EARTHQUAKE ASSESSMENTS OF JACK-UPS USING ISO 19905-1:2012 SCREENING PROCEDURES

Douglas J. Stock*
Digital Structures Inc.

John J. Stiff
Consultant

James N. Brekke
ABS

** corresponding author: dstock@digitalstructures.com*

ABSTRACT

Earthquake analyses are performed for a jack-up in different site conditions and seismic intensities. The analyses are conducted with equivalent jack-up models according to the ISO 19905-1:2012 screening procedures. Component force results are compared with storm load results to assess general performance demands. Sensitivity cases are included to better identify the source of earthquake loads. Recommendations are included to assist in the further development of the ISO standard, specifically spudcan mass definition, radiation damping modeling and additional study. A snapshot of jack-up rig site locations is used to identify the earthquake exposure of the worldwide jack-up fleet.

KEY WORDS: Jack-up; Seismic; Earthquake; ISO; Site-Specific Assessment; Benchmark; Sensitivity;

INTRODUCTION

This paper presents some of the results of analyses carried out by Digital Structures Inc. on the seismic screening assessment contained within ISO 19905-1:2012 [1], site-specific assessment of mobile jack-up units. The results presented supplement, and build upon, work that was carried out by Global Maritime [2] as part of a process to test the usability and reasonableness of the earthquake related clauses contained within ISO 19905-1.

BACKGROUND

ISO 19905-1 has its origins in the Society of Naval Architects and Marine Engineers Technical & Research Bulletin 5-5A [3], but the International Standard includes additional requirements and assessments that are not in 5-5A. This paper addresses one particular aspect of those new requirements, namely the assessments required of jack-ups operating in seismically active areas.

The normal expectation is that a site-specific assessment of a jack-up will be required on relatively short notice, so an attempt was made in the development of ISO 19905-1 to include a simplified seismic screening process. The purpose of this simplified assessment is to ascertain if a proposed unit would be suitable for operations at a site that is in a moderately seismically active area. The earthquake screening assessment uses a reduced seismic loading from that required for offshore facilities combined with an Ultimate Limit State (ULS) performance criteria and consequently is intended to be a conservative method (produce utilization results larger than expected from a more detailed, proper assessment).

Prior to the publication of ISO 19905-1 there was neither procedure nor written requirement for seismic assessment of jack-up units, however a few operators performed their own assessment studies at some, more severe seismic site locations. According to the general seismic criteria document ISO 19901-2:2004, earthquake assessments are required for structures situated in Zone 1 and above. In cases where earthquake loads are not significant and the storm loads are large, storm loadings often are more critical. In situations where storm loads are small or in high seismic areas, earthquake loads can be more severe. It is also possible that earthquake loads require higher demands on different components within a structure, than those designed by storm or other loads.

ISO 19901-2 requires offshore structures to be assessed to a $4x10^{-4}$ target probability of failure event (1/2,500 year event) to an Accidental/Abnormal Limit State (ALS). Since the analysis methods required to demonstrate this performance goal have higher uncertainties than those associated with normal "linear" ULS design conditions, the assessment earthquake is for an event of lower probability than a 2,500 year event.

JACK-UP LOCATION DATA

To supplement the original benchmarking analyses, Global Maritime workscope included obtaining jack-up rig locations for a point-in-time and determining the number of units that would need to be assessed for earthquakes, based on 19905-1. Reference [2] presents the results of that assessment for 26th September 2013, the rig location data being purchased from ODS-Petrodata. The results of the study have been reassessed and are included in this paper.

ODS-Petrodata supplied the locations of 535 jack-ups of which 424 were operational. The original hope had been that the data would include the latitude and longitude of all of the units, but unfortunately, in many cases, only a field name was supplied. In other cases (approximately 25%) only the country in which the unit was located was supplied.

The analysis results presented in [2] were intentionally a "worst case" scenario in order to get an upper bound on the number of units falling under the 19905-1 seismic assessment requirements. The jack-up location data had been subdivided into 15 geographic areas and in most cases there were a number of countries per area. The seismic zone for each of the jack-up locations was then determined based on:

- Available information on the jack-up location,
- 1-second horizontal spectral accelerations ($S_{a,map}(1,0)$) obtained from the maps in 19901-2 Annex B for the jack-up location[1], and
- The zone designation taken from Table 1 in 19901-2 (see Table 1 below).

A simple interpretation of the reference [2] results suggested that 30% of units were in Zone 0 (no seismic assessment required), 40% in Zone 1 (seismic assessment only required under certain circumstances[2]), and 30% in Zones 2 and above (seismic assessment required). In order to bound the likely number of jack-ups requiring an earthquake assessment, the location data was reassessed using a less conservative approach. As before, the reassessment was based on the 19901-2 Annex B maps, but the jack-up location was chosen based on likely drilling area rather than worst seismic zone.

Seismic Zone	0	1	2	3	4
$S_{a,map}(1.0)$	<0.03g	0.03g to 0.1g	0.11g to 0.25g	0.26g to 0.45g	>0.45g

Table 1 One Second Spectral Horizontal Accelerations for Zones given in ISO 19901-2:2004

[1] $S_{a,map}(1,0)$ is defined in ISO 19901-2 as "1 000 year rock outcrop spectral acceleration obtained from maps associated with a single degree of freedom oscillator period at 1 second" and can be used as one of the points in developing the seismic horizontal acceleration spectrum.

[2] ISO 19905-1, Clause 10.7 states:

"For seismic zone 1, an earthquake assessment should be considered when any of the following conditions apply:

- sites with the potential for cyclic mobility (e.g. liquefaction) (ISO 19901-2 site class F);
- sites with the potential for unacceptable additional leg penetrations if the preload reactions are exceeded (settlement limits can be reduced when operating adjacent to other structures);
- jack-ups where the ratio between the individual leg preload reaction at the seabed and the maximum still water operating reaction at the seabed is less than 1,25.

For most areas of the world the changes between the "worst case" assessment and the "likely" assessment were not large. In most cases, even when the 1 second spectral acceleration, $S_{a,map}(1,0)$, was reduced, the jack-up remained within the same seismic zone. This was not the case for the Arabian Gulf. Figure 1 is an extract from Annex B of 19901-2 showing the 1 second horizontal spectral accelerations, $S_{a,map}(1,0)$, for areas around the Arabian Gulf. It can be seen that on the east side of the Gulf, in Iran, the spectral acceleration is given as 0,3g, thereby putting the Iranian coast into seismic Zone 3. 100 miles to the west, at the northern end of the Gulf, the Saudi Arabian coast has a 1 second spectral acceleration of 0,02g putting that area into seismic Zone 0. However, when the jack-up rig locations were plotted, they were mainly operating out in the middle of the Gulf, half way between Saudi Arabia and Iran. Should they be categorized, therefore, as being in Zone 0, Zone 3, or somewhere in between? The assessment results presented in [2] put all the units into Zone 3 (25 of the 26 offshore Iran, 7 of the 12 offshore Qatar, and 30 of the 44 offshore Saudi Arabia – a total of 62 jack-ups in Zone 3). A probable likely compromise would be to put all the units into Zone 2, but for the current assessment it was decided that the seismic zone of a jack-up would be deemed to be that associated with the closest coastline of the country in which it was stated to be operating. Hence, the units operating in Iran were deemed to be in Zone 3, those operating in Saudi Arabia were deemed to be in Zone 0, and those operating in Qatar were deemed to be in Zone 1.

There are plans to revise the 19901-2 Annex B maps, and it is hoped that the new maps will include not just variation in spectral accelerations along the coast, but also perpendicular to the coast. This will allow a much better interpretation of the site specific seismic zone.

