COMPARING PRELOADING AND PUNCH THROUGH BEHAVIOR OF 3- VS 4-LEGGED JACKUPS

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ABSTRACT

Self-elevating units play a key role in many offshore operations around the world. Because they move from site to site, they must undergo a process known as preloading to ensure that when they are jacked up to the working airgap, the foundation is capable of supporting all potential loads.

In an ideal world, the soil at the sites of jackup operations would be uniform with ever increasing capacity with leg penetration. This is not necessarily the case for sites with layered soils, which sometimes have stronger layers underlain by weaker soil. This layered arrangement leads to a soil strength regression in the leg penetration curve. If a leg breaks through the strong layer and the weaker soils do not have the strength to support the load without an increase in penetration, there is a chance the jackup will experience a *Punch Through*. In general terms, a jackup goes through a “*Punch Through*” when one or more of its legs have leg penetration speeds that exceed the jackup’s *Jacking Speed* (i.e., one or more of the legs have a so-called *Leg Run*), producing unacceptable *Hull inclination* due to changes in leg penetration at the new equilibrium position. The difference in leg penetration immediately before and after a *Punch Through Event* is defined in this paper as the *Punch Through Drop*. Depending on the amount of *Punch Through Drop*, the consequences to the jackup and crew can range from mild to catastrophic.

Until recently, most jackups were 3-legged units used for offshore drilling operations, where a unit would work for extended amounts of time at a single location. The growth of the offshore wind market has created a need for jackups with increased elevated weight capacity and shorter preload times. Designers and builders have responded with 4-legged jackup designs that better match the requirements for building offshore wind farms. The majority of these new 4-legged jackups are wind turbine installation vessels (WTIVs).

Noting that it takes 3 vertical supports to provide a stable, statically-determinate foundation, 3-legged jackups carry out *Preloading Operations* by adding water into preload tanks in the hull, while jackups with 4 or more legs provide redundancy while supporting the hull and therefore can increase leg reactions by differential leg *Jacking*, commonly referred to as leg driving. While having more than 3 legs on a jackup introduces a level of redundancy during preloading, the risk of a *Punch Through* with the associated *Hull inclination* for units with 4 or more legs is not truly negligible.

Jackup operators cannot count on perfect soil at every site, the risk of a *Punch Through* is ever present, regardless of leg count. With an understanding of the mechanics of a *Punch Through*, the crew can work in a controlled manner to mitigate possible consequences of a *Punch Through Event*.

This paper has a simple aim – to highlight differences in the preload process for 3-leg and 4-leg jackups, as well as discuss the behavior of a jackup during a *Punch Through* and the possible resulting consequences.

KEYWORDS: Jackups, WTIVs, Self-Elevating Units, Preloading, Punch Throughs.

INTRODUCTION

This paper focuses on *Preloading Operations* of jackups, aiming to provide a physics-based understanding of the progression of leg loads as the preloading process takes place on sites with less-than-ideal soil conditions (*Difficult Sites*), noting that there are uniquely different aspects and risks in the preloading of 3-legged vs 4-legged jackups.

As defined in *JACK UP UNITS – A Technical Primer for the Offshore Industry Professional*, "[a] Jack Up is an offshore structure composed of a hull, legs and a lifting system…, [designed] to provide a stable work deck capable of withstanding the environmental loads." (Ref. 1). The term Jack Up (or jack up, or jack-up) refers to a broad array of vessels, also known as self-elevating units, liftboats, jackup barges and WTIVs (wind turbine installation vessels). For simplicity this paper will use the term jackup to encompass any/all of the above vessels. Jackups can be grouped by their number of legs (having either 3, 4 or more than 4 legs). In this paper, only 3- and 4-legged jackups are considered.

Given that jackups move from site to site, a typical cycle consists of a number of operations or conditions, as listed below (and defined in detail in a subsequent section of this paper):

1. Depart from Location 1 (either port or field) and Transit to Location 2 (this is often referred to as the transit condition)
2. Transition from the afloat condition to the elevated condition. This encompasses:
    a. Leg lowering
    b. Leg touch-down, sometimes referred to as Going on Location (and likely encountering leg to seabed impacts when done in the presence of waves)
    c. Preloading
    d. *Jacking* to the operating airgap (often referred to as elevating the hull)
3. Elevated condition (this encompasses operating and/or Storm Survival conditions)
4. Transition from the elevated to the afloat condition. This encompasses:
    a. Lowering the hull (first to a minimal airgap, then to a shallow draft to perform watertight integrity checks and eventually to a draft close to the loadline draft)
    b. Leg pulling (to remove the legs from the seabed)
    c. Lifting of the Legs above the seabed (also likely encountering leg to seabed impacts when done in the presence of waves)
5. Depart from Location 2 and Transit to Location 3 (or back to Location 1).

Upon arrival to a new site, a jackup must undergo a process known as preloading to ensure that when it is jacked up to the working airgap, the soil supporting the legs can withstand the anticipated operational loads as well as possible extreme environmental loads without inducing unacceptable changes in leg penetration. Preloading is carried out by increasing the reaction on each leg to reach the predetermined reaction set in the Marine Operations Manual or previously established by a site-specific analysis. While the preloading concept serves the same purpose for both 3- and 4-legged jackups, the process is distinctly different for each.

In an ideal world, the soil at the sites of jackup operations would be uniform with ever increasing capacity with leg penetration. This is not necessarily the case for sites with layered soils. Sites with a decrease in soil capacity with leg penetration are referred to as sites with *Punch Through* potential. Of course, if the soil regression is at load levels well past the target *Preload Reaction*, they are of no consequence.

The term *Punch Through* originated as the process that occurs when soil failure happens when the leg is resting on a strong soil layer that is supported by a weak soil layer and the soil gives way, inducing rapid or uncontrolled leg penetration. On 3-legged jackups, having a *Punch Through* automatically induces *Hull inclinations*.

The International Organization for Standardization ("ISO") document 19905-1 (Ref XX), defines P*unch Through* (spelled as punch-through) as "rapid, uncontrolled vertical leg movement due to soil failure in strong soil overlying weak soil." Furthermore, there is no definition for "rapid uncontrolled… movement" in the document. It is noted that the ISO 19905-1 document was written for jackups used in the oil and gas industry (i.e., typically 3-legged jackups) and that while not explicitly stated, the implication is that a *Punch Through* would induce *Hull inclination* (since these jackups have no redundancy), with an associated *Punch Through Drop* (defined below). Furthermore, the implication is that if *Punch Through Drop* is large enough, the jackup would experience damage. This gave rise to the labeling of sites as having "*Punch Through Potential*."

The term "*punch-through*" has evolved to have the connotation that the jackup was (or could have been) exposed to damage, since *Hull inclination* would be expected. With this in mind, when someone is informed that a jackup had a *Punch Through*, the most likely immediate follow-up question would be "was there damage?".

It is noted that 4-legged jackups can safely have their legs driven to the target *Preload Reaction* at sites that would traditionally be labeled as having "*Punch Through Potential*." In some of those cases, leg penetration speeds exceed the *Jacking* speed, thus having "rapid, uncontrolled vertical leg movement." So, based on the ISO 19905-1 definition for *Punch Through*, the jackup would have had one, but not necessarily having had significant *Hull inclination*, or having been in danger of inducing damage. For that reason, the authors propose slightly modified terminology, intended to be fully applicable to both 3- and 4-legged jackups. In particular, the authors propose that instead of defining *Punch Through* in and of itself, the terms *Punch Through Event* (or perhaps, "*Punch Through-like Event*") and *Rapid Leg Penetration* (or *Leg Run*) be used, with both of them having specific criteria for when they occur.

Noting that people involved in jackup operations have very different backgrounds and levels of familiarity with *Preloading Operations*, it is of paramount importance that a common language is established. To this effect, the next section offers key terms and the authors' version of their definition, as used herein.

TERMINOLOGY

A number of existing and forthcoming guidance Classification Notes, SNAME T&R Bulletins and ISO standards provide excellent definitions of the terminology involved in the preloading of jackups. However, the authors postulate that some of these definitions are not uniquely defined or were based on experiences with 3-legged jackups in mind and therefore in need of updating. Furthermore, many of the terms used in the below descriptions of the *Preloading Operations* for 3- and 4-legged jackups are not included in the definitions found in these documents.

While it is likely that the below definitions pertinent to *Preloading Operations* may be both challenged and improved upon, they are offered with the goal of providing clarity when comparing *Preloading Operations* of 3- and 4-legged jackups. If/when that happens, updated versions of the definitions (and this paper) will be created and can be requested subsequent to the initial publication of September 5, 2023 by contacting the corresponding author.

Hull Elevation is the vertical distance from a reference horizontal plane to a specified part of the hull (usually the keel, but not necessarily so). The reference horizontal plane can be located anywhere, but common locations are the stillwater level (SWL) or the nominal location of the seabed. To determine hull rotation, *Hull Elevations* at each leg are used. Ideally, these elevations would be at the center of each leg, but reference locations in the immediate vicinity of the legs with their geometric center at the center of the legs will work. When any *Hull Elevations* at the legs is different than the mean *Hull Elevation* of all the legs, either *Hull Inclination* or *Hull Torsion* is taking place (see definitions below).

Hull Inclination is associated with rigid body rotation of the hull and is defined as the angle off horizontal of a plane representative of the hull (ignoring sagging effects) based on the *Hull Elevation* at each of the legs. *Hull Inclination* is measured about the longitudinal axis (θ_x, which is positive starboard-side-down) and the transverse axis (θ_y, which is positive-bow-down). Since 3 points are needed to define a plane, 3-legged jackups do not experience hull torsion when the hull has different elevations at different legs. 4-legged jackups can experience both *Hull Inclination* and/or *Hull Torsion* when the hull has different elevations at different legs.

Longitudinal Hull Inclination Angle is defined as $\theta_x = ATan(\Delta z/LLS)$, where Δz is the difference in average *Hull Elevations* between the aft and forward leg(s) and LLS is the longitudinal leg spacing.

Transverse Hull Inclination Angle is defined as $\theta_y = ATan(\Delta z/TLS)$, where Δz is the difference in average *Hull Elevations* between the starboard and port legs and TLS is the transverse leg spacing.

Hull Torsion Angle is defined as $\tau = ATan(|\Delta z|/\Delta L)$, where Δz is the difference between the average elevations at the two diagonally-opposite sets of legs and ΔL is half the horizontal distance between diagonally-opposite legs.

Hull Deformation is associated with local strain-induced deflection of the hull. Hull sagging and hull hogging are examples of *Hull Deformation*. *Hull Deformation* does not change when there is rigid-body motion of the hull, unless the rigid body motions are accompanied by changes in the support loads (i.e., leg reactions).

Stillwater Reaction ("R_{SW}") is the reaction value on a given leg, once the hull transitions from a positive draft to a positive airgap, if only gravity effects are accounted for (i.e., ignoring the effects of wind/wave/current). As such, *Stillwater Reaction* values for each of the legs on the jackup are determined at the time the jackup is to transition from the afloat condition to the elevated condition. The "*Stillwater*" part of the term refers to the absence of waves (which by virtue of producing horizontal loads would alter the vertical leg reactions) and is extended to imply in the absence of any environment-related load actions such as those from wind or current. Per the above definition, and since cargo load is not constant and changes in CG would give different reactions on different legs, *Stillwater Reaction* is not a unique, constant value. Given that there is a relatively large variation in *Stillwater Reaction* of WTIVs in the light or heavy cargo conditions, *Leg Penetration Curves* are expected to show this range of variation instead of a single value.

A *Preloading Operation* (or simply *"Preloading")* is the process of increasing the soil reactions on the legs of a jackup beyond the *Stillwater Reaction*. This is done prior to elevating the hull to the operating/survival airgap, looking to ensure that after the hull is in the elevated condition, the soil supporting the legs is capable of withstanding the expected loads without inducing unacceptable changes in leg penetration. In this sense, the "pre" part of preloading refers to loading the soil ahead of the expected peak loads arising from weight shifts, crane lifts and/or environmental loads from wind, waves, and/or current. An underlying goal of the preload process is to force the legs to reach their final penetration in as controlled a manner as possible while the jackup and crew are prepared and in the best position to react and mitigate issues.

Preload Reaction is a leg reaction that is greater than the *Stillwater Reaction*. In the absence of a qualifier in front of it, *Preload Reaction* implies the maximum possible value achievable by the jackup. In addition to the maximum achievable *Preload Reaction* value, there are additional terms that are needed for specificity, such as the *Target Preload Reaction (“R_{TP}”)*, the *Actually-Achieved Preload Reaction* (sustained for a specified time with negligible change in leg penetration) and the *Instantaneous Preload Reaction* (i.e., the soil reaction at any given time during the *Preloading Operations*). It is noted that different legs may have different *Preload Reaction* values. The target *Preload Reaction* is determined from either the value indicated in the Marine Operations Manual for the jackup, or established from a Site-Specific Assessment (*SSA*), which, ideally, is to be performed for every location that a jackup intends to operate. The *SSA* considers all possible loading scenarios (operational loads like crane OTM, wind and wave loads, as well as storm survival loads) as well as the soil conditions for a specific site. At any given time during the preloading process, the leg or legs whose reaction is intentionally being increased is/are referred to as the *Preloading Leg(s)*. The other legs are referred to as the *Adjacent Legs*.

