SEABED MODELING EFFECTS ON JACK-UP RESPONSE WHILE GOING ON LOCATION

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ABSTRACT
This paper expands on a previous paper by the authors which compared vertical and lateral loads on a jack-up leg while going on location computed using a nondeforming seabed model to those of a more advanced deforming seabed model. The first seabed model uses a non-deforming block with constant stiffness to represent the seabed. The second model accounts for the deformation of the seabed after each leg impact. The horizontal reaction results from the two modeling approaches were qualitatively similar. However, the magnitude of the reactions from the deforming seabed model were lower. Comparison of motions induced by the different reactions from the two models shows that the differences in heave and pitch motions are relatively small. The effects on structural utilization of the leg and holding system were more pronounced.

KEY WORDS: Jack-ups, Going on Location (GoL), Self-elevating Units, Leg Impact Loads, Spudcan Impact Loads, Combined Eulerian-Lagrangian (CEL).

INTRODUCTION

A greater focus has recently been placed on the transition phases for a jack-up within the offshore industry. This paper specifically addresses one of those phases, the transition from the afloat mode to the elevated mode, known as “going on location” (GoL). Until recently, GoL limits provided in a unit’s marine operating manual typically are a single wave height or inclination angle for all conditions, regardless of direction and only occasionally depending on water depth, wave period, or broad “stiff/soft” soil conditions. While these limits have proved to be safe, the expectation is that they are extremely conservative, causing unnecessary waiting on weather delays.

To minimize waiting on weather delays, advanced analysis techniques, including time-domain analyses, have been implemented to try and establish more accurate limits for going on location. These new limits differ from the traditional, conservative single wave height values typically found in marine operation manuals as they are based on period, soil stiffness, jacking speed, wave directionality, water depth, and spudcan shape. A going on location analysis methodology was developed by three of the authors of this paper (Ref 1) to obtain permissible wave height curves (wave height vs period) for going on location.

The going on location analysis methodology (summarized in the next section) utilizes the commercial software OrcaFlex (Ref 2) to carry out the nonlinear, time-domain response analysis. It is noted that no representation of the seabed in OrcaFlex allows for the seabed to see permanent deformation after each impact of the spudcan.

This paper presents the results of a study which uses the spudcan motions from a time domain GoL analysis in OrcaFlex as input to a Combined Eulerian-Lagrangian (CEL) analysis completed in Abaqus (Ref 4). Henceforth, the simple linear (non-deforming) seabed model will be referred to as the “OrcaFlex” model and the more advanced (deforming) seabed model will be referred to the “CEL” model.

The resulting impact loads from both analyses were obtained for comparison. The effects of the impact loads on the demands of the structure and on the resulting motions of the jack-up were also evaluated.

GOING ON LOCATION ANALYSIS METHODOLOGY

In a 2017 paper by three of the authors of this paper, entitled *Using CEL to Account for Seabed Deformation Effects for Jack-ups Going of Location* (Ref 1), a GoL analysis methodology was outlined and is summarized below.

The GoL analysis methodology is made up of three types of analyses:

- *Frequency-domain diffraction analysis* to calculate the wave load as well as the added mass/damping coefficients of the jack-up at the target depth with its legs lowered near the seabed.
- *Structural analysis* to establish the structural capacity envelope of the legs (combinations of vertical force and moment reactions that cause either the pinions, chords or braces to reach their structural capacity).
- *Time-domain response analysis* to calculate the motions and spudcan loads during the jacking operations as the legs make contact with the seabed.

The time-domain response simulation is considered to be divided into four segments, as described in Table 1 and illustrated in Figure 1 (depicting regular waves, but also applicable to random waves).

TABLE 1: DESCRIPTION OF GOL TIME-DOMAIN SIMULATION SEGMENTS

Segment	Description
Ramping	Time prior to the actual start of the simulation, taken to be 100 seconds, during which all wave heights are gradually increased from 0 to the target value.
Free-Floating	Time starting at t=0 sec, to the first time there is contact between the seabed and any of the members representing the spudcans.
Transition	Time from the first time there is contact between the seabed and any of the members representing the spudcans, until all legs have made contact and the hull starts to come out of the water.
Elevating	Time after all legs have made and remain in contact with the seabed, resulting in minimal motions except for the elevation of the hull.

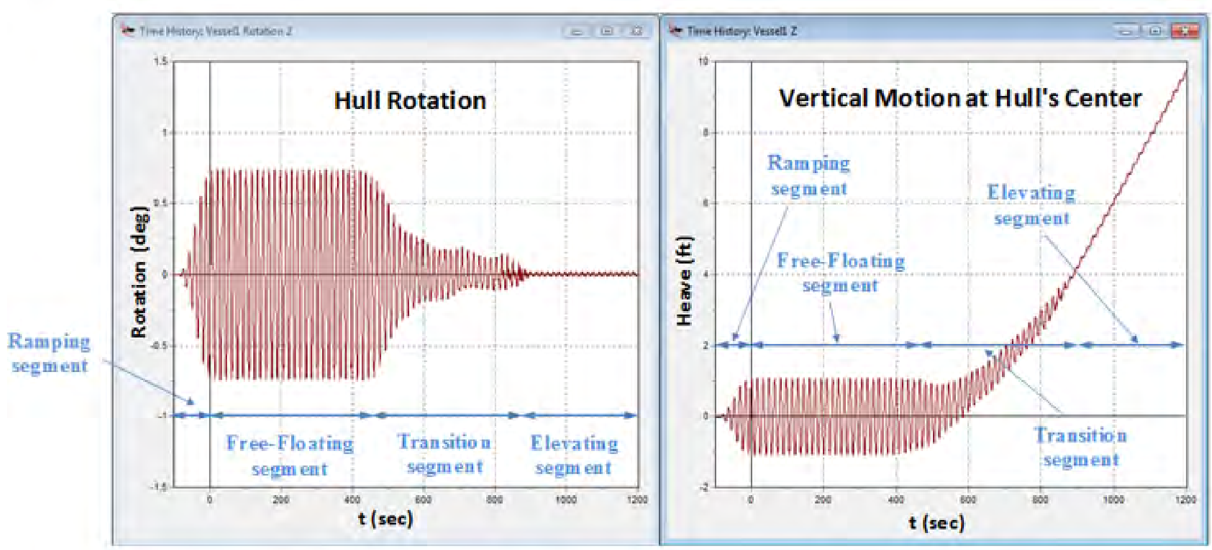

FIGURE 1: ILLUSTRATION OF GOL TIME-DOMAIN SIMULATION SEGMENTS

The methodology for establishing permissible wave height curves (for a given water depth and wave direction relative to the orientation of the hull and soil condition) has a number of simplifying assumptions, as listed below:

1. A structural capacity curve (combinations of leg axial load and bending moment) is established for the leg connected to the hull at a position corresponding to the target water depth.

2. Wind and current effects are ignored.

3. The diffraction analyses include the hull and spudcans (i.e., drag and inertial loads on the truss legs are ignored).

4. Wave excitation loads and added mass/damping coefficients are determined for a single tip-of-can position (typically 4 ft from the seabed).

5. Linear soil stiffness is used.

6. Lateral loads on the leg when it makes impact with the seabed are assumed to be proportional to the vertical impact load, as well as the relative magnitude of the lateral velocity of the spudcan.

7. A moving element with a calibrated contact stiffness is used to represent the relative movement of the legs and seabed (thereby simulating jacking of the legs).

The approach used for the time-domain analysis is to treat the hull and legs as a single body with the stiffness characteristics of the jacking system, legs and soil combined into an equivalent stiffness value. Ten (10) levels of contact elements outlining the shape and associated bearing area of the spudcan (see Figure 2). The contact elements are assigned appropriate stiffness values to reproduce the target Force vs Penetration plus the stiffness effects of the legs and jacking system.

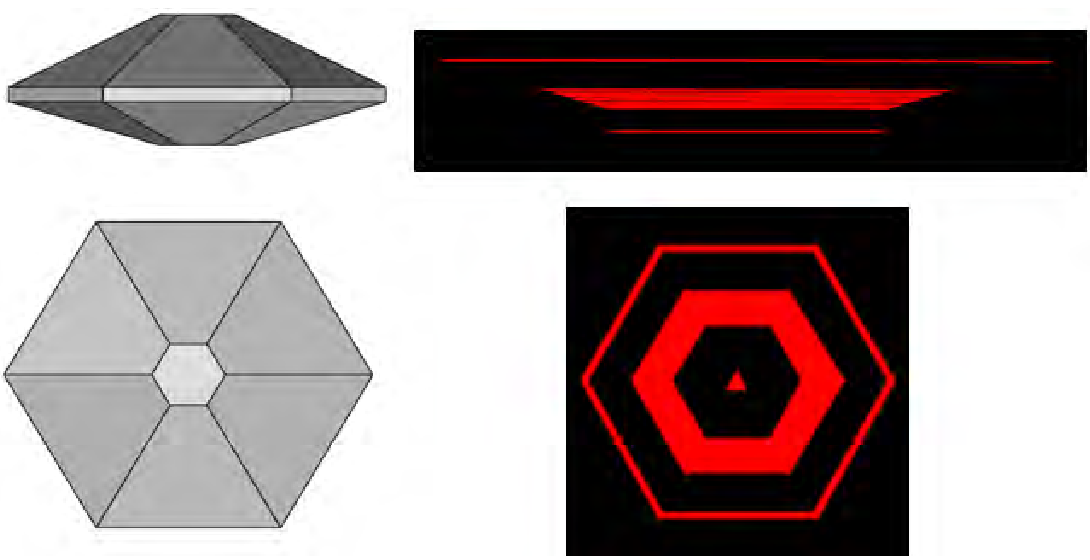

FIGURE 2: REPRESENTATION OF SPUDCAN IN ORCAFLEX USING CONTACT ELEMENTS

COMBINED EULERIAN-LAGRANGIAN MODEL

Analyses with the Abaqus program were used to provide numerical solutions for the soil reactions of the Forward spudcan while the jack-up is going on location. Abaqus [4] is a large, nonlinear, general purpose, commercial finite element analysis program with substantial soil mechanics capabilities. It has a long history of successful use in offshore geotechnical analysis [5]. The analyses reported here were performed using the Combined Eulerian-Lagrangian capabilities available in Abaqus.