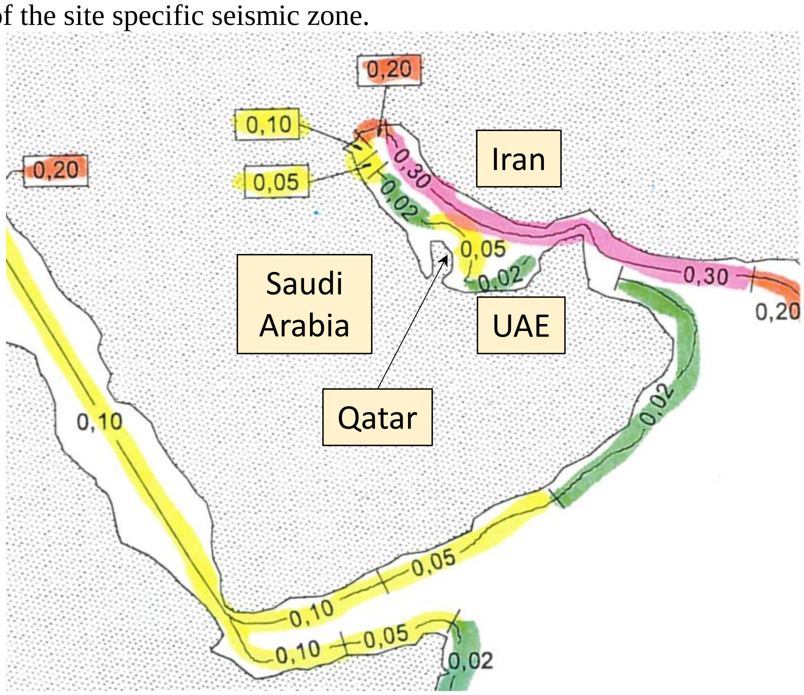


Figure 1 The 1.0 Second oscillator period accelerations for Arabian Gulf and Surrounding Area

While the Arabian Gulf was the most difficult to classify, there were some other areas that needed careful interpretation:

- The data for China tended to be classified as "Bohai Gulf" or "China", when no specific location data was supplied. It was assumed that any jack-up that was NOT specified as being in Bohai Gulf was operating in some other area offshore China. Bohai Gulf is in Zone 2; most of the rest of China is Zone 1.
- There were no jack-ups reported to be operating offshore New Zealand, a relatively seismically active area, much of it in Zone 3.

- The Adriatic is a narrow sea with the Italian coast in Zone 1 and the Croatian coast in Zone 2. As with the Arabian Gulf, the jack-ups were classified as being in the zone of the closest coast of the country in which they were operating.
- Jack-ups in the Mediterranean Sea offshore Egypt were assumed to be in Zone 1 rather than Zone 2. Most of the units appeared to be off the Nile delta (Zone 1) rather than further east in Zone 2.
- One jack-up in South America was operating the Bay of Guayaquil which is classified as Zone 4.
- There were no jack-ups operating off Tierra del Fuego, much of which is Zone 2. This is an occasional area for jack-up operations.
- There were two jack-ups in Cook Inlet, Alaska which is Zone 3.
- One Indonesian location at the west end of New Guinea off Salawati Island was put into Zone 4. The Annex B 19901-2 maps are ambiguous in this area, but a review of an Indonesian seismic hazard document [5] strongly suggested a Zone 4 rather than Zone 3 designation.
- Jack-ups offshore Indonesia that had no location designation were assigned to active drilling areas proportionately to the number of areas. The result was that 7 of the 8 rigs were put in Zone 2 and one in Zone 3.

The results of the assessment of jack-up location data are presented in tabular form in Table 2 and Table 3. They are also presented graphically in Figure 2 and Figure 3. Table 2 and Figure 2 present the results INCLUDING the jack-ups operating in the Arabian Gulf. Table 3 and Figure 3 present the results EXCLUDING jack-ups operating in the Arabian Gulf.

	Site Seismic Zones from 19901-2					
Region	0	1	2	3	4	Total per Region
Australia		3				3
Baltic	2					2
Caspian Sea	1		2			3
Central America				3		3
Far East		13	15			28
India		33				33
Black Sea		12	5			17
Mexico GoM		39				39
Middle East	46	34	13	25		118
Northwest Europe	34	8				42
South America	6				1	7
Southest Asia	33	16	17	1	1	68
Alaska				2		2
USA GoM	35					35
West Africa	10	14				24
Totals	167	172	52	31	2	424

Table 2 Number of Jack-ups in each Seismic Zone by Region INCLUDING Arabian Gulf

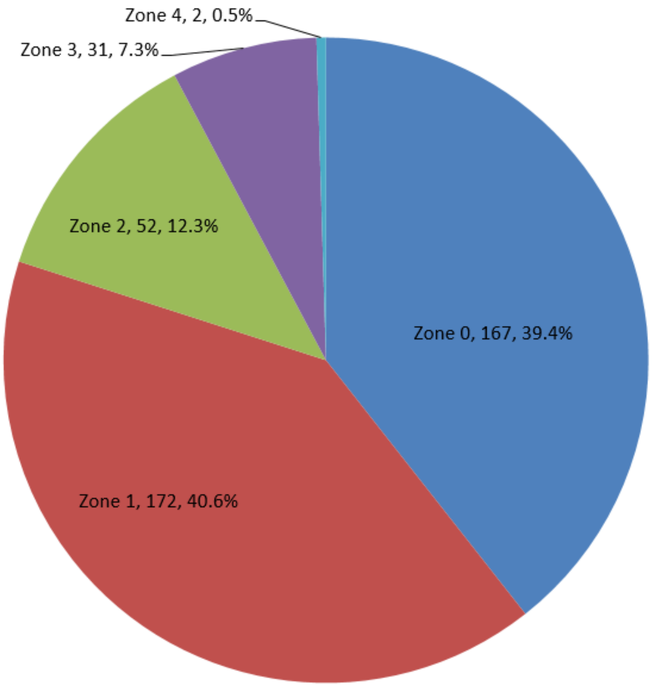


Figure 2 Number of Jack-ups in each Seismic Zone by Region INCLUDING Arabian Gulf

	Site Seismic Zones from 19901-2					
Region	0	1	2	3	4	Total per Region
Australia		3				3
Baltic	2					2
Caspian Sea	1		2			3
Central America				3		3
Far East		13	15			28
India		33				33
Black Sea		12	5			17
Mexico GoM		39				39
Middle East						0
Northwest Europe	34	8				42
South America	6				1	7
Southest Asia	33	16	17	1	1	68
Alaska				2		2
USA GoM	35					35
West Africa	10	14				24
Totals	121	138	39	6	2	306

Table 3 Number of Jack-ups in each Seismic Zone by Region EXCLUDING Arabian Gulf

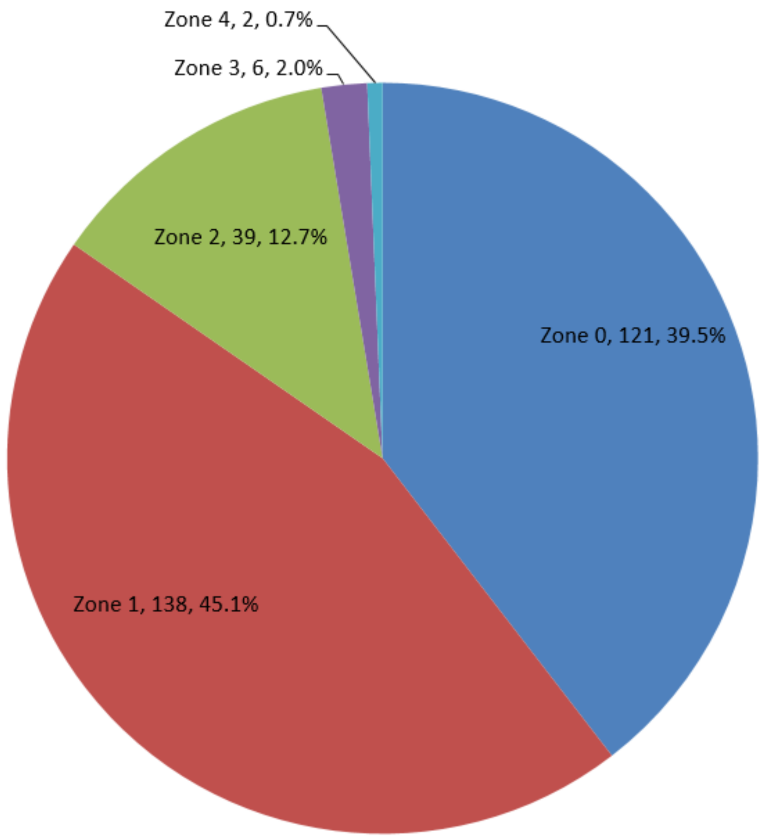


Figure 3 Number of Jack-ups in each Seismic Zone by Region EXCLUDING Arabian Gulf