Jacking is the process of activating the unit’s motors or pumps to induce relative motion of the leg(s) with respect to the hull. *Jacking* has two basic directions - up or down, but since the motions are relative rather than absolute, further definition is provided.

Jacking can be on all legs simultaneously, or on a single leg, or on selected legs. Since *Jacking* induces relative motion of the leg(s) with respect to the hull, *Jacking Hull Up* and *Jacking Legs Down* is induced by the same action, but the former implies that the legs are supported by the soil whereas the latter implies the unit is in the afloat condition.

Different *Jacking* scenarios take place as the operations proceed from arrival to departure, as outlined below.

1. *Jacking Legs Down* refers to the process of *Jacking* on all legs for the purpose of lowering the legs down towards the seabed, while the jackup is in the afloat condition. This process ends once the hull starts to elevate and there is a reaction from the soil.
2. *Jacking Hull Up out of the Water* refers to the process of *Jacking* on all legs for the purpose of decreasing draft to eventually reach a positive airgap. As this *Jacking* takes place, the speed at which the hull comes out of the water depends not only on the *Jacking* speed of the unit, but on the soil conditions at the site, as the hydrostatic stiffness (changes in hull buoyancy with draft) acts in series with the *Apparent Soil Stiffness*.
3. *Differential Leg Jacking or Jacking on Selected Leg(s)* is the process of *Jacking* on one or more legs at a different rate or direction relative to the other leg(s). While *Differential Leg Jacking* can be done while in the afloat condition, this term is usually reserved for cases when the jackup is at least partially supported on its legs. On 3-legged jackups, *Differential Leg Jacking* induces *Hull inclination*. On 4-legged jackups, however, *Differential Leg Jacking* may or may not induce *Hull inclination*, depending on which leg(s) is(are) being jacked. Both 3- and 4-legged jackups experience *Hull Deformations* from *Differential Leg Jacking*, but overstress from selected leg *Jacking* is more likely to occur on 4-legged jackups.
4. *Differential Leg Jacking* is done either to
    a. change *Hull inclination* (usually towards achieving even keel),
    b. increase soil reactions on 4-legged jackups (*Leg Driving*), or
    c. increase leg pulling load when a leg or legs are stuck.
5. *Jacking Hull Up to Operating/Storm Airgap* is the process of *Jacking* on all legs for the purpose of raising the hull to the desired airgap. This *Jacking* should only take place after preload operations have been completed.
6. *Jacking Hull Down After Completing Elevated Operations* is the process of *Jacking* on all legs for the purpose of lowering the hull to the desired airgap prior to starting the leg pulling operations. This *Jacking* brings the hull to within a short distance from the water prior to commencing leg pulling operations.

7. *Jacking Hull Down to Loadline Draft (or Overdraft)* is the process of *Jacking* on all legs for the purpose of lowering the hull to the desired draft. This *Jacking* is the start of the leg pulling operations (usually including a pause at a draft of 30-50% of the loadline draft to perform watertight integrity checks). If after reaching the target overdraft (at even keel), a leg or legs remain(s) stuck, then selected leg *Jacking* may take place to increase the pulling load to remove the leg from the seabed.

While the act of *Jacking on all Legs Simultaneously* with a positive draft increases leg reactions (and possibly leg penetration) as the draft is gradually reduced, if the reactions are below the *Stillwater Reaction*, this process is simply referred to as *Jacking Out of the Water*, not *Leg Driving*, which is defined below.

Leg Driving is the process of *Jacking* or easing on the brakes on one or more legs, but not on all legs, for the purpose of increasing leg reaction(s). In the offshore wind industry, the term *Leg Preloading* refers to leg driving at positive air gap which would induce reactions higher than the *Stillwater Reaction*. The term *Leg Predriving* (or just *Predriving*) refers to *Leg Driving* at positive draft (which may or may not induce reactions higher than the *Stillwater Reaction*). In this sense, the "pre" in *Predriving* refers to leg driving prior to reaching a positive airgap. It is noted that from the definition for *Preloading*, *Predriving* is only considered *Preloading* if the induced soil reaction is greater than the *Stillwater Reaction*.

Leg Penetration Curves are predictions of the soil's capacity to support a given leg reaction (with only vertical reaction and no horizontal load or moment acting on the spudcan) for different leg penetration depths. These curves are derived from soil properties from a given site and are specific to a jackup design, accounting for the full shape and area of the spudcan. Furthermore, for large leg penetrations, these curves account for a level of overburden load from soil that ends up on top of the spudcan. Given the non-homogenous nature of soil and ranges in the measured properties of the soil samples, typical *Leg Penetration Curves* include lower bound and upper bound curves and sometimes they also include "most likely" curves. A uniform soil produces *Leg Penetration Curves* that have ever-increasing load capacity with leg penetration. That is not necessarily the case for layered soils, which may have *Load Capacity Regressions* (i.e., sections of the leg penetration curve where the capacity decreases with leg penetration, thereby having a negative slope). Finally, Leg Penetration Curves can be created from field data, too, but unfortunately this is not common practice today, and (of course), they would likely not be available while performing an SSA.

Apparent Soil Stiffness refers to the rate of change in soil resistance with soil penetration, as obtained from the slope of a leg penetration curve. It is noted that leg penetration, z_p, is the distance between the bottom of the spudcan (or pad) and the seabed. Given that leg penetration is always positive and usually plotted on the vertical axis, increasing downward while the soil's resistance (or load capacity) is also positive and plotted on the horizontal axis, increasing to the right, then a positive slope exists when the tangent of the leg penetration curve slants downward and to the right. It is noted that *Apparent Soil Stiffness* is not the same as *Soil Stiffness*, which refers to the resistance (force or moment) per unit displacement (translational or rotational) of the spudcan interacting with the soil at a given penetration (and is not used during the operations pertinent to this paper).

Soil Regression Sections of the leg penetration curve are those with soil capacity values that are below a previous peak reached at a shallower penetration. The soil regression section begins when the *Apparent Soil Stiffness* becomes negative, where the soil capacity curve has a local peak (R_{r0}) and the leg penetration is z_{pr0}. The *Soil Regression Section* ends (at z_{pr2}) as soon as R_{r0} and a positive *Apparent Soil Stiffness* can be achieved again. Between z_{pr0} and z_{pr2}, there is a leg penetration value, z_{pr1}, where the soil capacity reaches a local minimum value (R_{r1}). Noting that it would be valuable to relate R_{ro} to the

*Stillwate*r and *Target Preload Reactions*, the authors propose using the terms *Soil Regression Extent, Soil Regression Intensity and Relative Soil Regression Index* (defined below*)* for additional clarity.

Soil Regression Extent ("*SRE*") is defined as the distance from z_{pr0} to z_{pr2} (i.e., *SRE* = $z_{pr2} – z_{pr0}$).

Soil Regression Intensity ("*SRI*") is defined as the percent reduction in soil capacity within a *Soil Regression Section* (i.e., $SRI= 1-R_{r1}/R_{r0}$).

Relative Soil Regression Index is defined as the ratio a specific reaction of interest to the reaction at the start of the *Soil Regression*. As such, two particular indices of interest are, the index relative to the *Stillwater Reaction* and the one relative to the *Target Preload Reaction,* given by $SRI_{SW} = R_{ro}/R_{SW}$ and $SRI_{TP}= R_{ro}/R_{TPR}$, respectively.

Rapid Leg Penetration or Leg Run refers to a leg of a jackup penetrating the soil at a speed greater than the speed of the *Jacking* system. It is noted that the process of having the soil reaction on a given leg decrease as its penetration increases, does not qualify as a *Leg Run*, unless it happens at a speed greater than the speed of the *Jacking* system. *Leg Runs* do not usually happen simply while holding. Rather, when *Leg Runs* happen, something is going on to induce larger leg penetrations. However, depending on the level of soil saturation and changes in soil capacity over time, it is actually possible for *Leg Runs* to occur without perceived *Jacking* or preloading actions. This behavior is possible on clay soils. While it is theoretically possible to have *Leg Runs* that happen simultaneously on all legs, this is highly unlikely due to the non-homogeneous properties of soil and the fact that even small wind/current/waves introduce variations in the leg reactions.

A *Punch Through Event or a Punch Through-like Event* ("*PTE*") happens when a jackup has one or more of its legs experience a *Leg Run*, resulting in a *Hull Inclination* that exceeds a pre-set limit. While this pre-set *Hull inclination* limit is not universally set, in this paper, the authors have chosen ½ degree, duly noting that the ½-degree value is arbitrarily set. Using this definition, if/when all legs of a jackup experience essentially equal drops due to regression in soil reaction capability with leg penetration, it is not considered a *PTE* (since there would be no *Hull inclination*). When a *PTE* takes place, the leg(s) that experience a *Leg Run* is/are referred to as the *punching leg(s).* The leg that experiences the soil capacity regression first is referred to as the *Initiating Leg.*

Punch Through Drop ("*PTD*") is defined as the difference in leg penetration from the beginning and end stages of a *PTE*. Using this definition, different legs could have different amounts of *PTD* from the same *PTE*. In most cases, 2 or more legs will have zero amounts of *PTD* during a *PTE*.

Punch Through Potential Sites or *Difficult Sites* are those for which *Leg Penetration Curves* contain sections with negative, zero, or very low *Soil Stiffness* in the range pertinent to the target *Preload Reaction* and extending beyond the known capacity of the unit. Sites with *no soil information* should be treated as *Difficult Sites*, or even not even be considered for jackup operations at all.

PRELOADING OF 3-LEGGED VS 4-LEGGED JACKUPS

This section presents the basics for the process of preloading 3- and 4-legged jackups. It is intended to be illustrative, rather than fully comprehensive for the sake of comparing the two processes. This section only covers preloading in general terms, with commentary pertinent to *Difficult Sites* included in a subsequent section. Furthermore, in what follows, there is an inherent assumption that there are no other loads besides the action of gravity. The effects of wind/wave/current are discussed in a subsequent section.

It is noted that preloading can be done in the air (at positive airgap), or with the hull in the water (at a positive draft). Preloading at a positive airgap allows the maximum preload to be achievable, whereas preloading in the water does not. As such, preloading in the water may require the final stage of preloading to be carried out with the hull at positive airgap.

3-Legged Jackups
Preloading of 3-legged units is achieved by pumping (or letting in) water into selected tanks in the hull. Because of the intent in using it, this water is referred to as preload water, and the tanks used to store the water are referred to as preload tanks. For clarity, when the preloading process is completed, all preload water is removed (dumped or pumped out). As preload water is added, leg reactions increase (at least on one leg), inducing larger leg penetration(s).

Preload Reactions on 3-legged jackups may be determined from load cells on the *Jacking* system and the known weight of the legs, but the most common way of determining *Preload Reactions* on these jackups is by calculating them from tank sounding measurements and the known geometries of the tanks which allow for a precise determination of the added water and its CG.

Simultaneous Preloading refers to the process of adding water to all preload tanks at the same time, thereby increasing the leg reactions on all legs simultaneously.

Single-Leg Preloading refers to the process of loading selected preload tanks, so as to increase the reaction of a single leg, the preloading leg.

Completing the preload process (i.e., having all legs reach and hold the intended peak *Preload Reaction* values before *Jacking* the hull up to operating airgap) takes longer when doing *Single-Leg preloading* than when doing simultaneous preloading. For this reason, *Single-Leg preloading* is usually reserved for *Difficult Sites* and for cases when a slightly higher *Preload Reaction* than what can be achieved from simultaneous preloading is required.

It is noted that some jackups can jack legs with full preload water onboard. Many do not. Therefore, some jackups require the release (dumping or pumping) of preload water prior to doing any *Jacking* during the preloading process.

It is also noted that some jackups have leg fixation systems to take (or assist with) the load transferred through the jacking system between the legs and the hull. While most preload operations are carried out with the fixation system disengaged (thereby allowing for relatively quick *Jacking* if needed), some jackups perform preload operations with the fixation system engaged. This is usually a slower process and is reserved for cases when the required *Preload Reaction* exceeds the jacking system's holding capacity. *Preloading* with the fixation system engaged should only be done at sites expected to have zero or negligible *Punch Through Potential*.

Hull Inclinations are considered part of normal *Preloading Operations* for 3-legged jackups, as long as they do not exceed allowable values. The stresses and jacking loads experienced at different levels of *Hull inclination* are related to the amount of deployed leg below the hull (which in turn is a function of leg penetration, water depth and airgap/draft), the jackup's elevated weight (including preload water if onboard) and CG. Generally speaking, higher elevated weights and larger deployed leg lengths yield higher stresses/loads for a given *Hull inclination*.

4-Legged Jackups
Preloading of 4-legged jackups is usually achieved without taking preload water onboard. On these units, leg reactions are increased beyond the *Stillwater Reaction* by performing *Jacking on Selected Legs*, usually two diagonally-opposite legs at a time.

Preload Reactions on 4-legged jackups are determined from load cells on the jacking system and the known weight of the legs. The amount of friction between the hull and legs may have a non-negligible effect on the displayed jacking system loads. A jackup utilizing strain gauges on the leg would provide a more accurate leg reaction.

