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Technical note

A comparison of jacket and jack-up structural reliability

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Abstract

This paper presents the methodology and key findings of a study aimed at comparing the reliability of a representative jacket platform with that of a representative jack-up unit. Both structures were assumed to operate at the same location under identical environmental conditions (typical of the North Sea). Each structure was designed to the limits of their relevant recommended practice (API RP2A LRFD and SNAME T&R Bulletin 5-5A for the jacket and jack-up, respectively) to ensure a consistent comparison. This was followed by component and system reliability analyses using detailed modelling for both structures. Initially, the foundation failure was suppressed to enable the structure response to be compared and then, in the final stage of the study, detailed foundation modelling was included to examine the effect of foundation reliability on the overall structural reliability. For the specific site and environmental conditions considered in the study, it is concluded that the structures do not realise substantially different structural system reliability levels when designed/assessed to their most recent practices.

Keywords: Reliability; Jacket; Jack-up; Foundations; Pushover analysis; Redundancy; Reserve strength

1. Introduction

Jacket and jack-up structures are increasingly deployed to achieve the same functions, namely to exploit oil and gas reservoirs. In this mode, there may be limited

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justification in them being required to comply with differing safety frameworks (i.e. codes and standards) and exhibiting differences in safety levels. However, due to the historical development of the structural forms, they are designed or assessed to different standards. As a first step in establishing the relative safety level, the Health and Safety Executive (HSE) commissioned MSL Engineering (MSL) to undertake a comparative reliability study of a representative jacket platform and a representative jack-up structure.

The objective of the study was, therefore, to compare the reliability levels (under extreme storm loading) associated with fixed and jack-up structures operating in the same environmental conditions. For the two structural types under consideration, reliability levels were compared for operating at the same location with the structures designed to the limits of their relevant recommended practice. The study aimed to ensure that a consistent approach was applied to the two structural types, to permit direct comparison of notional reliability levels.

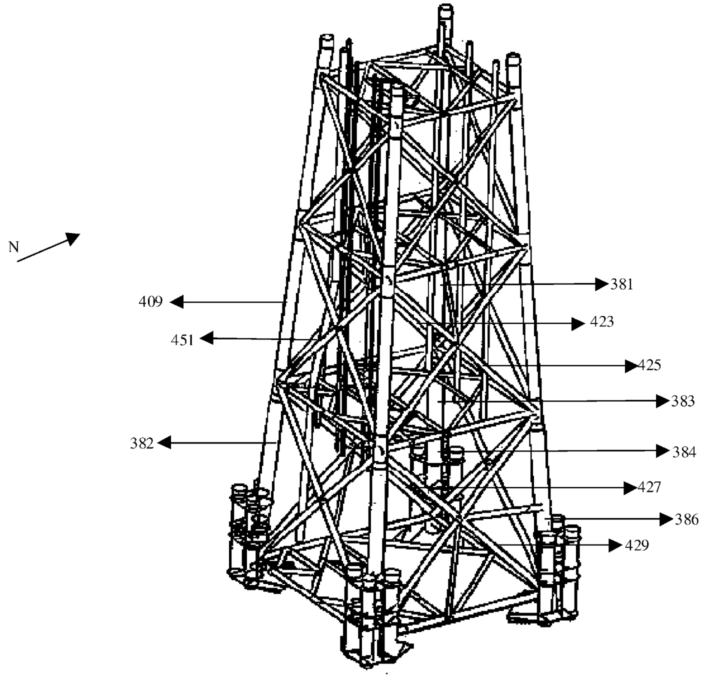
A late 1980s four leg jacket (similar to Shell's Kittiwake) and an independent self-elevating jack-up of three legs with four chords each (similar to LeTourneau's Gorilla) were chosen for study. These structures were re-sized to the limit of their respective codes for design and assessment, API RP2A LRFD [1] and SNAME T&R Bulletin 5-5A [2], respectively, to ensure a consistent comparison. This was followed by component and system reliability analyses using detailed modelling for both structures. Initially, foundation failure was suppressed to enable the structure response to be compared and in the final stage of the project detailed foundation modelling was included to study the effect of foundation reliability on the overall structural reliability. Every effort was made to ensure consistent, state-of-the-art modelling of both platforms. In pursuit of this objective, MSL Engineering Limited was advised by an Overview Group established by the HSE and consisting of leading representatives of the jacket and jack-up communities.