19905-1 states that jack-ups operating in Zone 2 and above shall be assessed for earthquakes. In addition, some Zone 1 jack-ups shall be assessed. The reassessment of the jack-up location data has reduced the number of jack-ups located in Zones 2 or above from the original assessment [2]. However, even when the jack-ups in the Arabian Gulf are excluded, over 15% of jack-ups (47 units) of the dataset studied were found to be operating in Zones 2 and above. These 47 units would require some level of earthquake assessment. Including the Arabian Gulf increases this to 83 jack-ups or 20% of the world operational fleet. In addition, there are between 40% and 45% of the fleet operating in Zone 1: Zone 1 jack-ups can be required to have earthquake assessments depending on certain operating parameters. Jack-ups operating in relatively benign areas are the most likely to fall into this Zone 1 requirement category, although any Zone 1 punchthrough area is also subject to assessment.

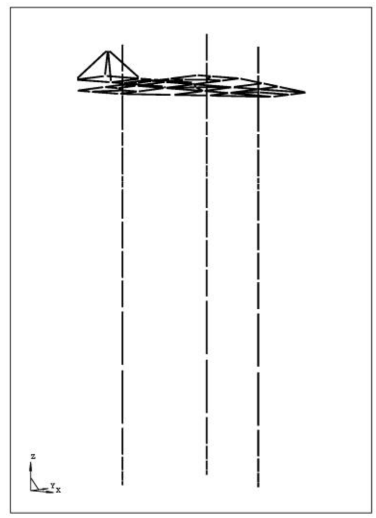
JACK-UP SEISMIC ANALYSES

The ISO 19905-1 standard is currently the only jack-up site assessment document that contains a provision for earthquake site assessment for locations where the seismic environment is Zone 2 or above (one second rock spectral acceleration, $S_{a,map}(1,0)$, greater than 0.11 g's) or within Zone 1 for special site/operating conditions. The screening assessment method can be used to avoid performing a more detailed Accidental/Abnormal Limit State (ALS) assessment as required by ISO 19901-2 for an earthquake that has a target annual probability of failure of at 4×10^{-4} (requires assessment to an event in excess of 2,500 years, typically a 3,500 to 5,000 year event).

The ISO 19905-1 screening process states that the response spectrum method should be used for a 1,000 year earthquake assessed with a ULS criterion. The response spectrum method is a modal combination method that essentially defines different phases for each dynamic vibration mode to develop the maximum dynamic response in all components. The modal combination is applied at the component level (global base shear, vertical spudcan reaction, chord axial load, chord bending moment, chock load, etc), which means that the modal phases for each component are possibly different and are unlikely to be consistent with any static loading condition. For a complicated structural system it is impossible to construct a static loading pattern that places similar demands to those developed from a response spectrum analysis on all components. The component responses from a response spectrum analysis have no signs and are uncorrelated, so the assessor must decide on the signs when combining response spectrum results with other loading conditions (e.g. dead load) needed to assess performance (ULS criteria).

This paper presents analytical results for a set of earthquake screening assessments of a jack-up in three different site conditions for two different seismic intensities (bottom and top of seismic Zone 2). The analytical model used is an equivalent stick model for a "nominal" jackup created for the earlier benchmarking work [2]. For a screening assessment using the response spectrum method, an equivalent model is not ideal in that it contains insufficient detail to estimate sub-component responses within the "equivalent" modeling. It is possible to take equivalent model forces with all sign permutations and superimpose them on top of dead load forces to a detailed sub-model to develop internal component responses. That effort and computational demand exceed the effort required to perform a response spectrum analysis on a detailed model. In addition the equivalent/sub-model results would be larger and more conservative. Consequently, the earthquake results from these equivalent model analyses will be compared to component forces from storm loads. From a practical standpoint, this model enables evaluation of general rig demands including the foundation but does not permit evaluation of structural member responses (e.g., chocks, chords, braces, etc.) and the analytical study costs are lower.

Figure 4 Equivalent Jack-up Model - Case 2

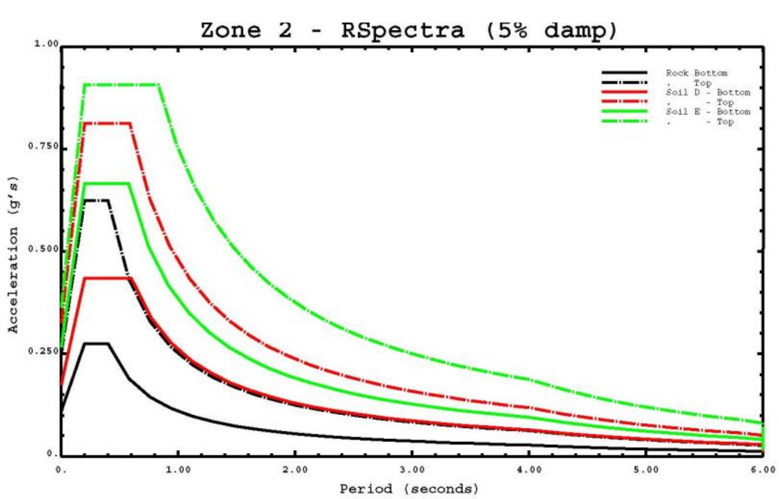


JACK-UP ASSESSED

The equivalent jack-up model properties used for these analyses, as developed for an earlier study [2], were selected as a middle property from several real rigs. The properties as used for this analytical work are summarized in Table 4. Qualitatively the rig might be considered to be a bit heavy for the leg/spudcan properties, but it still represents a rational analytical model that is reasonable for this study work. The cantilever/drill package was modeled in a possible operational condition that was skidded aft and not translationally (symmetric about the global X axis, bow-stern). The analytical model for the 100m deepwater Case 2 is shown in Figure 4.

ISO 19905-1 does not specifically indicate that P-delta large displacement effects are to be included in an earthquake screening assessment. It also does not specifically indicate it should not be included. Including P-delta effects acts to soften the system's stiffness, thereby increasing overturning and obviously dynamic amplification for a storm excitation. For earthquake excitation, the stiffness softening again increases the structural period but then reduces the spectral amplitude as the fundamental period is often well beyond the constant acceleration plateau (see Figure 5). ISO 19905-1 should be revised to indicate that P-delta effects should be included in all assessment models irrespective of the analysis being performed. For this study they have been included with a large displacement element formulation that more

Figure 5 ISO 19901-2 1,000 Year Response Spectra



properly captures the local leg stiffness reduction associated with the dead loading condition.

Clearly the spudcan mass includes the steel mass and any entrapped fluids or ballast. ISO 10095-1 indicates for seismic analysis added mass should be considered for the spudcan. Unfortunately no specific guidance is given on how much added mass should be assumed. For the previous analytical study [2] it was assumed that each spudcan's added mass was equivalent to about 1,000 tonnes, or about twice its water volume (see Table 4). This was chosen to represent the mass of soil displaced by the spudcan. For the shallow penetrations of only 3 meters it seems more reasonable to assume about half that amount representing the surrounding water at around 500 tonnes.

