기술보고

Structure & Installation Engineering for Offshore Jack-up Rigs

영문 안내

대한조선학회지의 국제화 및 외국인 회원들의 투고 활성화를 위해 대한조선학회지 54권 4호부터 영문 기고가 가능하게 되었음을 알려 드립니다. 한국인 공저자가 있는 경우 국문 요약을 함께 게재합니다. (편집인 주)

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요 약

잭업 드릴링 리그는 해양 원유 및 가스개발 분야에 폭넓게 사용되어지고 있다. 초기 모델은 수심 60미터 이하의 천수영역에서 운용되었고, 최근에는 대수심 150미터와 가혹한 환경조건에 대응하도록 개발이 되어 왔다. 본 기고에서는 북해 유전에 사용되는 잭업리그의 전선해석을 수치해석방법을 통하여 검토하였다. 첫번째로, 북해의 환경조건을 분석하고, 해저지질조사 보고서를 통하여 지질특성을 확인하였다. 조사자료를 근거로 기본도를 작성할 수 있는 설계사양을 수립하였다.

북해에 설치된 잭업리그의 동적특성을 규명하기 위해서, 전선해석 시 레그와 선체를 고려한 전도모멘트를 계산하고, 잭업리그 leg & 선체구조의 건전성 확인을 위하여, 국제코드를 활용한 구조강도 평가 수행으로 안전성을 검토하였다. 잭업하는 도중 발생할 수 있는 불확실성 요소들은 해저면의 특성에 크게 관련되어 있으며, 일반적으로 pre-loading하는 과정 중에 자주 발생한다. 이 기고에서는 잭업리그의 운용하는 사이클 내에서 발생 가능한 구조적 안전성을 검증하기 위하여 상세구조 및 설치엔지니어링 문제에 대해서 분석하였다. 이러한 목적에 부합하기 위하여 아래의 사항들을 검토하였다.

- 해저지질 조건을 고려한 구조붕괴거동
- Pre-loading 절차서 및 매개변수에 의한 붕괴모드
- 계측자료의 검증 및 구조엔지니어링 결과

Abstract

Jack-up drilling rigs are widely used in offshore oil and gas exploration industry. It is originally designed for use in the shallow waters less than 60m of water depth; there is growing demand for their use in deeper water depth over 150m and harsher environmental conditions. In this study, global in-place analysis of jack-up rig leg for North-sea oil well is performed through numerical analysis. Firstly, environmental conditions and seabed characteristics at the North-sea are collected and investigated measurements from survey report. Based on these data, design specifications are established and the overall basic design is performed. Dynamic characteristics of the jack-up rig for North-sea are considered in the global in-place analysis both leg and hull and the basic stability against overturning moment is also analyzed. The structural integrity of the jack-up rig leg/hull is verified through the code checks and the adequate safety margin is observed. The uncertainty in jack-up behaviour is greatly influenced by the uncertainties in the soil characteristics that determine the resistance of the foundation to the forces imposed by the jack-up structure. Among the risks above mentioned, the punch-through during pre-loading is the most frequently encountered foundation problem for jack-up rigs. The objective of this paper is to clarify the detailed structure and installation engineering matters for prove the structural safety of jack-up rigs during operation. With this intention the following items are addressed;

- Characteristics of structural behavior considering soil effect against environmental loads
- Modes of failure and related pre-loading procedure and parameters
- Typical results of structural engineering and verification by actual measurement

Keywords: Jack-up units, Leg structure, Soil properties, Overturning moment, Strength analysis, Punch- through

1. Introduction

Jack-up drilling rigs are widely used in offshore oil and gas exploration industry. It is originally designed for use in the shallow waters; there is growing demand for their use in deeper water depth and harsher environmental conditions. In order to extend the operating range of jack-up units, it has to be designed reliable analysis as well as eliminating excessive conservatism. The uncertainty in jack-up behaviour is greatly influenced by the uncertainties in the soil characteristics that determine the resistance of the foundation to the forces imposed by the jack-up structure. Among the risks above mentioned, the punch-through during pre-loading is the most frequently encountered foundation problem for jack-up rigs. In order to prevent from foundation failures during survival and operating conditions, the jack-up rig is pre-loaded during the initial stage of the installation procedure. During the pre-loading of a three leg unit, it is normally elevated to a minimum air gap and ballast water is gradually added to the pre-load tanks until the weight of the unit simultaneously loads the soil under the spudcan to a level equal to or exceeding anticipated spudcan loads for the design capacity of survival condition.