Traditionally, finite element analysis has been accomplished using what is now called a Lagrangian approach. In this approach, nodes and element boundaries are tied to material, and a fixed body of material is contained in each element. The mesh deforms with the material, and the amount of material deformation that can be achieved is ultimately limited by errors resulting from element deformation. With an Eulerian approach the nodes and element boundaries are fixed in space and material flows across element boundaries as material deformations occur without any element deformation. In this way arbitrarily large material deformations can be achieved without element performance problems. In Abaqus Combined Eulerian-Lagrangian (CEL) analysis, Lagrangian meshing for bodies with limited deformation can be combined with Eulerian meshing for bodies with large deformations, and the two kinds of bodies can interact.

In the analyses reported here, the spudcan was modeled as a Lagrangian body, and the seafloor soil was modeled as an Eulerian body. The geometry of the model used is shown in Figure 3. Note that this is a half-space model taking advantage of the symmetry of the spudcan and the fact that the motion studied is confined to a plane (the x-z plane in Figure 3). The spudcan was made rigid. The contact between the spudcan was modeled with a friction coefficient of 0.4 and was given no adhesion. Thus, the spudcan surface was free to separate from the soil surface when moving upward from the (deformed) soil surface. The soil was modeled as an elastic-plastic material with kinematic hardening. This model can produce cyclic and dynamic behavior quite representative of the known characteristics of soils, and this material representation has been used successfully on a number of offshore geotechnical analyses [6, 7, 8, 9], notably including extremely good agreement with centrifuge test data in double-blind comparison [7]. Specifically, the normalized stress-strain behavior shown as medium in Figure 11 of Reference [7] was used, with the stiff case being used for sensitivity. For the analyses of the present study, the referenced stress strain behavior was scaled to match the soil shear strengths desired here.

The CEL analyses include the dynamics of the soil. Soil inertial effects are modeled, including soil wave propagation. This is in contrast to the OrcaFlex analyses, in which the soil reactions are modeled without soil dynamics effects. As a result of this difference, variations with time are to be expected from the two types of analysis. Unlike the OrcaFlex model, foundation damping is inherently included in the CEL analyses, both from radiation effects and from material hysteretic losses.

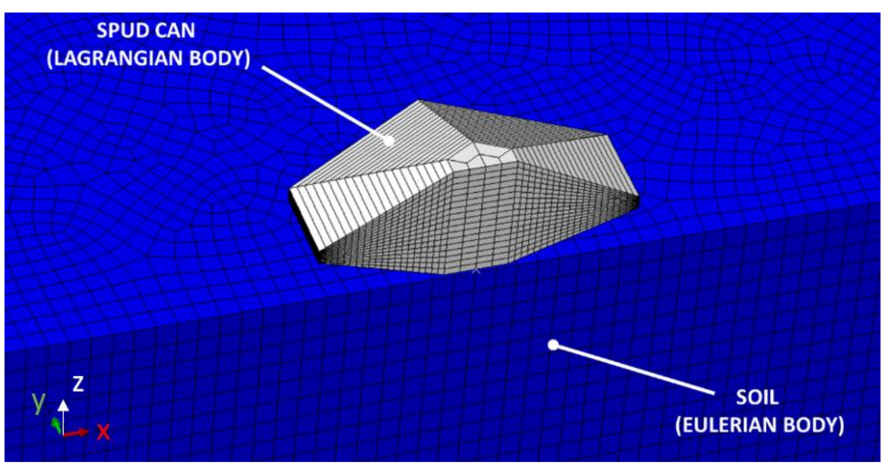

FIGURE 3: HALF-SPACE SPUDCAN MODEL IN ABAQUS

METHODOLOGY AND GOL CONDITIONS USED IN THIS STUDY

The methodology to compare loads between elastic soils represented in OrcaFlex and the nonlinear soils represented in Abaqus is explained below.

1. Select a water depth and wave (wave height, wave period and direction) to carry out a GoL analysis for the jack-up.
2. Select two representative soil conditions, corresponding to different penetrations at full preload (2ft and 10ft used in this paper).
3. Obtain motions. Due to symmetry in the 180-degree direction environment, only surge, heave and pitch were tracked.
4. Impose spudcan motions from the GoL simulation in OrcaFlex to the spudcan in the Abaqus CEL model.
5. Compare the results obtained from the two models.

Two clay soils were selected for the analyses, representing stiff and intermediate soils, producing leg penetrations of 2ft and 10ft (see Table 2). The specifics of the GoL analyses are listed in Table 3.

TABLE 2: PROPERTIES OF CLAY SOILS FOR THE STUDY

ISO Penetration Estimate (ft)	S_u (psf)
2	7,000
10	1,300

TABLE 3: SPECIFICS OF GOL ANALYSIS

Water Depth	300 ft
Wave Height	6 ft
Wave Period	13 sec
Wave Direction	Head seas
Jacking Speed	1.5 ft/min

The results of the GoL simulation (forward spudcan motions), which serve as input to the CEL simulation, are shown in Figures 4 and 5, for the stiff and intermediate soils, respectively.

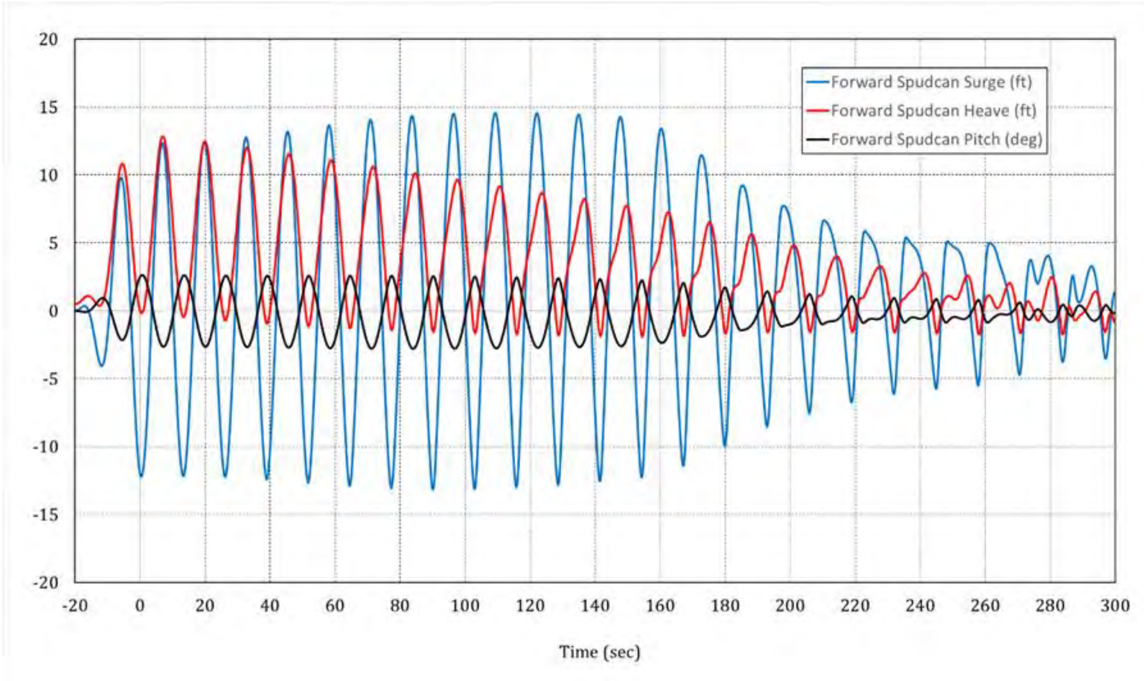

FIGURE 4: FORWARD SPUDCAN MOTIONS FROM GOL SIMULATION – STIFF SOIL

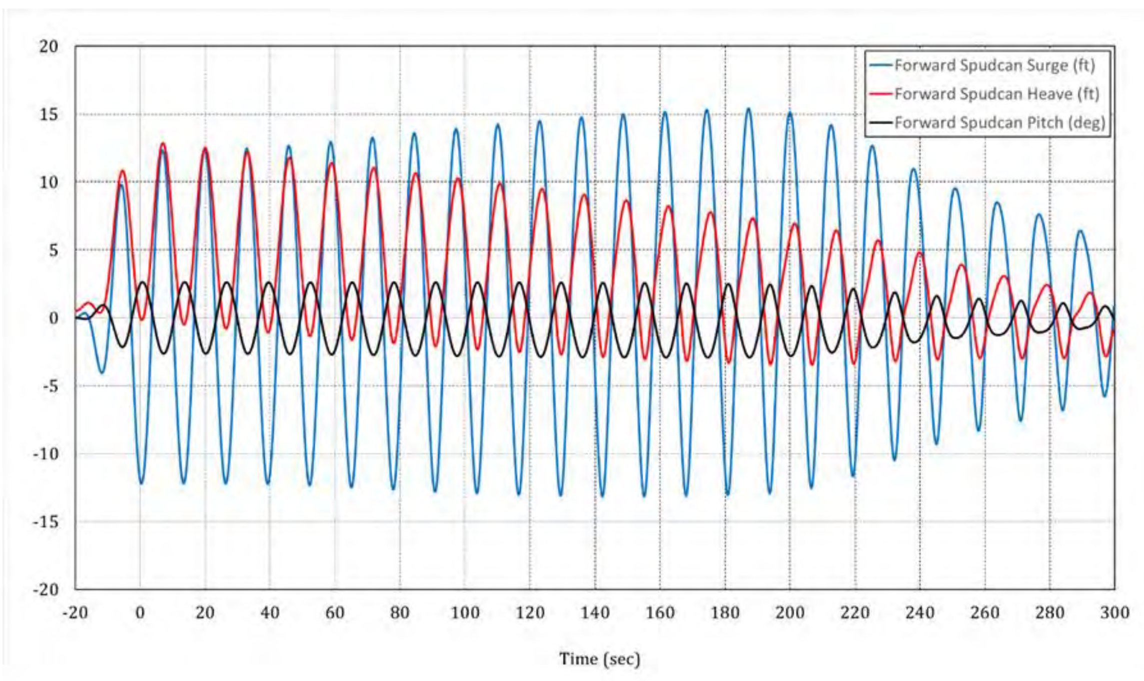

FIGURE 5: FORWARD SPUDCAN MOTIONS FROM GOL SIMULATION – INTERMEDIATE SOIL

VISUALIZATION OF SPUDCAN-SOIL INTERACTION IN ABAQUS

For visualization, Figure 6 illustrates the spudcan-soil interaction in CEL within Abaqus, showing the stress in the soil as the spudcan penetrates into the seabed.