The hull and the hull-leg connection (chocked) stiffnesses affect the global vibration modes in addition to the more local leg modes for the leg above and below the hull. Overall the equivalent model seems to be reasonable for this analytical study.

Table 4 Equivalent Model Properties

Leg length	150 m
Longitudinal leg spacing	40 m
Transverse leg spacing	46.19 m
Depth of hull	8 m
Airgap (all cases)	20m
Spudcan effective diameter	14 m
Preload capacity at level of the hull	98.1 MN
Total elevated mass	13,300 tonnes
Single leg dry mass	861 tonnes
Mass of each spudcan	330 tonnes
Mass of water within each spudcan	513 tonnes
Added mass each spudcan from earlier work [2]	1,000 tonnes
Total mass	21,400 tonnes
Storm Case Conditions	
Water Depth	100 m
Wind Speed	40 m/sec
Wave height	22 m
Current	0.75 m/sec
50 year storm Base Shear (approximate)	13 MN
50 year storm Overturning Moment (approximate)	1,700 MNm

EARTHQUAKE SPECTRA

Using the ISO 19901-2:2004 [4] simplified action procedure and the worldwide seismic intensity maps contained in its Annex B, it is possible to quickly develop a site response spectra for the 1,000 year earthquake including the effects of site soil characterization. This general seismic criterion standard is applicable to all offshore structural types (fixed steel, concrete, jack-ups, etc.) and has worldwide maps of spectral intensities for most of the offshore areas. Two maps exist for each region, one for rock spectral accelerations at 0.2 seconds ($S_{a,map}(0,2)$) and the other at 1.0 seconds ($S_{a,map}(1,0)$), with the latter value used for determining the seismic zone from Table 1. Given a site location on the maps, the rock anchor points can be obtained and, with the soil site type as identified in ISO 19901-2 Table 5, it is possible to develop 1,000 site response spectra that include soil amplification.

<table>
<tr><th colspan="5">Table 5 Site Cases and Seismic Zones</th></tr>
<tr><td>Seismic Case Properties</td><td>Case 1</td><td colspan="2">Case 2</td><td>Case 3</td></tr>
<tr><td>Water Depth (m)</td><td>40</td><td colspan="2">100</td><td>40</td></tr>
<tr><td>Soil/Spudcan Case-specific data</td><td colspan="3"></td><td></td></tr>
<tr><td>Soil type</td><td colspan="3">Sand</td><td>Clay</td></tr>
<tr><td>Site characterization</td><td colspan="3">D</td><td>E</td></tr>
<tr><td>Penetration (m)</td><td colspan="3">3</td><td>15</td></tr>
<tr><td>G, shear modulus (MN/m3)</td><td colspan="3">150</td><td>50</td></tr>
<tr><td>Mass density (kg/m3)</td><td colspan="3">2000</td><td>1750</td></tr>
<tr><td>Poisson’s ratio</td><td colspan="3">0.35</td><td>0.45</td></tr>
<tr><td>Vertical stiffness (MN/m)</td><td colspan="3">1,979</td><td>2,173</td></tr>
<tr><td>Horizontal stiffness (MN/m)</td><td colspan="3">1,593</td><td>1,547</td></tr>
<tr><td>Rotational stiffness (MN-m/rad)</td><td colspan="3">64,650</td><td>70,980</td></tr>
<tr><td colspan="5"></td></tr>
<tr><td>Zone 2 Response Spectra Anchor Point Accelerations</td><td colspan="2">$S_{a,map}$(0,2)</td><td colspan="2">$S_{a,map}$(1,0)</td></tr>
<tr><td>Bottom intensity (g’s)</td><td colspan="2">0.275</td><td colspan="2">0.110</td></tr>
<tr><td>Top intensity (g’s)</td><td colspan="2">0.625</td><td colspan="2">0.250</td></tr>
<tr><td>19901-2 Soil type site amplification</td><td colspan="2">D</td><td colspan="2">E</td></tr>
<tr><td>C_a – low periods</td><td colspan="2">1.3</td><td colspan="2">1.45</td></tr>
<tr><td>C_v – high periods</td><td colspan="2">1.9</td><td colspan="2">3.00</td></tr>
</table>

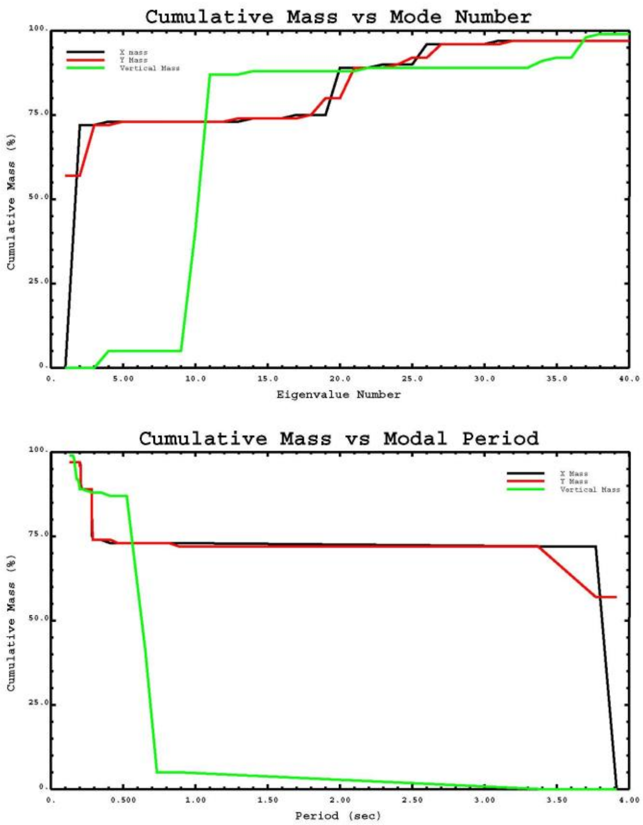
For this assessment study two different earthquake intensities are chosen one at the bottom of Zone 2 and the other at the top (see Table 1). The associated spectral acceleration anchor points at 0.2 seconds and 1.0 seconds ($S_{a,map}$(1,0)) as indicated in Table 5 are used to develop a 1,000 year rock acceleration spectra (site class A/B) as shown in Figure 5. Soil site amplification coefficients for the assumed soil site classes D (Cases 1 and 2, sand) and E (Case 3, clay) are also presented in Table 5 and the resulting 5% damped spectra are shown compared to the rock spectra in Figure 5. The C_a and C_v amplifications for stiffer soil site class C generally have smaller amplification values for the lower seismic zones (perhaps higher amplification for higher zones). The vertical spectra for the two different soil sites are 50% of the horizontal spectra. These soil response spectra in combination with the three model dynamic model eigensolutions are used to perform the response spectrum analyses as required for 19905-1 screening assessments.

EIGENSOLUTION

For the traditional wave loading jack-up assessment study, the first translational vibration modes are used to develop dynamic amplification. These modes are generally the only ones that participate in wave excitation as being the largest periods, they are still smaller than the primary wave excitation period, and considerably below the peak wave period. The other modes, which are vertical and local vibration modes, are generally much lower in period (higher frequency) and generally do not respond dynamically during a storm excitation. The first translational modes are in the range from 2 to 8 seconds. The vertical and local vibration modes are normally below a one second period.

For seismic excitation as shown in Figure 5, the excitation amplitudes (spectral acceleration) are much larger at lower periods and consequently higher mode vibrations can be excited more. For each case evaluated, 60 mode Eigensolutions were computed (see Table 6) and were used to determine seismic demands on the components within the equivalent models. Obviously the number of modes required is directly attributable to the model detail and the effort incorporated in the dynamic model creation.

