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Enhancing the Life Cycle of the Jack up Structure by Applying Alternative Foundation Methodologies in Geotechnical Engineering

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***Abstract:** A jack-up structure is a bottom-mounted floating unit having an adjustable hull and movable legs. Particular jack-up structures are more susceptible to hazards under environmental loads during their operation and life cycle in the ocean. Authors' attempts here to enhance its life cycle and sustainability in shallow to deep waters by correctly accessing soil behaviour and predicting its load carrying capacity. Here the numerical analysis of the substructure has been attempted. Simulation of load-deformation behavior under axial compression has been carried out for advancing research. The entire study has been carried out using three-dimensional finite element-based software Plaxis 3D A.E. 2017. The geometrical variation of substructure spud can have an inverted spud at the centre bottom from 120^0 to 180^0 has been studied for knowing behaviour under axial compression, axial tension, and lateral forces. The simulated numerical model is used to develop empirical expressions for axial capacities estimation. The numerical analysis results indicate that spud can have an inverted angle of cone 130^0 is most beneficial under the static combined vertical, moment, and horizontal loading (3D loading) in marine clay. The axial load carrying capacities in compression, tension, and lateral loading follow the same sequence in ascending order from 180^0, 175^0, 150^0, 130^0 and highest in 120^0. Stiffness and undrained shear strength of soft clay contribute more than the diameter of the spud and embedment depth in compression and tension.*

***Keywords:** Interaction of Leg Foundation of Constant Fixity With Marine Clay. Axial Capacities, Shaft Diameter, Spud Diameter, Plaxis 3d*

I. INTRODUCTION

The authors' research is to enhance the sustainability and life cycle of the mobile offshore drilling unit (M.O.D.U.) category of structures – Jack up used in shallow to deep water seabed formation.

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Due scarcity of oil and gas reserves and declining prices of crudes worldwide in the hydrocarbon industry, researchers are bound to move deep offshore locations, resulting in developments of floating systems similar to jackup and buoyancy structures. Unfortunately, this jackup is subjected to hazards and lost completely during extreme storm conditions. Jack et al. [9] Morandi et al. [9] observed from their research from the past couple of years that jackup hazards encountered from 1980 to 2004 were not due to bad weather conditions but inadequate overstressing of jack-up structural legs or foundation elements.
Following figure.1 and figure.2 are reproduced to highlight the background of this research and support the statements of Jack et al. and Morandi et al. [9]. Figure.1 indicates the author's research field visit to jackup structure in moderate to deep water zone to enhance reality.
Morandi et al. [9] also reported that jack-up also fails due to the wrong placement of the jack-up hull in the wave zone. Pisano et al. [12] studied the three-dimensional fully operational analysis of jackup spud can, which is essential due to its heavy use in the offshore industry. As marine gravity foundation caissons, spud can, and mat are the most widely accepted foundation elements in offshore foundation engineering for mitigating hazards of sinking, tilting, and punching shear in the soil during installation [13]. The benefit of spud can/mud mat compared to other foundations is still younger research in offshore geotechnical engineering.

Figure 1. At research field visit, photo taken for four legged jack-up in the Arabian sea of Gujarat region. India

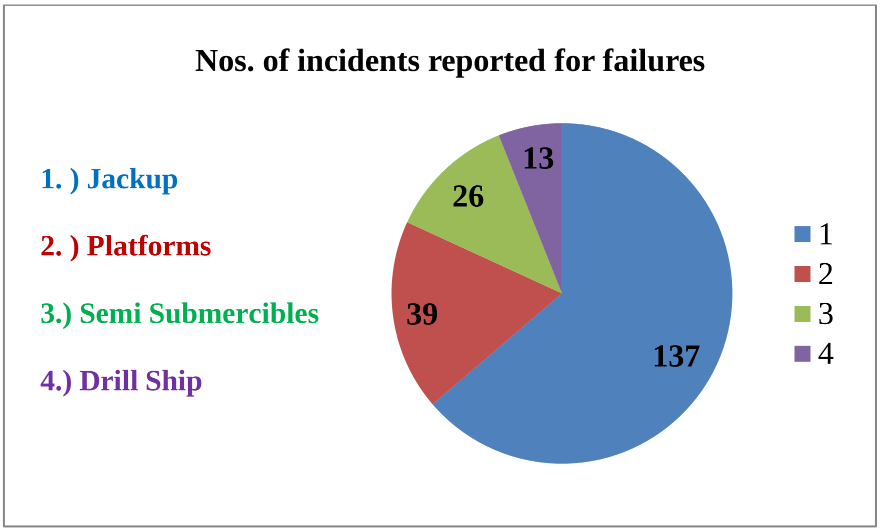

Figure 2 Reported nos. of accidental failures in case of various categories of marine structures

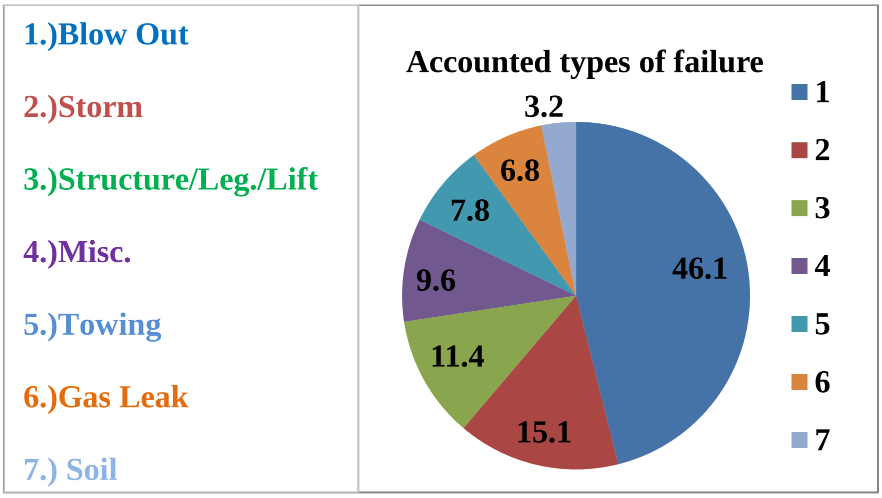

Figure 3 Failures reported from literature for jackup structures way back from its early use to till date.