In this study, global in-place of the jack-up rig leg for North-sea location is performed. Firstly, environmental conditions and seabed characteristics of North-sea are investigated and collected. And then design specifications are established and the overall basic design is performed. Based on these environmental conditions and the design specifications the structural integrity of the jack-up leg is verified through finite element analysis and the code checks. In order to prevent from punch-through phenomenon during pre-loading, we newly proposed a reasonable procedure with considering actual operating jack-up rigs. Among the key steps, site specific soil data is essentially needed to clarify the soil to spudcan penetration response so that it is highly increased engineering reliability as geotechnical stability point of view.

2. Design criteria and methodology

The jack-up is an independent 3-leg self elevating unit with cantilever drilling facility. Its overall length is 88.8 m, width 105.1 m and the hull depth is 12 m. The legs are of 3-chord open truss X-braced structure, 209m long with spudcans of area 380 m^2. This paper present the preliminary overall basic design checks for the unit, focusing on the elevated survival design conditions. The overall strength of the leg and the overturning stability of the unit verified. The jack-up unit consists of an almost triangular pontoon shape hull, three open truss legs, three sets of rack and pinion type elevating systems and three sets of hull-to-leg fixation system per leg. The jacking structures consist of three double columns, connected to the hull around the leg well at the lower side and by means of bracings at the top above the main deck. The jacking structures comprise the lower leg guides, the supports for the fixation systems and jacking units, and the upper leg guides is supported tip of rack as shown Fig. 1.

Effective member lengths were used for the SNAME RP code[1] checking as well as comply with API[2]. Buoyancy was included in all elements below the wave crest. Accurate mass and added mass distributions were used to ensure the natural periods of the platform were adequate. Hull sagging mode owing to dead weight was considered.

The objective of the global in-place analysis for leg structure is to ensure that the unit is capable of safety supporting the intended lightship, deck facilities and payload in the operating and survival environmental conditions. This paper includes

Fig. 1 A typical jack-up drilling unit

Table 1 indicates the main dimensions, weights and environmental loads in storm survival condition for the jack-up drilling rig

Description	Unit	Survival Condition
Limit State	-	ULS
Max. water depth	m	150.0
Max. wind speed	m/sec	45.0
Max. wave height	m	29.0

structural analysis procedure and design methodology of leg structures as well as hull part carried out for the in-place conditions. The simplified hull and detailed leg structures simulate using SACS IV computer structural analysis program version 10.0 which is developed and maintained by Engineering Dynamics, Inc. USA. All the hull loads and environmental loads properly included in the computer model. The members and joints calculated for combined bending and axial loads in accordance with the criteria of DNV-GL rule[3] and API & AISC [4]code.

SACS software used to carry out the modeling and in-place analysis of legs. All primary and secondary tubular are modeled including the joint cans. The C_D and C_M values assigned for leg members include presence of anodes and outfittings. The loads transfer from jacking system to the leg consisted of four sets of pinions per rack and chord. A simplified hull model is created by using beam elements as shown in Fig. 2. The loads applied on the entire model matching the weights and