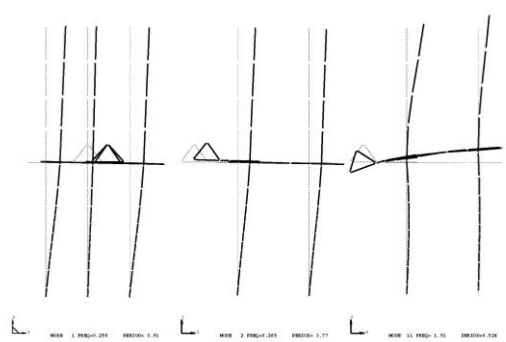
Figure 6 Case 1 - Eigensolution Cumulative Mass by Mode



Using the original model received from the prior work [2], Table 6 presents results for mode shapes, structural periods and percentage mass values for the analytical models with 1,000 tonne spudcan added mass. About 70% of the translational mass is represented in the first three modes: surge, sway and torsion with torsion coupled to the port/starboard sway motion (16% of global Y mass) as can be seen in the cumulative mass plots of Figure 6 for the Case 1 model. These graphs clearly demonstrate the mass contributions from the different modes for each translational direction. The translational mass is well represented by the first three modes (3.5 to 4 second periods) to about 73% of the total mass. Further significant jumps in cumulative mass occur around modes 20 (period 0.3 seconds) and 26 (period 0.2 seconds). About 81% of the vertical mass is contained in modes 10 and 11 at a period of about 0.6 seconds.

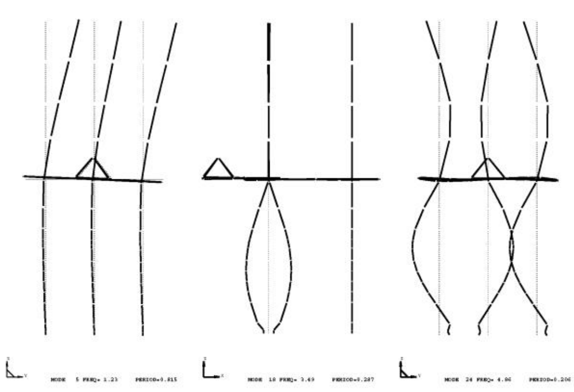
The left two images of Figure 7 show the Case 1 first two primary modes: sway mode one looking bow-on from X axis and surge mode two from the Y direction (transverse). The vertical modes are typically split into two to four modes, which collectively represent about 80% of the vertical mass (see right image of Figure 7, observe upward deformation, including at the spudcans).

Figure 7 Case 1 - Principal Mode Shapes



The leg modes above the hull become less important with less stick-up above the hull and do not generally contribute much to the overall percentage mass due primarily to their small relative mass. Since there are three legs and two translation directions (two directions for each cantilever leg to displace) there are always six of these modes. If the hull leg connection were infinitely rigid and the leg stiffnesses symmetric, one would expect all frequencies to be identical and represented with a variety of mode shape sets: six one leg deformation shapes (3-X translation and 3 Y translations, three each at 45 and 135 degrees etc). Completely equivalent to two legs independently moving in one direction would be symmetric and asymmetric deformations of the same two 2 legs (both inward and both in the same direction). Symmetric leg translation modes cancel to produce zero cumulative mass, however still develop forces similar to independent modes. Asymmetric modes develop twice the mass of a single leg mode.

Figure 8 Case 1 - Upper and Lower Leg Mode Shapes



The left image of Figure 8 shows all three upper legs moving in the sway direction (asymmetric mode) for one of the six modes of Case 1 (40m, sand), which has the largest length of leg above the hull. Since the hull framing and hull-leg connections are flexible, the bottom of these upper legs are not fixed and their vibration periods are not all exactly identical but there are still six modes that represent their dynamic behavior and they have similar frequencies and shapes. Due to the symmetry about the model global X axis (bow/stern) frequencies the port and starboard leg frequencies and shapes should be identical. The bow leg should be slightly different. Depending on the length of the legs above the hull, these modes can contribute to hull-leg connection forces, particularly for Cases 1 and 3 where the vibration periods are in excess of one half second. For the deep water Case 2 the vibration period for these modes are about 0.1 seconds and probably contribute very little to the hull-leg connection forces.

The leg dynamics below the hull is generally more important and similarly there are two sets of six modes that contribute around 20% to the cumulative translational mass as indicated in Table 6. For study expediency, the leg-below-the hull modal interpretations given in Table 6 are qualitative based on observed shapes, which is certainly suitable given the unknowns in the analytical model. With a more clearly defined analytical model, the actual modes can be more accurately identified and categorized. For these models [2], the 1st mode set is bowing of each leg with relatively small spudcan translation (see middle image of Figure 8, which shows a symmetric deformation of the aft legs). The 2nd mode set is almost a 2nd flexural mode with the rotation node just above the spudcan that includes spudcan translation (see right image of Figure 8, which shows asymmetric deformation of the aft legs and the bow leg being symmetric with the stern leg and asymmetric with the port leg). The upper legs also participate in this mode. The shape distortion at the very bottom of the model is undoubtedly a consequence of how the spudcan mass was uniformly distributed to the bottom 5m of each leg and the concentrated soil stiffness springs attached 1.5m above the bottom indicating that the results are sensitive to this modeling assumption. The vibration periods for the 1st set of these lower leg modes are controlled by the leg length below the hull and the spudcan stiffness and are over 0.5 seconds for the deep water Case 2 to around 0.35 seconds for the shallower water cases. The 2nd sets are all below 0.3 seconds.

Table 6 Model Eigensolution Periods (seconds)

Mode Description	**Case 1**			**Case 2**			**Case 3**		
	Period(s)	#EV	%m	Period(s)	#EV	%m	Period(s)	#EV	%m
Sway – global Y – port/starboard	3.91	1	57	7.46	1	53	4.49	1	55
Surge – global X – bow/stern	3.77	2	72	7.14	2	70	4.31	2	72
Yaw – torsion	3.37	3	15Y	6.39	3	17Y	3.86	3	16Y
Vertical – global Z	0.65-0.52	10-11	81	0.87-0.66	4-5	78	0.81-0.50	4-11	85
Leg above hull	0.88-0.73	4-9	0	0.10	49+	0	0.66-0.50	5-11	0
1st Leg below hull	0.28	16-21	15	0.64-0.53	6-11	3	0.34-0.41	14-20	11
2nd Leg below hull	0.20	22-27	7	0.27	16-21	15	0.22	22-27	13
Percentage mass (%)	**X**	**Y**	**Z**	**X**	**Y**	**Z**	**X**	**Y**	**Z**
10 modes	73	73	41	72	74	79	73	73	67
20 modes	89	80	88	90	80	83	84	84	86
40 modes	87	97	99	98	98	99	97	98	99
60 modes	99	99	99	99	99	99	99	99	99

SPUDCAN ADDED MASS

ISO 19905-1 states "For earthquake assessments, the spudcan internal entrapped mass should be included in the mass model and the spudcan added mass (surrounding water and/or soil) should be included where significant." The wording associated with added mass modeling is unfortunately not specific. For the original model used for this work [2], the added mass was assumed to be 1,000 tonnes per spudcan, which is roughly twice the mass associated with the entrapped water (see Table 4). Given the value selected, three model permutations are defined for this added mass quantity: 100% - suggesting an additional volume of soil acting with the spudcan; 50% - about an equal volume of water; and 0% (zero) added mass. The simple conclusion from results presented subsequently is that the modeling assumption of added mass is significant. The implication is that the 19905-1 wording should be: "added mass should be included"; but the value to be used has not yet been identified. It is hoped that some pending work on jack-up soil structure interaction (SSI) will help resolve this outstanding action item.