Figure.2 creates focus of attention towards facts that highest nos. of failures are attributed to jack up among comparable marine structures alike drill ships, submersibles and platforms. Figure.3 shows statistics of the failure cases indicate that jack-up structure's failures are attributed civil engineering related parameters are 37.50% among all engineering disciplines [6]. It does also indicate high time of applying changes in its design methodologies or its mitigation methods. Spud/mud mat elements also give better stability as lumped mass at jackup bottom, which helps resist nonlinear forces of sea waves or dynamic forces during operation of jackup. This spud also mitigates the overturning of the jackup leg due to its inverted conical shape geometry, which provides better stability during the operational life cycle. It also helps extract the jackup leg by a maintained air gap between the sea top surface and jackup deck bottom by preserving the center of gravity of the mass of the entire jackup structure, which creates the least unbalanced force and moments. The stability of jackup structures depends on Buoyancy, pullout, axial compression, and lateral forces acting on it in an offshore environment. Brinkgreve et al. [3] suggested the practical use of the material point method for offshore geotechnical applications due to the significant deformation phenomenon. Zhang et al [15]. Insafe JIP study was carried out to study failure probabilities in the Jackup foundation by Osborne et al. [11]. The American Bureau of shipping has produced guidance notes on the "geotechnical performance of spud can foundations" [5]. American petroleum institute (API) and international standard organization (ISO) [1] discuss spud can but in terms of shallow/ circular foundation. Buoyancy forces acting on spud foundations have detrimental effects on bearing capacity evaluation. [5]. It also forms a cavity that is backfilled immediately during installation. Mat supported jack-up foundation is advantageous, increasing bearing areas and efficiency [13]. Installation of jack-up spud can result in higher penetration due to the low shear strength of soil in initial seabed layers [13]. Here an attempt has been made to study various aspects of Jack up spud can/mud mat in the offshore seabed. Soil properties like stiffness and embedment depth are major affecting factors. The time lag between installation and operation affects the rotational stiffness of pinned connection of constant fixity between jack-up leg and spud can or mud mat. The preceding discussion is about the jackup spud can /mud mat and its various applications. It's essential to study aspects of current engineering design principles and adopted methodologies to predict its behavior. But estimation of the forces to predict installation and extraction under known pre-loading and soil layers conditions is still a question to avoid failure.

II. OBJECTIVES OF PRESENT INVESTIGATION

A significant research gap is found in the stability studies of a jack-up leg with foundation elements under combined static loading with different foundation soil stiffness. The instability mechanism caused for any offshore jackup legs is attributed to a.) Wave and wind loads and exceptional cases of a storm, typhoon, tsunami, etc., are responsible for generating overturning moments. b.) Environmental forces also play a role in soil erosion, creating undulations of the seabed, punching shear, and unpredicted changes in soil stress beneath the jack-up foundation, bearing failure, etc.

This research partially attributed to comment A.) 'Work needed' from ISO 19905-1 (ISO/ TC 67/SC7) clause 9 foundations sub-clause 9.3 geotechnical analysis of independent leg foundations (2007). B.) Yeager et al., Meyer et al. [10], and the team conducted an event through the international society of soil mechanics and foundation engg. For prediction of jack-up spud can behavior. Penetration response of spud can in layered sands had been also studied by Kim et al, Hossain et al, Edward et al and Wong et al. Penetration response in layered sand is very useful for prediction post installation behaviour of of spud to mitigate any hazard. [7] Moreover, spud can are classified as primarily conical foundations. It employs the method of jacking or driving with jack-up leg attachment to a founding stratum in offshore seabed soil. Because of that present investigation focuses on the derivation of axial compression, and uplift tension considering unit displacement with the help of the F.E.M. tool. It also emphasizes the impact of change in angle of the internal cone of spud (A.I.C.S.) with other parameters as constant. i.e., a diameter of spud can and jackup shaft leg. Figure.1 is developed to demonstrate development of leg stresses during loading of jack up. Figure.2 is ideally indicating sinking & tilting behaviour of jack-up through Finite element methodology. Figure.3 represent instability mechanism of jackup up foundation in cohesive offshore soil while installed on sea bed as follows.

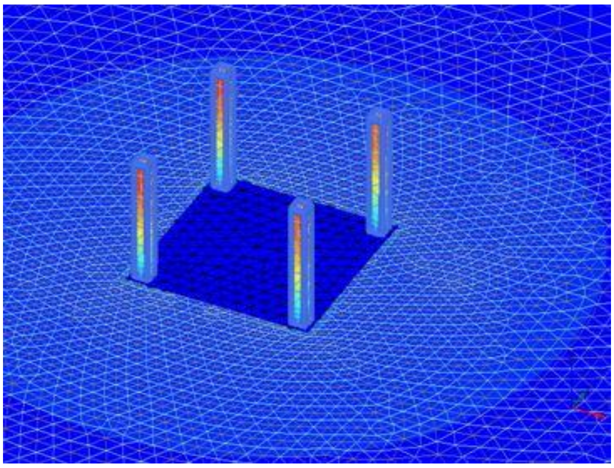

Figure 4 Demonstration of Stressing of jack-up legs in F.E.M.

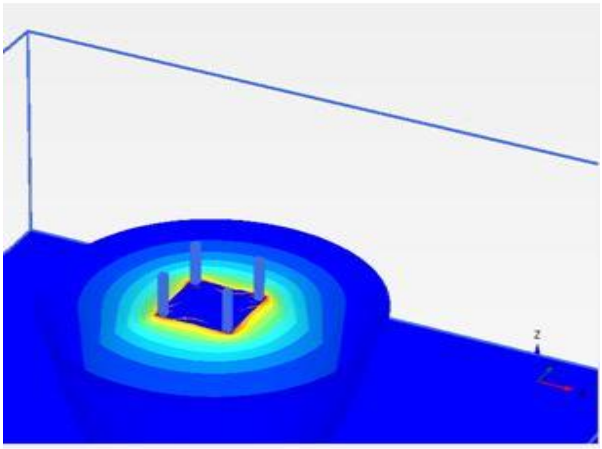

Figure 5 Demonstration of sinking & tilting of jack-up in F.E.M.

