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Experimental Study of a Puncture Warning System for a Jack-Up Offshore Platform

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ABSTRACT

During the operation of jack-up offshore platforms, the complex and variable seabed geological conditions involved can lead to serious accidents, such as pile leg punctures and platform tilt. The aim of this study is to introduce an early warning method for punctures that ensures the operational safety of these platforms. To accomplish this, a real-time monitoring and controlling system is designed using a programmable logic controller that shares data from sensors measuring displacement, tilt, and pressure. In addition, an experimental device is constructed to simulate a jack-up offshore platform in order to assess the safety response of the control system. The working state of the platform under different working conditions (puncture of one independent pile, same side or diagonal piles, and three-pile linkage) is evaluated by analysing the structural motion response, including platform tilt and foundation pressure. The findings reveal that the system developed in this study accurately detects the tilt condition of the offshore platform, and can ensure the operational safety of jack-up offshore platforms.

Keywords: jack-up offshore platform; puncture; warning; platform tilt; experiment

INTRODUCTION

A jack-up platform is a type of removable offshore equipment that stands on the seabed on three or four legs while it is operating. The processes of pile insertion and pile extraction are dangerous stages in the operation of a jack-up platform, and the pressure on the pile foundation can be significantly increased when lifting or pressing a pile. Due to the complex and variable seabed geological conditions involved, and particularly when the legs encounter a layered foundation with a layer of soft soil beneath a harder one, there is a potential risk of the legs abruptly and uncontrollably puncturing the harder soil layer, which is known as pile leg puncture. This can lead to damage to the pile legs, platform tilting, or even capsizing, and therefore poses a grave threat to the safety of offshore platforms. The analysis of puncture risk in jack-up platform piles, with the aim of ensuring the safety of offshore engineering installations, has been a prominent area of interest within the academic and industrial sectors.

Many researchers have predicted the penetration depth of the pile legs and the factors that influence them, with the aim of guiding the offshore operations of jack-up offshore platforms. Kong et al. [1] found that the peak bending moment in platform secondary piling occurs at the foundation surface (when the leg boots just touch the soil) and that the peak horizontal force is located at the bottom position line of the pit. In their study, they discussed the impacts of the pit depth, size, and various forms of eccentricity on the secondary piling of leg boots. Jun et al. [2] investigated the distinct properties of soft and hard clay through centrifuge experiments. They employed cutting tools to create two types of pits, based on an inverted cone and a cylinder, and subsequently examined the bearing characteristics of leg boots during soil penetration in proximity to these pits. In a study by Fan et al. [3], a special version of the linear contact bond model was introduced to replicate the strength distributions of offshore clay, and a novel discrete element-based method was proposed to simulate the continuous penetration process of jack-up foundations with various soil profiles. Kong et al. [4] developed a novel parameter estimation technique to enhance the accuracy of predicting the peak penetration resistance of spudcan footings in sand-over-clay and three-layer clay deposits. Xu et al. [5] proposed a piling calculation method for jack-up drilling platforms that took into consideration the effects of geological conditions, leg boot bearing capacity, and group pile effects. The penetration of jack-up drilling platforms during the piling operation was analysed using this method.

When studying the interaction between leg spuds and the foundation, the foundation is typically simplified as a linear spring [6-9]. Michalowski and Shi [10] found that the bearing capacity of leg spuds increases with the strength of the underlying clay. Wang and Carter [11] conducted further research and discussed the gradual development of plastic soil around the spudcan and the influence of soil weight on bearing capacity. Randolph et al. [12] and Hosain et al. [13] discussed the effects of loads, pile leg lengths and preload ratios on the bearing capacity and load-displacement relationship. Zhao et al. [14] assessed the puncture risk by calculating the full resistance profile for a spudcan deeply penetrating dense sand overlying clay. Zhang and Liu [15] analysed the ultimate bearing capacity of the bucket foundation, presented an ultimate solution for the bucket foundation, and discussed the influence of the bucket angle on the ultimate bearing capacity using the static allowable slip line field. They also found that increasing the burial depth ratio and the diameter could significantly improve the dynamic stiffness and lateral displacement of a single pile foundation [16].

Wind and waves are important factors affecting the dynamic behaviour of platforms [17,18]. Rozmarynowski [19] presented a first-order sensitivity and time invariant reliability analysis of a platform subjected to wind and wave loads. For relatively slender members of steel platforms, the majority of the damping forces of the vibrating system are produced by sea waves [20], and the subsoil-structure interaction effects introduce nonlinearity to the frequency range close to the first structural natural frequency [21]. Ghazi et al. [22] carried out a dynamic evaluation of a jack-up platform structure under wave, wind, earthquake and tsunami loads, and found that the jack-up platform hull experienced maximum deformation under high-intensity earthquake activity and tsunami waves at 45°.