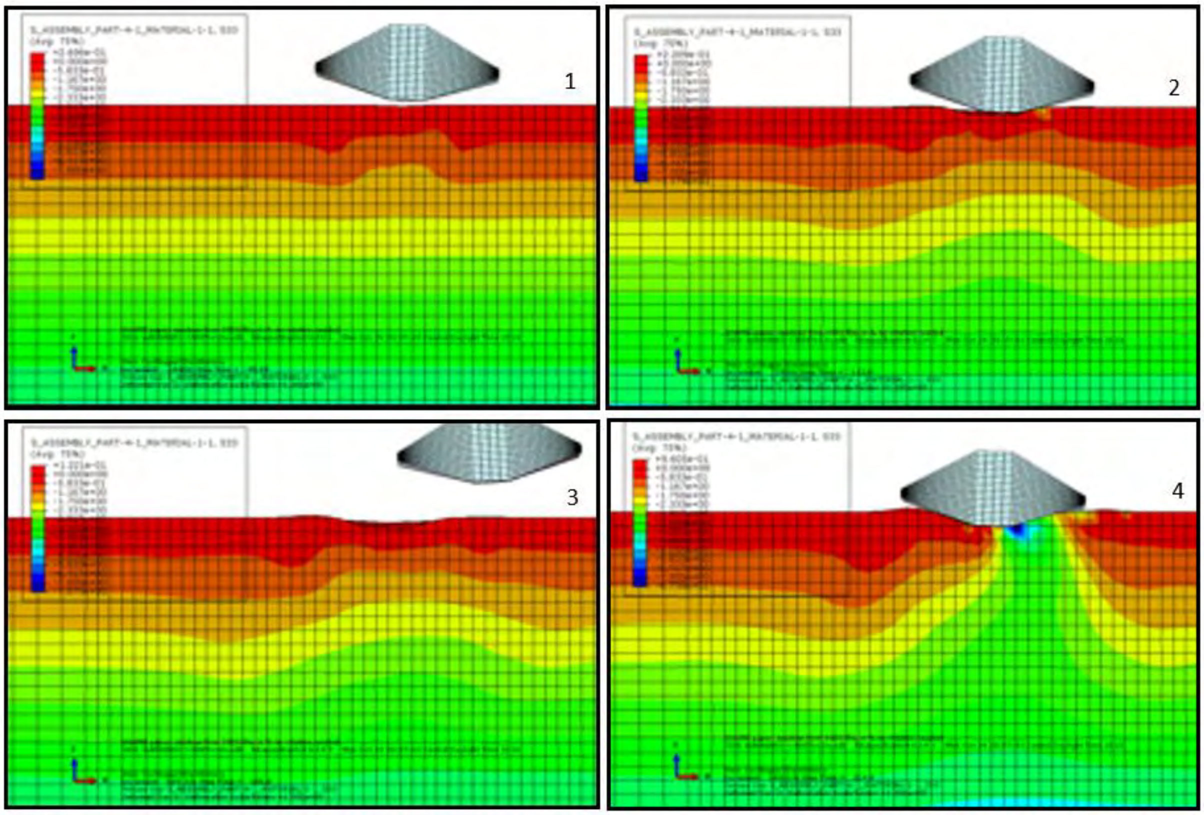

FIGURE 6: STRESSES DUE TO SPUDCAN-SOIL INTERACTION (FROM ABAQUS CEL MODEL)

FORWARD LEG REACTIONS DETAILS

Leg reaction results from the OrcaFlex and Abaqus models are presented in Figures 7 to 10 for stiff soils and in Figures 11 to 14 for intermediate soils. The simulations were carried out for 300 seconds (i.e., about 7.5ft of leg jacking).

Figure 7 shows a comparison of the vertical reactions for the environment of H=6ft, T=13sec obtained in OrcaFlex to those from the CEL Abaqus simulation. Figure 7 has three parts. The top part has a direct comparison of the vertical reactions from the two simulations (over the full 300 seconds). The middle and bottom parts of Figure 7 focus on the first ten leg impacts.

Figure 8 shows a comparison of the corresponding horizontal reactions. The horizontal reactions provide both positive and negative values. For the results from both OrcaFlex and Abaqus (CEL), the horizontal reaction at the forward spudcan corresponds to the direction of motion of the spudcan during the simulation (with the positive horizontal direction pointing from the center of the legs to the bow). Forward spudcan motion in the same direction as the positive horizontal direction provides positive horizontal reactions when in contact with the seabed.

It can be seen in both Figures 7 and 8 that the OrcaFlex results are more conservative throughout the time trace in comparison to the CEL results. The CEL vertical reaction results are approximately 80% to 90% of the reactions obtained from OrcaFlex. The CEL Horizontal reaction results are approximately 20% to 40% of the reactions obtained from OrcaFlex.

