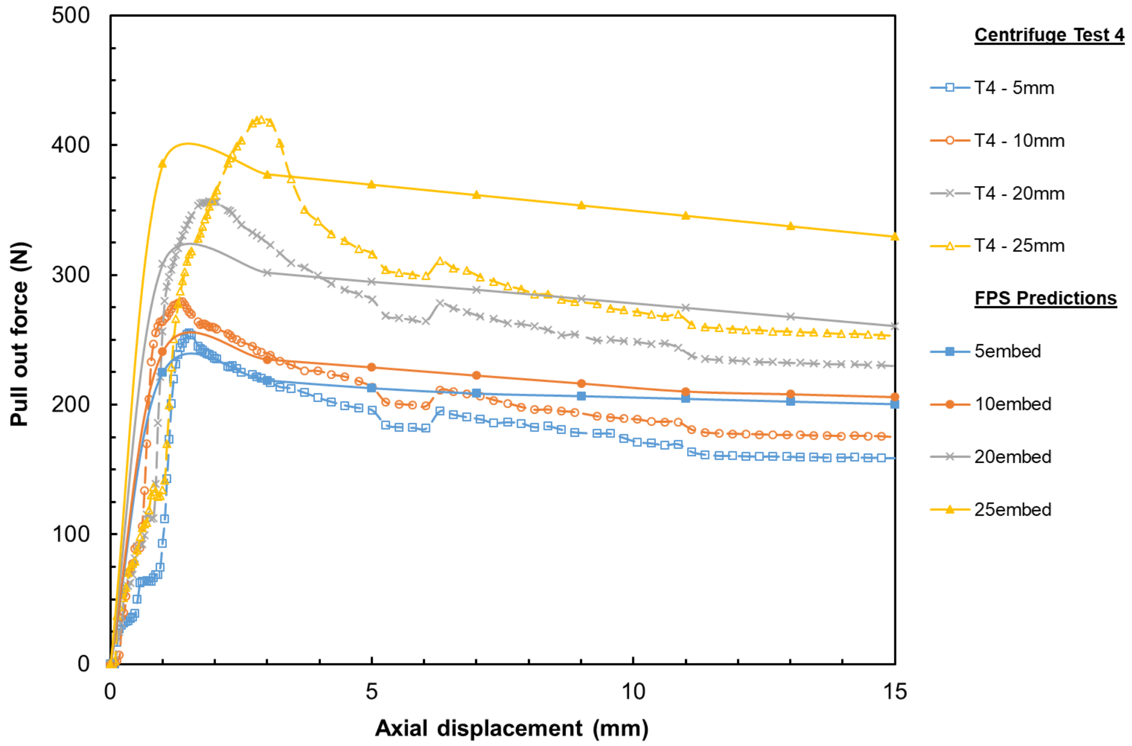
(a). Test 1 (120mm overburden, 17.5mmOD & 35mmOD casings, 10mm & 20mm embedment)



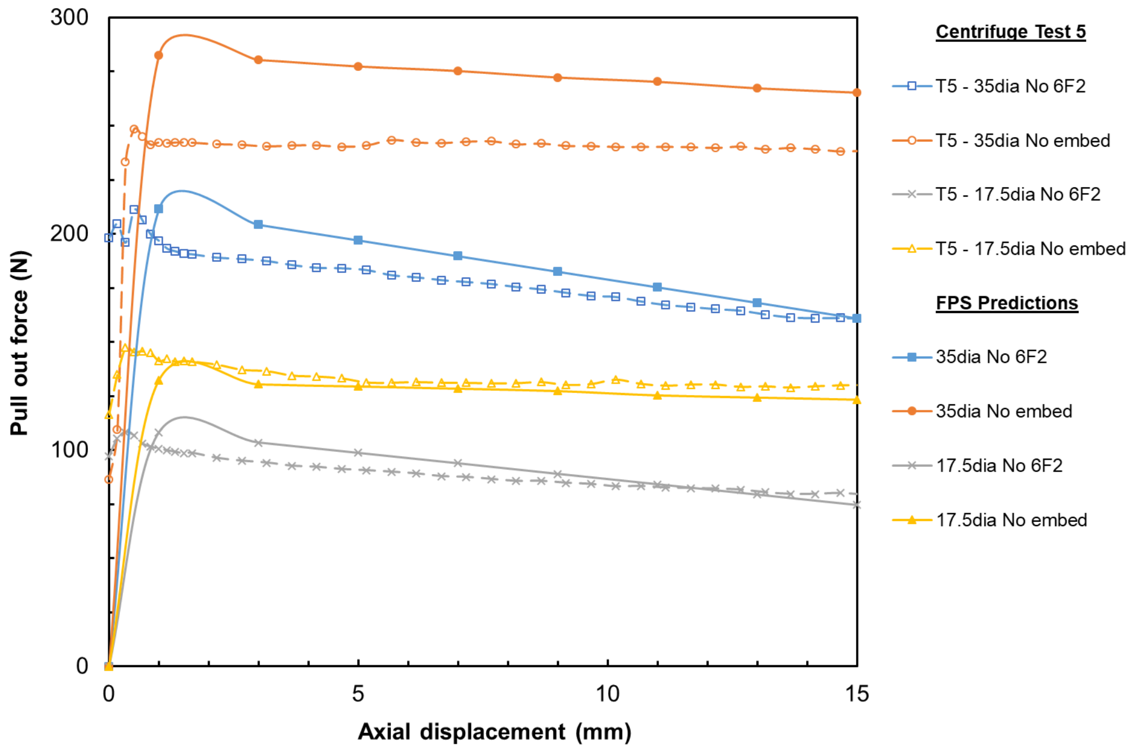
(b). Test 2 (60mm overburden, 17.5mmOD & 35mmOD casings, 10mm & 20mm embedment)