Leg Driving can be accomplished by performing *Hull-Up Jacking* on two diagonally-opposite legs so as to increase the reaction on the *Jacking* legs, which become the preloading legs (and in the process decreasing the reactions on the *Adjacent Legs*), or by performing *Hull-Down Jacking* (or easing on the brakes) on two diagonally-opposite legs so as to decrease their reaction (and in the process increasing the reactions on the other two legs, which in the process become the *Preloading Legs*). The former approach is referred to as *Active Predriving*, while the latter is referred to as *Passive Predriving*. The amount of hull-up or hull-down jacking needed to change leg reactions is relatively small during these operations, and it depends on the stiffness of both the soil and the hull.

4-legged jackups with the capability of utilizing preload water offer advantages over those that do not have this feature. With preload water onboard, a 4-legged unit can reach the *Stillwater Reaction* with the hull still in the water. Furthermore, the addition of preload water allows for *Leg Predriving* to start at reaction levels higher than the *Stillwater Reaction* and for *Preload Reactions* that are higher than those achievable by *Leg Driving* alone.

BEHAVIOR OF 3- AND 4-LEGGED JACKUPS WHILE PRELOADING IN DIFFICULT SITES

For preloading in *Difficult Sites*, and in the absence of waves, *Preloading* in the water is recommended for both 3- and 4-legged jackups, even when a second stage of *Preloading* with the hull completely out of the water is required. The rationale for *Preloading* in the water is the immediate benefit of increased buoyancy if a *PTE* were to occur.

Additionally, it is recommended to use *Single Leg Preloading* for 3-legged jackups in *Difficult Sites*. The benefit of *Single-Leg preloading* is the amount of preload water required to produce a given reaction on the preloading leg is less than would be required for simultaneous preloading and therefore the reduced elevated weight leads to a reduced P-Delta effect in the event of a *PTE* (See Figure 1).

The capacity of a jackup to withstand the effects of a *PTE* (even in the absence of waves) varies significantly with, among other things, water depth, initial (pre-*PTE*) leg penetration, nature of the soil supporting both the punching and non-punching legs, airgap or draft at the start of the *PTE*, hull shape (if buoyancy is involved) and the spacing between the punching and non-punching legs. As would be expected, the presence of waves only exacerbates the loads/stresses from a *PTE*.

The main difference in the behavior of 3- vs 4-legged jackups when encountering non-positive *Soil Stiffness* while preloading is that 3-legged jackups have no redundancy and 4-legged units do. 3-legged jackups will rotate about an axis between the spudcans of the *Adjacent Legs*, while 4-legged jackups will only rotate when 2 or more legs encounter a regression. Even in this case, the 4-legged jackup may or may not rotate, depending on which legs encounter the regression.

The lack of redundancy of 3-legged jackups (for supporting the elevated weight) means that when the 1st of the 3 legs reaches the point of soil capacity regression, there is no immediate re-distribution of leg reactions to balance the weight and as such, the *Initiating Leg* must increase its penetration until equilibrium can be restored. As this happens, the hull and legs will rotate about an axis through the spudcans of the *Adjacent Legs*, inducing a shift in CG towards the *Initiating Leg*. This shift in CG is not a shift relative to the hull itself, but relative to the spudcans. In the absence of hull buoyancy to counteract this shift, the required reaction on the *Initiating Leg* must increase to achieve equilibrium. This increased reaction will further increase the penetration of the *Initiating Leg*.

If the *PTD* is large enough, the *punching leg* and/or its jacking units connecting the leg to the hull can experience extreme loads and may lead to a catastrophic *PTE*.

The reason *Single-Leg preloading* is preferred/recommended for *Difficult Sites* is that if/when a *Leg Run* takes place on 3-legged units, *Hull inclination* follows and it leads to shifts in the position of the CG relative to the center of spudcans, which when combined with the unit's weight introduces the so-called "P-Delta" (or "PΔ") effect. The P-Delta effect is directly proportional to the elevated weight. Therefore, having a lower overall elevated weight (as would be expected when doing *Single-Leg preloading*) has a positive effect on the eventual *PTD* (where equilibrium is reached again) and associated stresses on the leg and loads on the jacking system.

By contrast, when the 1st leg on a 4-legged jackup reaches the point of soil capacity regression, the immediate response is for the *Initiating Leg* to increase its penetration while simultaneously reducing its reaction and inducing a re-distribution of reactions. If the soil is such that it allows for the reactions of the other legs to increase without significant leg penetration and without reaching their own soil capacity regression levels, then equilibrium is reached without the hull incurring noticeable inclination. If the soil conditions are such that increases in leg reactions on the non-*Initiating Legs* are not achievable and one or more of the *Adjacent Legs* enter a soil capacity regression section, then the hull and the entire jackup will rotate, causing the CG to shift with the subsequent increase in required reaction to achieve equilibrium for the *Initiating Leg* and any other legs towards which the CG shifts.

The above implies that for a 4-legged jackup to experience a *PTE*, there must be at least two *Adjacent Legs* experiencing *Leg Run*s. Furthermore, this is more likely to happen if the soil capacity regression is at below or not much greater than the *Stillwater Reaction* value, since if the regression section is for reaction levels above the *Stillwater Reaction*, the chances of a 2nd leg following the *Initiating Leg* in having a *Leg Run* are quite low.

EFFECT OF WIND/WAVES/CURRENT

In addition to introducing lateral loads, environmental loads from wind/wave/current also change the vertical reaction load on the legs due to the induced overturning moment. These effects are considered small due to the fact that *Preloading Operations* are carried out within specified weather windows, usually limited to 15knot to 20knot wind speeds and waves of 2m to 2.5m height. Additionally, most *Preloading Operations* take place with the hull out of the water, and as such wave and current loads act only on the legs, not the hull. When preloading in the water, wave/current loads are not necessarily negligible. Most importantly, wave/current loads can greatly increase if/when a PTE takes place. This is the subject for a different paper. In all simulations presented/discussed herein, it is assumed there is no wind/wave/current at all.

It is also noted that 3-legged jackups do not usually have a large variation on wind or wave load by direction, nor do they have a large variation on effective leg spacing, but that's not the case for 4-legged jackups, which usually have larger length to beam ratios. As such, 4-legged jackups tend to be slightly more sensitive to wind/wave direction than 3-legged jackups.

The degree to which environmental loads cause deviation of leg reactions from those due to gravity alone varies by water depth, hull shape, amount of leg above the deck, cargo, etc. As such, the pre-set environmental limits for performing *Preloading Operations* are not absolute.

While preloading in the water is considered a safer approach for *Difficult Sites*, that is not necessarily true once non-negligible waves are present.

SIMULATING PRELOADING ON *DIFFICULT SITES*

Modeling the Soils

The simulations for this paper were selected with specific intentions in mind. To this effect, specific soil variations for the *Leg Penetration Curves* are used, as described below and seen in Figure 2.

1. **SoilSWR100100** – This is the base soil profile, used to generate other soil profiles. As can be seen in Figure 2, SoilSWR100100 has its Soil Regression at 6,000t (which happens to be the *Stillwater Reaction* for both the 3-legged and 4-legged jackups). The *Soil Regression Extent* is 5.0m, and the *Soil Regression Intensity* is 7,500tm. The modified version of SoilSWR100100 (where the first 4.9m of the leg penetration curve are replaced with essentially zero *Apparent Soil Stiffness* so as to make possible for leg penetrations not decrease when the leg reaction reduces) is referred to as SoilSWRm100100.
2. **SoilSWRPPPRRR** and **SoilSWRmPPPRRR** are simple variations on SoilSWR100100 and SoilSWRm100100, respectively, where the PPP and RRR are percent multipliers. The PPP multiplier is applied to the entire profile, while the RRR multiplier is applied only within the *Soil Regression Section* of the profile. RRR=100% implies no change, and RRR=0 implies no Regression at all. With this naming convention, SoilSWR100100 implies multipliers of 100% for both PPP and RRR, producing a profile identical to the “base soil profile.”

Of the depicted soils, all of them would be considered *Difficult Sites*, except for SoilSWR462100 and SoilSWRm462100, since for this soil profile, the target *Preload Reaction* can easily be achieved without encountering negative slopes in the curves.

It is noted that all simulations performed herein are based on the assumption that the soil behavior is as predicted by the chosen leg penetration curve, even ignoring the standard difference in predictions between the lower bound and the upper bound *Leg Penetration Curves*. This is not quite true in reality.

Time-Domain Models

Representative 3- and 4-legged jackups models were developed using OrcaFlex software (Ref 6). The particulars of the models were chosen to be intentionally comparable (i.e., having similar *Stillwater Reactions*, leg stiffness and presumably similar spudcans and therefore similar *Leg Penetration Curves* when preloading at the same site.

The models have a number of assumptions and simplifications, as listed below:

1. Wind/Wave/Current effects are ignored.
2. Leg weight is assumed to be negligible.
3. Leg properties are based on chord spacing of 12m (39.4ft) and chord area of ~310sqin (0.20sqm).
4. Hulls are modelled as grillage with 3-5 longitudinal beams and 5 transverse beams, with cross-members from each of the intersections. Each of these beams have comparable EA and EI values as the leg members.
5. For buoyancy and hydrostatic stiffness, the effect of the legwells is ignored.
6. Hydrostatic stiffness (and therefore buoyancy) is modelled with a minimal number of non-linear springs located at the leg to hull grillage connection. These springs have no damping.

7. Hull dimensions were selected so as to have S*tillwater Reactions* of 6,000t for both the 3-legged and 4-legged jackups when assuming symmetric or doubly symmetric weight distributions.
8. Both models assume that the CG and CB are located at the center of the legs.
9. *Jacking* speed is assumed to be 0.5m/min.
10. The spudcans are restrained in the horizontal plane. Vertically, they are constrained by non-linear springs representative of the leg penetration curve.
11. The soil springs have a damping component with a damping coefficient of 1,500kN/(m/s), producing a restoring force of ~5,000t at 0.033m/s (with 0.033m/s = 2.0m/min being the speed that would cause a drop of 5m to take 2.5min=150sec if falling at a constant speed).
12. Water Depth is assumed to be 55m (unless otherwise noted).
13. All simulations start with the hull at the arrival draft and the bottom of the legs in the immediate vicinity of the seabed. At this time, 100% of the weight is supported by buoyancy. Upon *Jacking* hull up (or legs down) on all legs to a target draft/airgap the start of the meaningful part of the simulation starts with the legs having penetrated the soil that produces static equilibrium.
14. Since the initial part of the simulation is of no relevance to the preloading process, this initial *Jacking* is performed using *Jacking* speeds much greater than the assumed 0.5m/min *Jacking* speed of the jackups. In order to ensure that if/when the leg reaction values are reduced from the initially-achieved values, the *Leg Penetration Curves* used in these models are the modified profiles. This initial part of the simulation is performed over 360 seconds, prior to the designated (official) start time (i.e., all simulations start at t=-360sec), and all results of interest are between t=0 and t=1,000sec.
15. The simulations use a time step of 0.1sec, with results reported at 10-sec intervals.
16. For 3-legged jackup models, preloading is simulated by adding a gradually-increasing load (or combination of loads) at the hull level to represent the weight of the preload water. The rate at which the preload water weight increases in these models is much faster than real pumping times, but this speed is of no consequence to the results.
17. For *Simultaneous Preloading*, equal loads are added in the immediate vicinity of each of the leg-to-hull connections.
18. For *Single-Leg Preloading*, the gradually increasing load is applied only in the immediate vicinity of the leg-to-hull connection for the leg being preloaded.
19. For 4-legged jackup models, *Active Leg Driving* (*Predriving* or *Preloading* as the case may be) is simulated by *Jacking* hull up (or leg down) on the designated diagonally-opposite pair of legs at the assumed 0.5m/min speed for the jackups, while *Passive Leg Driving* is simulated by *Jacking* hull down (or leg up) on the designated diagonally-opposite pair of legs. The speed of this *Jacking* was assumed to be much slower than 0.1m/min (i.e., 20% of the assumed speed of *Jacking* for the jackups).
20. For these simulations, when any *Jacking* is stopped, it is assumed to be immediate.

Parameters of Interest

1. Leg Penetration, Leg Reactions, and Hull-to-Leg Connection Elevations are obtained directly from the simulation results.
2. *Hull inclination* and Leg Penetration Speed are derived from the simulation results.
3. Given the 10-sec time intervals for the output, the calculated hull rotations and leg penetration speeds are not necessarily instantaneous values, but representative values.
4. *Hull inclination* (rotation about the x- or y-axis) is derived from the hull-to-leg connection elevations and the known leg spacing values.
5. When calculating rotation about the longitudinal axis (θ_y), the average elevations of the port and of the starboard legs are used.
6. When calculating rotation about the transverse axis (θ_x), the average elevations of the forward and aft legs are used.

7. Leg penetration speed is calculated from the difference in leg penetrations at the 10-sec time intervals of the results.
8. When the leg penetration speed on a given leg exceeds the assumed *Jacking* speed (0.5m/min for this paper), the leg is having a run.
9. If, as a consequence of a leg or legs having a run, there is a *PTE*, then its duration is determined from the time segment with continuous *Leg Penetration Speed* greater than the unit's *Jacking* speed and a *Hull Inclination* exceeding ½ degree.