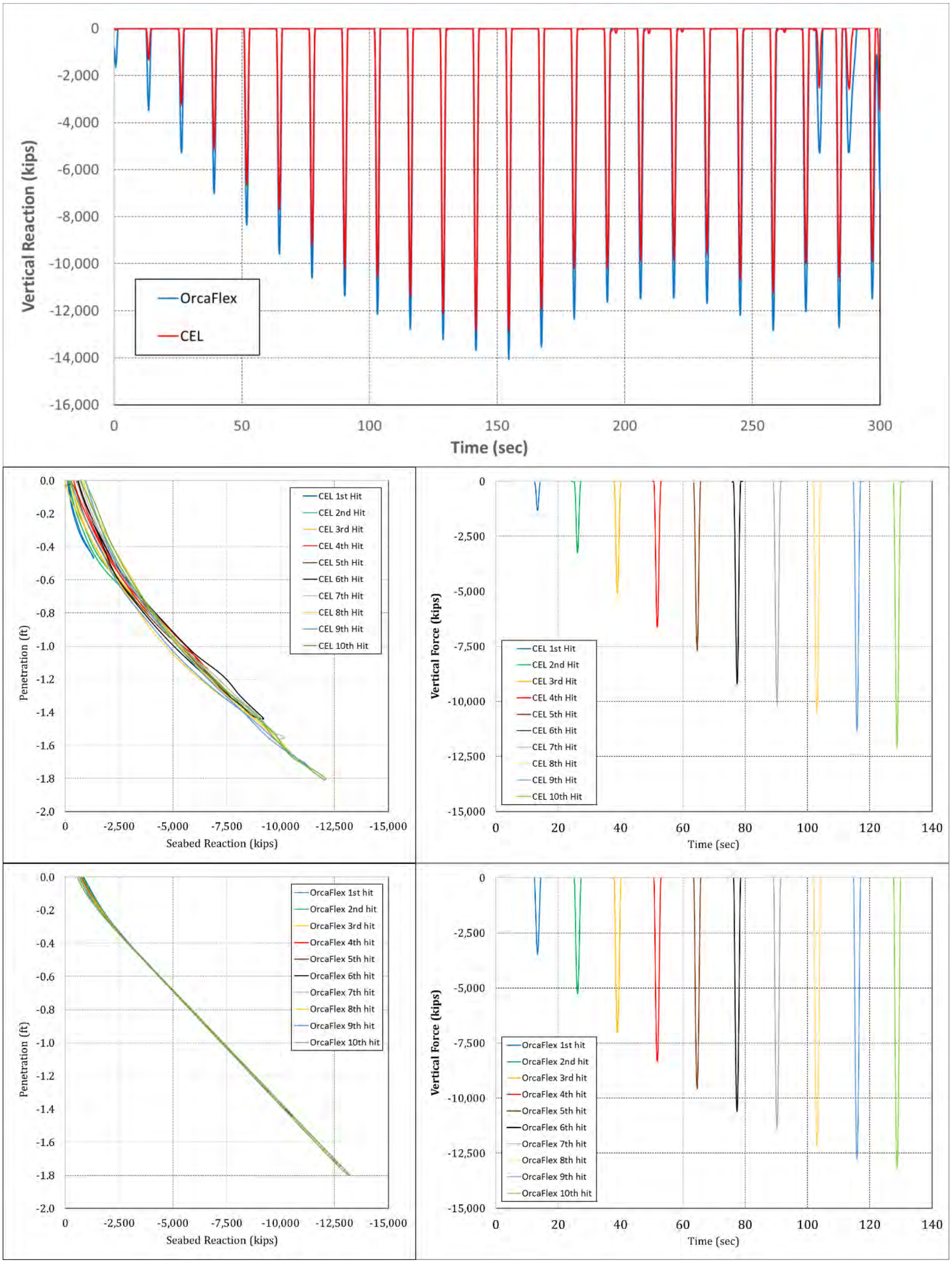

FIGURE 7: VERTICAL REACTIONS FOR STIFF SOIL

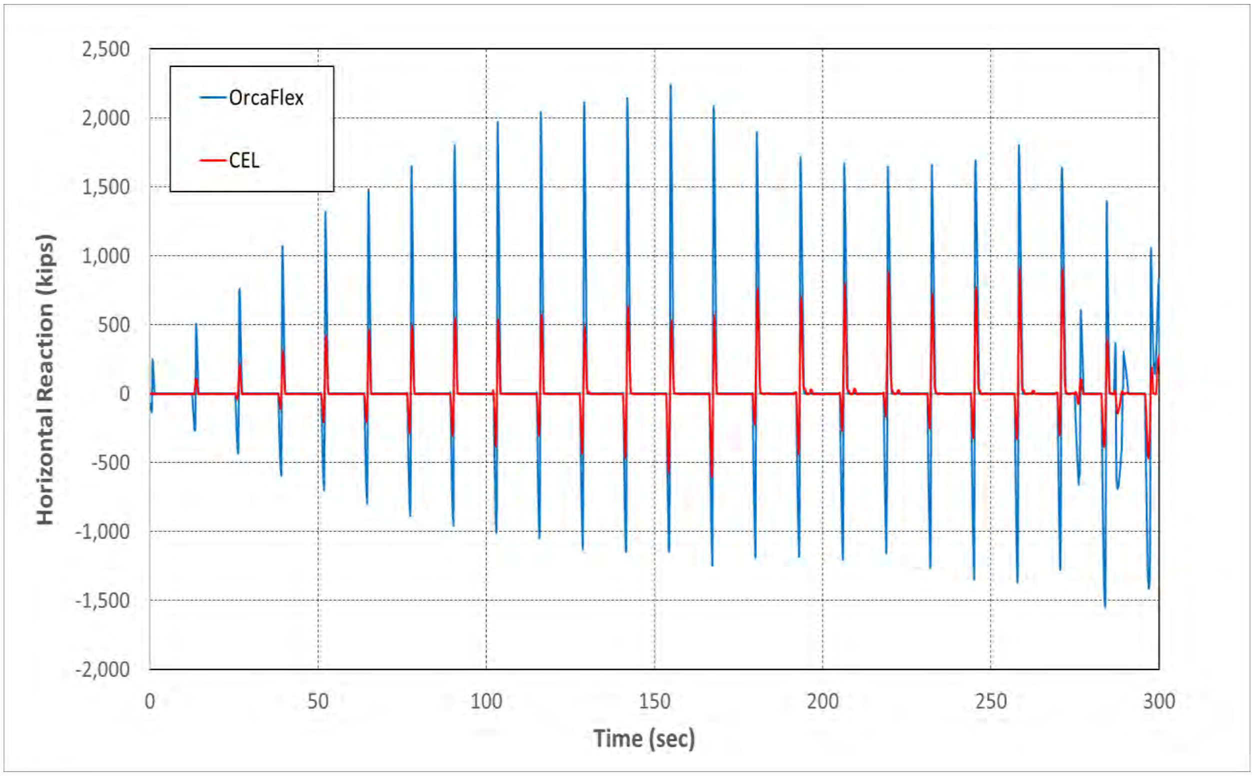

FIGURE 8: HORIZONTAL REACTIONS FOR STIFF SOIL

As discussed previously regarding the horizontal loads, there are both positive and negative horizontal reactions due to the change in horizontal direction of the forward spudcan while it's in contact with the soil; however, it is noted that there is not an immediate shift from the negative to positive values throughout the time trace. As seen in Figure 9, a gradual shift occurs over a time period of about 0.7 to 0.8 seconds for the CEL results (i.e., there is a shift in horizontal force from t = 2.0 seconds to t = 2.8 seconds). Figure 10 shows the horizontal loads from the OrcaFlex simulation for the exact same motion and penetration of the spudcan into the soil. As shown in both Figure 9 and Figure 10, there is a similar behavior between the OrcaFlex and CEL models in regards to the shift of horizontal loads while the spudcan is in contact with the seabed. The time stamps in the Figures 9 and 10 do not represent the actual time trace but rather are used to distinguish the beginning and end of this sample of horizontal load, which represents the 9^{th} soil to spudcan impact.

Figure 11 shows a comparison of the vertical reactions for the environment of H=6ft, T=13sec obtained in OrcaFlex to those from the CEL Abaqus simulation. Figure 11 has three parts. The top part has a direct comparison of the vertical reactions from the two simulations (over the full 300 seconds). The middle and bottom parts of Figure 11 focus on the first ten leg impacts. Figure 12 shows a comparison of the corresponding horizontal reactions. As was the case in the stiff soil results, the horizontal reactions provide both positive and negative values.

It can be seen in both Figures 11 and 12 that the OrcaFlex results are more conservative throughout the time trace in comparison to the CEL results. The CEL vertical reaction results are approximately 60% to 90% of the reactions obtained from the OrcaFlex. The CEL Horizontal reaction results are approximately 20% to 50% of the reactions obtained from the OrcaFlex.

Similar plots to those given in Figures 9 and 10, are shown in Figures 13 and 14 for the intermediate soil. Again, a gradual shift occurs over a time period of about 0.7 to 0.8 seconds regarding the change in direction of the horizontal load.

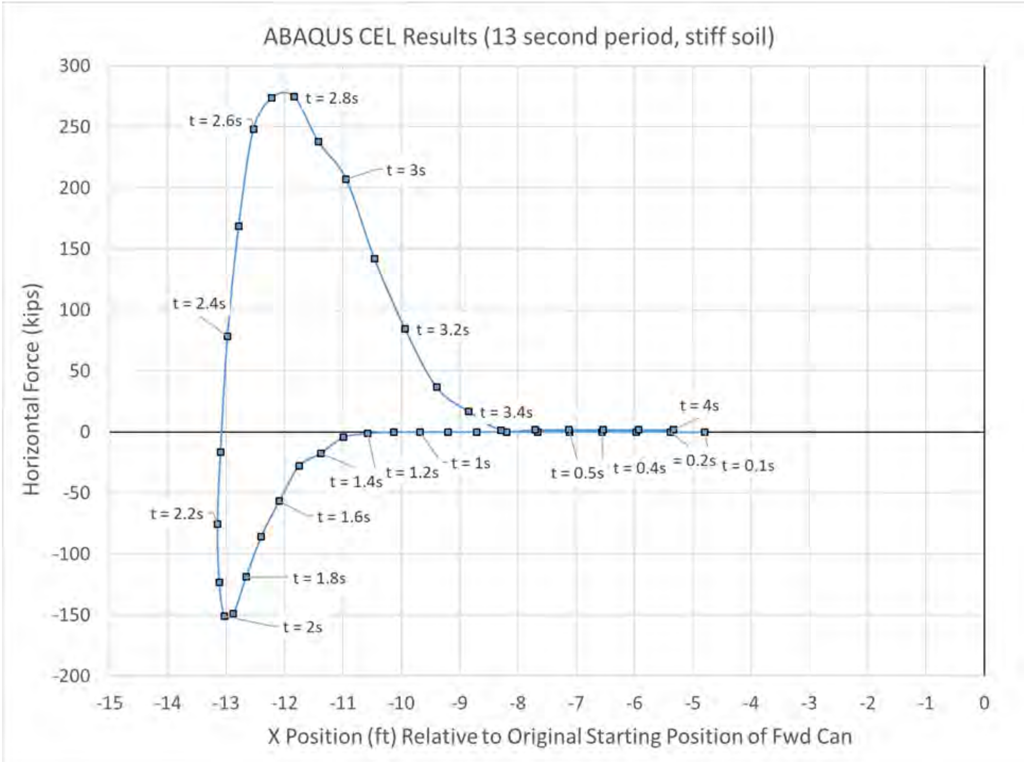

FIGURE 9: HORIZONTAL REACTIONS FOR 9TH HIT BETWEEN SPUDCAN AND SOIL (ABAQUS)

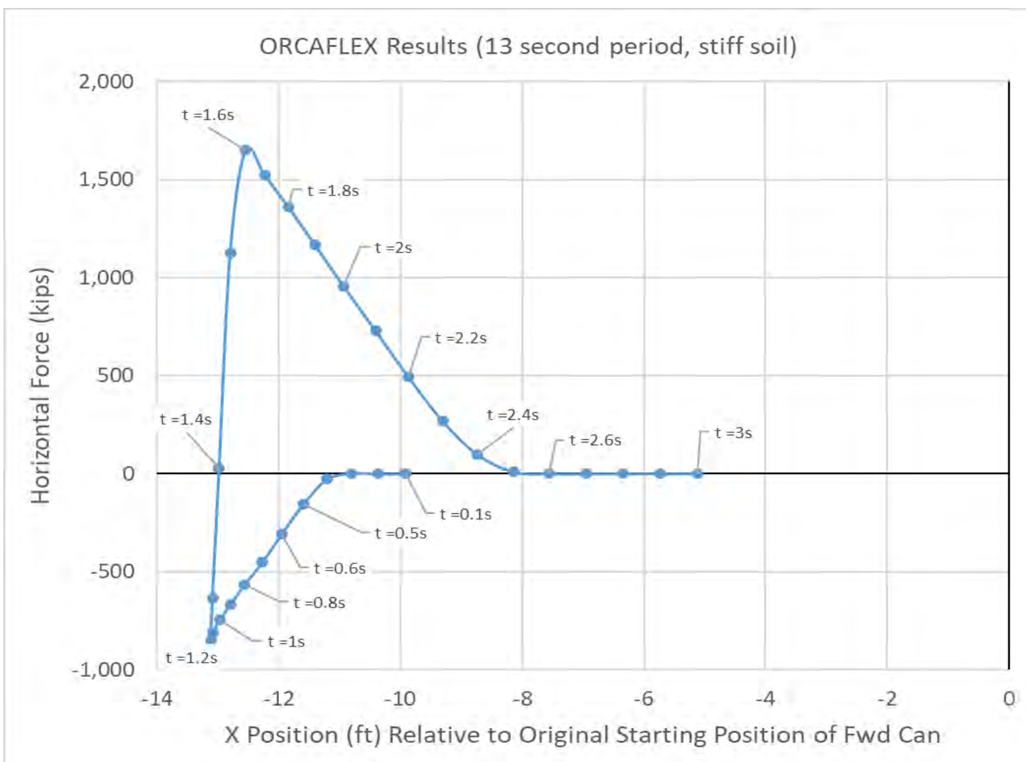

FIGURE 10: HORIZONTAL REACTIONS FOR 9TH HIT BETWEEN SPUDCAN AND SOIL (ORCAFLEX)