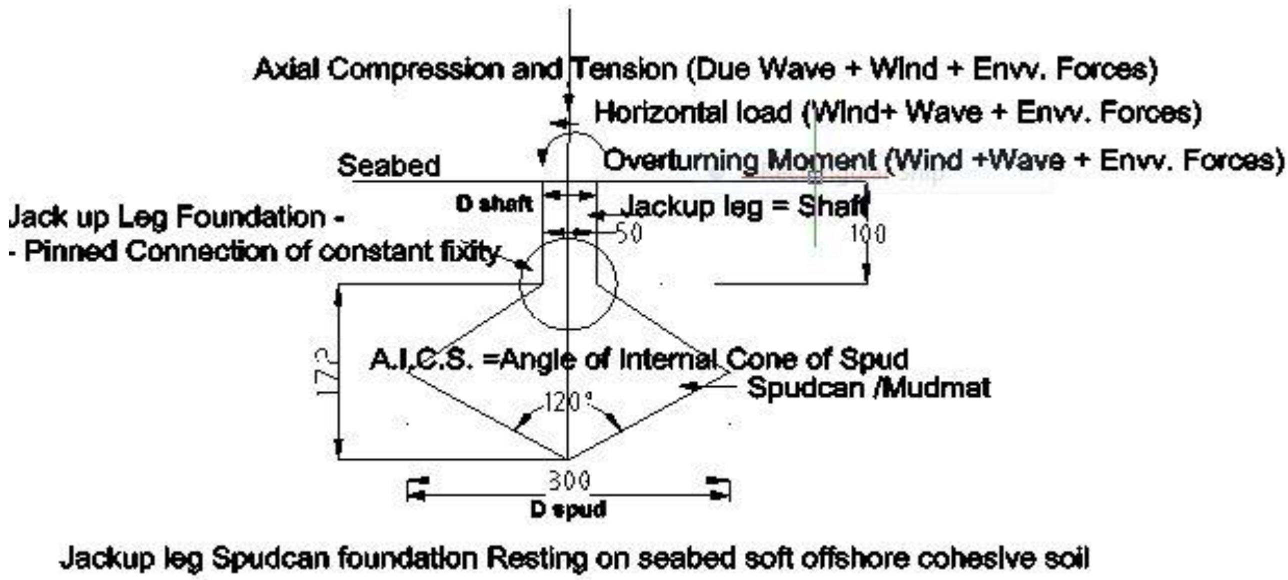

Figure 6 Instability mechanism of jackup up foundation in cohesive offshore soil

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III. MODELLING OF JACK-UP SPUD CAN IN 3D F.E.M. IN GEOTECHNICAL ANALYSIS

For analysis in the F.E.M.-based program Plaxis 3D A.E. 2017, offshore seabed soil is modeled as 10 node tetrahedral volume elements. All structural / foundation elements are selected as 6 node two dimensional planar plate elements. The soil failure characteristics are chosen as the Mohr-Coulomb model. The mohr-Coulomb model is most widely used due to its elastoplastic characteristics. Mohr-coulomb model is a linear, perfectly plastic model based on hook's law of isotropic elasticity, and failure criteria are perfectly plastic. The Mohr-Coulomb model is ideal for dividing strain increments into elastic (recoverable) and plastic (irrecoverable) parts. This soil model is ideally suited for static analysis in simulating field conditions. Spudcan element is treated as combined plate elements in the derivation of axial capacities. While under combined Vertical Moment and Horizontal loading, the spud can element is treated as a rigid element. Numerical modelling is based on 3D continuum modelling of cohesive soil with linear increments of undrained shear strength and stiffness with increasing depth. Authors attempted to analyze results are derived assuming constant fixity of jackup leg with foundation for static loading case.

Applying boundary conditions to the numerical model follows assumed extensions of failure stresses in soil media. Horizontal boundaries of the numerical model are placed at a distance of five times the diameter of the spud can/mud mat in both directions. The upper boundary is free. The bottom boundary is placed at five times dia. of the spud can/mud mat below the tip of the inverted angle of the spud can/mud mat. These boundaries are established so that installation or load application on stresses generated should not be affected. In static analysis, boundary conditions are set to fix in all directions except allowable deflection direction to determine compression and tension capacities. In static analysis, the mohr-coulomb failure model has been selected as constant to maintain the characteristic behaviour of soil. The mohr-Coulomb model is effectively used because it can extend for dynamic analysis by introducing damping to characterize soil behaviour ideally.

Under combined loading foundation element is considered rigid hence there is no effect of the kinematics of motion on it in an offshore environment. The interface factor between the spud can element, and surrounding soil (R_{inter}) was taken as nearly equivalent to the coefficient of friction between marine clayey soil and steel. The particular interface behaviour is dependent on the stiffness of offshore soft clay. Soft clay provides the least resistance to the downward movement of spud can in comparison to loose sand.

IV. VALIDATION OF PRESENT METHODOLOGY BY PHYSICAL AND NUMERICAL MODELLING

4.1 Validation for numerical modelling

Numerical modeling of seepage and tension beneath plate anchors by Maitra et al. [8] was considered a milestone for validation of numerical modelling. Verification is carried out through results obtained by Abaqus software for reference research paper [8]. Plate anchors from the Abaqus - numerical model have been reproduced in Plaxis 3D.. The soil properties used in the benchmark problem are described herein Table.1.