Results for when foundation failure was suppressed have been previously presented [3]. In this paper, attention is focussed on the reliability of the platforms including the effects of foundation behaviour. Further details of the study may be found in the project summary report which will shortly be available as an Offshore Technology Report [4].

2. Design of structures

The two structures were assumed to operate at the same location in the North Sea. The selected location is typical of the central North Sea being in 88 m of water.

The jacket is X-braced with horizontal perimeter plan members and grouted pile sleeve connections (see Fig. 1). It stands 108 m high on a 38 m × 38 m base and supports 16 conductors, six caissons, four J-tubes and two risers. It was designed to API RP2A [1] for the extreme 100-year wave with the associated current and 1-hour wind speeds given by joint probabilities. In seeking to realise a structure that is representative of North Sea designs without performing a full design cycle, a number of North Sea jacket designs were inspected and the governing load cases and member

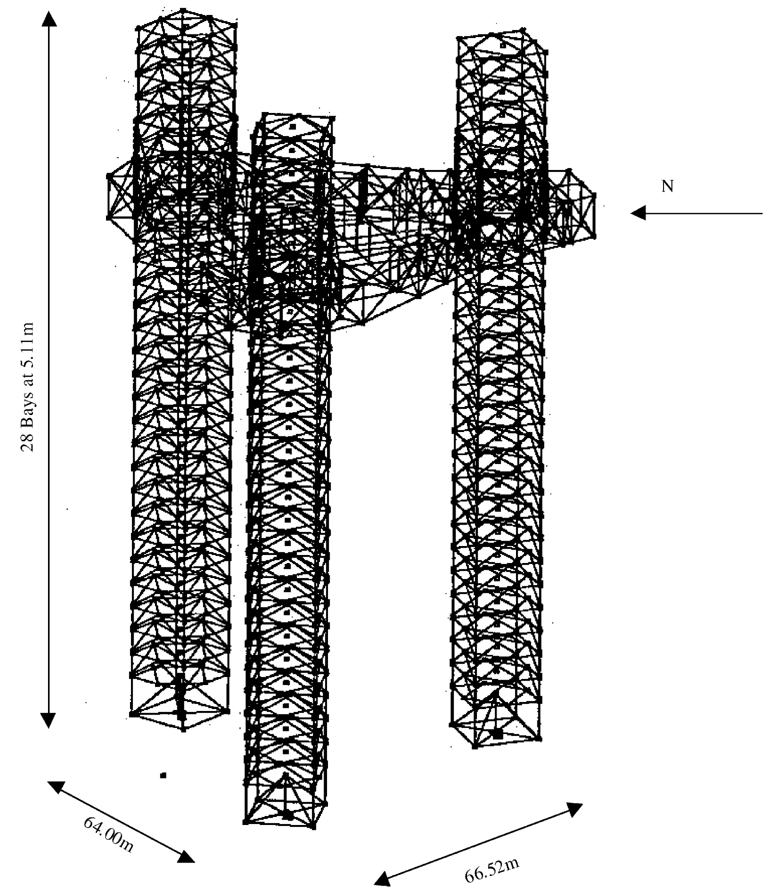


El. Number	Type	N	NW	W	SW	S
384	Leg	0.84	1.00	0.81	0.53	0.41
383	Leg	0.74	0.92	0.76	0.46	0.38
381	Leg	0.75	0.91	0.80	0.58	0.49
382	Leg	0.41	0.57	0.80	0.89	0.69
409	Leg	0.47	0.63	0.81	0.86	0.71
386	Leg	0.84	0.54	0.41	0.41	0.41
423	X-Brace	1.00	0.99	0.89	0.57	0.50
427	X-Brace	0.99	0.79	0.40	0.37	0.34
425	X-Brace	1.00	0.76	0.51	0.53	0.50
429	X-Brace	0.98	0.74	0.22	0.34	0.33
451	X-Brace	0.53	0.58	0.85	0.79	0.66

Fig. 1. Critical jacket members — utilisation for different wave directions.

utilisations were determined. This information was then used to achieve a similar distribution of utilisation ratios in the jacket design used in this study.