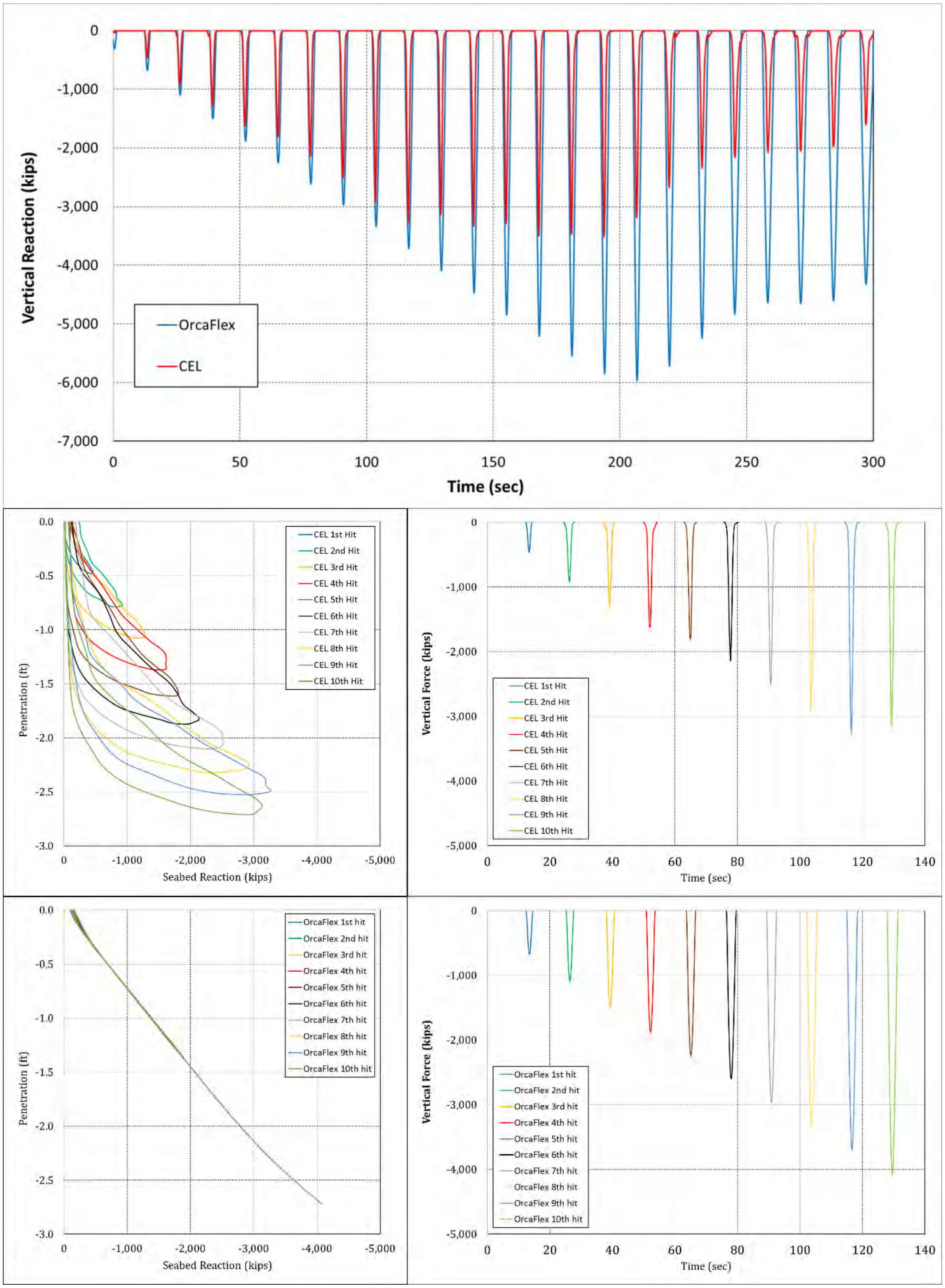

FIGURE 11: VERTICAL REACTIONS FOR INTERMEDIATE SOIL

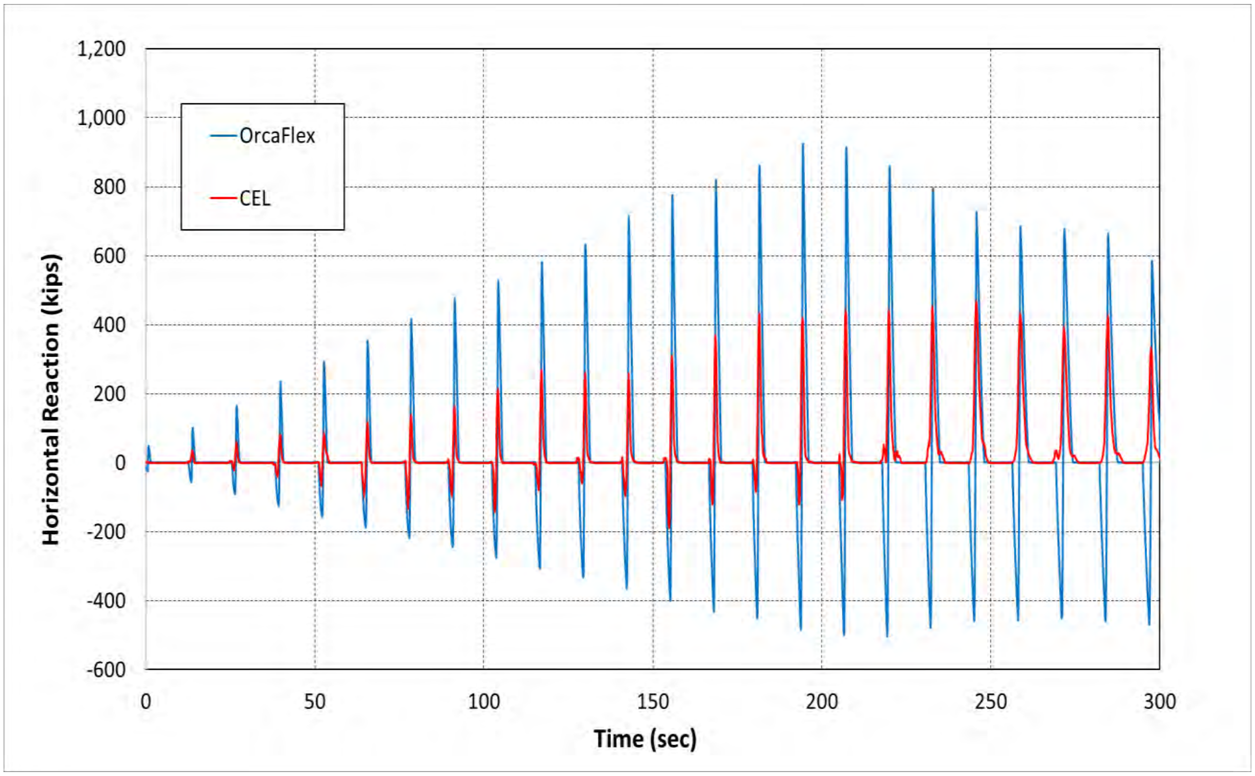

FIGURE 12: HORIZONTAL REACTIONS FOR INTERMEDIATE SOIL

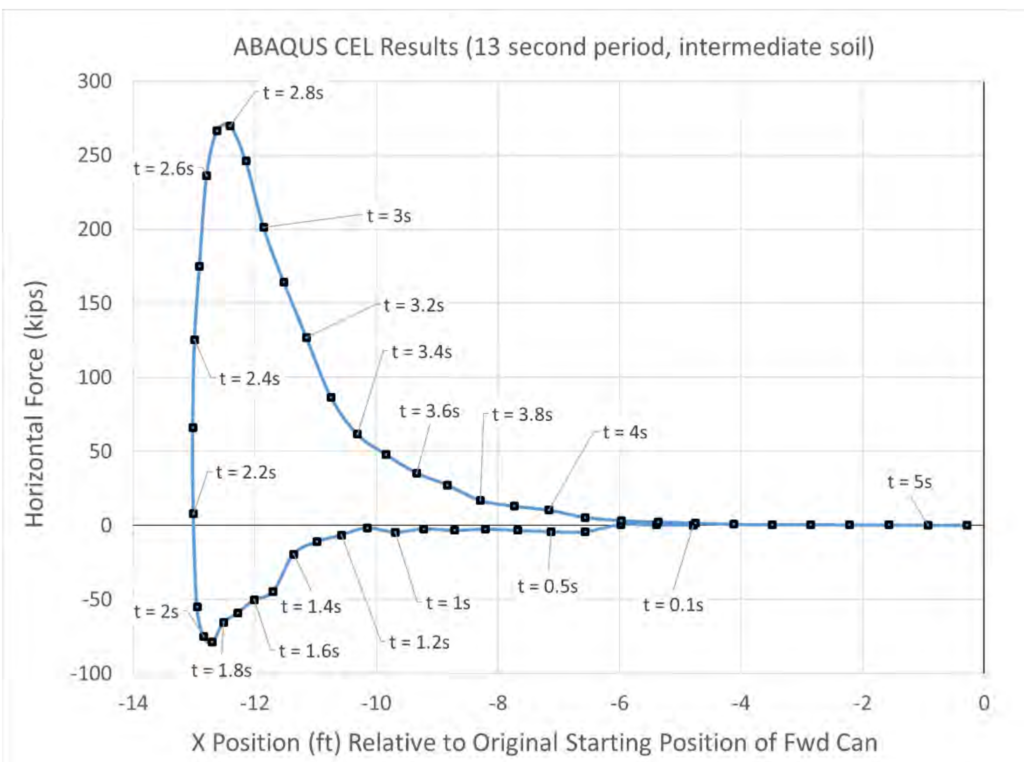

FIGURE 13: HORIZONTAL REACTIONS FOR 9TH HIT BETWEEN SPUDCAN AND SOIL (ABAQUS)