The aforementioned research has primarily focused on examining the foundation bearing capacity, predicting safe piling depths, and assessing penetration risks for jack-up platforms on unsTable seabeds. Current approaches to determining the ultimate bearing capacity of such foundations relies heavily on empirical formulas, whose applicability and limitations remain uncertain due to the intricate and fluctuating nature of an unsTable seabed. Furthermore, the need to adapt conventional puncture assessment methods gives rise to significant challenges: for example, predictions of the puncture risk at a given well site may not translate to an actual puncture during the platform's operational lifespan. Conversely, claiming that there is no risk of puncture at a particular site might unexpectedly lead to a puncture incident. Existing research is therefore inadequate in terms of monitoring the safety of operations and providing early warning of the potential hazards faced by jack-up platforms situated on laminated soil with a hard upper layer and a softer under-layer.

In the author's previous work, the motion response of offshore platforms was examined under varying water depths [23], and under wind and waves [24], using both experimental and simulation methods. The present study diverges from those previous endeavours by focusing specifically on the prediction of puncture warnings for jack-up offshore platforms. To achieve this objective, a comprehensive safe operation control system is devised for such platforms, and an onshore simulated experimental device representing a jack-up offshore platform is constructed to test the safety response of the control system. This device includes a monitoring and control system, pile insertion and lifting mechanisms, and a variable seabed foundation, thus enabling the simulation of catastrophic scenarios such as platform tilting due to pile puncture. The operational behaviour of the platform is then evaluated through the monitoring and analysis of key parameters, including the pile insertion depth, lifting height, platform tilt angle, and foundation pressure.

ONSHORE SIMULATION EXPERIMENT WITH A JACK-UP OFFSHORE PLATFORM

EXPERIMENTAL PLATFORM

In this study, an onshore simulated experimental device is crafted to represent a jack-up offshore platform, in order to evaluate the efficacy of its safety control system, as depicted in Fig. 1. The primary dimensions of the experimental platform are a length of 15 m, a width of 10 m, and a height of 1.5 m. The simulation platform comprises four pile legs, each standing 10 m tall and constructed from a seamless pipe measuring 353 mm in diameter and with a thickness of 16 mm. The experimental platform primarily consists of three integral components: the mechanical transmission system, the hydraulic system, and the electrical control system. The mechanical transmission system includes the frame of the platform and the hydraulic lifting unit, while the hydraulic system functions as a power provider and transfer medium, encompassing pumps, hydraulic pipelines, connectors, and valves. Finally, the control system, situated in the control room, represents the platform's remote control system and alarm system.

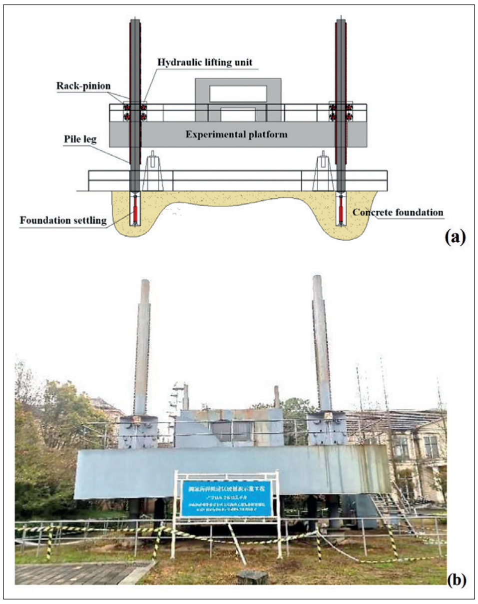

Fig. 1. Onshore experimental simulation device for a jack-up offshore platform: (a) design drawing, (b) constructed experimental platform

Fig. 2. Pile leg with gear rack

Fig. 3. Lifting drive unit

Fig. 4. Locking device

The experimental platform is controlled by the operating system, and can simulate three types of actual operational environments for a jack-up offshore platform, including pile lifting, foundation settling, and wave-tide conditions. Pile lifting operations are executed through four hydraulic-powered rack-and-pinion devices, as illustrated in Figs. 2 and 3. During lifting, power is transmitted via the engagement of the rack-and-pinion mechanism, which is designed with ample strength to withstand the maximum load encountered during testing. A fourfold safety factor is incorporated into the rack-and-pinion design to ensure that the maximum working pressure remains below 16 MPa. To prevent platform collapse accidents, the lifting drive unit is equipped with a locking device, as shown in Fig. 4. The simulation experiment effectively replicates the ascending and descending movements of the platform, and remote computer control is used to individually operate each pile leg. This setup facilitates the monitoring of the platform's performance under various conditions. A detailed list of experimental platform parameters is given in Table 1.