The jack-up is shown schematically in Fig. 2. Its overall length is 90.53 m, width 89.0 m and the hull depth is 9.14 m. The forward-aft leg spacing is 57.61 m and between port and starboard 64.0 m. The legs are 4 chord lattice type, 153.5 m long with spudcans of area 318.0 m^2. Leg rack chords are of the unopposed pinion type on a pitch point spacing of 14.02 m. The jack-up was assessed in accordance with the requirements of SNAME T&R Bulletin [2] for the independent 50-year extreme values of wave, current and 1-minute wind speed.



Legs 152.5m long with 4 chords of unopposed pinion type
Fixation by pinion and guides only
Conductor tension: 250000 lb

Fig. 2. Jack-up particulars and FE model.

The FE model shown in Fig. 2 incorporated detailed leg models while the main decks and bulkheads were modelled through a simplified representation. The contact problem arising from guide clearance and pinion backlash was modelled in detail including the use of gaps to model guide clearance and pinion backlash. Waves were stepped through the structure to obtain maximum forces. Utilisation ratios greater than unity were obtained which were overcome by increasing the yield stresses as appropriate.

The CAP/SeaStar Finite Element suite [5] was used to conduct the analyses of the structures, both for design and subsequent pushover analyses for input to the reliability model. The same FE suite was used throughout the study so that consistency of structural and hydrodynamic modelling was maximised in all stages, thereby reducing the potential for modelling-based inconsistencies.

3. Reliability methodology

3.1. General

Reliability analyses were generally conducted using a FORM procedure. This essentially calculates the probability of a certain function (the limit state function) being less than zero. In simple terms, the limit state function is the structural resistance minus the load, where the structural resistance and the load are based on pertinent probabilistic variables (eg. yield strength, wave height, etc). Further details may be found in [3]. It is sufficient here to summarise the probability density functions (pdf) and associated biases and COVs (see Table 1).

It should be noted that several wave directions were considered as both resistance and load are a function of wave attack angle, and in order that potential intermediate failure surfaces were not overlooked.

3.2. Foundation modelling

Whereas the jacket piles and jack-up spudcans were sized in design using the provisions of API RP2A and SNAME provisions, respectively, more accurate models for foundation behaviour including foundation failure were sought for the reliability analyses. The models adopted are based on the Imperial College (IC) method for jacket piled foundations [6] and on the Oxford method [7,8] for jack-up spudcan foundations.

3.2.1. Jacket pile foundation

The soil–structure response for piled foundations is usually modelled by uncoupled springs (*p–y*, *t–z*, *q–z* springs) which are empirically derived on the basis of soil test

Table 1
Summary of probabilistic modelling of uncertainties

Variable	Pdf	Bias	COV (%)
Significant wave height	Normal	1.00	10.0
Wave + current loading	Normal	1.00	15.0
Wind, dead and live loading	Normal	1.00	8.0
Inertial loadset	Normal	0.90	15.0
Column + bending failure of tubulars	Normal	1.036	9.9
Local + bending failure of tubulars	Normal	1.096	2.9
Rack chord failure	Normal	1.00	10.0
Pushover analysis	Normal	1.00	12.0
Yield strength	Log-normal	1.12	4.0

Table 2
Uncertainties in pile capacity prediction methods [6][a]

	Bias – API	COV – API (%)	Bias – IC	COV – IC (%)
65 Tests in sand, shaft capacity	1.16	65	1.03	30
42 Tests in sand, end bearing	1.30	80	1.00	20
55 Tests in clay, shaft capacity	1.02	34	0.99	18
31 Tests in clay, end bearing	0.94	98	1.18	30

[a] Bias defined as measured/calculated.

data. Whilst covering end bearing and cyclic effects, the IC method [6] has focussed on understanding the development of pile shaft friction in terms of effective shear stress in contrast to the semi-empirical total stress methods of API. Certainly, the IC method tends to give better predictions of pile axial capacity than API as shown in Table 2. The jacket piled foundation modelling is summarised below:

- A non-linear, quasi-static foundation model was used in both design and reliability analysis. It was assumed that increased strength due to rate effects offset cyclic soil strength degradation.
- Axial shaft capacity was evaluated, in design, using the method given in the API Commentary but evaluated, in reliability analysis, using the IC method.
- Lateral capacity: evaluated, in design and in reliability analysis, using the API method.
- Shape of the *p–y* and *q–z* curves: the curve shapes suggested by API were used in design and in reliability analysis. For lateral behaviour, the cyclic *p–y* curves were used.
- Shape of *t–z* curves: in design, no residuals were used in connection with the API commentary capacity predictions. In reliability analysis, residuals were used in connection with the IC capacity predictions where appropriate.
- Pile group action was modelled in design and reliability analysis by reducing the spring stiffness of the individual piles using appropriate factors.