Simulations Considered
The simulations are divided into four sets, each having different intentions, as outlined in Table 2. Variations within a given set of simulations are referred to as Cases. The results of the simulations are presented in three forms, as listed below.

- Figures 5 to 11 show comparisons of results on the critical leg from various sets or subsets of simulations. For those results, the key leg was identified as the one which experienced the highest leg penetration speed. These Figures all have five graphs, labeled (a) to (e) for ease of reference. Since *Hull Torsion* is not an issue on 3-legged jackups, the (d)-graphs show reaction vs time as opposed to *Hull Torsion* vs time for the 4-legged jackups. The other four graphs are all for the same parameters. Some of the Figures have numbered clouds, included to call attention to a particular result or issue specifically mentioned in the discussion section below.
- Figures 12 to 15 show results for all legs, but only for one case of each set of simulations. This is done in the interest of brevity. Similar Figures were produced for each of the simulations and can be made available (along with animations of selected results, by reaching out to the corresponding author).
- Table 3 shows a summary of peak values for *Leg Reaction*, *Leg Penetration*, *Hull Inclination, Leg Penetration Speed* and, *Hull Torsion (for 4-legged jackups only), Duration of Leg Run, Duration of Punch Through* and *Apparent Speed of Punch Through*.

DISCUSSION OF RESULTS

Simulations 3L1-A to 3L1-C: Simultaneous of 3-legged jackup in Good Soil
Figure 5 shows the results the simulations for preloading a 3-legged jackups in good soil. While these simulations are in good soil, the soil conditions are slightly different under different legs. As a result, even the case simulating Simultaneous Leg Preloading has non-negligible Hull Inclination (0.4 degrees). When Single Leg Preloading is performed, Hull Inclination exceeds the 0.5-deg threshold at t=240sec. Simulations 3L1-B and 3L1-C show the effect of ignoring Hull Inclination and the effect of making one adjustment.

A review of the 3L1-C results shows a curious cluster of data points in the (c)-graph (see cloud I in Figure 5) This reduction in leg penetration as the hull is re-leveled is an "issue" with the OrcaFlex models used for these simulations, which do not have the capacity to account for the fact that leg penetration does not reduce when leg reactions decrease after having reached a given value. This issue can be corrected by using PYTHON scripts (a feature of OrcaFlex) to model the soil springs, but that option was not implemented in the present simulations (Ref 6). The issue could also be addressed by using multiple springs to represent the soil and deactivating them at appropriate times of the simulation. Since in this case, preloading resumes and the leg penetration increases again, this issue is of no consequence to the final results and no attempt was made to correct it.

Something else to note in the (c)-graph of Figure 5 is the fact that between t=350sec and t=500sec, the hull inclination was actually negative, but the plots are showing absolute values (see cloud II). The negative Hull Inclinations were the result of purposefully having performed the Differential Jacking to not just level the hull but to start at a slight angle with the bow up, in anticipation of further inclination once the Preloading Operation continues. As can be seen, however, that was not enough, and a second pause should have carried out around t=720sec. Since this adjustment was not carried out, the final Hull Inclination for this simulation was 0.95 degrees.

From the (d)-graphs in Figure 5 and Table 3, it can be seen that Peak reactions are slightly larger than the target value of 11,500t. Furthermore, these values are different for the three cases (11,892t for the *Simultaneous Preloading* case, 12,624t for the *Single Leg Preloading* case that disregarded hull inclination and 12,262t for the case when one *Hull Inclination* correction was performed). This is attributed to the final *Hull Inclination* (with its associated shift in CG relative to the aft legs). These peak values are short-lived, as they occur because in these simulations, the speed at which preload water was being added was much higher than realistically possible, and the leg penetration speed was exaggeratedly high, and having a small contribution from damping all the way through he PTE, until the legs finally came to rest at the final penetration.

Simulations 4L1-A to 4L1-C: Simultaneous of 4-legged jackup in Good Soil
Figure 6 shows the results the simulations for preloading a 4-legged Jackups in good soil. Simulations 4L1-A and 4L1-B are for *Active and Passive Preloading*, respectively. Both of these simulations are for models with hull having the stiffness mentioned above. Simulation 4L1-C is for Active Preloading, but with hull members having half as much stiffness as the base model. In all of these cases, the legs being preloaded are the AS/FP legs.

The (d)-graph shows that, as expected, there is a difference in peak *Hull Torsion* between simulations 4L1-A and 4L1-C, due to the different stiffness values of the hull members.

Simulations 3L2-A to 3L2-D: Simultaneous to Compare Peak Leg Penetration Speed vs Damping and when Ignoring Buoyancy
Figure 7 shows the results for the simulation of *Single Leg Preloading* of 3-legged jackups in a *Difficult Site*. This site (hereafter referred to as *Difficult Site 2*) is particularly difficult in that R_{r0} is within 5% (lower) than the *Target Preload Reaction*, plus the fact that it has weaker soil with higher *SRI* value under the forward legs (SRI = 50%, SRI_{PT} = 96.5%) than under the aft legs (SRI=10%, SRI_{PT} = 99.1%).

Simulation 3L2-A is the base case (with damping of 1,500t/(m/s) as listed above, and accounting for buoyancy once part of the hull enters the water. Simulations 3L2-B and -C have damping coefficients of 500t/(m/s) and 2,500t/(m/s), respectively. Simulation 3L2-D is similar to simulation 3L2-A, but the effects of buoyancy are ignored.

From the (e)- graphs in Figure 7 and Table 3, the differences in *Leg Penetration Speeds* are evident, and as expected. Also as expected, with no buoyancy effects, the post-PTE reaction and penetration values are higher, inducing higher PTD values than when buoyancy was included. These effects would be more pronounced if instead of starting with a 1m airgap, other airgap (or draft) values were used to start the preloading.

Simulations 3L2-E and 3L2-G: Simultaneous to Compare Peak Single Leg vs Simultaneous Preloading and Leg Being Preloaded
Figure 8 shows the results for the simulation of *Single Leg Preloading* of 3-legged jackups in *Difficult Site 2*. The difference between Simulation 3L2-E and the base case is that the jackup was re-oriented 180 degrees so that as the forward leg is being preloaded, it now experiences its PTE on the soil that has *SRI*=10% (whereas the base case had *SRI*=50% for the soil under the forward leg). At the end of the process, both simulations have the same final reaction and inclination, but the simulation with the more severe SRI (i.e., Simulation 3L2-A) had reached higher Leg Penetration Speeds and had a shorter *PTE* duration.

Simulation 3L2-F has the same jackup orientation as the Simulation 3L2-E, but this time, the port leg is being preloaded. As such, the pertinent comparison is to simulation 3L2-A (since that was the case where the soil under the leg being preloaded had SRI=50%). Because of the jackup's leg spacing (LLS=39m and TLS=45m), the distance from the port leg to the other two legs (38.95m) is essentially the same as the distance between the forward leg and the aft legs (i.e., LLS=39.0m). Therefore, the results for Simulation 2L2-F are essentially the same as for those for Simulation 3L2-C. The slight differences in final reactions are due to the fact that in Simulation 3L2-A the two non-preloading legs had the same "slightly better" soil with SRI_{PT}=99.1%, whereas in Simulation 3L2-F, the non-preloading legs had different soils under them. That minor difference means that PTD (if measured from the difference in penetration of the leg that had the PTE and the average penetration of the other two legs), is slightly lower for Simulation 3L2-F. Table 3 also shows a difference in peak Hull Inclinations (6.6 degrees vs 7.7 degrees). That is due to the way in which Peak Hull Inclination was defined (as the largest of $|\theta_x|$ or $|\theta_y|$), indicating that perhaps a better definition is in order.

Simulation 3L2-G has the same jackup orientation as Simulation 3L2-A, but this time, *Simultaneous Preloading* is being performed. As can be seen, the final reaction and leg penetration values for this simulation are noticeably higher than those of the base case. The reason is the extra elevated weight and associated increase in the P-Δ effect.

Simulations 3L2-H and 3L2-I: Simultaneous to Compare the Effect of Water Depth
Figure 9 shows the results for the simulation of *Single Leg Preloading* of 3-legged jackups in *Difficult Site 2*, in three different water depths (55m for the base case, 75m for Simulation 3L2-H and 35m for Simulation 3L2-I. As expected, the case with the largest water depth had the largest final reaction and leg penetration values.

Simulations 4L3-A to 4L3-C: Simultaneous of 4-legged jackup in Difficult Site 2
Figure 10 shows the results for the simulation a 4-legged jackup in *Difficult Site 2*. The simulations correspond to *Active Preloading* starting at 1m airgap (4L3-A), *Active Preloading* after having added 4,000t of preload water and starting at 1m airgap (4L3-B), and *Active Preloading* after having added 4,000t of preload water, but starting at 0.3m draft (4L3-C). In all cases, the legs being preloaded are the AP/FS legs. The results for Simulation 4L3-A are seen to have discontinuities for the short segment of time 310sec $\leq$ t $\leq$ 350sec, which corresponds to leg penetrations between 7.2m and 7.6m for the AP/FS legs (see cloud I in Figure 10). Though not explicitly shown in Figure 10, these discontinuities occur because the reaction on the non-preloading (AS/FP) legs have reduced below 1,000t and as such they have moved to the section on the modified soil profile which has negligible *Apparent Soil Stiffness* for penetrations shallower than 4.8m (see cloud I in Figure 10). While this issue is related to the way in which the soil is modelled (unable to have leg reactions decrease without inducing a reduction in leg penetration), in this case it has more to do with the SRI_{TP} value being so close to 100% (99.1%), but more importantly almost half the elevated weight, inducing almost zero reactions on the non-preloading legs. This behavior (both real and due to the simplification of the modelling) goes away once 4,000t of preload water is added prior to performing the preloading, as seen in the results for Simulations 4L3-B and 4L3-C.

It is noted that while peak *Leg Penetration Speeds* exceeded the 0.5m/min threshold for the simulations performed at 1.0m airgap, *Hull Inclinations* were quite low for all cases. Therefore, Simulations 4L3-A and 4L3-C had *Leg Runs*, but none of these cases had *PTEs*.

Finally, it is noted that while Simulation 4L3-A had a short period of time when the reaction reached the target preload value of 11,500t, the final reaction came short of reaching the target preload. For the other two simulations with the 4,000t of preload water, the final reaction easily reached the *Target Preload Reaction*, even after the effects of damping faded away (see Table 3 and cloud II in Figure 10).

Simulations 4L4-A to 4L4-G: Simultaneous of 4-legged jackup in Difficult Site 3
Figure 11 shows the results for the simulation of a 4-legged jackup in a *Difficult Site*. This site (herein referred to as *Difficult Site 3*) is particularly difficult in that it has *SRI*=50% and SRI_{SW} values of 80% (forward legs) and 90% (aft legs) for the *Stillwater Reaction* of 6,000t.

For Simulation 4L4-A, jacking hull up is set to continue until a positive airgap, disregarding the any soil information (or perhaps not having had access to soil information) and also disregarding the response of the jackup. (This, of course, is not standard practice). As expected, the forward legs enter the *Soil Regression Section* before the aft legs do, and that induces *Hull Inclination* which in turn causes the CG to shift towards the forward legs, increasing the required reaction to reach equilibrium and increasing their *Leg Penetration Speed*. Eventually, the aft legs catch up with the forward legs and after having experienced a short-lived *PTE*, by the time the hull reaches a positive airgap, both the *Leg Penetration Speed* and the *Hull Inclination* values are low.

Simulation 4L4-B starts the same way as Simulation 4L4-A, but upon exceeding the 0.5-deg *Hull Inclination* threshold, jacking stops. The results are not much better as far as the jackup experiencing a short-lived ***PTE***. The main differences between these two cases is that when jacking stopped, the peak *Leg Penetration Speed* was lower than when it did not, but the peak *Hull Inclination* remained essentially the same. Not only that, but the amount of time that the *Hull Inclination* exceeded the 0.5-deg threshold was higher for the case when jacking was stopped than when it was not.

Simulations 4L4-C to 4L4-E show the benefits of *Leg Predriving*. For these cases, the legs being predriven are the AS/FP legs. The differences among these three cases is the amount of hull weight (representing variations of +/-1,000t of cargo weight from the 4L4-A simulation). While all cases have *Leg Runs*, none of them experience a *PTE*, although they came close.

The results for simulations 4L4-F and 4L4-G are not easily compared in the same way as the previous cases, since more than one leg is of interest. For that reason, the format of Figure 12 is different than the previous comparisons. These two simulations show the (possible) extreme consequences of not performing *Leg Predriving* (at positive draft) before performing *Leg Preloading* (at positive airgap) when having slightly different soils under different legs and "particularly" difficult soils.

Both simulations have the same soils are used as for Simulation 4L4-A, but the elevated weight (representing a light cargo condition) is reduced and the corresponding *Stillwater Reaction* was changed from 6,000t to 4,700t. With this lower *Stillwater Reaction*, the SRI_{SW} values are changed (from 80% and 90% on the forward and aft legs) to 102% and 115%) so as to allow for the hull to be jacked up out of the water without incident.