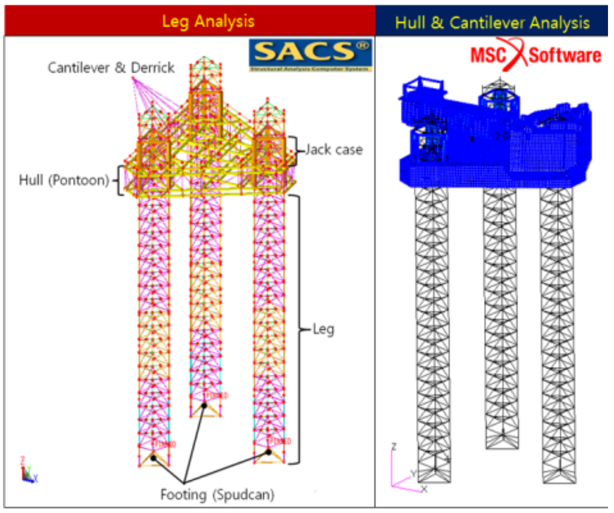


Fig. 2 Analysis model of jack-up rig

CoG based on the weight summary report. The P-Δ effect of the hull swaying during environmental loading considered in in-place analysis as well as modal analysis. The stress check for interface structures between legs and hull will be carried out in the global in-place analysis for hull. No stiffness will be considered from crane foundation and living quarter structures, however, the weights considered in this analysis.

The FE model of hull & cantilever has been created entirely of 2-dimensional shell and 1-dimensional beam elements by paying great attention in accurately replicating each one of the individual components that make up the overall arrangement based on the structural drawings of construction plan. The element size is in compliance with the frame spacing which is sufficient accurate for the global analysis as shown Fig. 2. The various assumptions involved in the structural analysis and design are listed below:

- Members are assumed to be coincidental at work points. Brace offsets are modeled as node where the brace offset value is more than 25% of the diameter of the pipe.
- Deterministic/regular wave is used to calculate the hydrodynamic loads on the structure. To account for the conservatism involved the deterministic approach a kinematic reduction factor of 0.86 is used.
- As per SNAME and API requirements the in-place analysis is carried out for a range of wave periods.
- Current blockage factor is taken as 0.92 for all heading.
- Hydrodynamic loads on individual members are calculated using Morison's Equation. No shielding or interaction effects within the structure are considered.
- The wave force on non-tubular and/or complex geometries is calculated using an equivalent diameter. The equivalent diameter is based on the circumscribing circle
- The basic drag and inertia coefficients are increased by 5% for submerged members to account for wave forces on the anode and other miscellaneous members.
- Modal analysis of the structure is carried out with the above mentioned loads to arrive at the first and second natural frequency of the structure. Dynamic amplification factors and inertial load sets are calculated using MDOF(Multi Degree Of Freedom) model based on the nonlinear dynamic simulation with time domain approach.

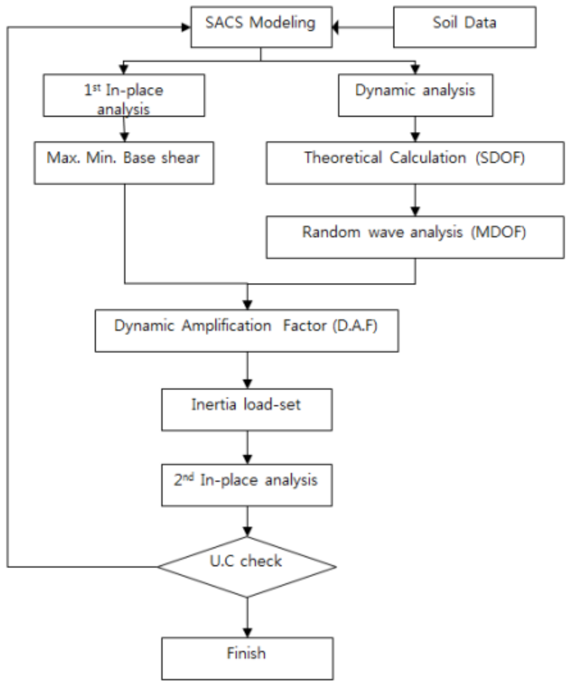


Fig. 3 Flow-chart of global in-place analysis for leg

The flow chart of global in-analysis for jack-up rig is shown in Fig. 3. During the first step of calculation, static results both base shear at the end of the spudcan are estimated. And then natural frequency based on SDOF & MDOF model using the Dynpac module is estimated during the second step of calculation. Dynamic amplification factor is defined by using SDOF & MDOF method based on the previous results depending on the wave heading angles. After these procedures, re-analysis is performed to consider the newly updated inertia-loads by using MDOF model.