3.2.2. Jack-up spudcan foundation

Jack-up spudcan foundation assessment, as recommended by the SNAME T&R Bulletin [2], is usually based on conventional shallow circular flat foundation concepts, with empirical corrections to account for the differences between conventional foundations and spudcans. Engineering judgement in interpreting soil properties also plays a major part in these assessments. In the present study, the jack-up foundation was designed on the basis of the revised SNAME practice (1997), which implemented a number of changes based on an extensive review of the theoretical, experimental and fields measurements [9], and according to the site specific environmental and geotechnical data.

The Oxford foundation model, which is based on recent research [7,8], was used for reliability analysis as it tends to give better predictions when compared to test results.

However, it was observed that in this case the SNAME and the Oxford failure surfaces do not differ substantially. The main points of the foundation modelling are summarised below:

- A non-linear, quasi-static hardening foundation model was used in both assessment (SNAME Practice — via an iterative procedure) and reliability analysis (Oxford model – explicitly). It was assumed that increased strength due to rate effects offset cyclic soil strength degradation.
- The shear modulus recommendations in the revised SNAME practice were used in both assessment and reliability analysis. The effect of uncertainty associated with these values was investigated during this study.
- Both bearing failure of the leeward leg and sliding failure of the windward leg were explicitly modelled in the pushover analysis used in the reliability estimates.
- In jack-up spudcan foundations, the variability of the soil properties tends to affect the penetration under preload and the foundation fixity but a smaller uncertainty is associated with the spudcan foundation failure surface as it is mostly dictated by the preload value which is known with little uncertainty.

For implementation in the CAP/SeaStar pushover analyses, spudcan–soil interaction incorporated an incremental plasticity model applicable to clay soils. The incremental plasticity model was approximated, within CAP/SeaStar, with the use of a beam–column element capable of modelling plastic hinges at its ends. The beam–column parameters were calibrated against independent analyses performed at Oxford University consisting of simplified 2-D models of the structure combined with the detailed incremental plasticity model. Two cases were considered for calibration:

- Case 1: Typical results published in the open literature [8].
- Case 2: Consisting of a separate 2D model with geometrical properties adjusted to match the pinned and fixed global (in terms of deck displacement) response of the 3D model of the sample jack-up used in the present study.

The calibrated beam–column elements were then introduced in the 3-D model of the jack-up used in the present study.

The main uncertainties are those related to the following parameters:

- The soil shear modulus which influences the stiffness of the spudcan–soil interaction
- The accuracy of the incremental plasticity model in predicting soil yielding and failure.

The effects of varying the soil shear modulus by $\pm 50\%$ were investigated. As far as the global response is concerned such large variations were found to have an impact on the first soil yield but only a limited influence (of the order of 3%) on the final failure load. Such a small variation in failure load did not justify the inclusion of the soil shear modulus in the response surfaces for system reliability.

A similar trend was observed in the local response. The effect of varying the shear modulus by 50% on the axial load of critical members was 1–10%, therefore, this parameter was not included in the response surface calibration for component reliability analysis. However, this variation was accounted for by a 3% modelling uncertainty factor associated with the member force calculations in the component reliability analysis.

The eccentricity parameters in the incremental plasticity model used may be associated with a COV of about 20% [8] while small uncertainty is associated with the other parameters in the equation. Overall the incremental plasticity model used is expected to predict soil yielding with a COV of 10%. As the validation of the behaviour of the incremental plasticity model after first yield has been based on a smaller number of test results, a larger COV of 13% was assumed for the modelling uncertainty associated with prediction of spudcan soil final failure in the system reliability analysis.