For Simulation 4L4-F, once at 1m airgap, *Active Leg Preloading* of the AS/FP legs begins, but within 30 seconds, the FP leg starts to experience a *Leg Run* (see cloud I in Figure 12). As *Leg Preloading* continues on the AS/FP Legs (since Hull Inclination is well below the threshold of 0.5 degrees), their reactions continue to increase. By t=110sec, the *Hull Inclination* (about the longitudinal axis) reaches 0.5deg with the average *Hull Elevations* being 0.92m and 1.22m on the port and starboard legs, respectively. Because *Hull Inclination* reached the 0.5-deg threshold, *Leg Preloading* stops, but not before the start of the *PTE* with the 4-legged jackup behaving in a similar manner as a *3-legged jackup* (i.e., having CG shifts due to *Hull Inclination* that require higher reactions on the *Initiating Leg* to achieve equilibrium). So, despite the fact that *Active Leg Preloading* stopped at t=110sec, the *Leg Runs* continue and the *Hull Inclination* continues. The PTE ends when the forward legs have reached leg penetrations in excess of 7m. At that time, the leg penetration on the aft legs (which had the "stronger soil") remain near their starting 5.0m penetration level.

In this simulation, the final *Hull Inclination* was found to be 3.05 degrees. However, this value is slightly higher than it should be due to the modelling issues which allow the leg penetration on the AS leg to reduce as its reaction is reducing by ~0.5m between t=120sec and t=220sec. If a simple 0.5m correction on the *Hull Elevation* of the AS leg is made, the final Hull Rotation Angle would be 2.8 degrees. However, since part of the hull made it into the water plus the fact that with the reduced *Hull Inclination*, the shift in CG relative to the aft spudcans would have been less, even the 2.8-deg estimate is conservative. This issue will be investigated at a later time. However, these results – even if not totally correct – are included herein to make the point that these *PTEs* can happen.

Simulation 4L4-G is similar to Simulation 4L4-F, but assuming the jackup was rotated 90 degrees (and therefore the port legs have different soil under them than the starboard legs. As expected, a similar *PTE* takes place, but the final Hull Inclination increased from 3.05deg to 4.48deg (i.e., an increase of 46%). This is as should be expected, given the difference leg spacing for the jackup which has LLS/TLS = 1.44).

Complete results from simulations 4L4-F and 4L4-G are presented in Figures 17 and 18. Figures 13 to 16 are self-explanatory and no discussion is offered (in the interest of brevity).

SUMMARY

This paper covers the key differences in preloading of 3-legged vs 4-legged jackups. For this purpose, the authors seek to establish clear and specific terminology used to describe both preloading and *Punch Through Events ("PTEs")*. The authors acknowledge that while most of this material is common knowledge to many in the offshore industry there is still a need to for clear and updated definitions of certain terms, as some of those terms (originally developed for 3-legged jackups) may not be fully applicable to 4-legged jackups. The authors further acknowledge that many in the industry have developed their own terminology and do not dispute the validity of those definitions. However, referring to the same thing using different names allows for confusion when discussing preloading and/or *PTEs*.

In addition to the above, simulations were created to capture the behavior of 3- and 4-legged jackups while preloading.

- The first set of simulations focused on a site with good soil.
- The second set of simulations focused on parameters that change the Leg Penetration Speed during a *PTE*.
- The third set of simulations focused on the preloading of a 4-legged jackup on a *Difficult Site* where the soil capacity at the start of the soil regression section of the leg penetration curve is very close to the target *Preload Reaction*. These simulations show the possible benefits of having the ability to use preload water on a 4-legged jackup, as it allows for reaching higher levels of *Preload Reaction* and even allowing the possibility of doing so with the hull in the water.
- The fourth set of simulations focused on the benefits of *Leg Predriving* on sites with soils having *Soil Regression Sections* with local peak reaction below the *Stillwater Reaction* and also having 10% variation in capacity for the soil under the forward legs and under the aft legs.

All simulations are intended to be representative and many approaches other than those considered herein could be taken to make those same points and/or to improve the validity of the results. While the models developed in OrcaFlex are meaningfully valid, they do lack the capacity to maintain leg penetration values after having reached a reaction level and then experiencing reductions in reaction. This issue will be addressed in an updated version of this paper that will use PYTHON scripts to enforce the desired behavior.

The chosen simulations and their results offer insights as to the behavior of both 3-legged and 4-legged jackups when performing *Preloading Operations*, confirming a number of assertions made in the earlier sections of this paper. Overall, the response of a 3-legged jackup being preloaded at a *Difficult Site* is more easily predictable (if the soil information is to be trusted) than the response of a 4-legged jackup. The redundancy of a 4-legged jackup offers the possibility of driving the legs through the *Soil Regression Section* of the leg penetration curve without the jackup experiencing a *PTE*. However, 4-legged jackups can certainly go through *PTEs*, especially if the characteristics of the site are not well known, or deviate from the expected characteristics.

While this paper does not delve into the specifics of mitigation techniques, it is clear that some actions may lead to more dire consequences. Jackup operators must account for the risk of a *PTE* and plan accordingly, whether they are of the 3- or 4-Legged type. Some sites are simply too risky for *Preloading Operations* and as such, it would be expected that a *Site Specific Assessment* would indicate that preloading (and therefore operating) at such sites is not to be performed.

CONCLUSIONS

In the absence of buoyancy and environmental loads (from wind, waves or current), when the soil's capacity under a given leg (the *Initiating Leg*) starts to reduce with penetration as that leg enters the *Soil Regression Section* on the leg penetration curve, this is what can happen:

1. **On a 3-legged Jackup**, that *Initiating Leg's* penetration increases, and (unless the other two legs also enter soil regressions and penetrate the soil at the same rate), the Jackup will rotate about the spudcans of the *Adjacent Legs*. In turn, this will cause the hull to move away from the supports of the *Adjacent Legs* (i.e., towards the *Initiating Leg*), requiring an even higher reaction on the *Initiating Leg* to achieve equilibrium. This means that the leg will penetrate through *Soil Regression Section* of the soil (since there is no help from buoyancy in this scenario) and beyond it until the soil is capable of providing the reaction needed to achieve equilibrium.

2. **On a 4-legged Jackup**, the *Initiating Leg's* penetration will start to increase, but as soon as it does, it will also induce *Hull Deformation* and due to the redundancy, initiate a load redistribution (i.e., part of its load will transfer to the *Adjacent Legs*), by virtue of being connected to a hull which has stiffness. As such, the effect of a decrease in reaction on the *Initiating Leg* can be thought of as having a downward force applied to a Jackup which only has 3 usable legs (since the *Initiating Leg* is not capable of providing the needed reaction to maintain equilibrium), with an overhang load. From here, a number of things can happen. These are two bounding extremes:

A) The *Adjacent Legs* have sufficient soil capacity to accept the required increase in reaction to achieve equilibrium with minimal (or in the best extreme case, zero) additional penetration (and in the process reducing the reaction on the leg that is diagonally-opposite to the *Initiating Leg*). So, in this case, even if the *Initiating Leg* has a non-negligible increase in leg penetration relative to the other kegs (since the hull is not infinitely stiff), it induced mostly *Hull Deformation*, as opposed to pure *Hull inclination*. Therefore, equilibrium can be reached without the need for the reaction on the *Initiating Leg* to increase.

Or,

B) one or more of the *Adjacent Legs* is/are at a position where the soil under it/them lacks the capacity to accept the increase in reaction needed to achieve equilibrium. For that to happen (i.e., for any of the Adjacent Legs not to have the capacity to accept an increase in reaction without experiencing a non-negligible increase in penetration), the leg(s) must have been on the brink of entering a *Soil Regression Section* of their own. As this takes place, there will be at least a 2nd leg entering the *Soil Regression Section*. Then, the *Initiating Leg* and one or more of the *Adjacent Legs* will increase their penetration values (though not necessarily by the same amounts), inducing *Hull inclination* with an associated shift in CG towards the penetrating legs and therefore increasing the required reaction needed to maintain equilibrium (much in the same way as happens on 3-Legged Jackups). In subsequent discussions, this is referred to as *Scenario 2B.*

The authors envision two possible sets of conditions that would lead to *Scenario 2B*, as listed below.

Possible Condition Set 1, leading to Scenario 2B

- Assume that the site has soils with *Soil Regression Sections* that have local peak reaction values lower than the *Stillwater Reaction*.
- Further assume that the soil conditions are also slightly different for at least two sets of legs (either the forward and aft legs, or the port and starboard legs).
- Perform simultaneous hull-up *Jacking* to bring the hull out of the water.
- As *Jacking* hull up takes place, if the *Soil Regression Sections* have sufficient intensity, *Leg Runs* may take place, and if the reactions and soils are not equal on all legs, *Hull Inclinations* will also happen, creating the conditions suitable for short-lived *PTEs*. If, through all this, simultaneous *Jacking* hull-up continues, the legs will go through their respective *Soil Regression Sections* and eventually the hull will have a positive airgap, with all legs fully supported by the soil and in many such cases, the hull will even be close to having no inclination.

Possible Condition Set 2, leading to Scenario 2B

- Assume that the site has soils with *Soil Regression Sections* that have local peak reaction values slightly higher than the *Stillwater Reaction*.
- Further assume that the soil conditions are also slightly different for at least two sets of legs (either the forward and aft legs, or the port and starboard legs).
- Assume there was no *Leg Prediving* prior to having the hull at a positive airgap.
- Perform simultaneous *Active Leg Preloading* on either the AP/FS or the AS/FP legs.
- Unbeknownst to the operator (as they would have otherwise performed *Leg Predriving* prior to reaching a positive airgap), all legs are sitting on the brink of their respective Soil Regression Sections. Therefore, almost immediately after *Leg Preloading* starts, one of the *Preloading Legs* will enter its *Soil Regression Section*, necessitating increases in reaction on its *Adjacent Legs* to maintain equilibrium. But, given the assumed small differences in soil capacities at this site, one of the *Adjacent Legs* will enter its *Soil Regression Section*. Then, If the *Soil Regression Sections* have sufficient intensity, *Leg Runs* as well as *Hull inclination* will take place. As *Hull inclination* takes place with the accompanying shift in CG relative to the spudcans and necessitating increases in leg reaction to maintain equilibrium can happen the conditions are suitable for the 4-Leggd Jackup to behave in a comparable way as a 3-legged Jackup and likely experiencing a *PTE*.

Given the number of assumptions listed in the above two sets of conditions to produce *Scenario 2B*, it is not surprising that some people think and have stated that 4-legged jackups can't have *PTEs*. While *PTEs* for 4-legged jackups are rare, they are not impossible, especially if *Jacking* and/or *Preloading Operations* are not performed with the appropriate care and valid information on the site. The reason *PTEs* are rare on 4-legged jackups, is that it would require a site with *Soil Regression Sections* that fall within close proximity of the *Stillwater Reaction(s)*, as that would be the only way that once an *Initiating Leg* enters a *Soil Regression Section*, at least one of the *Adjacent Legs* also enters a *Soil Regression Section* from a relatively small increase in required reaction to maintain equilibrium.

Stated in a different way, one could say that it would require either *Jacking* without regard for the soil conditions, or an unfortunate set of soil conditions with soil regressions in the vicinity of the *Stillwater Reaction* for 4-legged jackups to experience a *PTE*.

Having said that, proper *Leg Predriving* (i.e., *Leg Driving* with the hull at positive draft) to reach reaction levels well over the *Stillwater Reaction* before ever coming out of the water can greatly improve the odds for avoiding even short-lived *PTEs* on a 4-legged Jackup.

Another key aspect needed for making the appropriate assessment of risk for future and as-performed *Preloading Operations* of both 3-legged and 4-legged jackups is having accurate soil information with which can be trusted to predict the leg penetration vs reaction behavior. One way to improve these predictions is to capture not just the final leg penetration and preload reaction levels achieved, but the as-experienced reaction levels vs leg penetration on each of the legs as they were being preloaded, AND share this information with the engineering teams preparing the leg penetration curves so they can improve their models.