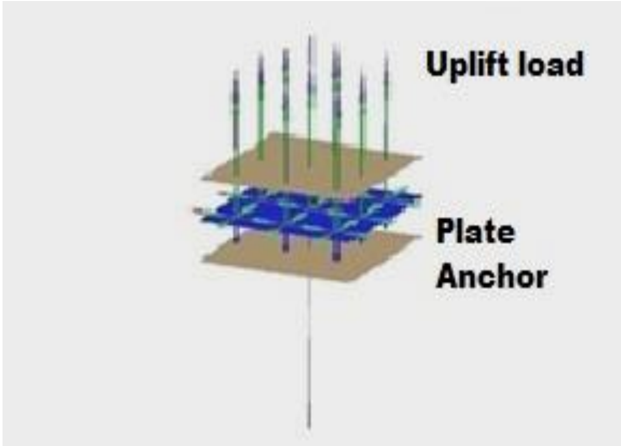

Figure 7 Reference modelling of plate anchors in PLAXIS 3D

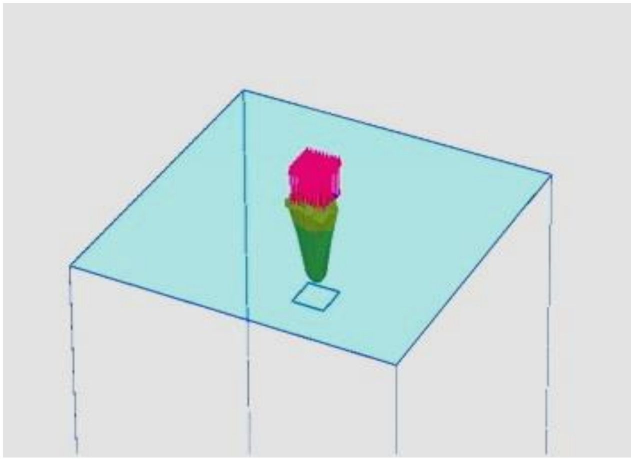

Figure 8 Deformed pattern for plate anchor in plaxis 3D

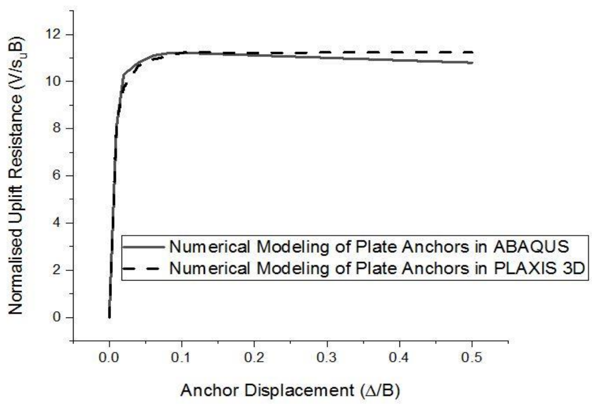

Figure 9 Validation for numerical modeling from ABAQUS to PLAXIS 3D from reference research paper [8]

The figure.7 represents plate anchors and applied uplift load in plaxis 3D. The figure.8 represents deformation patterns of plate anchors in Plaxis 3d. Figure.9 represents the normalized uplift resistance vs anchors displacement in plaxis and abaqus, Plaxis 3D & Abaqus results are in good agreement.

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Table 1. Soil parameters used for analysis in numerical validation

Parameters	Values
Material Model(Soil)	Mohr- Coulomb Analysis
Drainage Type	Undrained Material (C)
Soil Density ($\Upsilon_{Submerge}$) kN/m^3	10
Void ratio (e)	0.5
The angle of Internal Friction (θ)	0 degree
Dilation angle (φ)	0 degree
Poisson's Ratio (μ)	0.3
Undrained shear strength (Su) kN/m^2	10
Specific Gravity (G)	2.65
Deformation Modulus (E_{soil}) kN/m^2	500 Su = 500*10 =5000

4.2 Validation for physical modelling

Validation is also carried out from field load tests on helical pile reported in Canadian Geotechnical Journal by Elsherbiny and E.I. Naggar et al. [4]. The typical soil profile of the test site is shown below. The piles are made up of a central shaft of steel with a wall thickness of 8.2 to 9.3 mm with welded helices. Pile P1 has a shaft diameter of 273 mm and a helical blade of 610 mm installed to a depth of 5.5m. Pile P2 has a shaft diameter of 219 mm and a spiral blade diameter of 508 mm installed to a depth of 5.6m below the ground surface. The validation graphs for physical modelling of helical piles P1 and P2 are produced and reported here as figure.10 and figure.11 respectively. The material properties and soil properties are reproduced in Table.2

Table 2. Soil & pile parameters used for analysis in physical modelling validation

Parameter Soil	**Value**
Unit Weight γ (kN/m^3)	20
Young's Modulus E (Mpa)	80
Poisson's Ratio (μ)	0.3
The angle of internal friction Φ in degree	30
Friction Factor (R_{int})	0.4
Parameter Pile	Value
Modulus of Elasticity (E) Gpa	200
Poisson's Ratio (μ)	0.3

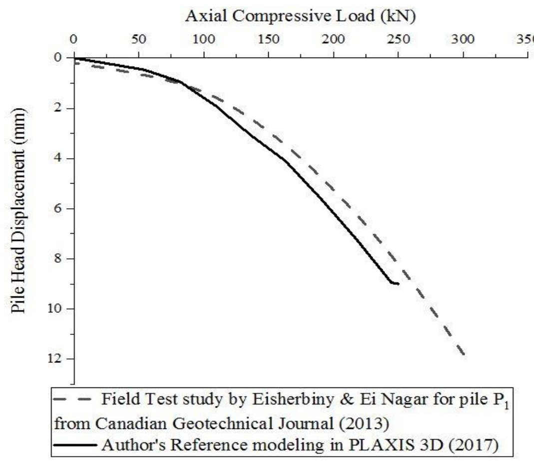

Figure 10 Validation for physical modeling for pile P1 Helical Pile

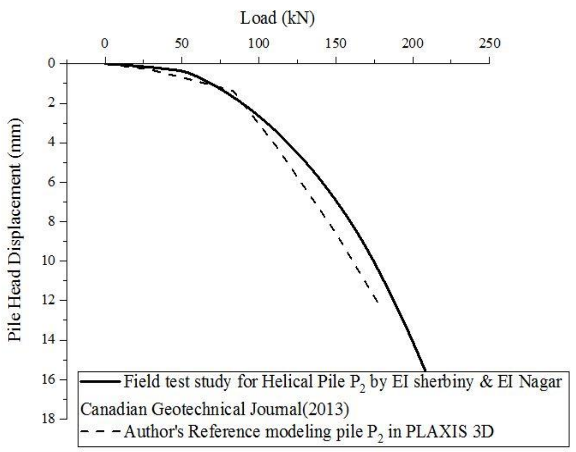

Figure 11 Validation for physical modeling for pile P2 Helical Pile

V. PHILOSOPHY FOR STATIC LOADING IN 3D FINITE ELEMENT MODELLING

Under the static loading case, the operational sequence of Plaxis 3D has been carried out in three stages. The initial phase in the present numerical analysis stimulates soil conditions alone. Other parameters were kept silent. These include earth pressure calculation as 1-sin Φ. The initial soil stress values are encountered in studies. The second stage evaluates the installation or embeds spud can/mud mat into a soft clay bed with defined boundary conditions. As the spud can expand downwards, the cavity also forms. The cavity expansion is dependent on soft clay resistance against penetration. Formation of cavity expansion is considered in Plaxis by encountering effects in volumetric strain. But the impact of volumetric strain is very low compared to the higher magnitude of forces applicable for installation and extraction. [2]. The effect of volumetric expansion in soft offshore cohesive soil is no more influential parameter in installation and extraction. Installation, an extraction of jackup foundation element, distorts heavy soil volume and soil stresses. In the third and final stage, all structural components are activated, and prescribed displacement is applied in axial directions, either in compression, tension, or lateral.