4. Results

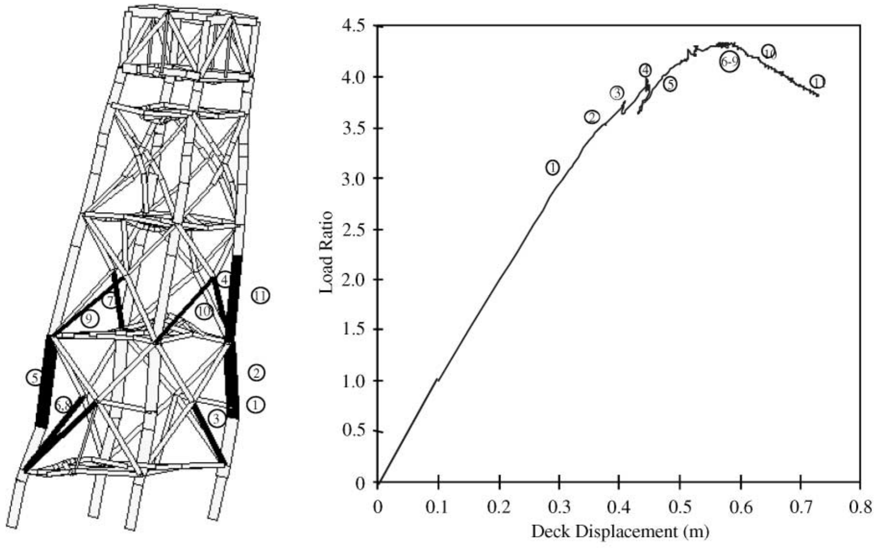
The results presented below are generally in terms of the safety index β and apply over the platform lifetime (taken as 20 years for both the jacket and the jack-up).

4.1. Jacket

Table 3 presents the β index values for critical components for the simple foundation model (piles fixed 12 m below mudline) and for the detailed foundation model (see Section 3.2 above). These results can be seen to be reasonably correlated to

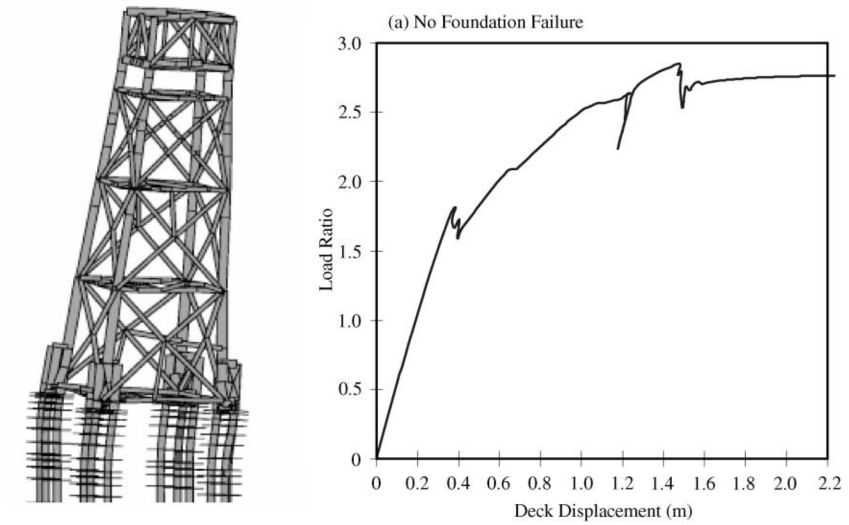
Table 3
Jacket component reliability (β index)

Element no. (see Fig. 1)	Simple foundation	Detailed foundation model	Critical wave direction
Legs			
384	3.85	3.78	NW
409	4.76	4.85	SW
382	4.50	4.23	SW
383	4.13	4.56	NW
381	4.42	4.81	NW
386	4.62	4.48	N
X-*braces*			
423	4.08	3.99	N
425	4.08	3.99	N
451	5.31	5.16	SW
427	3.88	5.52	N
429	3.88	5.52	N



Jacket Pushover - No Foundation Failure - Northwest

(a) No Foundation Failure



Jacket Pushover-with foundation Failure-Northwest

(b) With Foundation Failure

Fig. 3. Jacket pushover analysis (northwest direction).

the member utilisations presented in Fig. 1, although differences in the proportion of loading due to 'static' load in relation to wave loads lead to small relative differences in the structural reliability. It can also be seen that the component reliability of the majority of the critical members has shown little variation when the detailed foundation modelling is introduced.