For the Case 3 model (not dissimilar to Case 1 shown earlier), eigensolution results for the 2nd set of lower leg modes shapes for Mode 26 are shown in Figure 9 for different added mass assumptions and distributions. This mode is in the same 2nd set of lower leg modes to Case 1 right image in Figure 8. As opposed to the Case 1 24th mode shape shown in Figure 8, this shape is asymmetric within the lower legs with all three legs bowing toward the bow, the spudcans translating toward the stern and the legs above the hull not participating. The middle image is the same distributed spudcan mass, but zero added mass and the final image is with 100% of the added mass (1,000 tonnes) but the complete spudcan mass is lumped at the soil spring node 1.5m from the bottom of the leg. Table 7 presents the eigensolution variability for the different modeling conditions, which is quite significant. Even without any added mass assumption (condition B), this mode still represents a significant 7% of the cumulative system mass and increases to 20% with 1,000 tonne added mass, lumped at the soil spring node. It is also interesting that condition A has a larger vibration period than condition C where the spudcan mass is lumped at the soil spring. It is difficult to believe the spudcan bending deformation in either the distributed mass conditions A or B and certainly one would need to do more detailed study before accepting them as realistic. With limited knowledge, the condition C is a more reasonable shape.

Figure 8 Case 3 Lower Leg Mode Shape 2nd Set Variability

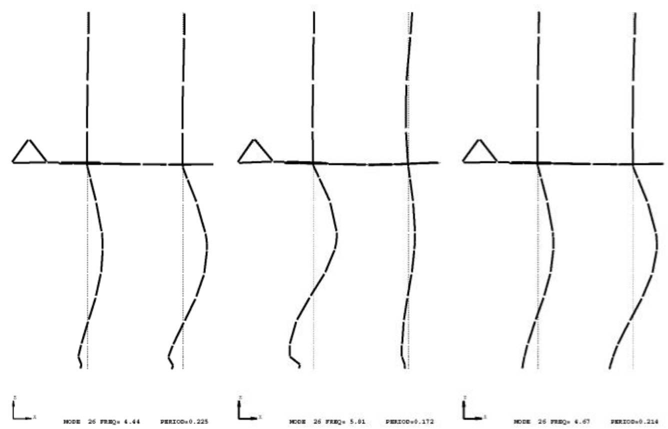


Table 7 Case 3 26th Mode Spudcan Mass Sensitivity			
Model permutation condition	**A**	**B**	**C**
Added mass assumed (%)	100	0	100
Mass distribution	Even	Even	Lumped
Period (seconds)	0.225	0.173	0.214
% Surge, X mass	12	7	20

For the sand, shallow penetration Cases 1 and 2 where the spudcan embedment is 3m and the equivalent model seems to have a spudcan length of 5m, assuming that a soil added mass equals 100% of the its volume is likely an overestimation of the added mass. It is probably more reasonable to choose something closer to 50% (effectively the water volume instead of a soil volume). Sensitivity studies are presented to show the effect of the spudcan added mass modeling.

RADIATION DAMPING DEVELOPMENT

The modal radiation damping allowed in ISO 19905-1 for modal analysis appears to be too small by a factor of the number of spudcans. The modal damping equation was apparently derived from the Lysmer Analogy [6], which defines a dashpot coefficient for the vertical damping of a disk on a halfspace, that can be used under each spudcan within a time simulation. There is also a possibility that the coefficient in that equation is slightly incorrect by about 10% (should be 0.213 instead of 0.232), but that will only be resolved with further investigation and verification.

The damping values used in the earlier work [2] were based on the equation published, which developed modal damping values in the range of 4% to 10%. In the majority of this work, the same equation was implemented, but the lower bound number was limited to 5%. After the number of spudcan factor was realized, two cases were evaluated to demonstrate the relative effect of the factor of three in the modal damping. The increased damping results in about a 1/3 reduction in the global vertical reaction and in up to 30% vertical mode damping. In an internal study conducted several years ago, Digital Structures performed some time history analyses using Lysmer dashpots and concluded that the vertical modal damping should be between 20% and 30% for response spectrum analyses, which is consistent and supports incorporating the spudcan factor in the standard's existing equation.

Table 8 Case 2 Storm Conditions for Comparison [2]			
Storm Case Conditions – 50 year storm			
Water Depth	100 m		
Spudcan Penetration	3 m		
Wind Speed	40 m/sec		
Wave height	22 m		
Wave period	13.8 sec		
Current	0.75 m/sec		
50 year storm – Results			
Base Shear (approximate)	13 MN		
Overturning Moment (approximate)	1,700 MNm		
Worst Spudcan – storm load only	Vertical (MN)	Shear (MN)	Moment (MN-m)
Tension	40.5	4900	144
Bearing	-31,2	4125	129

STORM LOAD ANALYSIS FOR COMPARISON

In the earlier work [2], storm loads were computed to compare with seismic loads. That project team thought this rig should be able to operate in the three site cases evaluated here for the 22m wave conditions in Table 8. Selected results from their storm load analyses are also indicated for the critical site Case 2. It should be noted that these values do not include P-delta effects or dynamic amplification, which would increase the values presented, but they do include the 1.25 environmental factor. The SDOF dynamic amplification for Case 2 from Table 6 is about 1.55.

RESULTS OF ANALYSIS

Most of the analyses conducted were based on the model as developed in the earlier work [2] with the 1,000 spudcan added mass but with nonlinear large displacement P-delta effects for the equivalent legs and 100% of the small strain spudcan-soil rotational stiffnesses. Selected results are included to demonstrate the sensitivity of the added mass, the spudcan mass distribution and higher vertical radiation damping. The seismic loads include the 19905-1 seismic load factor of 0.9. The storm loads from the earlier work include a 1.25 environmental factor.

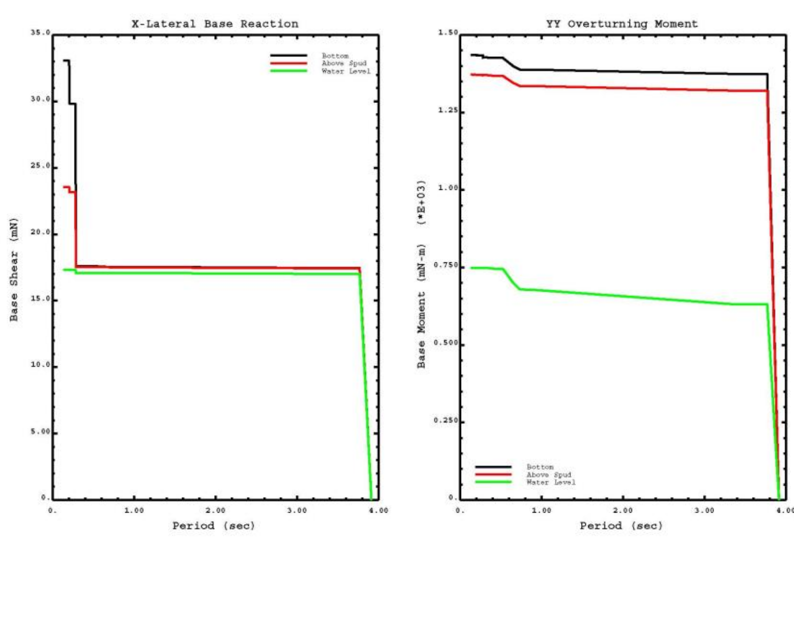
Base Reactions - Global base reactions (leg centroid, below spudcans) are presented in Table 9 as compared to the static storm load results (without P-delta or dynamic amplification). Although the calculation has not been done, one might expect a 30% increase in storm load from P-delta and dynamic amplification. Earthquake results are presented for the global X direction base shear and the YY overturning moment. The Y shears and XX moments are about 5% and 20% smaller, respectively. If one wanted to do a resultant calculation (which is not strictly correct) the values presented would increase by about 30% to 40%. The earthquake overturning moments are very small for the deepwater Case 2. The shallower water bottom Zone 2 moments are considerably below the storm moment. Even the Case 3 top Zone 2 moments are probably not larger than the storm with dynamic amplification. The overturning moments are primarily a result of the principal modes and are not sensitive to the spudcan added mass modeling. The earthquake base shears are sensitive to the added mass assumption and are all larger than the storm shear except bottom Zone 2 shallow penetration Cases 1 and 2 with an assumed 50% (water) added mass. Reducing the added mass to 50% results in a 70 to 85% reduction in base shear. For the top Zone 2, Case 3 with zero added mass the base shear reduces to 70% of the 100% added mass assumption, but still remains twice the storm shear.