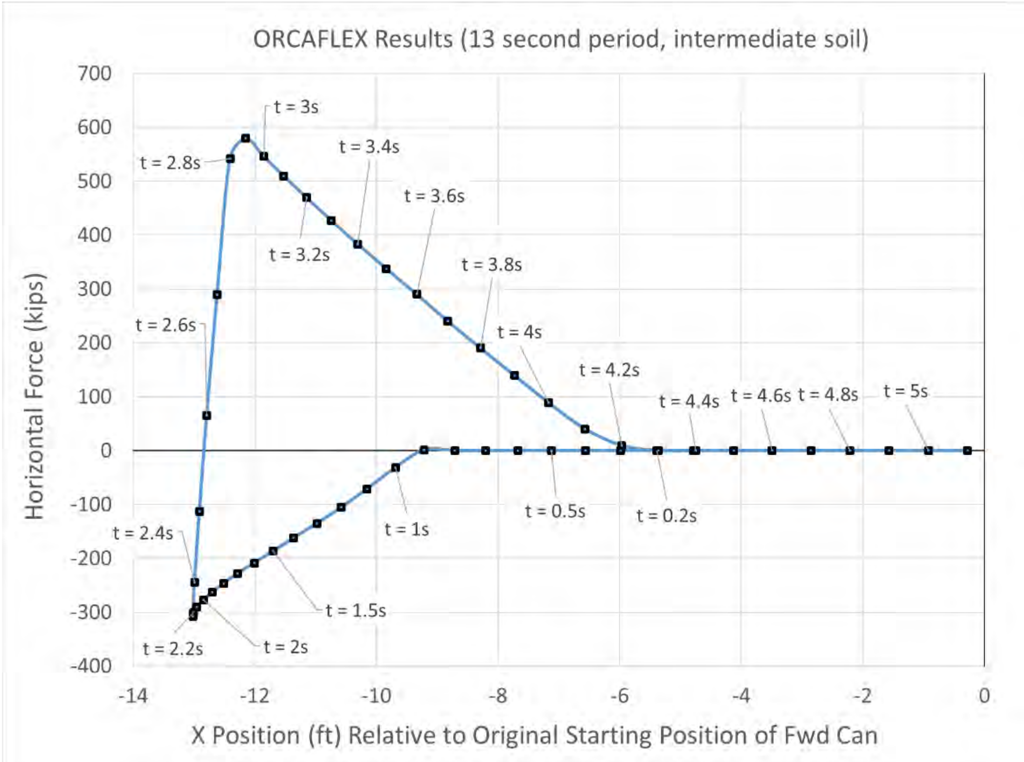

FIGURE 14: HORIZONTAL REACTIONS FOR 9TH HIT BETWEEN SPUDCAN AND SOIL (ORCAFLEX)

A comparison of the resulting peak vertical and horizontal reactions from the OrcaFlex and the CEL analyses is given in Table 4 for the two soil stiffness values analyzed.

TABLE 4: COMPARISON OF ORCAFLEX AND CEL PEAK LOADS

Soil Stiffness	Reaction	OrcaFlex	CEL	Ratio (CEL/OrcaFlex)
Intermediate	Vertical	5,968k	3,505k	59%
	Horizontal	921k	467k	51%
Stiff	Vertical	14,052k	12,811k	91%
	Horizontal	2,227k	905k	41%

COMPARING VESSEL MOTIONS

With significant differences in peak reactions, the authors sought to test if the CEL loads will affect the motions of the vessel. This was tested by running the same environment as before in OrcaFlex but imposing the loading from the CEL model on the forward spudcan instead of allowing the program to calculate the loading itself.

Figures 15 to 18 show the vessel motion comparisons. As can be seen, there is very little difference in both heave and pitch motions for the stiff soil. For the intermediate soil, there is little difference in pitch motions, but there appear to be some difference in heave motions after a few impacts (i.e., from about 200 to 300 seconds in Figure 17). The authors believe it makes sense that the heave amplitude is being reduced at a slower rate for the CEL model because the forward spudcan is deforming the seabed after every impact; therefore, the seabed level is being slightly lowered after every impact, causing more freedom for the vessel to heave.

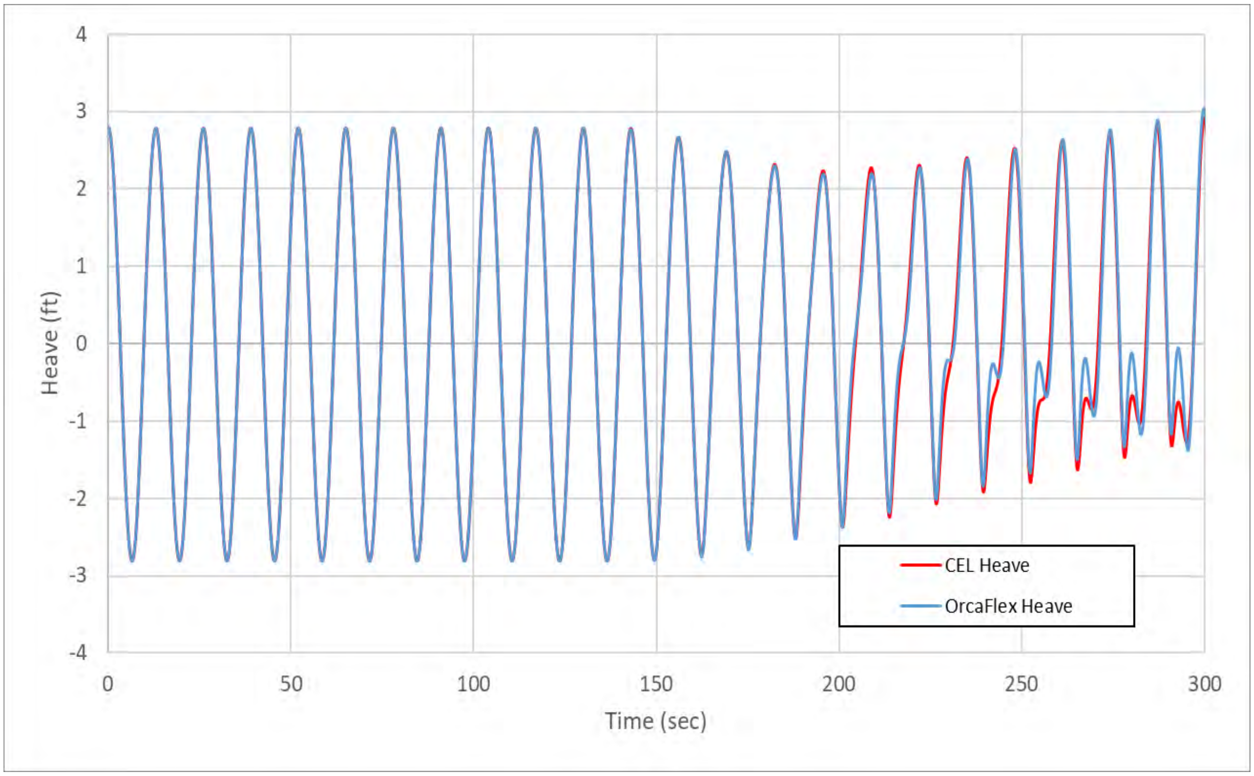

FIGURE 15: HEAVE OF JACK-UP WITH ORCAFLEX AND CEL LOADING (STIFF SOIL)

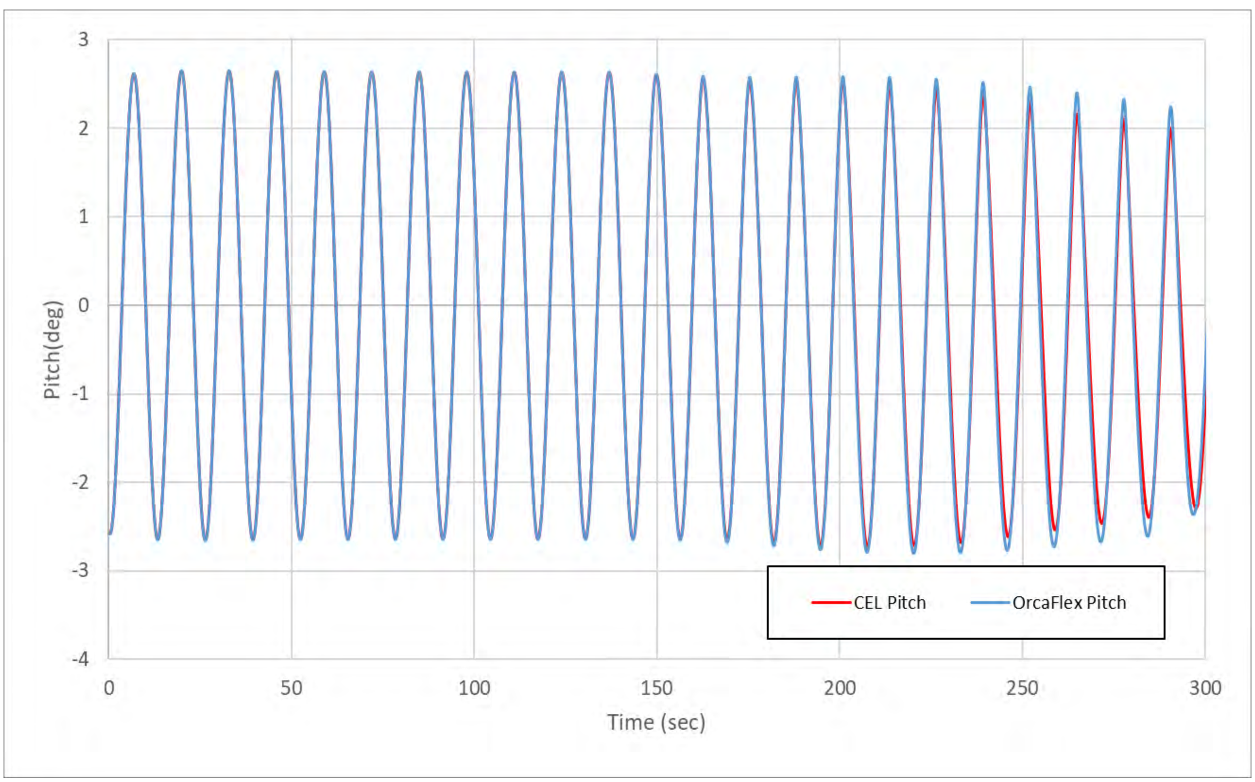

FIGURE 16: PITCH OF JACK-UP WITH ORCAFLEX AND CEL LOADING (STIFF SOIL)