The global in-place analysis for hull structure has been carried out in accordance with flow chart as shown in Fig. 4.

In a first step, the global in-place analysis for leg is carried out to select the most severe condition among load conditions. In this step, environmental loads of wave, current, wind and inertia forces considering the dynamic amplification factor are considered. The loads acting on legs calculated from the first step are transferred to the same location of F.E Analysis model. In order to verify the accuracy of analysis loads, the reaction forces at center of leg footing calculated from both analyses are compared as well as comparing of both stress and displacement. Based on the verified analysis loads, the global strength including buckling strength is evaluated hull, cantilever and living quarter structures in accordance with the acceptable criteria of rules or regulations.

The allowable criteria are adopted in the structural safety assessment for accommodation structure in accordance with DNV-OS-C104 [5]. The allowable equivalent stress and shear stress of ULS conditions are determined by considering material factor of 1.15 and the material factor of 1.0 under SLS and ALS condition is imposed.

3. Results

The design requirement checked for the most unfavorable direction and combination of loads. It is normally assumed that

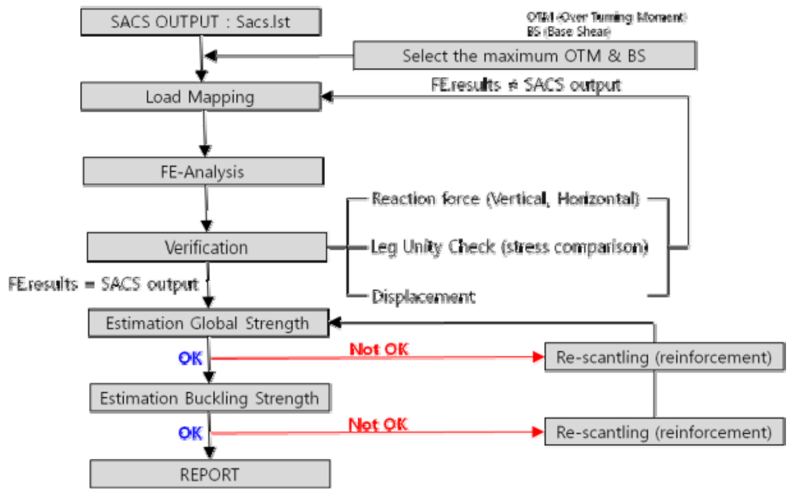


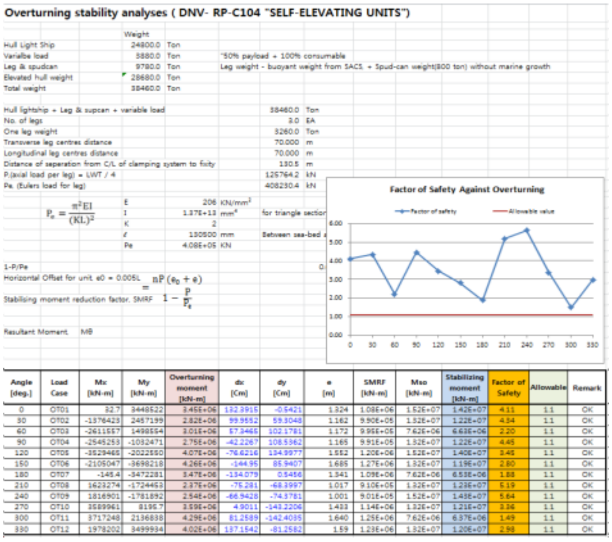
Fig. 4 Flow-chart of global in-place analysis for hull & cantilever structure

wind, waves, and current are coincident in direction. The stability check result against overturning moment is shown Fig. 5. The 2.2 of minimum safety factor is calculated and it is seen that the designed jack-up rig has enough safety margin as comparing DNV requirement [5] of 1.1.