Table 4
Summary of jacket system reliability results

	N — no found. fail.	NW — no found. fail.	N — with found. fail.	NW — with found. fail.
Safety index	4.46	5.63	1.53	2.13
Base shear (MN) *at design point*				
Wave/Current	41.78	40.72	23.90	22.50
Wind	3.85	3.85	3.85	3.85
Pushover	45.63	44.57	27.76	26.35
Wave height (m) *at design point*				
Significant	14.92	14.58	12.51	12.10
Extreme	27.57	26.94	23.11	22.36
Sensitivity factors				
Signif. wave height	0.32	0.23	0.10	0.06
Wave force calcs.	0.16	0.1	0.05	0.03
Wind + dead + live	0.01	0.01	0.01	0.01
Structural capacity	0.51	0.66	—	—
Pile capacity	—	—	0.84	0.87

When the detailed foundation modelling was introduced in the pushover analysis, it was found to dominate the capacity. Fig. 3 shows pushover results for the Northwest direction using the simple detailed foundation model. Detailed foundation modelling both reduces the collapse load and increases the deck deflection at collapse, compared to the simple model. Response surfaces were developed relating system strength to pile capacity. The system reliability results obtained are summarised in Table 4. The large impact of foundation failure is apparent in the results. The pile capacity dominates the results as can be seen in the sensitivity factors.

4.2. Jack-up

The critical jack-up members are shown in Fig. 4. Table 5 summarises the results of the component reliability analysis for the most critical members with and without the inclusion of foundation fixity. Cases with Safety Index greater than 6 lead to negligible failure probabilities. Inspection of Table 5 indicates the substantial beneficial effect of foundation fixity on component reliability. This effect is a consequence of the reduction in member forces due to fixity provided foundation failure does not occur. If foundation failure occurs, then the member forces tend towards those obtained for pinned foundations and the pinned component reliability values of Table 5 apply.

The results of the pushover analysis for the most critical direction (Northwest) are shown in Fig. 5 together with the results of the pinned case. These results indicate that foundation failure dominates system behaviour. Similar results were obtained for the North direction. The system reliability results obtained for the jack-up are given in

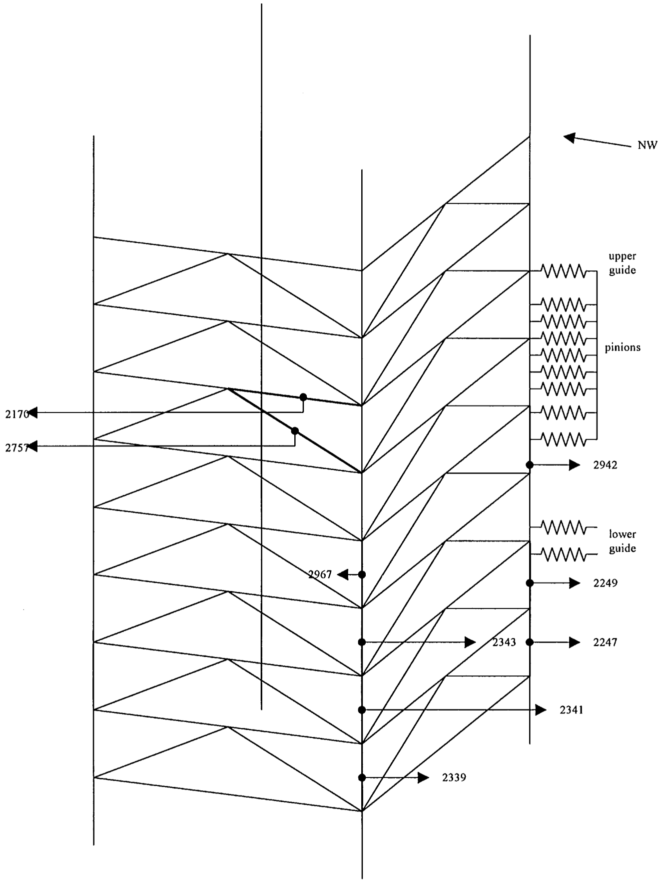


Fig. 4. Critical jack-up members (NW).

Table 6. The large impact of foundation failure is apparent in the results. The foundation capacity dominates the results as can be seen in the sensitivity factors.