VI. PARAMETRIC STUDY

The numerical analysis was further extended to conduct the parametric study to understand the phenomenon involved in load-carrying mechanisms in-between different angles of an internal cone of spud for uniaxial compression,

uniaxial tension, and lateral loading. Parameters are chosen so that most identical behavior from the field of cohesive offshore soil can be justified. The various dimensions of spud can are selected to exhibit distinguished parametric variation on a large scale.
The Parametric study extended for variations of shaft diameter of 0.5m, 1.0 m, and 1.50m for the constant diameter of spud can as 3m. The angle of an internal cone of spud (A.I.C.S.) varies from 120^0, 130^0, 150^0, 175^0, and 180^0, for the constant diameter of a spud can as 3m. The spud can was considered embedded in cohesive offshore soil, impacting the identical stiffness value of cohesive offshore soil. In general, the particle size of representative offshore cohesive soft clay varies in range of less than 0.002 mm. The impacts of varieties of parametric studies are summarized in the following paragraphs.

6.1 Impact of the angle of internal cone of spud can (A.I.C.S.)

Fig.12 represents D_{spud} =3m, D_{shaft} =1m with an internal cone of spud angle varying from 120^0 to 180^0 in increasing order in compression. Fig.13 represents D_{spud} =3m, D_{shaft} =1m with an internal cone of spud angle varying from 120^0 to 180^0 in increasing order in tension. The study reveals impacts of (A.I.C.S.) angle of the internal cone of spud in compression and tension.

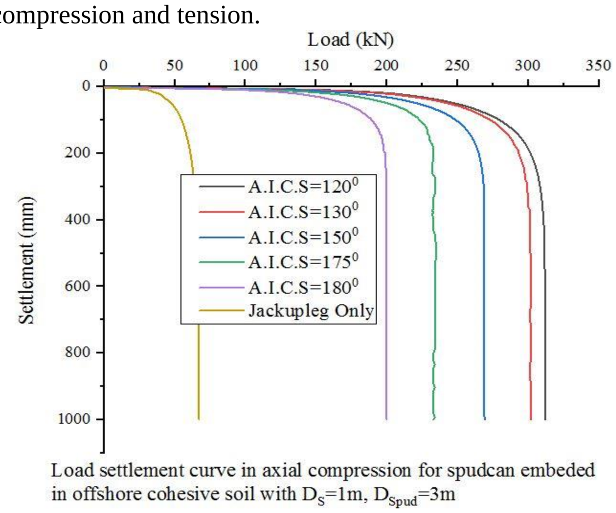

Figure 12 Impact of the increasing angle of spud can for axial compression in cohesive offshore seabed with Ds=1m, Dspud=3m

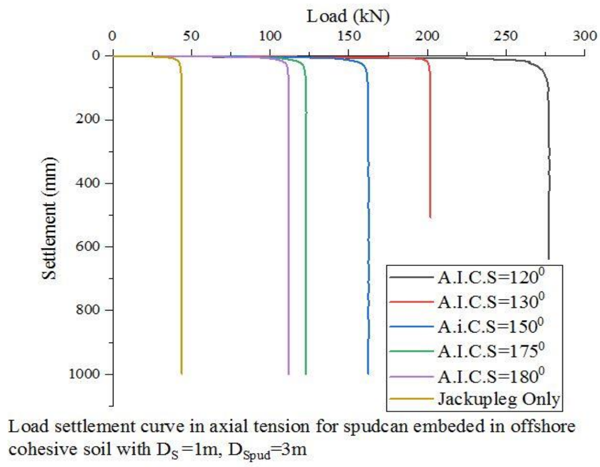

Figure 13 Impact of the increasing angle of spud can in axial tension in offshore cohesive seabed soil with Ds =1m, Dspud=3m

Fig.14 represents the lateral loads applied at the top edge of the spud can, which is identical to sea wave force under static loading conditions. It shows lateral load capacity of spud can in offshore cohesive seabed soil with increasing order of angle of the internal cone of spud (A.I.C.S.), which varies from 120^0 to 180^0. It is observed here that the highest lateral load is carried by 120^0 spud can, which subsequently reduces with increasing angle of spud.

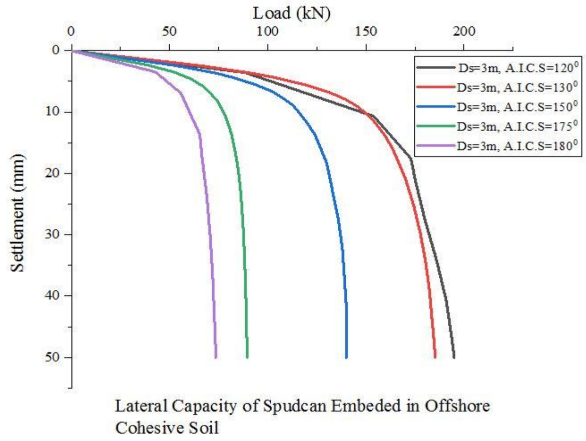

Figure 14 Impact of increasing order of angle of spud on the lateral capacity of spud can in offshore cohesive soil

6.2 Impact of the depth of installation (Di)

Fig. 15 and Fig. 16 are developed to find individual variation of ultimate load-carrying capacity in axial tension and axial compression with four different depths of installation (Di) with constant shaft diameter (Ds) as 1m and diameter of spud (Dspud) as 3m. Here four installation depths are 1.065m, 2.065m, 3.065m, and 4.065m. Here spud can foundations are embedded in three different stiffness values of clay.i.e. 5000 kN/m², 6000 kN/m² and 7000 kN/m². The resulting axial compression and tension behavior will be identical for all other types of spud with different angles of an inverted cone of spud.