Tab. 1. Parameters for the experimental platform

Characteristic parameter	Value
Hydraulic drive pressure for lifting system	16 MPa
Individual leg lifting force	400 kN
Foundation bearing capacity	20 MPa
Lifting speed of the leg	1.5 m/min
Lifting speed of the platform	0.6 m/min
Warning inclination	±0.3°
Design service life	15 years

The hydraulic system beneath the pile boots of the experiment platform is used to simulate the actual seabed foundation conditions, as depicted in Figs. 5(a) and (b). A hydraulic transmission system is embedded in the foundation, where a hydraulic pump drives the hydraulic cylinder by pushing hydraulic fluid. The movement of the hydraulic cylinder controls the lifting and lowering of the pile legs, thereby simulating the phenomenon of puncture caused by foundation settlement. Since the platform's weight is supported by buoyancy while it is being towed, the four hydraulic cylinder components are installed at the bottom of the platform, as shown in Fig. 6. The vertical motion response of the platform in waves is simulated by regulating the periodic telescoping of the hydraulic cylinder, with varying cycles and amplitude.

Various sensors are also employed on the offshore platform to monitor the real-time status of the internal hydraulic transmission system and the platform, as shown in Fig. 7. The drawstring displacement sensor (Model ESA02) is employed to monitor the subsidence displacement, and uses retracTable stainless steel rope wrapped around a threaded hub and connected to a precision rotary sensor to convert the mechanical energy of the stainless steel rope into an electrical signal. The dual tilt sensor (Model LCA328) is used to measure platform tilt angle in orthogonal directions. The pressure of the hydraulic transmission system (shown in Fig. 5) is measured using a pressure sensor (Model PCM300) to reflect the foundation pressure of the pile legs. Via a wired transmission system, the real-time operational status information of the platform is transmitted to the control centre.

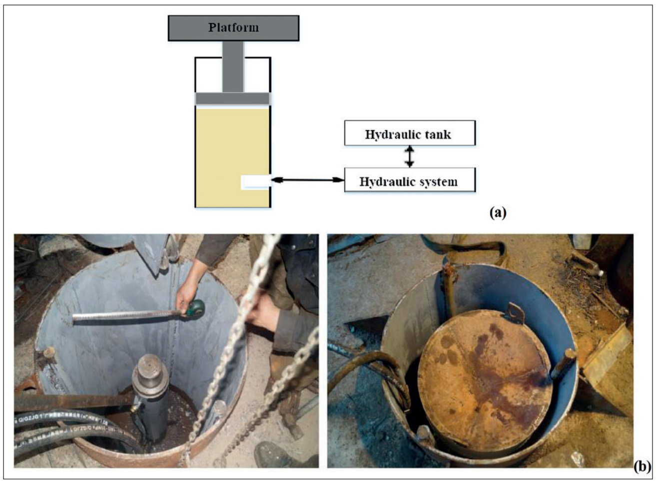

Fig. 5. Foundation settlement simulator: (a) schematic diagram, (b) experimental device

Fig. 6. Hydraulic cylinder components

Fig. 7. Data collection sensors for the jack-up offshore platform: (a) displacement sensor, (b) dual inclination sensor and (c) foundation pressure sensor

SAFETY CONTROL SYSTEM

Fig. 8 illustrates the safety control system designed in this study. The console was manufactured and tested in accordance with the standards of the International Electro-technical Commission [25]. The primary method of collecting platform state data for a jack-up offshore platform in the simulated experimental device is via hardware components, including displacement sensors, pressure sensors and inclinometers. The collection device transfers the collected data to the programmable logic controller, a core component of the remote control system, as shown in Fig. 9. The programmable logic controller possesses robust signal transmission capabilities, thus enabling the expansion of operational modules on the experimental platform, such as the pile lifting, pile puncture, and vertical motion of the platform due to tidal waves, through configuration, mode modification, and the addition of compiled programs. An Ethernet module is installed on the programmable logic controller, and a mobile 4G internet card is used to send the collected data from the platform to a remote computer. The configuration software (supervisory control and data acquisition) on the remote computer communicates with the programmable logic controller, thereby forming a monitoring system that shares data and allows real-time observation of performance parameters during testing.