As shown Fig. 6, the maximum combined stress and axial stress are both within the yield stress limit giving a unity check 0.75 and 0.72, separately. The present leg design has a more than enough structural safety against design specifications.

In case of maximum survival condition as shown Fig. 7, the maximum combined stress and axial stress are both within the yield stress limit giving a unity check 0.97 and 0.93, separately. All of the structural members withstand the applied environmental loading with adequate factors of safety with respect to failure modes of the ASTM Grade B steel pipe used for the structure. The critical loading condition takes place at around 300 degrees under maximum base shear condition owing to big incensement of overturning moment.

Based on the global in-place analysis results of hull and cantilever, the yielding & buckling strength assessment for structures have been performed based on the DNV-GL criteria [6]. The von-mises stress distribution at the main deck is shown Fig. 8, maximum stress took place at the hole edge around the leg well. From the strength assessment results, it is found that the yielding/buckling check ratios of critical area are lower than the allowable criteria, 1.0.



Angle [deg.]	Load Case	Mx [kN-m]	My [kN-m]	Overturning moment [kN-m]	dx [Cm]	dy [Cm]	e [m]	SMRF [kN-m]	Mso [kN-m]	Stabilizing moment [kN-m]	Factor of Safety	Allowable	Remark
0	OT01	32.7	3448522	3.45E+06	132.3915	-0.5421	1.324	1.08E+06	1.52E+07	1.42E+07	4.11	1.1	OK
30	OT02	-1376423	2457199	2.82E+06	99.9552	59.3048	1.162	9.90E+05	1.32E+07	1.22E+07	4.34	1.1	OK
60	OT03	-2611557	1498554	3.01E+06	57.3465	102.1781	1.172	9.95E+05	7.62E+06	6.63E+06	2.20	1.1	OK
90	OT04	-2545253	-1032471	2.75E+06	-42.2267	108.5362	1.165	9.91E+05	1.32E+07	1.22E+07	4.45	1.1	OK
120	OT05	-3529465	-2022550	4.07E+06	-76.6216	134.9977	1.552	1.20E+06	1.52E+07	1.40E+07	3.45	1.1	OK
150	OT06	-2105047	-3698218	4.26E+06	-144.95	85.9407	1.685	1.27E+06	1.32E+07	1.19E+07	2.80	1.1	OK
180	OT07	-145.4	-3472281	3.47E+06	-134.079	0.5456	1.341	1.09E+06	7.62E+06	6.53E+06	1.88	1.1	OK
210	OT08	1623274	-1724463	2.37E+06	-75.281	-68.3997	1.017	9.10E+05	1.32E+07	1.23E+07	5.19	1.1	OK
240	OT09	1816901	-1781892	2.54E+06	-66.9428	-74.3781	1.001	9.01E+05	1.52E+07	1.43E+07	5.64	1.1	OK
270	OT10	3589961	8195.7	3.59E+06	4.9011	-143.2206	1.433	1.14E+06	1.32E+07	1.21E+07	3.36	1.1	OK
300	OT11	3717248	2136838	4.29E+06	81.2589	-142.4035	1.640	1.25E+06	7.62E+06	6.37E+06	1.49	1.1	OK
330	OT12	1978202	3499934	4.02E+06	137.1542	-81.2582	1.59	1.23E+06	1.32E+07	1.20E+07	2.98	1.1	OK

