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Letter

Failure mechanisms of a spudcan penetrating next to an existing footprint

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ABSTRACT

Reinstallation of mobile jack-up rigs next to existing footprints is a problematic operation because the spudcan located near the footprints is subjected to eccentric and/or inclined loading conditions. Geotechnical centrifuge studies have measured these loads for combinations of changing footprint geometry, footprint soil properties and the offset of the reinstallation from the footprint centre. These tests have been of full model spudcans in order to accurately measure the combined loads developed. They have not provided information on the mechanisms of failure occurring during this complex installation. Observations from a visualisation test, where a half spudcan is penetrated against a transparent window in a geotechnical centrifuge, are reported in this paper. The mechanisms of failure at different stages during the penetration are presented.

Jack-ups are self-elevating mobile units operating in oil and gas fields and typically consist of a floatable hull and three independent retractable truss-work legs each resting on a spudcan footing. The spudcans are between 10 and 20 m in diameter [1,2]. Jack-ups often return to sites were previous operations have left footprints in the seabed. Reinstallation next to these footprints is a problematic operation because the spudcan is subjected to eccentric and inclined loading conditions. Previous experimental studies have attempted to measure the combined loading on a spudcan reinstalling at different offset distances [3–8].

A further experimental investigation is presented that focuses on understanding the mechanisms that create the development of vertical, horizontal, and moment loads during reinstallation. This was achieved by penetrating a flat-base footing nearby a manually cut footprint cavity. The main objective of the experiment was to identify the effect that the footprint geometry has on the soil flow mechanism, and subsequently the reinstallation response. The experiment was conducted in a drum centrifuge on a half-footing model penetrating slightly over-consolidated kaolin clay. Digital images were captured during the full penetration using a digital camera. The particle image velocimetry (PIV) methodology coupled with close-range photogrammmetry correction is used to present the digital output as a series of velocity vectors and velocity contours to determine the soil failure mechanism during penetration. An overview of the experimental techniques is presented, followed by a detailed description on the experimental apparatus, testing procedures and a discussion of the results. The test presented here represents just one of eight tests conducted and reported in Ref. [9], where further analysis of the other tests that investigate different offset distances and footprint shapes can be found.

PIV analysis allows precise quantification of soil flow patterns and distortion zones by comparing pairs of images. The GeoPIV8 programme developed by White et al. [10] was adopted in this study to process the digital images. From each digital image the area of interest was cropped before being divided into interrogation patches, each covering a zone of soil approximately 1 mm^2. Each of these patches was tracked using a cross-correlation algorithm, to identify the movement of that patch of soil between a pair of images, with a measurement precision of 10 μm for the field of view used during the experiments. Before processing, each image was corrected for image distortion arising from the non-coplanarity of the image and object planes, and non-linearity within the image resulting from lens aberrations.

The tests were performed at 100 g in the drum centrifuge facility at University of Western Australia (UWA) [11]. The use of PIV analysis requires a half-symmetrical footing model, to be

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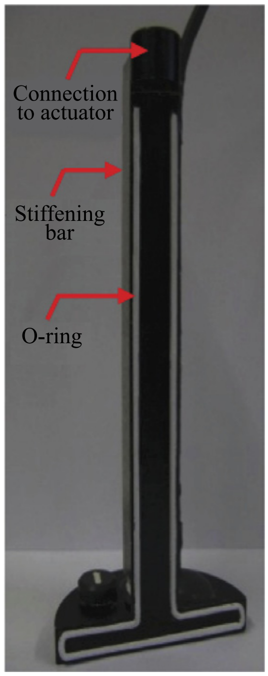

Fig. 1. Half-footing model.

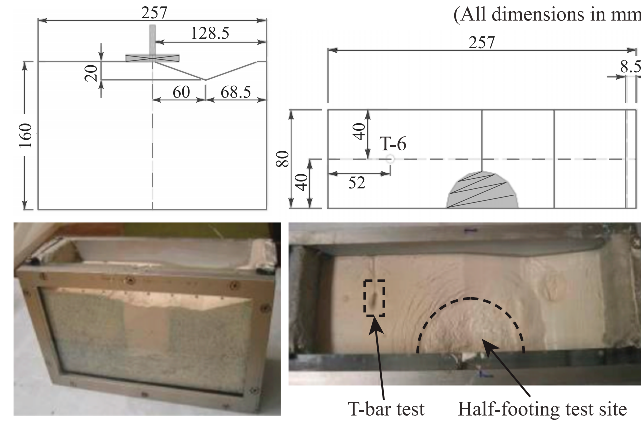

Fig. 2. Box after the completion of half-footing reinstallation test.