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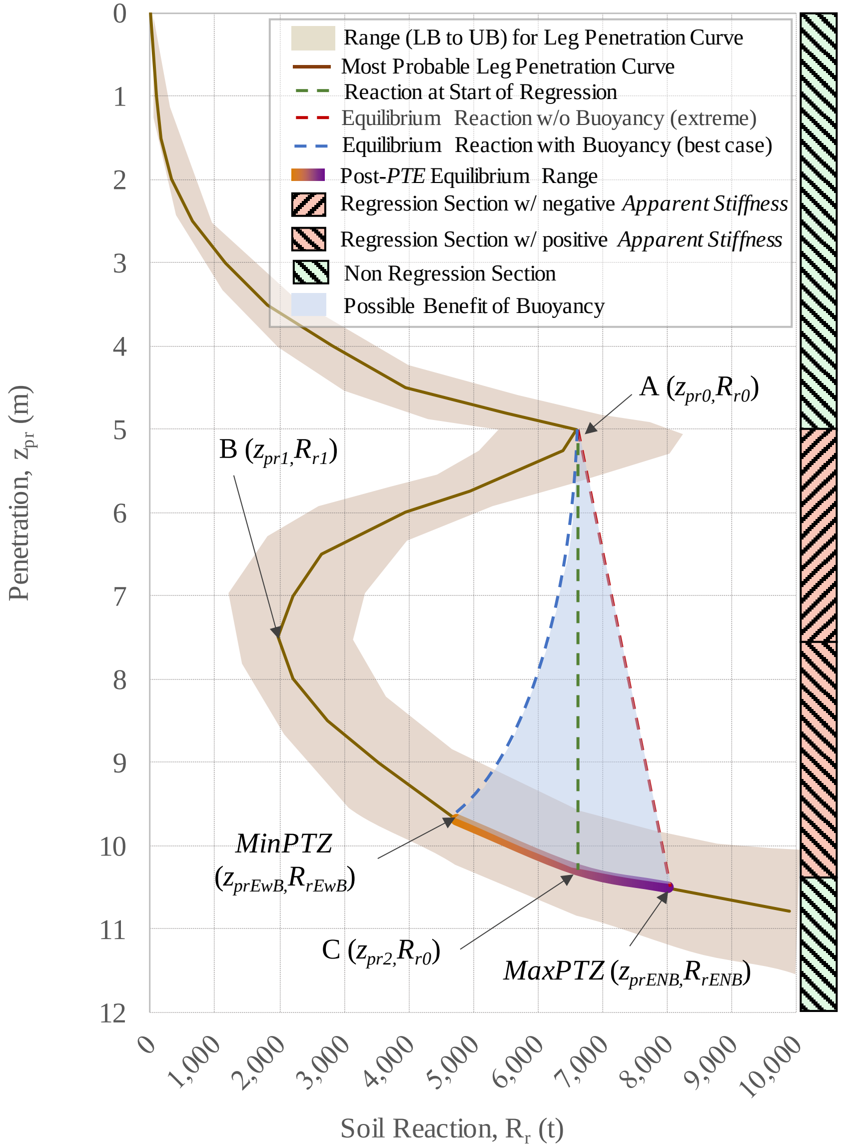
FIGURES



A - Start of the Regression Section, at leg penetration z_{pr0} and reaction R_{r0}.

B - Transition Point within *Regression Section* (where *Apparent Stiffness* becomes positive), at leg penetration z_{pr1} and reaction R_{r1}.

C - End of *Regression Section*, at leg penetration z_{pr2} and reaction R_{r0}.

Post-*PTE* Equilibrium Range covers the possible range for *Leg Penetrations* immediately after a *PTE*. The actual *Leg Pentration* where the jackup comes to rest is a function of deployed leg length, hull weight, the extent of benefits from buoyancy (if any) and for 3-legged jackups whether *Single Leg or Simultaneous Preloading* was being carried out.

MinPTZ - This point represents the post-*PTE* equilibrium position with the maximum contribtion of buoyancy.

MaxPTZ - This point represents the post-*PTE* equilibrium position with no contribtion of buoyancy at all.

In this example,
A: (z_{pr0},R_{r0}) = (5m, 6,600t)
B: (z_{pr1},R_{r1}) = (7.5m, 1,980t)
C: (z_{pr2},R_{r0}) = (10.3m, 6,600t)

Soil Regression Extent, *SRE* = z_{pr2} - z_{pr0} = 10.3m - 5.0m = 5.3m.
Soil Regression Intensity, *SRI* = *1* - R_{r1} / R_{r0} = 1 - 1,980t/6,600t = 70%

At *MinPTZ*:
(z_{prEwB},R_{rEwB}) = (9.70m, 4,730t)
Associated *Punch Through Drop* = 9.7m-5.0m = 4.70m.

At *MaxPTZ:*
(z_{prENB},R_{rENB}) = (10.51m, 8.000t)
Associated *Punch Through Drop* = 10.51m-5.0m = 5.51m.

Figure 1 – Leg Penetration Curve with Soil Regression Showing Possible Post-*PTE* Equilibrium Positions

	Base Profiles		Site 1		Site 2		Site 3	
PPP	100%	100%	462%	462%	190%	190%	80%	90%
RRR	100%	100%	100%	100%	20%	100%	100%	100%
Penetration (m)	SoilSWR100100	SoilSWRm100100	SoilSWR462100	SoilSWRm462100	SoilSWRm190020	SoilSWRm190100	SoilSWRm080100	SoilSWRm090100
0.00	0	0	0	0	0	0	0	0
2.00	650	65	3,000	300	124	124	52	59
2.90	1,235	124	5,700	570	235	235	99	111
3.00	1,300	130	6,000	6,000	247	247	104	117
3.50	1,800	180	8,308	8,308	342	342	144	162
4.00	2,400	240	11,077	11,077	456	456	192	216
4.50	3,600	360	16,615	16,615	684	684	288	324
4.80	4,800	480	22,154	22,154	912	912	384	432
4.90	5,400	540	24,923	24,923	1,026	1,026	432	486
4.95	5,800	5,800	26,769	26,769	11,020	11,020	4,640	5,220
5.00	6,000	6,000	27,692	27,692	11,400	11,400	4,800	5,400
5.25	5,800	5,800	26,769	26,769	11,324	11,020	4,640	5,220
5.75	4,800	4,800	22,154	22,154	10,944	9,120	3,840	4,320
6.00	4,300	4,300	19,846	19,846	10,754	8,170	3,440	3,870
6.50	3,500	3,500	16,154	16,154	10,450	6,650	2,800	3,150
7.00	3,100	3,100	14,308	14,308	10,298	5,890	2,480	2,790
7.50	3,000	3,000	13,846	13,846	10,260	5,700	2,400	2,700
8.00	3,200	3,200	14,769	14,769	10,336	6,080	2,560	2,880
8.50	3,600	3,600	16,615	16,615	10,488	6,840	2,880	3,240
9.00	4,200	4,200	19,385	19,385	10,716	7,980	3,360	3,780
10.00	6,000	6,000	27,692	27,692	11,400	11,400	4,800	5,400
11.00	9,000	9,000	41,538	41,538	17,100	17,100	7,200	8,100
12.00	15,000	15,000	69,231	69,231	28,500	28,500	12,000	13,500

R_{r0} (t)	6,000	6,000	27,692	27,692	11,400	11,400	4,800	5,400
R_{r1} (t)	3,000	3,000	13,846	13,846	10,260	5,700	2,400	2,700
SRI	50%	50%	50%	50%	10%	50%	50%	50%
SRI_{SW} (1)	100%	100%	462%	462%	190%	190%	80%	90%
SRI_{TP} (2)	52%	52%	241%	241%	99%	99%	42%	47%