4.3. Comparisons

The component and system lifetime (20 years) reliabilities, in terms of the β index and probability of failure (P_f), are summarised in Table 7. The overall safety margins were found to be much smaller for foundation design/assessment compared to structural design/ assessment. This is mainly associated with:

- The large modelling uncertainties involved in foundation capacity prediction when compared to structural capacity predications. This particularly applies to the jacket.

Table 5
Jack-up component reliability

Member	Pinned critical	Pinned N	Pinned NW	With fixity critical	With fixity N	With fixity NW
Braces						
2170	3.29	4.05	3.29	5.15	> 6	5.15
2757	3.41	5.24	3.41	4.46	> 6	4.46
Chords						
2247	4.33	> 6	4.33	4.45	> 6	4.45
2249	4.56	> 6	4.56	4.49	> 6	4.49
2942	3.66	> 6	3.66	4.49	> 6	4.49
1479	4.20	4.20	> 6	5.21	5.21	> 6
1481	4.11	4.11	> 6	5.18	5.18	> 6
1483	3.88	3.88	> 6	4.53	4.53	> 6
1485	4.18	4.18	> 6	4.98	4.98	> 6
2339	4.17	4.17	5.04	5.10	5.10	5.31
2341	3.89	3.89	4.66	4.49	4.49	5.11
2343	4.24	4.24	5.06	4.95	4.95	5.58
2918	3.85	3.85	> 6	5.24	5.24	> 6
2967	3.85	3.85	4.81	4.77	4.77	> 6

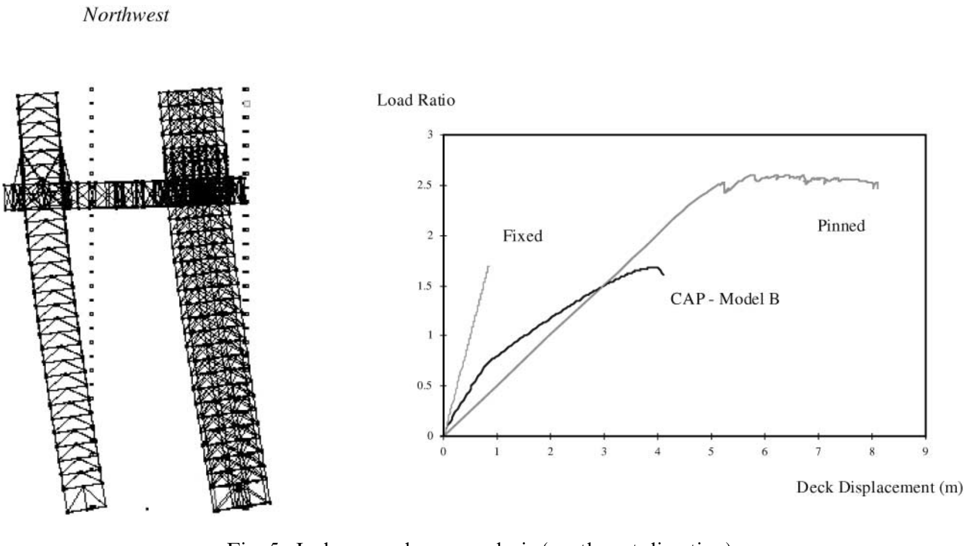


Fig. 5. Jack-up pushover analysis (northwest direction).

- The clayey soil type in this study led to a smaller predicted foundation capacity in the reliability analysis (IC method) when compared to the design (API).
- A substantial part of the pile capacity is mobilised to resist dead and variable loads. It follows that a reduction in pile capacity (as seen in the reliability design point)

Table 6
Summary of jack-up system reliability results

	N – no found. fail.	NW – no found. fail.	N – with found. fail.	NW – with found. fail.
Safety index	4.49	3.92	2.023	1.67
Base shear (MN) *at design point*				
Wave/current	37.89	34.82	26.67	24.15
Wind	4.71	4.71	4.78	4.66
Inertial loadset	5.63	5.63	5.70	5.41
Pushover	48.23	45.16	37.15	34.23
Wave height (m) *at design point*				
Significant	14.74	14.09	13.22	12.60
Extreme	27.25	26.04	24.44	23.28
Sensitivity factors				
Signif. wave height	0.29	0.33	0.31	0.32
Wave force calcs.	0.13	0.14	0.14	0.14
Wind + dead + live	0.01	0.01	0.01	0.01
Inertial loadset	0.01	0.01	0.01	0.01
Structural capacity	0.56	0.51	—	—
Foundation capacity	—	—	0.53	0.52