placed in a rectangular testing box, against a transparent Perspex window (viewing window). During the test the half-footing penetrates into the soil and digital images of the soil movement can be continuously acquired through the viewing window. The footing was made from aluminium and was comprised of a 60 mm diameter flat-base footing and a 130 mm long leg section (Fig. 1). To prevent soil or water ingress between the half-footing model and the viewing window of the soil container, a 1 mm diameter o-ring was attached to the face of the footing. The model also featured a stiffening bar, attached to the back of the leg. This was to avoid losing the seal due to the bending of the leg during penetration. A digital camera with high resolution (4000 × 3000 pixels) was placed in front of the testing box to capture images at a rate of 1.5 frame per second (15 frame per millimeter of footing penetration depth, for footing penetration rate of 0.1 mm/s). The camera was mounted on a frame, bolted tightly onto the drum channel. A digital clock, attached to the viewing window aided to identify the time difference between images. To improve the quality of images, a lighting frame comprised of rows of LED lights and a cooling fan were also mounted on the drum channel.

The kaolin clay sample (see Refs. [12,13] for soil properties) was firstly consolidated using a press and then consolidated again under the high gravity environment in the drum centrifuge. A large watertight strongbox of 360 mm × 650 mm × 325 mm (width × length × depth) was used. The soil sample was consolidated using a consolidation press. The consolidation pressure was applied in stages to the target pressure of 28 kPa. When the change in sample height under the final consolidation pressure increment reduced to below 0.1 mm/h, consolidation was considered to have been achieved. The large strongbox containing an over-consolidated soil sample was then removed from the consolidation press. The soil sample was then cut into 80 mm × 257 mm × 160 mm blocks using a blade. Each block was put into the testing box and covered with geo-fabric (saturated with water) to prevent drying of the soil. The testing box was then fitted into the drum channel and consolidated at 120 g under self-weight for 2 days. Each testing box contained an over-consolidated sample 120 mm deep.

The testing box was 80 mm in width and was too narrow to accommodate idealised footprint with a circular shape. Therefore, the idealised footprint cavity was simplified to a "V" shape slope. The cutting blade was mounted on top of the testing box, and was slid across the testing box to remove the soil until the targeted footprint depth (z_F) was reached. The test with a cavity of 60 mm width ($1D$) and 20 mm depth ($1/3D$) is reported (see Fig. 2). Coloured flock was sprinkled on the face of soil sample facing the viewing window in order to provide the necessary contrast to run the subsequent PIV analysis. A viewing window with control markers was installed onto the soil sample. This allowed visual inspection on the soil flow during the penetration test and provided reference to quantify the soil movements in subsequent PIV analysis.

The testing box, digital camera, and other accessories for digital photography were installed onto the drum channel. The drum centrifuge was then spun up to 100 g for at least 3 h, allowing pore pressure in the soil sample to reach hydrostatic equilibrium. The top of the soil sample was filled with water to maintain the saturation of the sample. The tests were performed at 100 g and started with penetration of the half-footing model into the soil sample at a velocity (v) of 0.1 mm/s. This ensured undrained response in the soil as the normalised velocity vD/c_v of ∼94 was greater than 30 [14–16]. This was essential as installation of spudcans in clay soils offshore is undrained [17]. During penetration, the digital camera operated at a frame rate of 1.5 frame per second. After reaching the depth of 60 mm below the soil surface ($z = D$), the half-footing model was then extracted from the soil. The half-spudcan was penetrated at an offset of 60 mm (one diameter) from the centre of the footprint (see Fig. 2). This offset was chosen as it was shown to induce the largest combined loading in the full spudcan tests of Ref. [8]. In the testing program of Kong [9] it was entitled TB-10D-HF. Figure 2 shows the layout and the testing box after the completion of the test. Inspection shows the soil deformed radially but was well within the walls of the testing box and the boundaries should have limited effects on the testing results.

The undrained shear-strength distribution within the sample is shown in Fig. 3. This was deduced by multiple T-bar tests through and next to the footprint, on a sample prepared in the same way as the half-spudcan test. The undrained shear strength was slightly different to the theoretical strength within 0.5D from the footprint centre (30 mm from footprint toe). This is likely due to slight soil disturbance during preparation. However, the agreement with the theoretical strength improved with increasing depth and distance from the footprint centre. The theoretical profile was derived according to the empirical relationship $s_u = a\mathrm{OCR}^n\sigma'_v$ [18], where OCR is the over-consolidation ratio and σ'_v is the effective vertical stress. For UWA kaolin clay in the centrifuge, the equation parameters adopted were $a = 0.17$ and $n = 0.7$, which are within the range suggested in Refs. [12,13].