(c). Test 3 (120mm overburden, 17.5mmOD & 35mmOD casings, 15mm & 25mm embedment)



(d). Test 4 (120mm overburden, 25mmOD casings, 5mm, 10mm, 20mm & 25mm embedment)



(e). Test 5 (17.55mmOD & 35mmOD casings with either 20mm embedment or 120mm overburden)

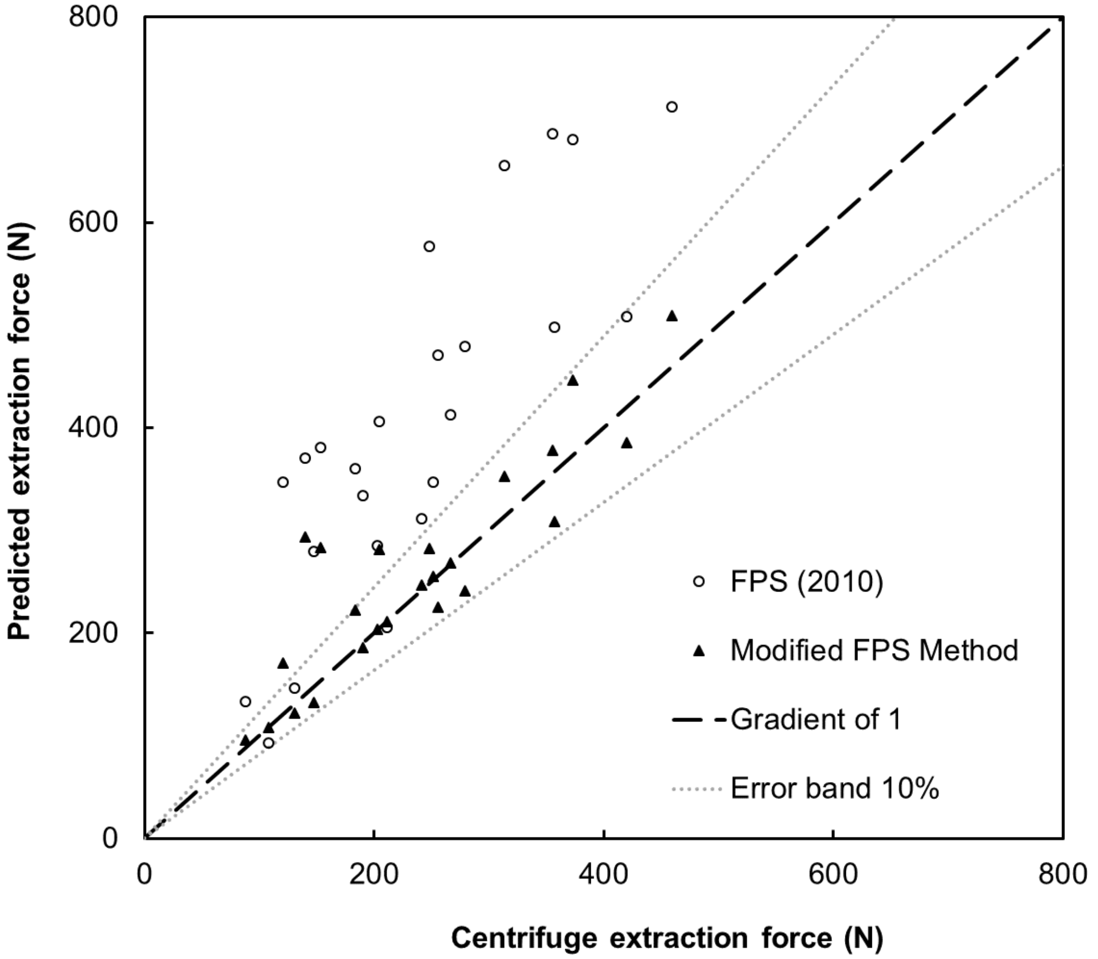


Figure 8. Comparison of centrifuge test results against predictions made using the FPS (2010) method and modified FPS method