The configuration software designed for this experimental platform is divided into three main sections: the pile lifting system, the foundation settlement system, and the wave motion system. The lifting operations of the platform are achieved by the pile lifting system, using the hydraulic motors on the legs through gear engagement. The phenomenon of foundation puncture is simulated by adjusting the hydraulic system at the bottom of the pile boots in the foundation settlement system. The wave motion system is used to simulate the periodic vertical motion of the platform due to waves through hydraulic cylinders located at the bottom of the platform.

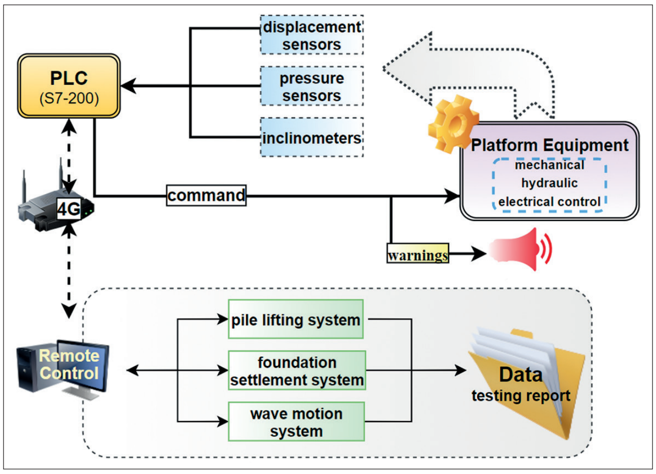

Fig. 8. Schematic diagram of the remote safe operation control system

Fig. 9. Programmable logic controller (PLC: S7-200)

The remote computer control response interface primarily consists of monitoring and lifting control interfaces, thereby granting operators the ability to remotely oversee the operational status of the lifting system and the working conditions of various devices. Moreover, the hydraulic motors positioned on the pile legs are furnished with lifting buttons, enabling operators to seamlessly control the lifting actions of the four pile legs via the intuitive control panel, as depicted in Fig. 10. Notably, the lifting operations of these four pile legs are individually managed by four distinct handles, ensuring precision and flexibility in operation.

The control panel of the platform offers flexibility by allowing users to switch between the centralised and local control modes. In the centralised mode, the central handle seamlessly orchestrates the coordinated movement of all four pile legs. Conversely, in the local mode, the operation of each pile leg is contingent on its respective control handle. The foundation settling system is responsible for closely monitoring the pressure values of the four pile legs that support the foundation. Moreover, the position of the foundation can be dynamically adjusted using switches, thus enabling the operators to observe the changes in pressure at any given moment. The precise pressure readings for these four foundations are crucial in levelling the platform's foundation during the experiments, and preventing potential pile leg suspension and bending damage, thereby extending the overall lifespan of the platform.

To empower operators with the ability to monitor the platform's status in real time on a remote computer, the carefully designed remote monitoring interface encompasses a main monitoring screen, a warning panel, a real-time curve interface, and a historical curve interface. The primary remote monitoring interface prominently displays crucial real-time parameters, control modes, and alert signals related to the platform's operational status, such as the pile leg height and foundation pressure, as depicted in Fig. 11. In this study, the safety rating for the operation of the experimental platform is determined by taking into account both the platform's inclination and the bearing capacity of the simulated foundation, as outlined in Table 2. Specifically, the warning system is activated when the platform's tilt angle reaches 0.3°, ensuring prompt action and prevention of potential risks.

Tab. 2. Safety rating of the platform operation

Safety rating	Platform inclination θ (°)	Bearing capacity of foundation F (MPa)
A	$-0.3<\theta<0.3$	$F<10$
B	$-0.5<\theta\leq-0.3$ or $0.3\leq\theta<0.5$	$10\leq F<20$
C	$\theta\leq-0.5$ or $0.5\leq\theta$	$20\leq F$

Level A represents the highest rating for safe operation, and means that the experimental platform is functioning normally, enabling the successful completion of test tasks without any hindrance. Level B is classified as a moderately safe operational level, where the platform's tilt exceeds 0.3°, requiring the resolution of any warning indicators before proceeding with further operations. Level C serves as a warning level, and signifies that critical parameters have surpassed their predetermined thresholds, necessitating the immediate execution of security callback operations. Before resuming platform testing, additional password permissions are required.