Table 9 Response Spectrum Analysis - Global Base Reactions

Loading	Model	% Spud Amass	Vertical (MN)	Shear (MN)		Overturning (MN-m)	
				X	/storm	YY	/storm
Zone 2 Bottom	Case 1	100	24.4	17.9	1.37	783	**0.46**
		50	22.9	14.2	**1.09**	776	**0.45**
	Case 2	100	24.6	15.3	**1.18**	433	**0.25**
		50	23.4	10.8	**0.83**	425	**0.25**
	Case 3	100	33.4	25.1	1.93	1051	**0.62**
		50	31.8	20.5	1.57	1042	**0.61**
Zone 2 Top	Case 1	100	45.2	33.2	2.55	1435	**0.84**
		50	42.5	26.2	2.01	1422	**0.84**
	Case 1 3*Rdamp	100	32.6	Same			
		50	30.6				
	Case 2	100	45.0	28.6	2.20	788	**0.46**
		50	42.8	20.2	1.55	755	**0.44**
	Case 3	100	53.5	37.9	2.91	2061	**1.21**
		50	50.5	32.3	2.48	2047	**1.20**
		0	47.6	26.3	2.02	2036	**1.20**
	Case 3 Lumped	100	53.5	48.8	3.75	2049	**1.21**
		50	50.5	36.1	2.77	2040	**1.20**
		0	47.6	27.1	2.08	2032	**1.20**
	Case 3 3*Rdamp 30% LLeg2	100	40.4	30.8	2.37	2021	**1.19**
		50	37.7	26.2	2.01	2009	**1.18**
		0	35.3	23.7	1.82	2001	**1.17**
Storm	Case 2	0	0.0	13.0	1.00	1700	1.00
	Case 2 * 1.3			16.9	1.30	2210	1.30
Bold ➔ earthquake response values are less or similar to Storm * 1.3							

For the top Zone 2, model Case 1, Figure 10 shows the X base shear and YY overturning moments plotted versus mode periods for three different reaction heights: below spudcan, above spudcan and at the water level. The X shear increases to almost 10 Mn with the 1st bow-stern mode (just below 4 seconds as T_{surge} = 3.77 sec). The further increase in shear occurs below 0.3 seconds where about 50% of the increase can be attributed to the lower leg and the other 50% from the 2nd set, which includes spudcan translation. The two discrete steps are associated with the 1st and 2nd

Figure 10 Top Zone 2, Case 1 - Base Reactions by Mode



sets of lower leg modes (see previous eigensolution discussion). For the YY overturning moment, very little increase occurs after the 1st bow-stern mode.

The top Zone 2, Case 3, lumped spudcan mass has a 30% increase in base shear for the 100% added mass assumption. The increase reduces to 12% and 3% for 50% and 0% added mass. An additional top Zone 2, Case 3 result is presented for a model with three times vertical radiation damping (14% to 22%) and 30% 2nd set lower leg modal damping. For this model the X shear reduces 20% for the added mass conditions and 10% with no added mass. The overturning moments are not affected.

The vertical earthquake reactions are an expected difference from the storm loading case and from an individual spudcan-soil perspective are similar to the overturning moment effects. The vertical radiation damping as defined in 19905-1 results in modal damping ratios for the vertical modes in the range of 5% to 12%. With three times the damping ratio applied to the top Zone 2, Case 1 model, the vertical reactions reduce to 72%. The shears and overturning moments are not affected and consequently are not presented. The vertical reactions are rather insensitive to the assumed spudcan added mass, with about a 10% reduction in total reaction for each 50% spudcan added mass reduction.

Spudcan Reactions for the previous seismic cases are presented in Table 10, which show that the bow vertical reactions are all larger than the aft legs. The vertical seismic spudcan reactions are smaller than the factored storm reactions. The bow resultant shears and moments are about 5% smaller than the port and starboard values presented. The bottom Zone 2 vertical reactions are considerably smaller, but the resultant shears are larger and the moments just a slightly larger for the deepwater Case 3. The spudcan capacities were not provided [2], but based on the low vertical loads and comparison with the factored storm, these reactions should produce lower utilization than the proper storm load case (P-delta and DAF). So assuming the storm results are satisfactory, the lower Zone 2 likely would also satisfy the acceptance criteria.

For the top Zone 2 spudcan reactions, Cases 1 and 2 would likely pass the seismic assessment, with about 50% of the storm vertical, similar moments and high shears. It is unlikely the Case 3 reactions with both very large moments and shears would satisfy the assessment criteria.

Spudcan dead load values must be combined with the earthquake to develop the forces needed for an assessment and since the response spectrum forces have no signs, then need to be combined with the dead loads with the worst possible signs assumed. As a simplification, lets ignore the shears and moments (relatively small values), then the dead load vertical reaction differences between the earthquake operating reactions and the more uniform storm values in Table 10 are about +/-8MN for the Bow/P&S legs, respectively. The vertical reactions values presented can be simply increased by 8Mn and compared directly with the storm reactions. For the bottom Zone 2, the largest Case 3 100% added mass vertical reaction for the bow leg increases from 21.3MN to 29.3MN which is considerably smaller than the amplified storm vertical of 52.6MN. For the top Zone 2, sand Cases 1 and 2, the largest earthquake vertical increases from 29.4MN to 37.4MN, still considerably smaller than the storm value. For Case 3 the biggest 38.4MN value increases to 46.4MN, which is not far from the storm value. Obviously if the differences between the operating dead load reactions and the storm conditions are larger, then the combined earthquake loads become even more critical.

Table 10 Response Spectrum Analysis - Spudcan Reactions

Loading	Model	% Spud Amass	Vertical (MN)		Shear (MN)		Moment (MN-m)	
			Bow	P & S	Result	/storm	Result	/storm
Zone 2 Bottom	Case 1	100	**15.9**	**13.0**	8.5	1.73	152.0	**1.06**
		50	**15.4**	**12.7**	6.8	**1.39**	151.5	**1.05**
	Case 2	100	**13.5**	**9.4**	7.2	1.47	92.5	**0.64**
		50	**12.9**	**9.0**	5.1	**1.04**	92.1	**0.64**
	Case 3	100	**21.3**	**17.2**	12.0	2.45	217.0	1.51
		50	**20.8**	**16.7**	9.8	2.00	216.2	1.50
Zone 2 Top	Case 1	100	**29.4**	**23.9**	15.9	3.24	278.1	1.93
		50	**28.5**	**23.3**	12.6	2.57	277.3	1.93
	Case 1 3*Rdamp	100	**24.7**	**21.1**	Same			
		50	**24.2**	**21.6**				
	Case 2	100	**24.6**	**17.2**	13.4	2.73	169.3	**1.18**
		50	**23.6**	**16.5**	9.5	1.94	168.4	**1.17**
	Case 3	100	**38.4**	**31.7**	18.1	3.69	425.2	2.93
		50	**37.5**	**31.1**	15.5	3.16	424.1	
		0	**36.5**	**30.5**	12.7	2.59	423.1	
	Case 3 Lumped	100	**38.3**	**31.4**	21.3	4.35	423.3	
		50	**37.4**	**30.9**	17.2	3.51	422.7	
		0	**36.5**	**30.4**	13.0	2.65	422.3	
	Case 3 3*Rdamp 30% LLeg2	100	**33.7**	**29.8**	14.8	3.02	425.0	
		50	**33.0**	**29.2**	12.7	2.59	423.9	
		0	**32.4**	**28.2**	11.5	2.35	423.0	
Storm	Case 2	0	up	40.5	4.9	1.00	144.0	1.00
			down	-31.2	4.1	0.84	129.2	0.90
	Case 2 * 1.3		up	52.65	6.4	1.30	187.2	1.30
			down	40.6	5.3	1.09	168.0	1.17
Dead	**Cases**		**Bow**	**P & S**	**Shear**		**Moment**	
Equake	All		-45.1	-61.1	0.7		24	
Storm			-52.9	-52.9	0		0	
Bold ➔ earthquake response values are less or similar to Storm * 1.3								

Leg Forces below the hull for the previous seismic cases are presented in Table 11, which show that the vertical loads and moments are all below the amplified storm results, except the top Zone 2, Case 3 moments that are slightly larger. The shear forces are all larger except for the deep water Case 2 (both earthquake levels). For the bottom Zone 2 the shallow water cases are twice the storm shears. For the top Zone 2 the shears ranges from a factor of 3.6 to 5.4. The spudcan modeling has little effect on the shears and moments.