Notes

1. Relative to a *Stillwater Reaction* of 6,000t
2. Relative to a *Target Preload Reaction* of 11,500t

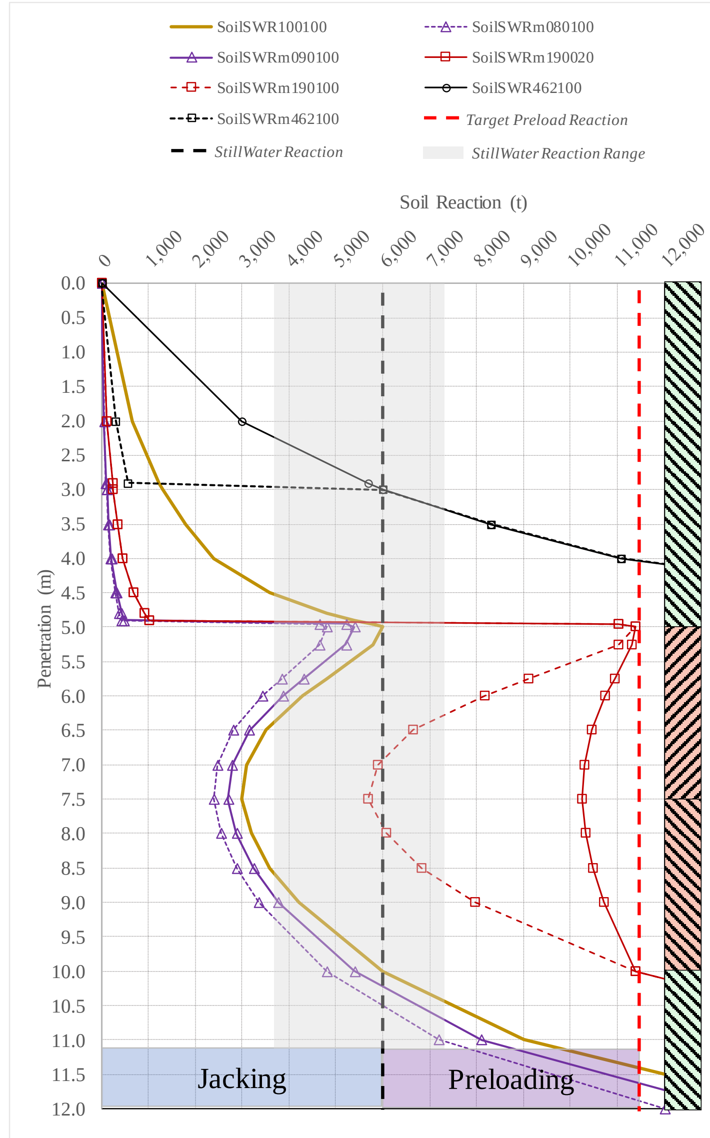


Figure 2 – Representative Leg Penetration Curves

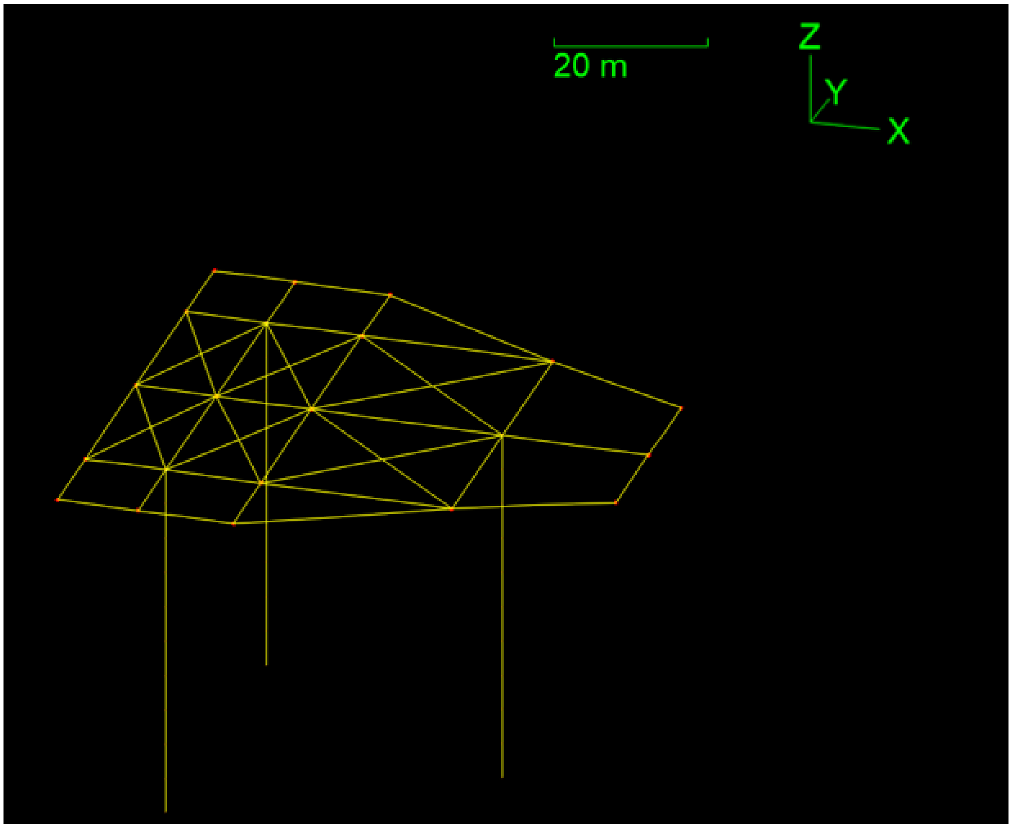


Figure 3 – OrcaFlex Model of 3-Legged Jackup

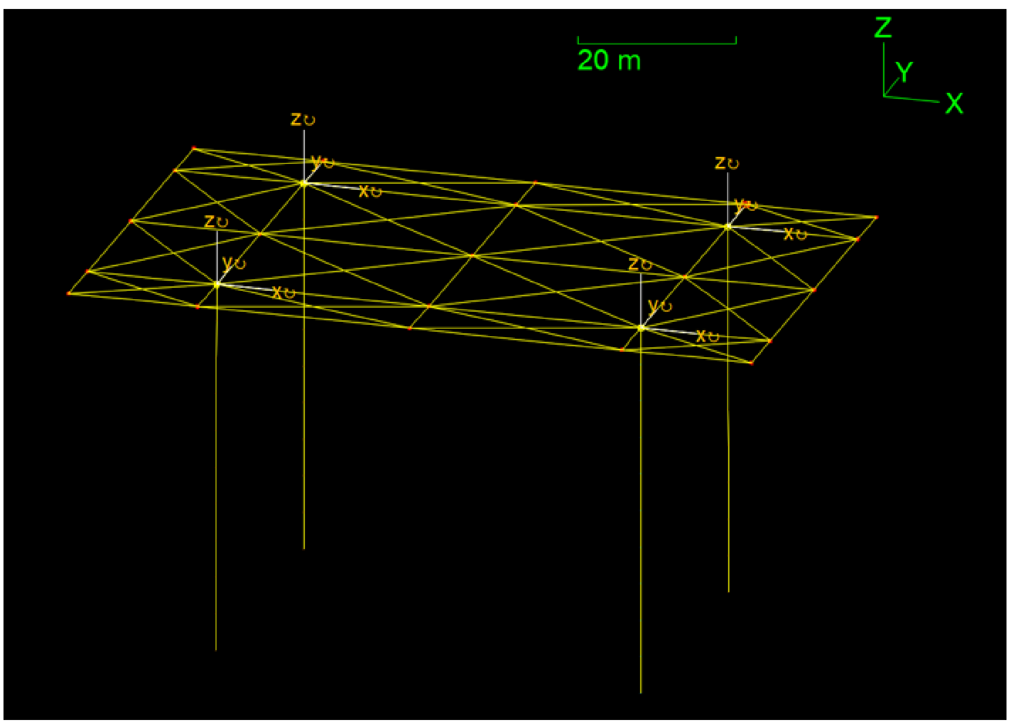
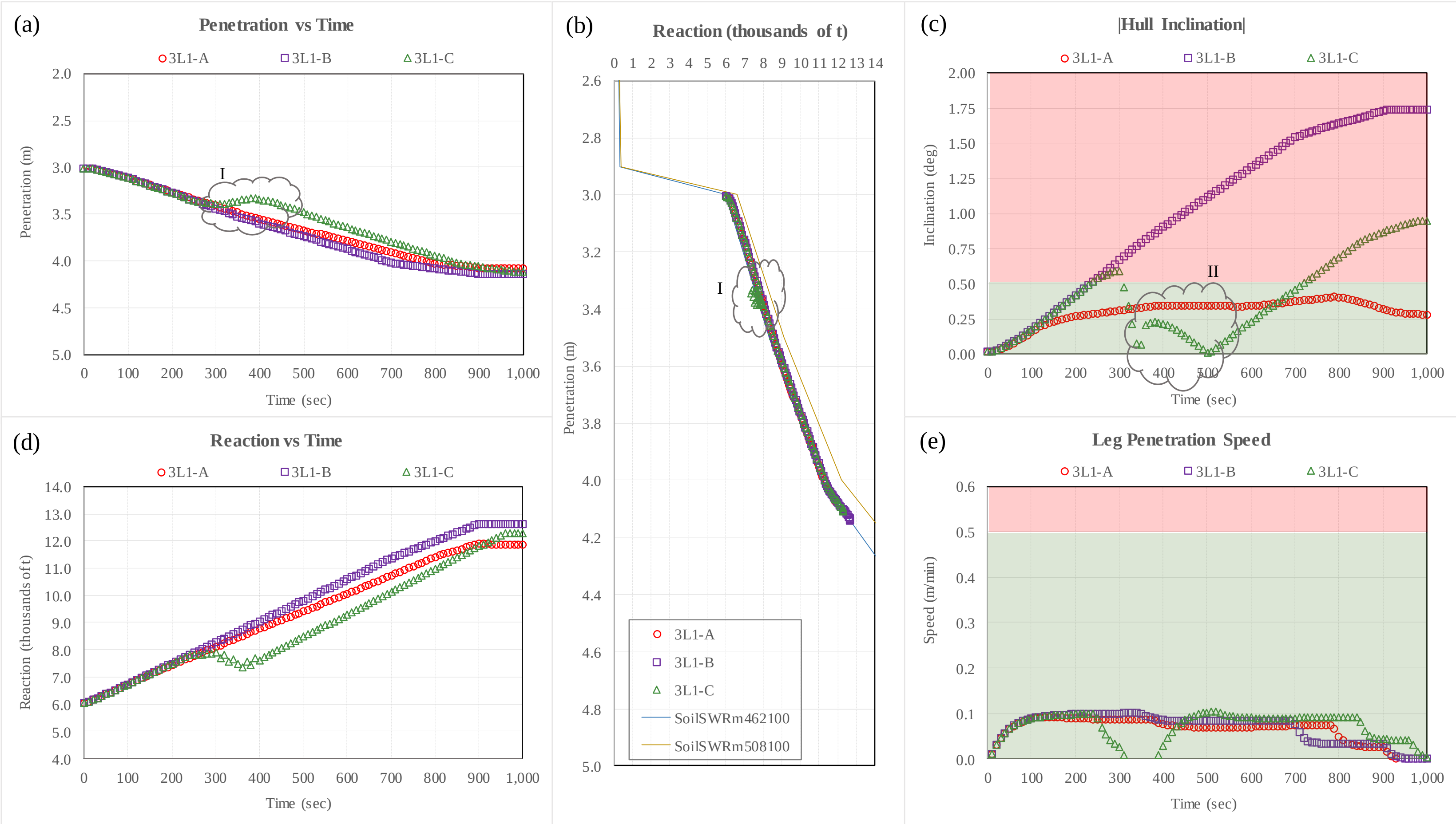
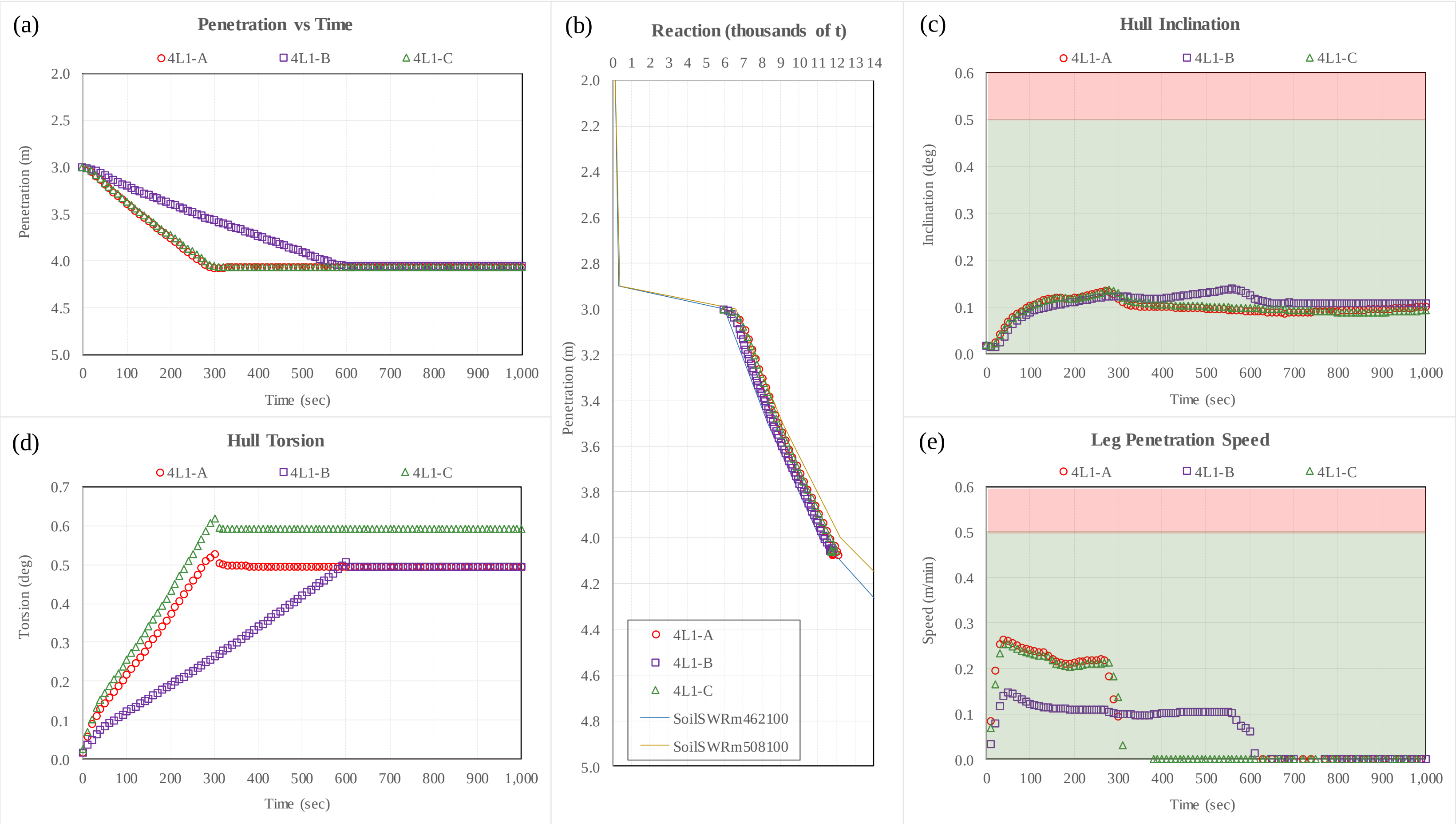


Figure 4 – OrcaFlex Model of 4-Legged Jackup



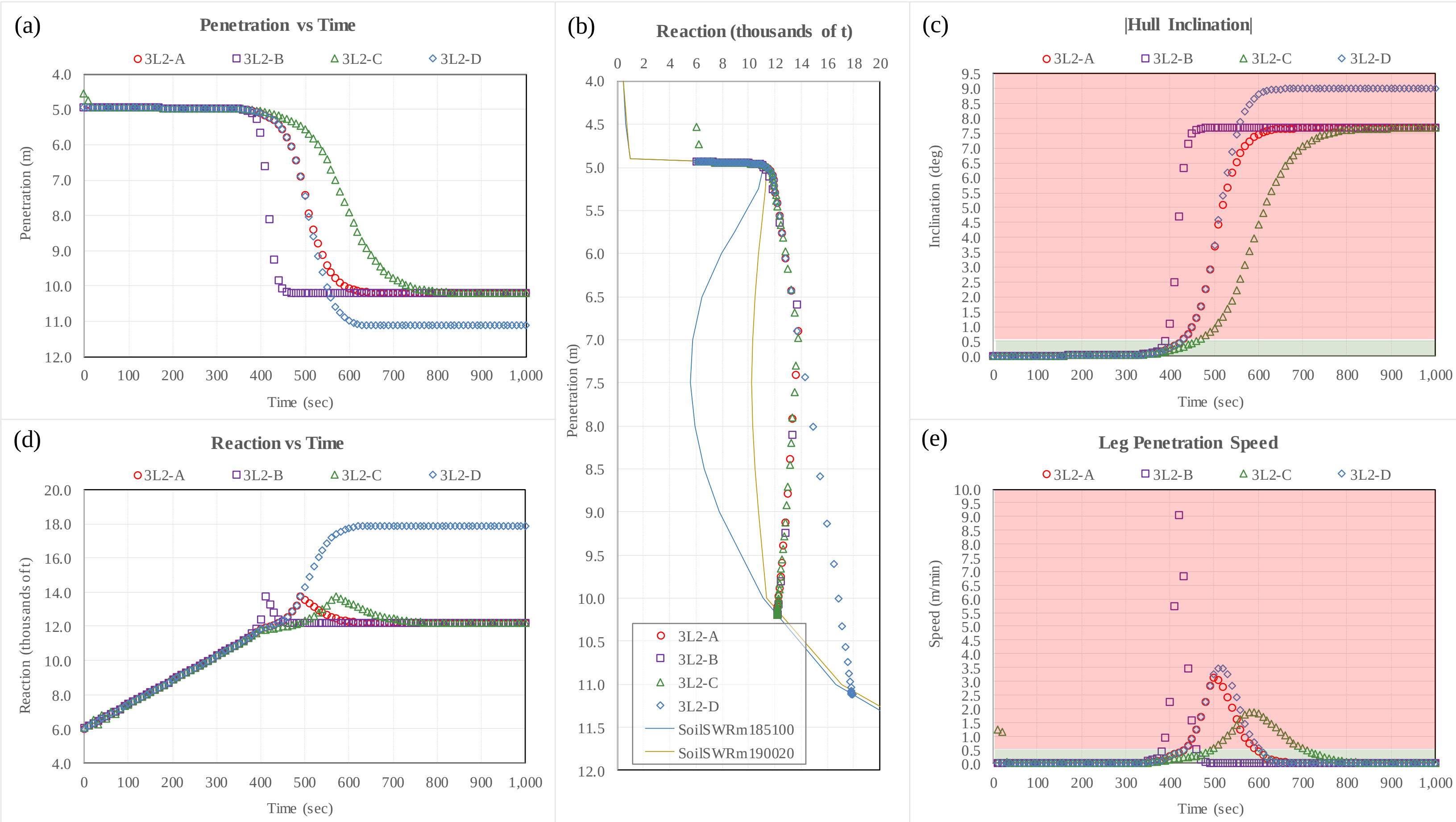
Simulation	Intent
3L1-A	*Simultaneous Preloading* at *Good Site*, Starting at 1m Airgap.
3L1-B	*Single Leg Preloading* of Forward Leg on "Good Soil" (Ignoring Excessive *Hull Inclination*).
3L1-C	*Single Leg Preloading* of Forward Leg on "Good Soil" (Correcting Excessive *Hull Inclination* - Once).