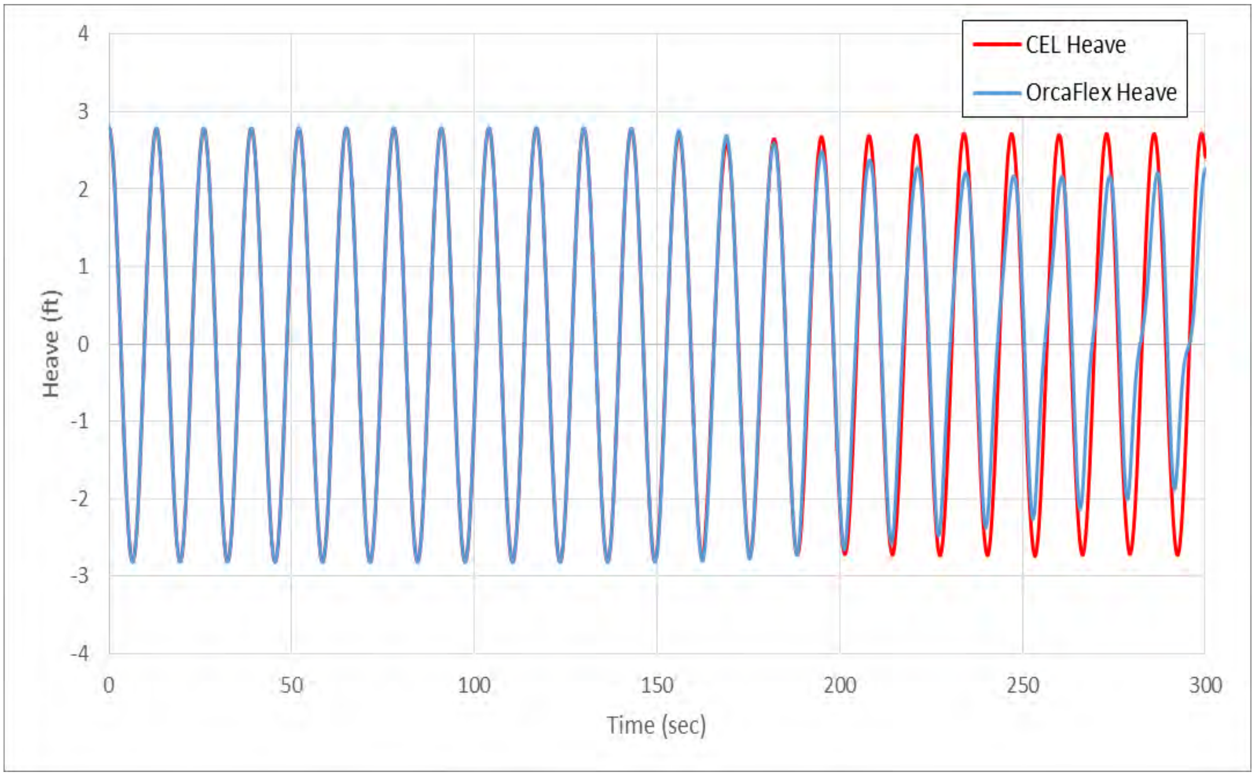

FIGURE 17: HEAVE OF JACK-UP WITH ORCAFLEX AND CEL LOADING (INTERMEDIATE SOIL)

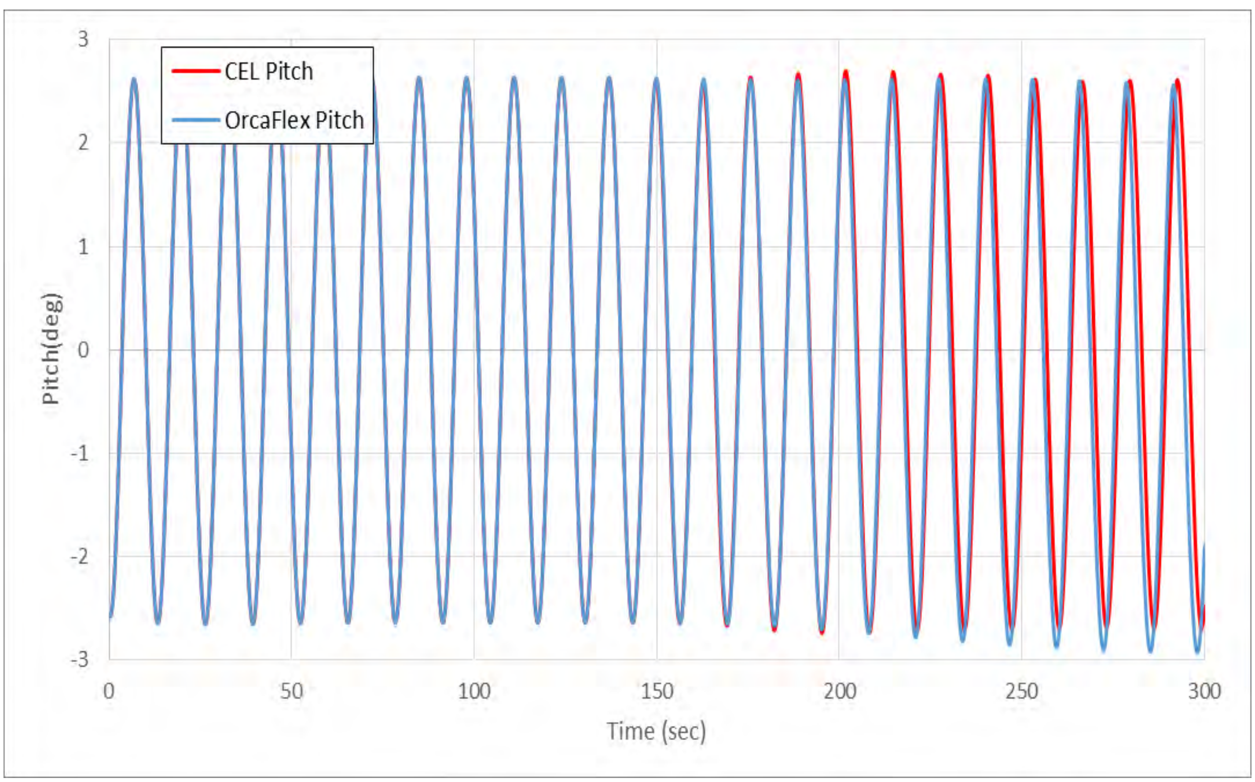

FIGURE 18: PITCH OF JACK-UP WITH ORCAFLEX AND CEL LOADING (INTERMEDIATE SOIL)

FORWARD LEG UTILIZATION RATIO CALCULATIONS

As noted in Table 4, the magnitude of the CEL reaction results is less than the magnitude of the reaction results obtained from OrcaFlex. This is true for both the horizonal reactions and vertical reactions. Therefore, it is obvious to expect comparable reductions in the structural utilization ratios for the jack-up legs and holding system. Since the structural utilization ratios are usually compared against 1.0 (or unity) to determine whether they are acceptable or not, they are referred to as unity checks, or UC values for short.

To better understand how these differences in load from the ORCAFLEX and CEL models affect the leg strength calculations, utilization ratios for the forward leg were determined using both sets of impact loads. The calculation of the utilization ratios for the leg first required calculating the leg bending moment in the vicinity of the lower guide by multiplying the total shear on the forward spudcan by the water depth and adding the moment on the forward spudcan due to the eccentricity. By plotting vertical reaction and leg bending moment, a series of datapoints are obtained to represent the total vertical load and moment at each time step while the forward spudcan is in contact with the seabed. To obtain UCs, these datapoints can be compared to a capacity curve (see Figure 19). The capacity curve is obtained by loading a structural model with different horizontal loads at set vertical loads at spudcan to obtain limiting points (or a curve) corresponding to the leg's structural utilization ratio being equal to 1.0.

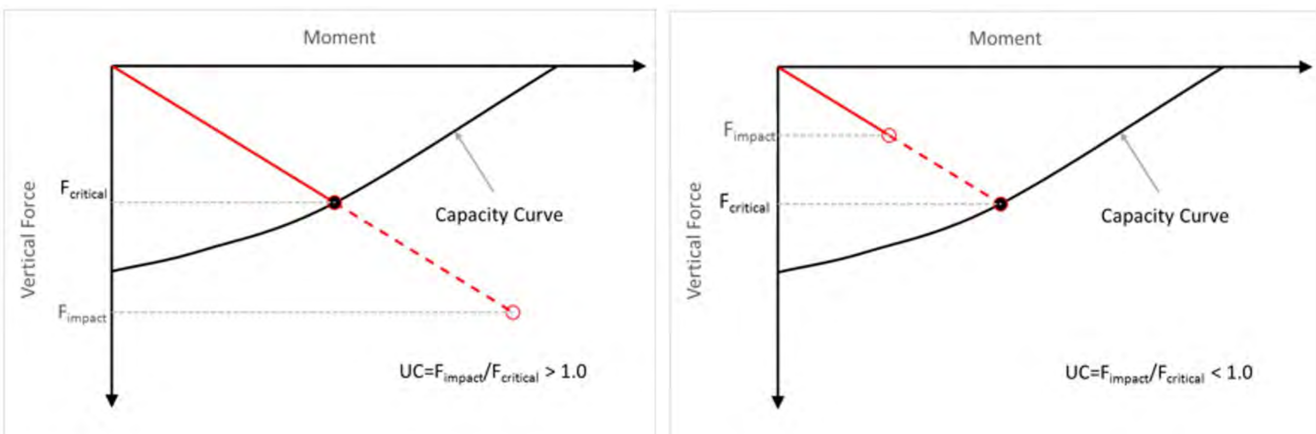

FIGURE 19: DEPICTION OF UTILIZATION RATIO CALCULATION

Figures 20 and 21 compare the capacity curve to the datapoints obtained from the OrcaFlex and CEL models for the two soil stiffness cases considered. From Figure 19, the peak UC values for the stiff soil case are seen to be ~0.98 for the CEL model results and ~2.0 for the ORCAFLEX model results. From Figure 20, the peak UC values for the intermediate soil case are seen to be ~0.46 for the CEL model results and ~0.84 for the ORCAFLEX model results. Expanding on the ratios from Table 4, Table 5 shows the ratios of peak loads and peak UC values from the two models.