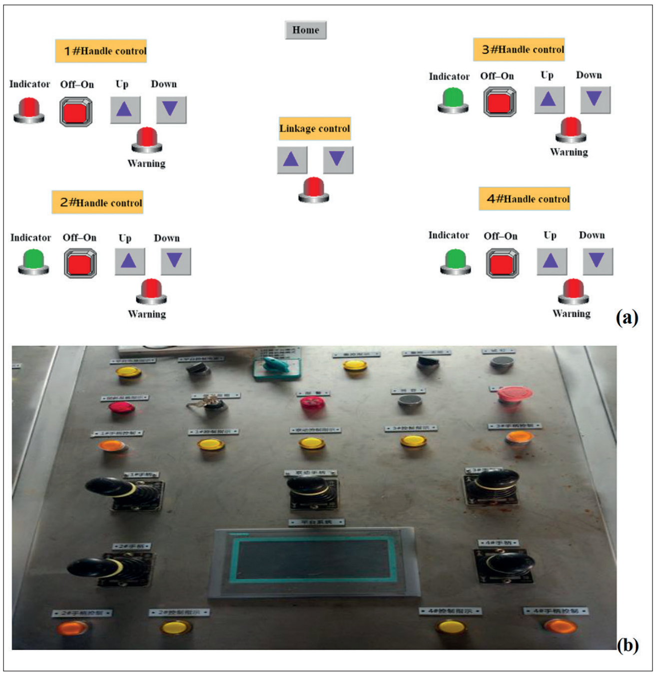

Fig. 10. (a) Remote control interface, (b) actual control interface

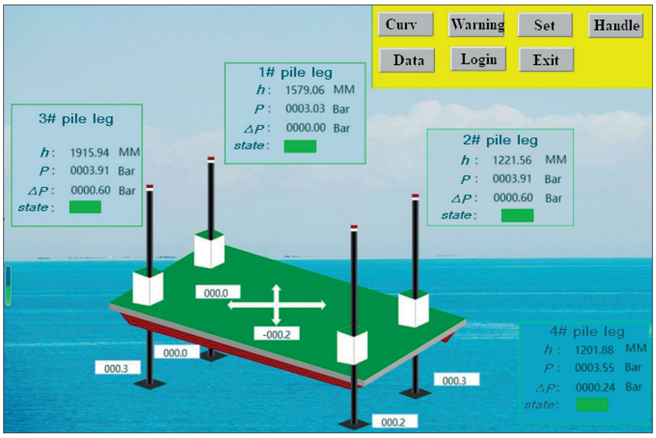

Fig. 11. Main interface for remote computer monitoring

RESULTS AND DISCUSSION

In this study, the tilt angle of the experimental platform and the pressure of the foundation are used as observation parameters in a safe operation control system to evaluate the stability and safety of the platform lifting operation and the risk of puncture accidents. To assess the efficacy of the platform's operation control system, we analyse the patterns of variation in the platform's tilt angle and foundation pressure during the operation of individual piles, piles on the same side or on diagonal corners, and three-pile linkage configurations.

RESULTS AND ANALYSIS OF PILE LEG LIFTING EXPERIMENT

Pile leg lifting height and platform tilt angle

The preloading operation is pivotal in terms of ensuring the stability of the foundation. For a jack-up offshore platform with four pile legs, self-weight preloading can be achieved by adjusting the weight distribution among the pile legs. In this study, the lifting device was operated to increase the pressure from the pile leg on the ground by raising the height of the platform on the pile leg. Fig. 12 shows the correlation between the lifting height and the platform tilt angle response under different pile leg linkage conditions. Here, the X-direction is perpendicular to the Y-direction, where the Y-direction passes through the axes of pile legs 2 and 3 (as shown in Fig. 11). When a single pile leg ascends, it noticeably affects the balance at one specific corner of the platform, as illustrated in Fig. 12(a). Within a limited range of ascent distances for pile leg 1 (0–25 mm), the tilt angles in both the X and Y directions of the platform experience a negligible change of less than 0.4°. However, when pile leg 1 ascends significantly (25–70 mm), the tilt angle in the X direction rapidly increases to 1.1°, while the Y direction tilt angle remains relatively sTable after a certain threshold.

The X and Y tilt angles for the platform exhibit similar trends during the ascent of adjacent pile legs on the same side, as shown in Fig. 12(b). When adjacent pile legs (pile legs 2 and 4) rise by 33 mm, the tilt angles in the X and Y directions increase by 0.52° and 0.65°, respectively. As the pile legs continue to ascend, the tilt angle changes in X and Y directions remain consistent. However, when the adjacent pile legs have ascended by 140 mm, the platform tilt angle becomes significantly pronounced, prompting the safety operation monitoring system to issue continuous warning alarms, resulting in the temporary halt of the ascent operation for adjacent pile legs.