Table 7
Summary of reliability results

Quantity	Simplified foundation model		Detailed foundation model	
	Jacket	Jack-up	Jacket	Jack-up
Component β	3.85	3.29	3.78	4.45
System β	4.46	3.92	1.53	1.67
Component P_f	5.91×10^{-5}	5.01×10^{-4}	7.84×10^{-5}	4.29×10^{-6}
System P_f	4.10×10^{-6}	4.43×10^{-5}	6.30×10^{-2}	4.75×10^{-2}

will leave a smaller reserve for resisting the overturning moment due to the environmental loading.

It must be emphasised that the reliability values obtained suggest unduly high failure rates which requires further investigation as it may suggest that current prediction methods for foundation capacity are unduly conservative.

Similar foundation reliabilities were observed for the structures (minimum $\beta = 1.5$ and 1.7 for the jacket and jack-up, respectively). This is a consequence of the following effects:

- While the failure surfaces in SNAME for spudcan foundations agree reasonably closely with the Oxford model, in the case of piled foundations large discrepancies are observed between the API recommendations and the IC method.
- Jack-up foundation capacity is dictated by preload and less affected by natural soil variability, while jacket foundation utilisation is more affected by dead and live loads.
- The above factors, which are favourable to the jack-up, are balanced by the smaller bias implied partly by the smaller safety factors recommended in jack-up foundation assessment as compared to the jacket. The minimum load factors (on 20-year return period) at system failure were found to be 2.03 for the jacket and 1.5 for the jack-up.

5. Conclusions

On the basis of simplified foundation models the critical lifetime structural component reliabilities values were $\beta = 3.85$ for the jacket and $\beta = 3.29$ for the jack-up. The system reliability values were $\beta = 4.46$ for the jacket and $\beta = 3.92$ for the jack-up. However, if recent developments in jacket design are taken into account (reduced wave kinematics factor and location-dependent load factors) both platforms will tend to realise similar levels of structural system reliability. When detailed foundation modelling was included, both platforms showed a similar level of notional system reliability ($\beta = 1.53$ for the jacket and 1.67 for the jack-up). These latter values would appear to be conservative.

The jacket global structural behaviour was not greatly affected by the more refined foundation modelling from the point of view of ultimate strength. However, bending moments at joints tended to be more substantially affected — the implications for fatigue life prediction are expected to be important and deserve future investigation. The jack-up global structural behaviour was greatly affected by the more refined foundation modelling. If a unit has been found to be suitable for a particular location on the basis of a pinned assessment, the presence of foundation fixity may have a substantial effect in increasing structural reliability, provided it can be demonstrated to be present at high loading levels.

The results of this comparative study correspond to representative units and sensitivity studies are needed to determine to what extent this choice may affect the relative safety levels. Jack-ups with three-chord legs and split tubular chords may not have the same redundancy as the jack-up unit considered in the present study. Most older jackets are more redundant than the four-leg unit here considered, but many of them may not have joint cans in which case system failure may be dominated by joint failure. The results of the study are site specific and sensitivity studies are required to establish whether the conclusions are applicable to other regions. Other locations may show a larger variation of metocean data with return period — different return periods are used in jacket assessment as compared to jack-up assessment and the comparison of reliabilities could be affected. This suggests the need for a study to examine lifetime reliability based on a range of different water depths. The foundation reliabilities could be greatly affected by the soil type. In particular, the discrepancy between the Imperial College and the API predictions could work in favour of the jacket in other types of soil.

Both units tend to have a similar operational life and the same lifetime period was chosen for both units in the present study. However, jack-ups operate at the same location for a more limited period of time than jackets and tend to be inspected before being installed in a new location. The potentially more frequent inspection and repair procedures in the case of jack-ups can have a beneficial impact on the comparative reliabilities if the long-term effects of fatigue on system strength are taken into account.

The study has demonstrated, for the particular structures and location selected, that the platforms do not realise substantially different structural system reliability levels or foundation notional reliability levels when designed/assessed to their respective most recent practices [1,2].

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