Fig. 5 Stability check sheet against overturning moment

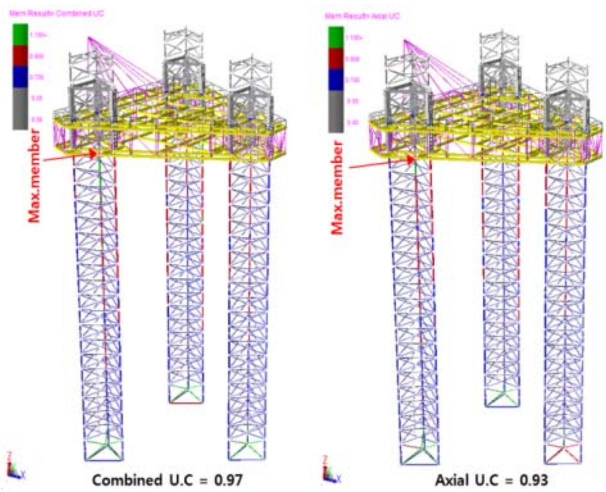


Fig. 7 Maximum unity check under survival condition

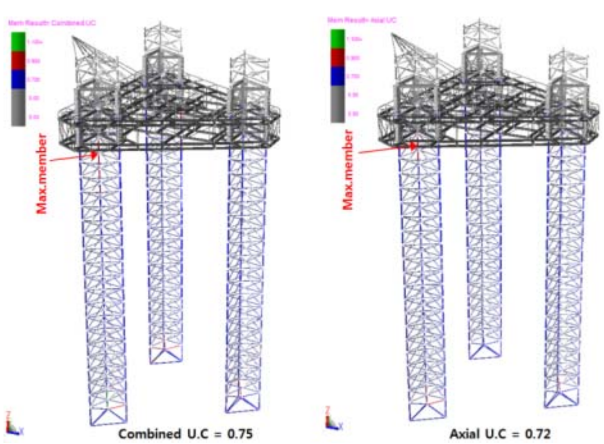


Fig. 6 Maximum unity check under operating condition

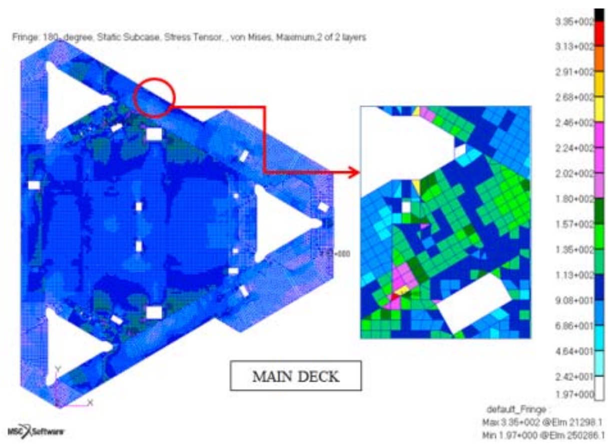


Fig. 8 Von-mises stress distribution at main deck plan of hull structure (survival condition, heading angle : 180degrees)

The principal stress distribution to X-direction around cantilever is shown Fig. 9, maximum stress took place at the top plate owing to global bending movement.

In order to prevent from punch-through phenomenon during pre-loading, we newly developed a reasonable flow-chart with considering actual operating jack-up rigs as shown in Fig. 10.

Among the key steps, site specific soil data is essentially needed to clarify the soil to spudcan penetration response so

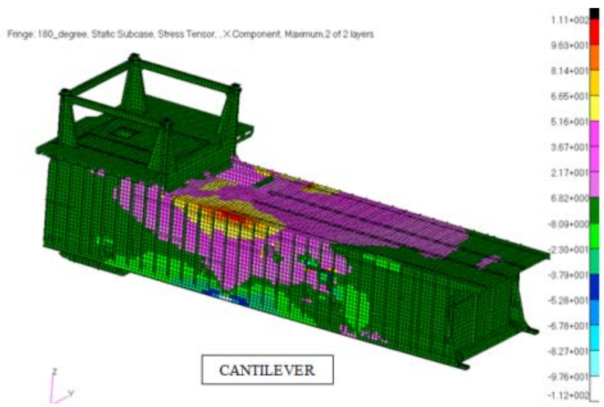


Fig. 9 X-directional stress distribution at cantilever (survival condition, heading angle : 180degrees)