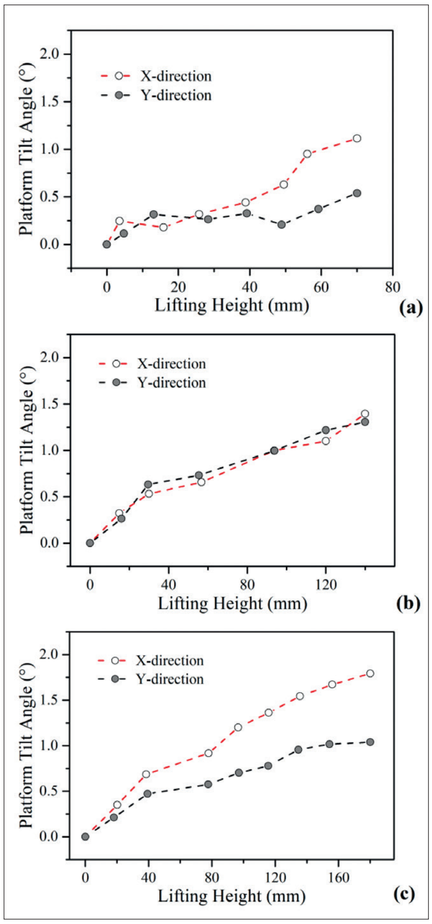

Fig. 12. Variation in platform tilt angle with lifting height: (a) one independent pile leg; (b) two pile legs on the same side; (c) three-pile linkage

Fig. 12(c) shows the monitoring results for the simultaneous ascent operation of three pile legs (1, 2, and 4). As the simultaneous ascent of the three pile legs reaches 40 mm, the tilt angles in the X and Y directions of the platform increase by 0.7° and 0.48°, respectively. During the subsequent ascent process, the difference in the tilt angles between the X and Y directions significantly increases. Specifically, when the three legs ascend to 180 mm, the tilt angle in the X direction increases to 1.8°, while the tilt angle in the Y direction increases to 0.9°. The platform's safety operation monitoring system continues to issue warning alarms, prompting the temporary suspension of the ascent operation of adjacent pile legs.

Pile leg lifting height and foundation pressure

When pile leg 1 ascends, the pressure applied on its foundation increases to 265 bar, while leg 4 on the diagonal experiences a rise in foundation pressure to 220 bar, as shown in Fig. 13(a). This phenomenon is attribuTable to the redistribution of the platform's gravity onto the foundations of pile legs 1 and 4. Consequently, the foundation pressures of pile legs 2 and 3 decrease to 122 bar and 98 bar, respectively. These findings suggest that the foundation pressure of the pile leg exhibits a nonlinear pattern of increase and decrease during the ascent and descent of a single pile leg, potentially leading to an unsTable platform state.

Fig. 13(b) illustrates the test results obtained from the simultaneous upward movement of adjacent pile legs. As the displacement of pile legs 2 and 4 increases, the corresponding foundation pressure exhibits a continuous rise. Specifically, when pile legs 2 and 4 ascend by 140 mm, the foundation pressures undergo increases of 200 and 175 bar, respectively. In contrast, the change in the foundation pressure for pile leg 1 is considerably smaller, with a value of less than 20 bar within the 0–140 mm displacement range. Furthermore, the foundation pressure in pile leg 3 diminishes to 138 bar, meaning that the platform's weight is mainly borne by the foundations of pile legs 2 and 4. When adjacent pile legs 2 and 4 ascend by 140 mm, the platform tilts to one side.

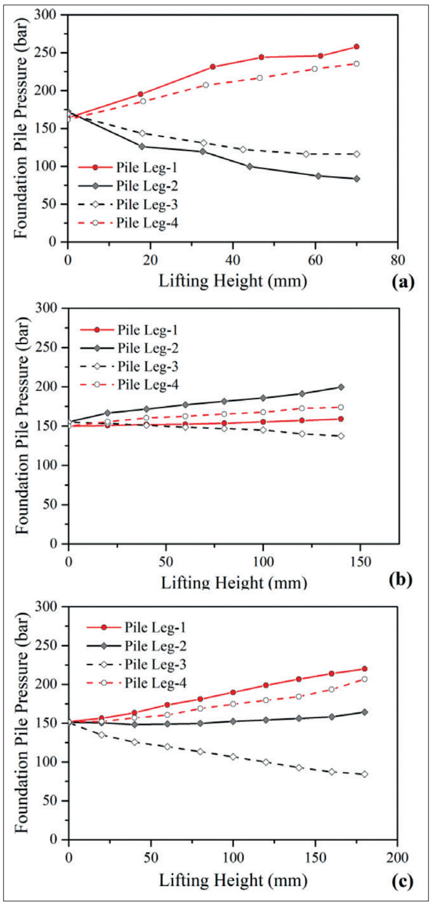

Fig. 13. Variation in foundation pressure with lifting height: (a) one independent pile leg; (b) two pile legs on the same side; and (c) three-pile linkage