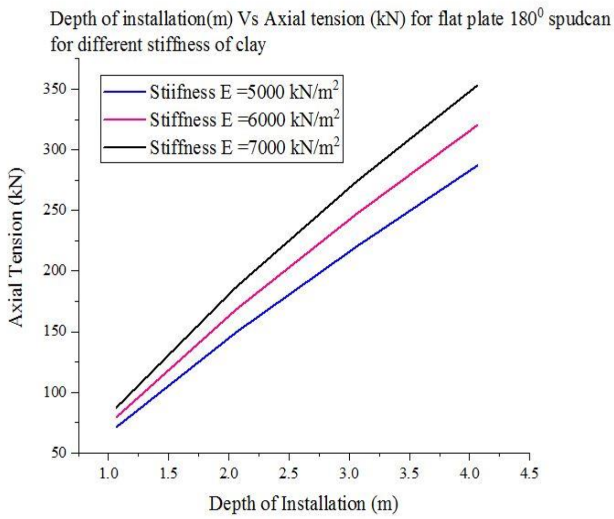

Figure 15 Depth of installation Vs axial tension for varying stiffness of clay

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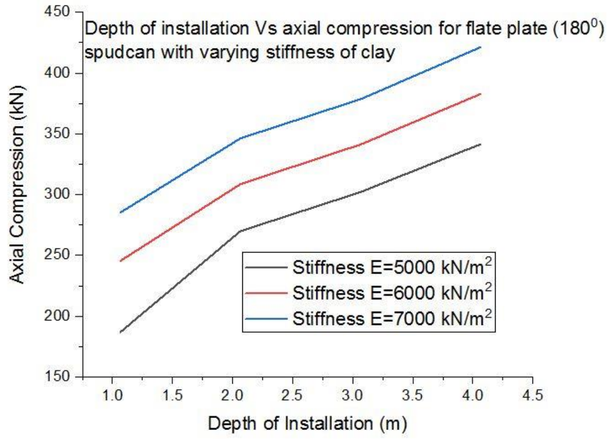

Figure 16 Depth of installation vs axial compression for varying stiffness of clay

6.3 Impact of increasing angle of internal cone of spud on axial capacity (Ds= Dia. of Shaft) against constant spud dia. (DSpud=3m)

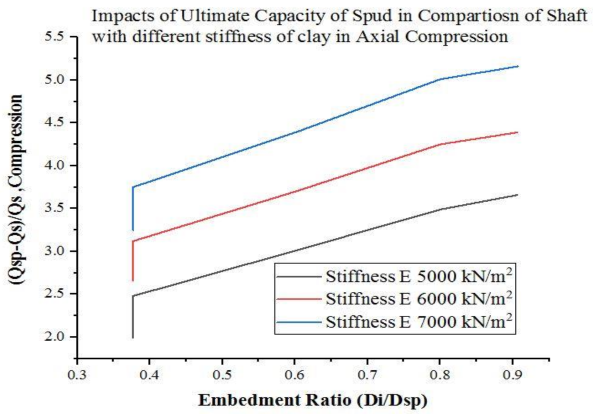

Figure 17 Influence of increasing angle of an internal cone in spud in compression against embedment depth for different stiffness of clay

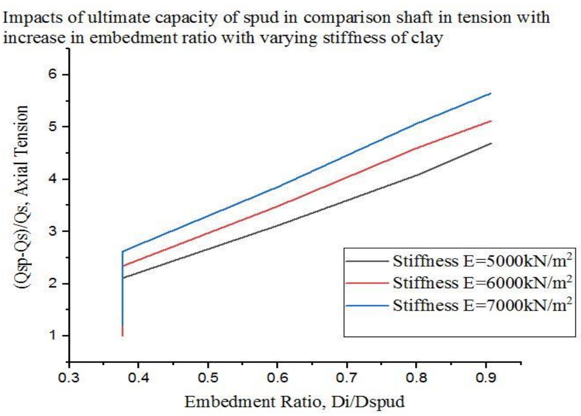

Figure 18 Influence of increasing angle of an internal cone in spud in tension against embedment depth for different stiffness of clay

Fig.17 and Fig.18 respectively studied for knowing effects of spud can against jackup leg for increasing embedment ratio in developing axial capacities.

6.4 Impact of jack-up leg diameter on axial capacity (Ds= Dia. of Shaft) against constant spud dia. (DSpud=3m)

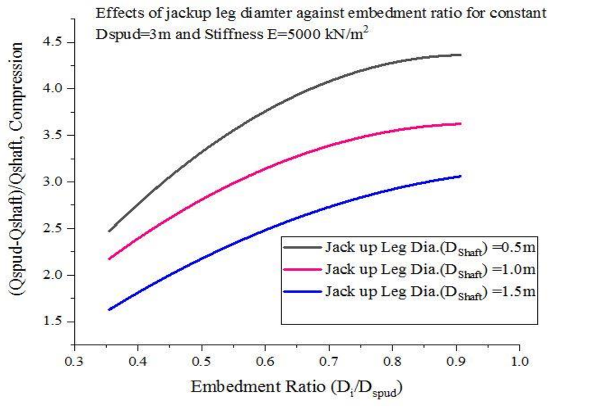

Figure 19 Effects of increments of jack up leg dia. in comparison of constant spud dia. on ultimate compressive capacity

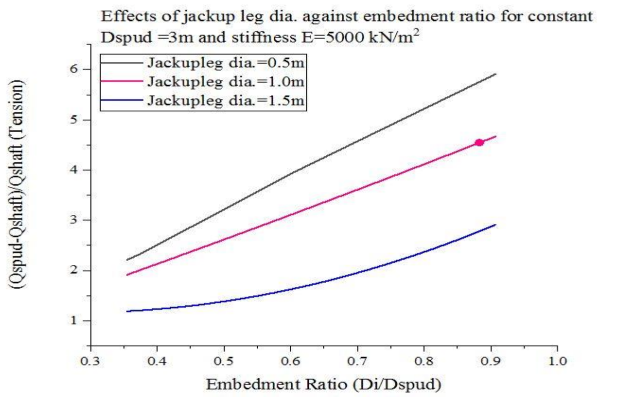

Figure 20 Effects of increments of jack up leg dia. in comparison of constant spud dia. on ultimate tension capacity

Fig.19 and Fig.20 are developed to know the impacts of increments of jack-up leg diameter **(**D_{shaft}=0.5m 1.0m, 1.5m) against constant spud dia. (D_{spud}=3m) for various increasing angles of the internal cone of spud (A.I.C.S.) in axial compression and axial tension respectively.