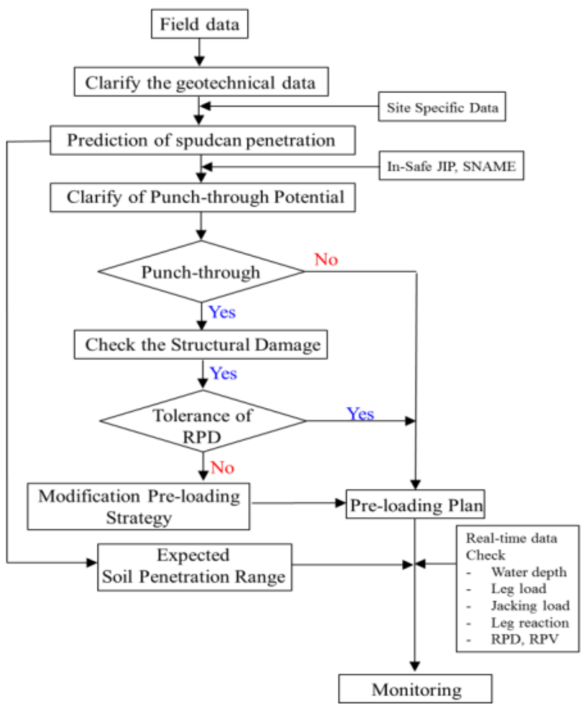


Fig. 10 Pre-loading and installation flow-chart

Table 2 The classified strata characteristics of the site survey [7]

Borehole number	Sedimentary layer		Weathered layer		Basement rock layer	Total
	Silt-clay layer	Sand-gravel layer	Weathered soil layer	Weathered rock layer	Soft rock layer	
BH-1	6.0	5.3	6.5	5.6	1.0	24.4
BH-2	5.1	4.7	3.7	3.0	-	16.5
BH-3	6.1	3.3	6.0	4.9	-	20.3
BH-4	8.5	1.9	2.6	3.0	-	16
BH-5	6.3	4.7	5.0	5.3	1.0	22.3
BH-5	5.8	3.0	6.5	1.5	1.5	18.3
Total	37.8	22.9	30.3	23.3	3.5	117.8

that it is highly increased engineering reliability as geotechnical stability point of view. Prior to jack-up rig installation, specifically for an independent leg jack-up drilling unit, rig foundation stability can be evaluated by analyzing site soil data and developing a curve of soil resistance versus spudcan penetrations. The purpose of the geotechnical site investigation for a rig movement is to collect the geotechnical ground conditions at the site, identify geotechnical units, asses the behaviour of the spudcan during penetration, estimate the total penetration under maximum vertical load and evaluate the possibility of a punch-through or rapid leg penetration condition. Table 2 indicates the detailed soil properties referred by soil investigation report.

The governing soil parameters applied in the formulas are unit weight, friction angle (for drained materials) and undrained shear strength (for undrained materials). If the pre-load is smaller than the strength of the soil where the punch-through starts, there is no problem. If not, then there is an actual risk for punch-through. Therefore, for every location that generated a punch-through profile, a corresponding safety factor is calcu-lated in order to identify the actual risk. This factor of safety (FOS) is defined as equation (1);

$$FOS = \frac{\text{Punch-through Peak [MN]}}{\text{Preload [MN]}} \qquad (1)$$

The threshold between risk and no risk was set at 1.5. If the FOS≤ 1.5, then there is an existing risk for punch-through. Even though there is a vertical ground profile configuration with significantly alternating stronger and weaker layers, in case of FOS≥1.5 there is no actual risk for punch- through. Since the high FOS value indicates that the stronger layer can withstand the applied maximum pre-load. As shown Fig. 11