Fig. 13(c) presents the test results for the foundation pressures during the simultaneous ascent of pile legs 1, 2, and 4. Following a vertical ascent of 130 mm, the foundation pressures of pile legs 1 and 4 increase to 200 bar and 175 bar, respectively. The foundation pressure rise in pile leg 2 is comparatively small in comparison to legs 1 and 4. Moreover, the foundation pressure in leg 3 undergoes a decrease from 150 bar to 100 bar, indicating that legs 1 and 4 bear a larger foundation load, while leg 3 bears a smaller foundation load. As the ascent height of the pile leg reaches 180 mm, the disparity in foundation forces intensifies, thereby placing the platform in a precarious state.

RESULTS AND ANALYSIS OF PILE LEG PUNCTURE EXPERIMENT

Insertion depth of pile leg and platform tilt angle

In this study, the developed simulation device was used to perform puncture tests on independent pile, as well as piles located on the same side and diagonally. Fig. 14 shows the relationship between the insertion depth of the pile leg and the tilt angle of the platform. When a single pile leg (leg 1) undergoes puncture, the tilt angle in the Y direction shows a more significant change, increasing by 1°, as shown in Fig. 14(a). Moreover, a shallow puncture depth has a relatively minor influence on the tilt of the platform in both the X and Y directions; however, as the puncture depth gradually increases, the tilt angle of the punctured platform becomes significantly more pronounced.

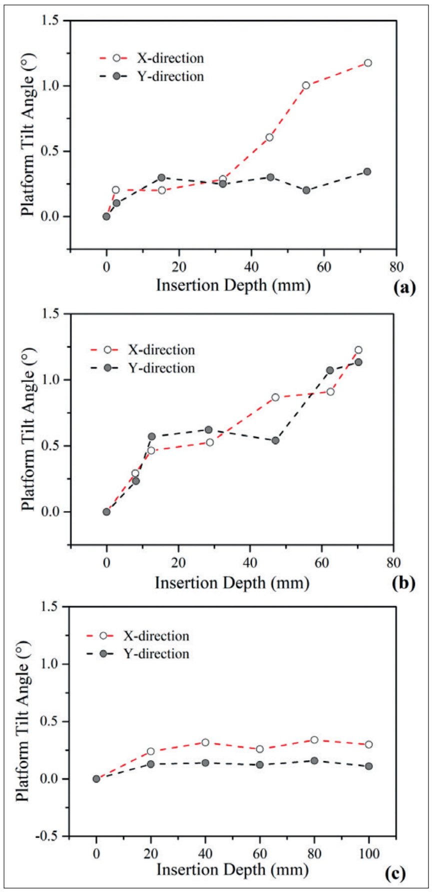

Fig. 14. Variation in platform tilt angle with insertion depth: (a) one independent pile leg; (b) two pile legs on the same side; (c) two legs on diagonal corners

Fig. 14(b) shows the changes in the tilt angle of the platform when pile legs on the same side undergo puncture. As the puncture depth gradually increases, the tilt trends in both the X and Y directions remain largely consistent. When the puncture depth reaches 70 mm, the tilt angles in the X and Y directions are 1.2° and 1.3°, respectively, suggesting that substantial tilt will occur when the pile legs on the same side are punctured. The tilt angle escalates rapidly with increasing puncture depth. It is therefore crucial to promptly implement preventive measures to safeguard the platform's stability in the event of pile leg punctures on the same side.

Fig. 14(c) depicts the variation in platform tilt angle resulting from puncturing by diagonal pile legs. It is evident that the tilt angles in both the X and Y directions of the platform exhibit fluctuations within a sTable range. Notably, the tilt angle in the direction of pile leg puncture surpasses the corresponding value in the direction without leg puncture.