6.5 Impact of spud can diameter on axial capacity (DSpud= Dia. of Spud) against constant jack up leg dia. (Dshaft=0.5m)

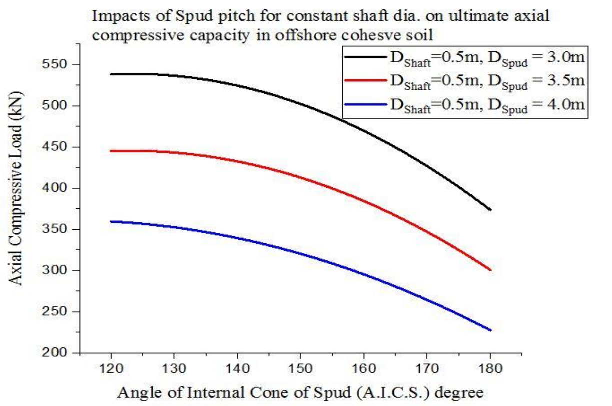

Figure 21 Impacts of increase in dia. of spud against constant jackup leg shaft dia. in axial compression

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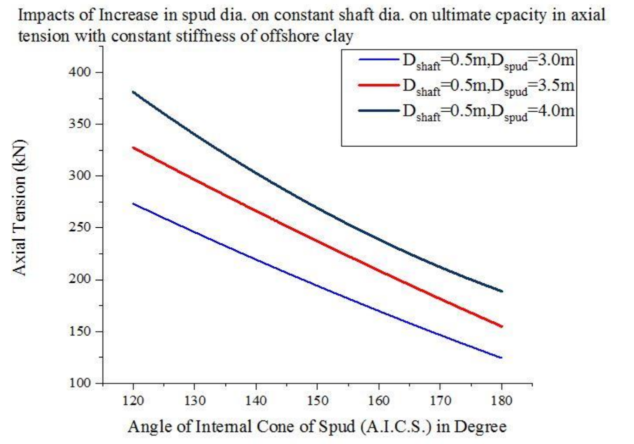

Figure 22 Impacts of increase in dia. of spud against constant jackup leg shaft dia. in axial tension

Figure 21 and Figure 22 indicate Impacts of spud can diameter are required to study material consumption and cost optimization to a more significant extent. Jackup spud can be analyzed here from various aspects of offshore soil conditions and offshore adverse loading conditions. Hence, the combination of study- i.e., effects of spud can diameter over jackup leg diameter against each other – is helpful for maximum possible design and material consumption optimization.

6.6 Impact of combined vertical, horizontal, and moment (V.H.M.) loading on jackup spud can foundation

Fig. 23 is developed as a phenomenal and most exciting research gap to understand the behavior of jackup spud can foundations in soft offshore cohesive seabed soil under combined vertical and horizontal loading and moment. Here an attempt has been made to analyze the impact of some fixed magnitude of vertical load, biaxial moment, and horizontal load to stimulate adverse offshore loading conditions to the extent possible through the F.E.M. program.

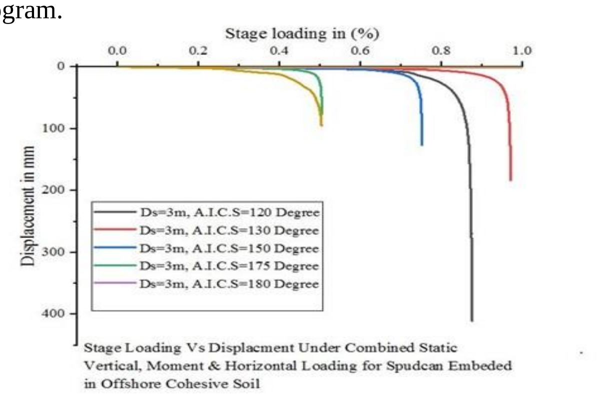

Figure 23 Stage Loading Vs Displacement under combined static vertical, moment & horizontal loading for spud can embedded in cohesive offshore soil

6.7 Theoretical relationship

6.7.1 Axial Capacity

Authors propose theoretical axial capacity is based on the following pre assumptions. Effective area (A) will be of the broadest cross-section of spud. As the spud can penetrate the seabed, backfilling occurs, which creates a detrimental effect on axial capacities. At the same time, the Buoyancy of soil is equivalent to the weight of soil displaced by the volume of spud. Reduction Factors are introduced to achieve physical significance, as mentioned below, depending on the angle of the internal cone of the spud. (A.I.C.S.). Modified equation is presented here from our research.

$Qv= [\{SuoNcA + r'(V+Ah)\}-W_{BF}+Bs]*R_f$ ....(1)

Qv	=	?					
S_{uo}	=	10	kN/m^3				
Nc	=	5.14					
r'	=	10	kN/m^3	=	10000	N/m^3	
AICS	=	120	130	150	175	180	Degree
D_{eff}	=	2.73	2.4	1.8	1.13	1.13	m
A	=	7.07	m^2				
V	=	6.43	5.66	4.24	2.66	2.66	m^3
h	=	2.73	2.4	1.8	1.13	1.13	m
h	=	Cavity formation is not considered in analysis, hence it is same as Effective depth					
Dia. of Spud.	=	3	3	3	3	3	m
Considering Quarter Values for Volume and area							
AICS	=	120	130	150	175	180	degree
A	=	1.7675	1.7675	1.7675	1.7675	1.7675	m^2
Vquarter	=	1.6075	1.415	1.06	0.665	0.665	m^3
Vd	=	8	7	4	1	1	
Qv	=	155.18	147.42	133.26	117.47	117.47	kN
FEM Comp.	=	312	302	269	233	199	kN
FEM Tension	=	277	201.75	162	122	112	kN
W_{BF}	=	117	107	88	67	67	kN
Bs	=	80	70	40	10	10	kN
Qv final	=	192.18	184.42	181.26	174.47	174.47	kN
Rf	=	0.615962	0.6107	0.6738	0.7488	0.8767	Comp.
Rf	=	0.693791	0.9141	1.1189	1.4301	1.5578	Tension

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Table. 3 Proposed reduction factor

	Angle of Internal Cone of Spud (AICS) (Degrees)				
	120	130	150	175	180
Rf (Comp.)	0.615962	0.6107	0.6738	0.7488	0.8767
Rf(Tension)	0.693791	0.9141	1.1189	1.4301	1.5578

VII. DISCUSSION

Figure.1 indicates research field visit to jack up structure in the Arabian Sea., India

Figure.2 indicates mobile offshore drilling platforms – M.O.D.U. The category of structures (Jack-up) is more vulnerable to accidentential failures than other comparable marine structures.

Figure.3 indicates 37.5 % failure are attributed to probably civil engg and natural phenomenon.

Figure.4 indicates development of stresses in jack up legs under applied loading.

Figure.5 indicates demonstration of soil conditions during sinking and tilting of jack up structure.

Figure.6 represents generalized indication of instability mechanism of jackup foundation in offshore cohesive soil caused due offshore environmental loading.

Figure.24 Author has carried out reference modeling of plate anchors in PLAXIS 3D for numerical validation purpose.