TABLE 5: RATIOS OF PEAK LOADS AND PEAK UC VALUES FROM TWO MODELS

Soil Stiffness	Reaction	Ratio of Peak Reactions[(1)]	Ratio of Peak UC Values[(1)]
Intermediate	Vertical	59%	54%
	Horizontal	51%	
Stiff	Vertical	91%	48%
	Horizontal	41%	

(1) Ratio = (Value from CEL Model) / (Value from ORCAFLEX model)

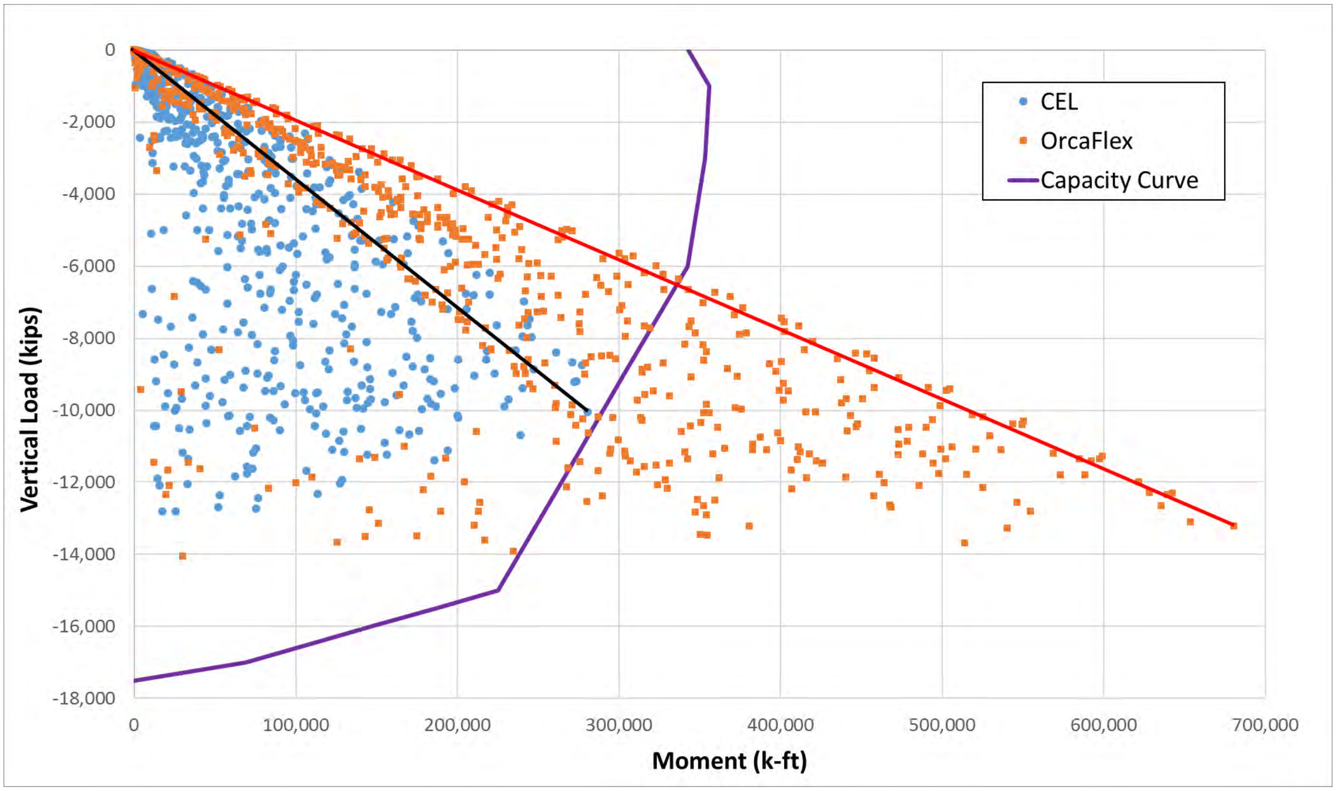

FIGURE 20: VERTICAL LOADS AND MOMENTS FOR UC APPROXIMATION (STIFF SOIL)

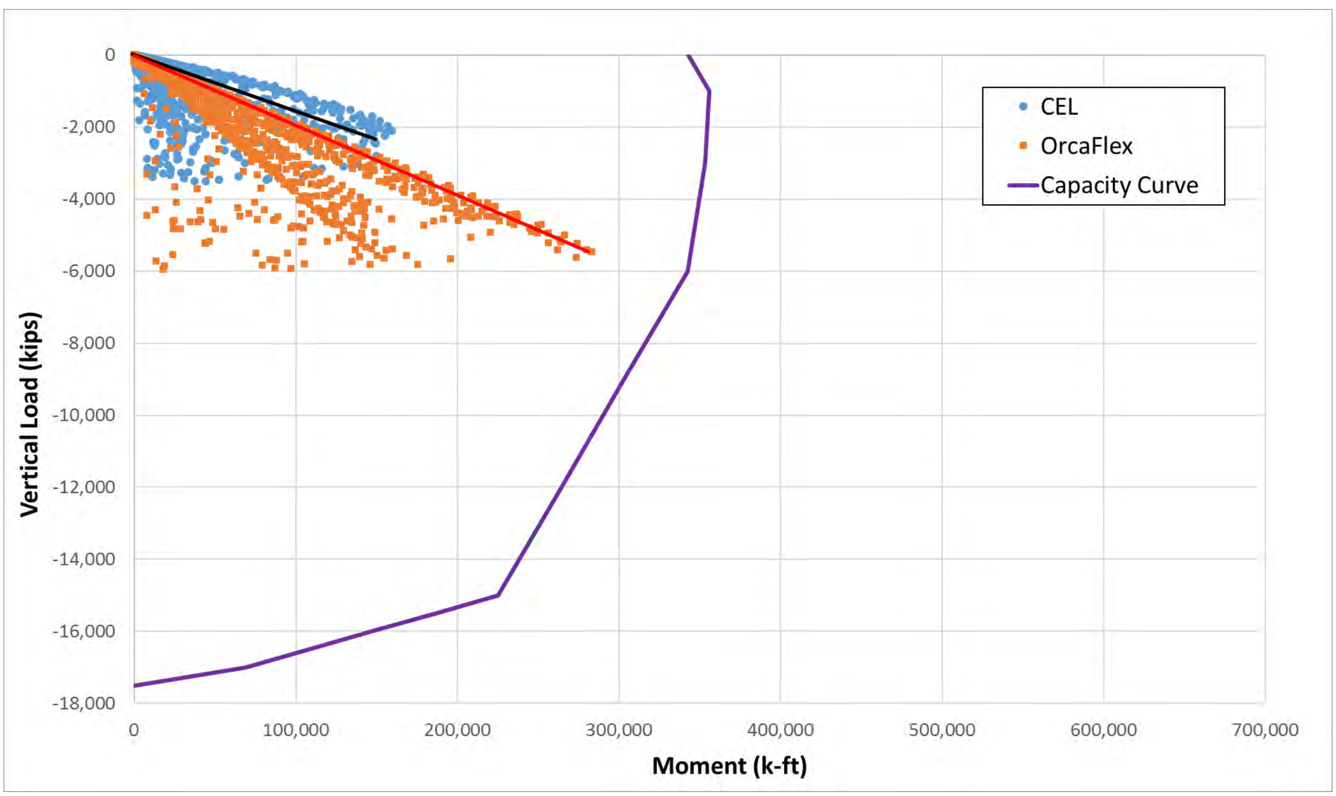

FIGURE 21: VERTICAL LOADS AND MOMENTS FOR UC APPROXIMATION (INTERMEDIATE SOIL)

SUMMARY AND CONCLUSIONS

A comparison of two different methods to model the seabed during a GoL analysis was performed using OrcaFlex and Abaqus. A GoL analysis methodology was introduced using OrcaFlex to calculate jack-up rig motions and leg reactions during the GoL phase. However, this methodology does not incorporate a seabed that plastically deforms after a spudcan impacts its surface; therefore, the time domain solver has the spudcans impacting an elastic undeformed seabed (i.e., linear spring) at each impact with the seabed. To investigate the effects of plastic deformation and energy dissipation of the seabed during the GoL phase, the motions obtained for the forward spudcan during an OrcaFlex run were input to a CEL Abaqus model. In conclusion, the GoL methodology using OrcaFlex produces conservative, yet reasonable, results in comparison with loads obtained from a highly nonlinear CEL model from Abaqus. It was found that:

1. OrcaFlex (the model with the nondeforming seabed) produced greater vertical and horizontal loads on the forward leg in comparison to the Abaqus CEL model.
2. Both the OrcaFlex model and the CEL model produce a slope in the horizontal load during the spudcan's change in direction, which indicates both models provide a gradual shift from max negative friction force to max positive friction force.
3. There is minimal change in jack-up motions when using the loads on the forward spudcan from either the nondeforming seabed (OrcaFlex) or the deforming seabed (CEL) on the forward spudcan.
4. A calculated utilization ratio further highlights the conservatism inherit to a model using a linear spring to model the seabed (i.e., modeling a non-deforming seabed). For instance, the stiff soil example provided in this paper shows a peak UC obtained from OrcaFlex to be approximately 2.03/0.98 = 2.1 times greater than the peak UC obtained from the CEL model.

With the ultimate goal to reduce conservatism while maintaining safety for all personnel on the rig, continuous improvements to going-on-location analyses are needed to better quantify the proper limitations. The results of this paper show that conservatism is likely present in the current analysis techniques in regards to the modeling of the seabed. Future work will look to implement methodologies that can incorporate the beneficial effects of a plastic seabed into current analysis techniques to further reduce this conservatism.

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