Insertion depth of pile leg and foundation pressure

Fig. 15 illustrates the relationship between the pile leg insertion depth and the foundation bearing pressure. When pile leg 1 undergoes puncture independently, the pressure from the pile leg on the foundation decreases from an initial value of 160 bar to zero, as shown in Fig. 15(a). Concurrently, the foundation pressure of pile leg 4 decreases to 100 bar, while the foundation pressures of pile legs 2 and 3 increase to 221 bar and 275 bar, respectively. This indicates that when one pile leg undergoes puncture, the load-bearing capacity of the leg diagonally opposite to it decreases, while the load-bearing capacity of the other two pile legs increases. The platform is then in an unbalanced state, making it prone to accidents.

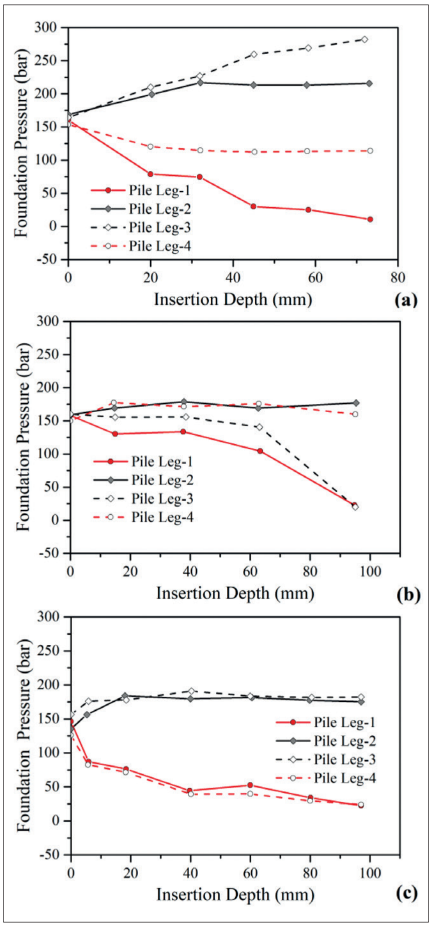

Fig.15. Variation in foundation pressure with insertion depth: (a) one independent pile leg; (b) two pile legs on one side; (c) two legs on diagonal corners

Fig. 15(b) shows the variation in foundation pressure when pile legs on the same side of the platform undergo puncture simultaneously. When the puncture depth of pile legs 1 and 3 reaches 62 mm, the foundation pressures decrease to 108 bar and 140 bar, respectively. Subsequently, as the puncture depth increases from 62 mm to 97 mm, the pressures of pile legs 1 and 3 show rapid declines to 33 bar and 21 bar, respectively. Meanwhile, the foundation pressures of pile legs 2 and 4 increase during the puncture process. This suggests that the simultaneous puncturing of pile legs on the same side leads to tilting of the platform towards the side of puncture, thereby enhancing the load-bearing capacity of the unpunctured pile legs.

Fig. 15(c) illustrates the changes in foundation pressure when diagonal pile legs (1 and 4) undergo puncture simultaneously. As the puncture distance extends to 61 mm, the foundation pressures of pile legs 1 and 4 decrease to approximately 100 bar, while the foundation pressures of pile legs 2 and 3 increase to around 180 bar. This indicates that when diagonal pile legs 1 and 4 undergo puncture, the platform weight is primarily supported by pile legs 2 and 3. Under these conditions, pile legs 2 and 3 are subjected to prolonged excessive loads, giving rise to a potential risk of puncture and platform overturning.

CONCLUSION

This study has presented an experimental investigation into the safety operation control response to lifting and pile leg puncture for a jack-up offshore platform. The reliability of the safety control system was assessed by monitoring and analysing the platform tilt angle and foundation pressure during the operation of one independent pile leg, legs on the same side or on a diagonal, and a three-pile linkage. The main conclusions are as follows:

(1) Compared with the case where pile legs on the same side are ascending, the difference in the platform tilt angle in the X and Y directions is greater when a single pile leg is ascending. The maximum inclination angle (1.8° in Fig. 12) is reached when three pile legs are ascending together.

(2) Large puncture depths lead to an unbalanced force distribution on the pile legs, causing the tilt angle of the platform to suddenly increase and putting it in a dangerously unsTable state.

(3) The tilt angle of the platform for puncture by adjacent pile legs changes more rapidly in both the X and Y directions compared to a single pile leg puncture (as shown in Fig. 14), making the platform prone to lateral tilting.

In this paper, we have presented research on safety control technology in which we developed and designed a safety operation control system and simulated experimental device for a jack-up offshore platform. In actual offshore operations, the risks faced by jack-up offshore platforms are more complex and varied, and the impact of adverse sea conditions on operational safety should therefore be considered in subsequent research.

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