Figure. 25 Results and deformed pattern for plate anchor in plaxis 3D for reference numerical modeling.

Figure.26 Validation for numerical modeling from ABAQUS to PLAXIS 3D from reference research paper [18].

Figure.27 Validation for physical modeling for pile P1 Helical Pile

Figure.28 Validation for physical modeling for pile P2 Helical Pile

Figure.12 indicates that the highest compressive force is required by 120^0 spudcan, and at least one is required by 180^0 spudcan. Looking to other curves of different internal angles of spud can indicate a higher loss of applied axial compressive force in installation in descending order from 180^0 degrees to 120^0.

Figure.13 reveals that the highest uplift force is attained by 120^0 spud can while the lowest uplift force is required by 180^0 spudcan.

Figure. 14 The lateral load-carrying capacity sequence is observed in 120^0, 130^0, 150^0, 175^0, and 180^0. The highest lateral load carrying capacity is kept in the case of a spud can with an angle of internal spud between 120^0 to 130^0.

Figure.15 And Figure.16 indicates an increase in installation depth and a subsequent increase in soft cohesive soil stiffness parameters. The ultimate axial load capacity increases in axial tension and axial compression.

Figure.17 highlights visualized downfall from the peak of achieving the highest axial capacity in compression and later visualized behavior of increasing in embedment ratio will not give any fruitful result.

Figure. 18 show impacts of embedment ratio on axial tension capacity for knowing the impact of spud against installation depth. Here the particulate graph indicates constant leg dia., and for increasing embedment depth, the spud angle will be helpful between 120^0 to 180^0 only. With an increase in stiffness value of clay, the graphs initially have a narrow difference, indicating the presence of buoyancy force. Further increase in embedment ratio in uplift the lines has a broader difference, meaning that only in the initial stages does buoyancy force play a pivotal role in lifting. The impact of Buoyancy gets reduced after a specific minimum uplift force.

Figure. 19 and Figure. 20 are identical to each other except effect of holding buoyancy force in uplift to a smaller extent. Both figures prove that for a constant diameter of spud can (Dspud = 3m), the increase in jackup leg diameter did not fetch an increase in axial capacities. This behavior is likely to be interpreted as an effective area concept. I.e., the Area in contact between the surrounding soil and the entire assembly of jackup spudcan. Fig. 19 and Fig. 20 prove that the horizontal part or maybe inclined surface of a spud can contact the surrounding earth has a significant role in developing ultimate capacities.

Figure. 21 and Figure. 22 indicates that for a constant diameter of the jack-up leg (Dshaft =0.5m), if spud pitch or the diameter of spud can increase, then axial capacities in compression and tension are likely to increase significantly. Hence, spud can diameter plays a more significant role in achieving axial capacities compared to jack-up leg diameter. The reason behind this behaviour can be interpreted as an effective area concept.

It is observed in figure.23 of stage loading vs. displacement that 80 % of the load in compression is taken by balancing the deflections and moments in six degrees of freedom of the foundation element. These indicate load path distribution. Behaviour in combined loading varies significantly depending on the degree of angle of the internal cone of spud (A.I.C.S.), which ranges from 120^0 to 180^0. The highest load carrying capacity is observed in the angle of the internal angle of spud as 130^0. In the case of combined Vertical Moment and Horizontal loading, the load-carrying capacity followed in descending order is 130^0, 120^0, 150^0, 175^0, 180^0. The soft offshore cohesive soil properties are kept constant under combined loading. The magnitudes of vertical load, horizontal load, and bidirectional moment are also constant. Optimum geometrical configuration is internal angle of cone of spud as 130^0 for providing resistance to unbalance force and moment.

Table .3 represents reduction factors (R_f) to be applied in formula for different angle of internal cone of spud to get corrected value as per equation.1

Authors had studied various codes alike.

- Technical Bulletin of S.N.A.M.E. (2008), [14]
- API RP2 GEO Geotechnical and Foundation Design 2021 and ISO 19901-4:2003 (Modified), (Part.4) for Offshore structures [1].

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- Indian Standard I.S. 6403 (2002).
- American Bureau of Shipping (A.B.S. 2018) [6]

For the computation of axial load carrying capacity with the provision of Buoyancy and cavity for spud can foundations, the author believes that equation .1 mentioned in clause 5.7.1 of these particular research articles is most vulnerable in the assessment of axial capacity spud can foundations for M.O.D.U. (Jack-up) structures.

VIII. SUMMARY AND CONCLUSIONS

Following remarks are compatible with the provision of international codes of practices. And it was proved to produce minimum hazard. One can easily design substructure geometry economically and safely for jackup leg for prevailing environmental loading in marine cohesive soil conditions by accomplishment of following observations.

1) Optimum substructure geometry is flat plate (180^0) spud, i.e., jack up mud mat under static cases of axial compression, uplift tension, and lateral loading. Flat plate (180^0) spud can require the least magnitude of forces in installation and extraction in cohesive offshore soil.
2) The effectiveness of an increase in diameter of spud can (D_{spud}) is much helpful in achieving higher axial capacities for constant jackup leg diameter (D_{shaft}) with a combined increase in embedment ratio and stiffness of cohesive offshore soil.
3) The increase in jackup leg diameter (D_{shaft}) does not help achieve higher axial capacities for a constant diameter of spud can (D_{spud}) with a combined increase in embedment ratio and stiffness of cohesive offshore soil.
4) Research reveals undrained shear strength (Su) and stiffness (E) of cohesive offshore soil play a significant role in developing stability compared to jack-up spudcan elements.

Notations

A.I.C.S= Angle of an internal cone of spud
D_{shaft} = Diameter of shaft = Diameter of jackup leg
D_{spud} = Diameter of spudcan
Di = Depth of Installation of spudcan
Qv= Vertical axial capacity of spudcan
Suo= Undrained shear strength at the lowest depth of maximum plan area
Nc= Bearing capacity factor of shallow spud can in clay prior to any backflow in homogeneous clay layer (Φ=0). =5.14 as per I.S. 6403 (2002) assuming conical foundation
γ'= Submerged soil unit weight
D_{eff}=Effective depth of spudcan
A= Spudcan maximum cross-sectional Area in m^2
V= Volume of Spudcan below the mud line
h=hc = Height of cavity of formation
W_{BF}= Weight of backfill
Bs = Buoyancy of soil
R_f = Reduction Factor
Data and Analysis Files

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COMPETING INTERESTS AND FUNDING

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Conflict of Interest

The authors reported no potential conflict of interest.

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