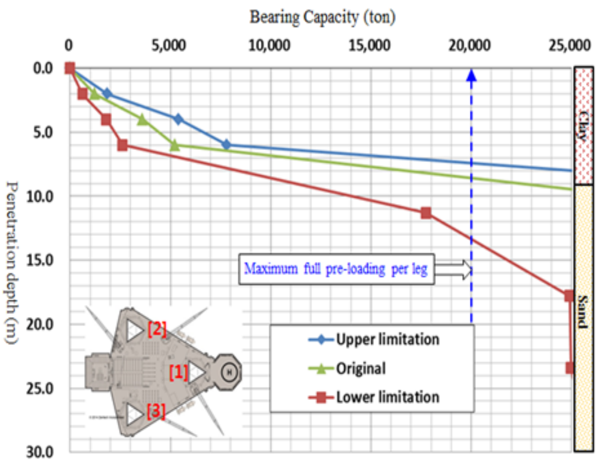


Fig. 11 Spudcan penetration curve of isolated leg

illustrates relationships of between soil bearing capacity and spudcan penetration depth according to the locations of leg. The bearing capacity of soil gradually increases within clay layer, and then rapidly changes to meet a sand layer. It means that these combinations of soil layer (clay to sand) are favorable condition to prevent big penetration risk of leg structure.

In this study, the maximum value to the bearing capacity was consistently fixed at 20,000 ton. This value is reasonable considering the governing pre-loads for the three legs that

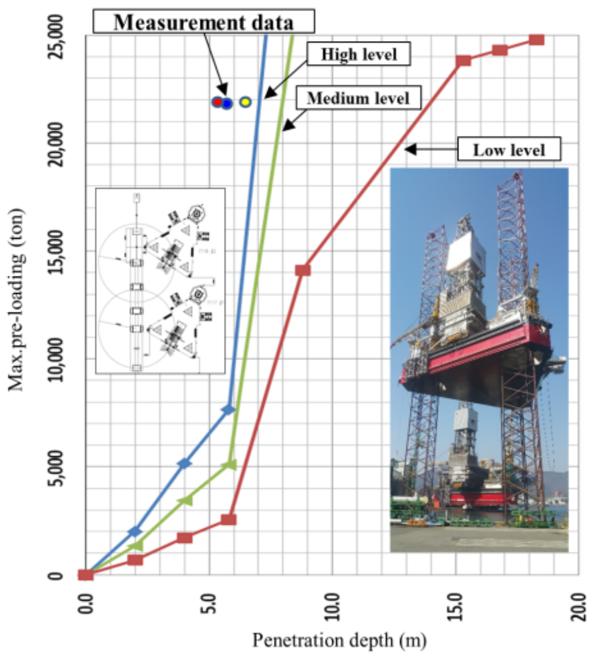


Fig. 12 A comparison of simplistic calculation with actual measurement during pre-loading

are analyzed. Based on results from bearing capacity curves, we already known that the possible punch-through peaks above 40,000 ton. Therefore, result in FOS>1.5 and thus can be considered as "safe".

It can be known that the actual measurement values show good agreement for maximum pre-loading and penetration depth with calculate high level conditions. From the comparative results, it can be confirmed possibility to apply the on-site installation engineering.

4. Conclusions

In order to achieve the novel jack-up rig design, this paper performed global in-place analysis of leg, hull & cantilever and pre-loading analysis to verify the structural safety during field operation as well as installation stage.

It has been demonstrated this paper that structural engineering & installation procedure can be established for jack-ups to enable optimized structure engineering, potential punch-through risk, reasonable pre-loading plan and actual monitoring activity. Combined with data typically available for operating jack-ups, such an integrated procedure is capable of providing the essential information at every step during installation. The results of this study can be expected to provide practical and useful data for performing the structural engineering as well as installation of jack-up rigs.

[1] The critical loading condition takes place at around 300 degrees under maximum base shear condition owing to big incensement of overturning moment.

[2] The MDOF method makes it possible to predict a DAF more accurately than SDOF and to make a reasonable leg design.

[3] From the strength assessment results, it is found that the yielding/buckling check ratios of critical area are lower than the allowable criteria.

[4] The present soil condition has a FOS bigger than factor of 1.5, there is no actual risk for punch- through.

[5] A new installation procedure of pre-loading was developed and reliability of the engineering was verified by com-parison with actual measurement.

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