The dead load leg forces below the hull-leg connection are indicated below. Again the differential between the operating and storm rig configurations cause the seismic loads to be less balanced, with larger differences as the cantilever and drilling rig are extended further from the rig centroid. The storm values have been estimated as the dead load only results were not provided within the storm results [2]. The earthquake dead load vertical differences range from +11 to +14MN and -5 to -7 MN and for the bow and aft legs, respectively. Unfortunately the bow's earthquake vertical reactions are larger than the aft legs. The dead load shear forces are relatively small compared to the earthquake shears, but the moments are on the order of 10% of the storm leg moments.

For the bottom Zone 2 cases the combined seismic forces are still likely lower than the storm case, but it is less obvious for the top Zone 2 cases. It is impossible to extrapolate from these equivalent leg forces to brace and chord utilizations for the framing members around the hull-leg connection. The critical modal phasing for internal framing members could be quite different from what causes the maximum leg reactions. A detailed model analysis would be required to best resolve this unknown.

Table 11 Response Spectrum Analysis – Leg Forces Below Hull

Loading	Model	% Spud Amass	Vertical (MN)		Shear (MN)		Moment (MN-m)	
			Bow	P & S	Result	/storm	Result	/storm
Zone 2 Bottom	Case 1	100	14.5	**12.3**	4.99	1.97	200	**0.52**
		50	**14.4**	**12.1**	4.91	1.94	199	**0.52**
	Case 2	100	**11.3**	**8.1**	2.13	**0.89**	108	**0.28**
		50	**11.2**	**8.0**	1.99	**0.79**	107	**0.28**
	Case 3	100	**19.4**	**16.0**	5.99	2.37	268	**0.70**
		50	**19.3**	**15.8**	5.80	2.29	266	**0.70**
Zone 2 Top	Case 1	100	**26.8**	**22.5**	9.15	3.62	366	**0.96**
		50	**26.5**	**22.3**	8.99	3.56	364	**0.95**
	Case 1 3*Rdamp	100	**23.4**	**21.1**				
		50	**23.3**	**20.9**				
	Case 2	100	**15.8**	**11.4**	2.1	**0.84**	144	**0.37**
		50	**15.6**	**11.2**	1.9	**0.74**	141	**0.37**
	Case 3	100	**35.8**	**30.1**	11.2	4.44	524	
		50	**35.5**	**29.9**	11.0	4.36	522	
		0	**35.1**	**29.6**	10.9	4.30	520	
	Case 3 Lumped	100	**35.7**	**35.7**	11.0	5.35	521	
		50	**35.4**	**29.7**	10.9	4.30	520	**1.36**
		0	**35.1**	**29.6**	10.8	4.28	519	
	Case 3 3*Rdamp 30% LLeg2	100	**32.2**	**28.5**	11.1	4.39	522	
		50	**32.9**	**28.3**	11.0	4.33	520	
		0	**31.7**	**28.1**	10.8	4.33	518	
Storm	Case 2	0	48.9		2.53	1.00	383	1.00
				-23.4	1.82	0.72	352	0.92
	Case 2 * 1.3		63.6		3.29	1.30	498	1.30
				-30.4	2.37	0.94	458	1.19
Dead	**Cases**		**Bow**			**P & S**		
			Vert	**Shear**	**Momt**	**Vert**	**Shear**	**Momt**
Equake	1		-37.7	0.12	16.3	-53.7	0.65	45.4
	2		-33.8	0.09	11.3	-50.4	0.29	37.8
	3		-36.7	0.11	15.3	-57.8	0.55	47.9
Storm ****	1		-48.4	0	0	-48.4	0	0
	2		-44.9	0	0	-44.9	0	0
	3		-50.7	0	0	-50.7	0	0

Bold ➔ earthquake response values are less or similar to Storm * 1.3
**** ➔ estimated from average of Equake verticals – not available from [2]

CONCLUSIONS

Per ISO 19905-1:2012, earthquake assessments are to be done for all rigs in sites that are above Zone 1 and for certain operational foundation conditions within Zone 1. The worldwide rig snapshot site survey indicated that with and without the Arabian Gulf, there are 20% and 15% operating above Zone 1, respectively, which means that a significant number of jack-up sites would require seismic assessments to be performed prior to going on location. Due to the large variation in seismicity across the Arabian Gulf (Zones 0 to 3), it is difficult to use the ISO 19901-2:2004 maps to develop a site specific earthquake response spectra. In such areas, where there is a large change in seismic intensity, the maps need refinement.

Earthquake screening analysis results are presented for an equivalent jack-up model with three site conditions for seismic intensities at the bottom and top of Zone 2. Contrary to storm analysis experience, results are more severe for shallower water depths and stiffer foundations. In that earthquakes are not forecast, the operating condition is the dead loading state that is combined with the earthquake loads to evaluate component performance, which is a less balanced leg condition than the storm configuration. Consequently, the components are closer to their yield states under the dead loading conditions and have less available distance to capacity for resisting earthquake demands.

The analytical model used the 100% small strain spudcan-soil springs and includes large displacement P-delta effects for the response spectrum analysis method. The response spectrum analysis method makes it virtually impossible to evaluate leg framing member utilizations from an equivalent leg model. For this analysis method, it is simpler, less computationally expensive and less conservative to use a detailed model for evaluating leg framing member utilizations. An equivalent model is sufficient for determining spudcan-soil reactions that can be used directly in assessing foundation performance. It would be very difficult, perhaps impossible, to develop a set of static pushover loading patterns that place the proper earthquake demands on a jack-up structure.

Spudcan reactions likely meet the ISO 19905-1 acceptance criteria for bottom Zone 2 excitation for all site cases and the top of Zone 2 for sand Cases 1 and 2 (soil class E). The clay Case 3, because of it being soil class E, it has a much higher site amplification that results in larger seismic excitation and because of the relatively short leg length below the hull (75m), it would likely not meet the 19905-1 performance criteria. The spudcan reactions are sensitive to added mass and damping modeling, but without a proper soil-structure interaction analysis study, it is difficult to identify what quantities should be specified.

Earthquake vertical loads and moments in the equivalent leg just below the hull-leg connection are smaller than the amplified storm loads. Except for deepwater Case 2, the shears are larger by factors of two and 3.6-5.4 for the bottom and top Zone 2 earthquakes, respectively. When the earthquake equivalent loads are combined with the dead load forces, the bottom Zone 2 cases are likely lower than the storm case, but it is less obvious for the top Zone 2 cases. From these equivalent leg forces, it is impossible to extrapolate to member utilizations within the upper leg near the hull. A detailed leg model would be required to evaluate framing member utilizations.

ISO 19905-1 should be revised to indicate that:

- P-delta effects should be included in all assessment models irrespective of the analysis being performed.
- The equivalent modal damping for earthquake vertical modes should be factored by the number of spudcans participating in each mode and the equation A.10.4-3 coefficient should be verified.
- Need better guidance on lateral spudcan stiffness/damping modeling for earthquake loading. Need to complete SSI study to determine appropriate spudcan mass and radiation damping for lower leg modes.

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