Figure 5 – Comparison of Critical Leg Results for Simulations 3L1-A to 3L1-C (3-Legged Jackup Preloading in Good Soil)



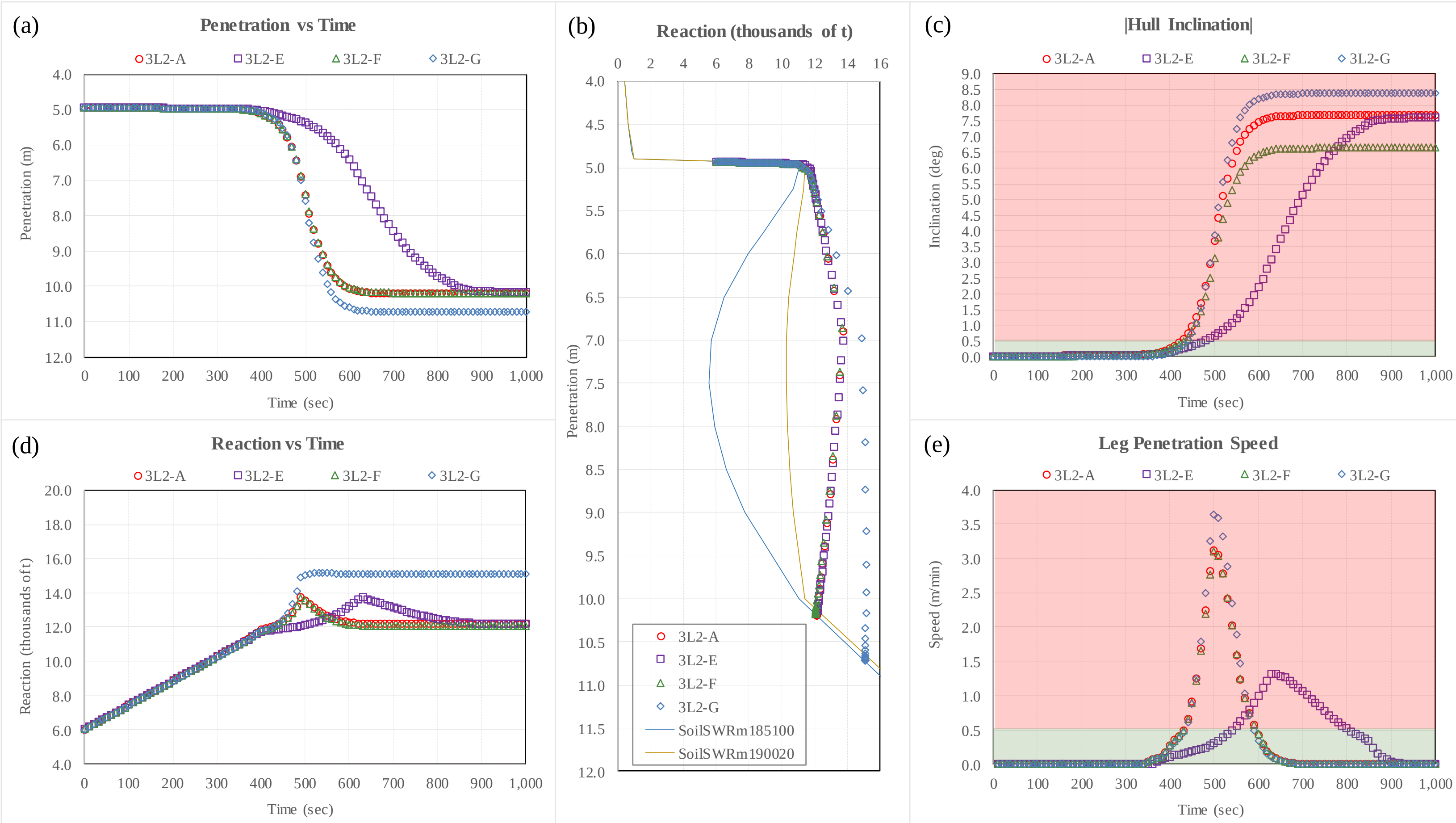
Simulation	Intent
4L1-A	*Active Leg Preloading* of AP/FS Legs at *Good Site*, Starting at 1m Airgap.
4L1-B	*Passive Leg Preloading* of AP/FS Legs on "Good Soil"
4L1-C	Same as 4L1-A, but with Reduced Stiffness of Hull Members by Factor of 2.

Figure 6 – Comparison of Critical Leg Results for Simulations 4L1-A to 4L1-C (4-Legged Jackup Preloading in Good Soil)



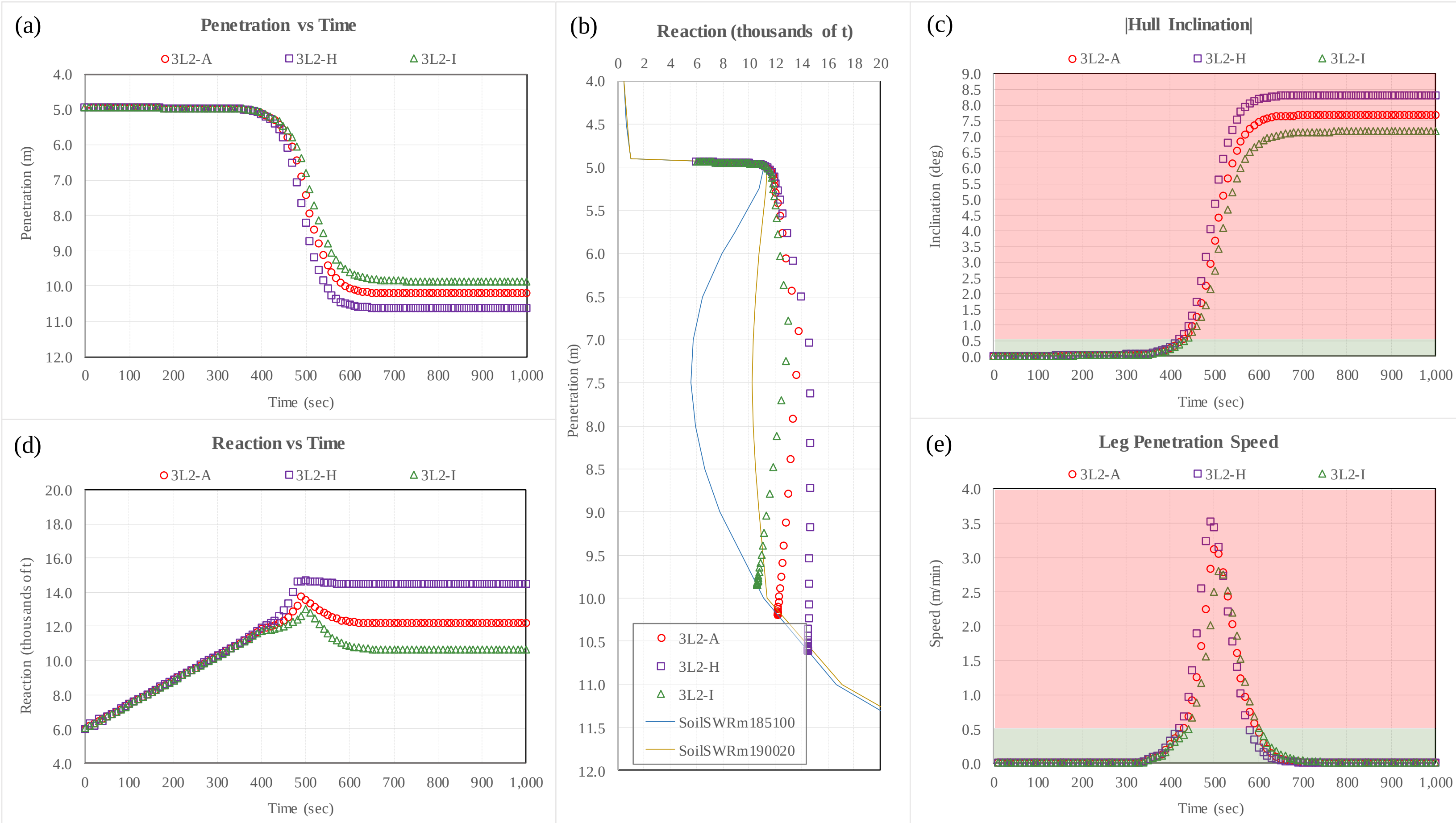
Simulation	Intent
3L2-A	*Single Leg Preloading* of Forward Leg, at *Difficult Site 2*, Starting at 2m Airgap
3L2-B	Same as 3L2-A, but Damping=500KN/(m/s).
3L2-C	Same as 3L2-A, but Damping=2,500KN/(m/s).
3L2-D	Same as 3L2-A, but Ignore the Effect of Buoyancy.

Figure 7 – Comparison of Critical Leg Results for Simulations 3L2-A to 3L2-D (Effect of Damping and Buoyancy)



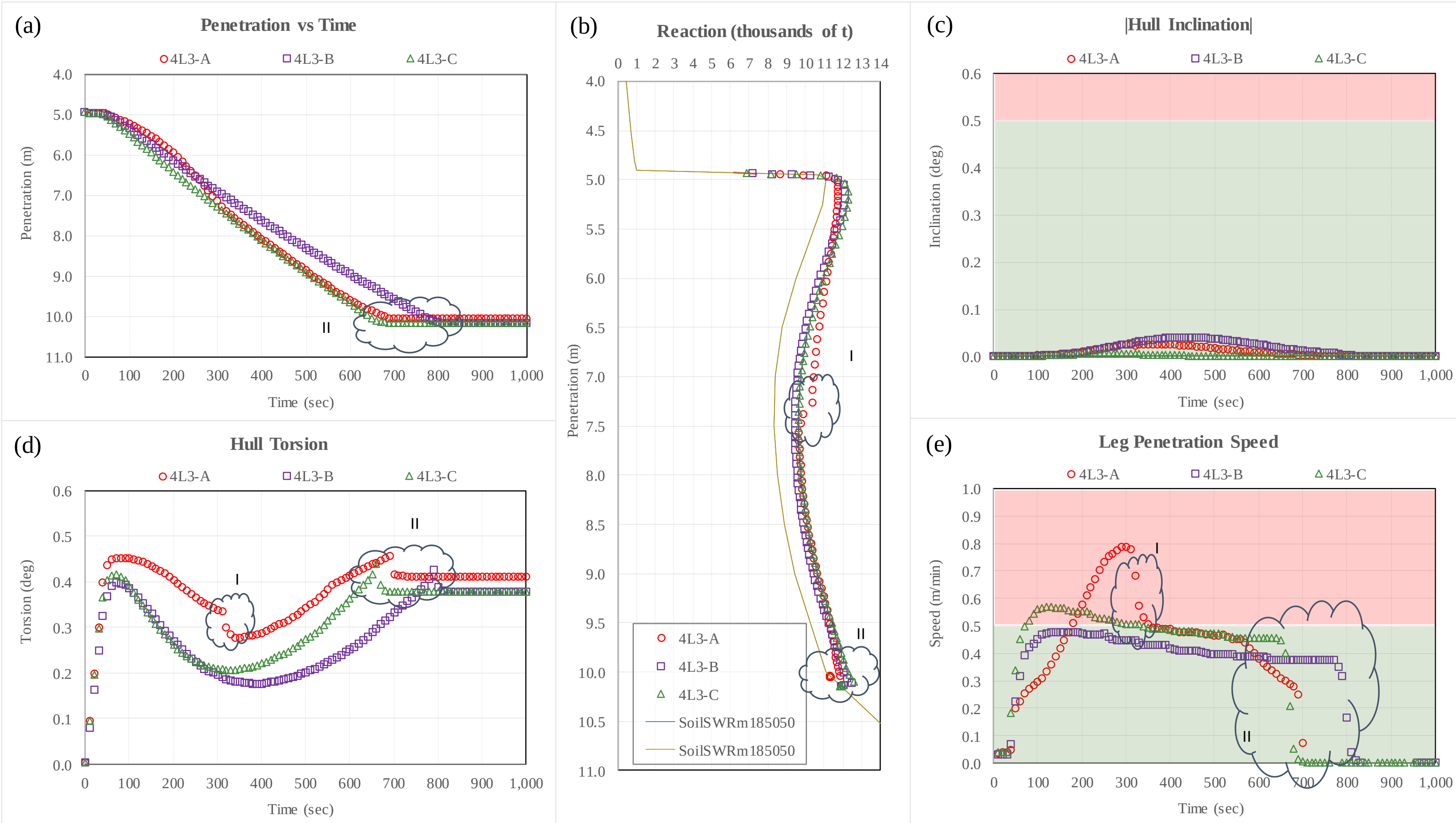
Simulation	Intent
3L2-A	*Single Leg Preloading* of Forward Leg, at *Difficult Site 2*, Starting at 2m Airgap
3L2-E	Same as 3L2-A, but Rotate Jackup 180 Degrees.
3L2-F	Same as 3L2-E, but Perform *Single Leg Preloading* on Port Leg.
3L2-G	Same as 3L2-A, but Perform *Simultaneous Preloading*.

Figure 8 – Comparison of Critical Leg Results for Simulations 3L2-A + 3L2-E to 3L2-G



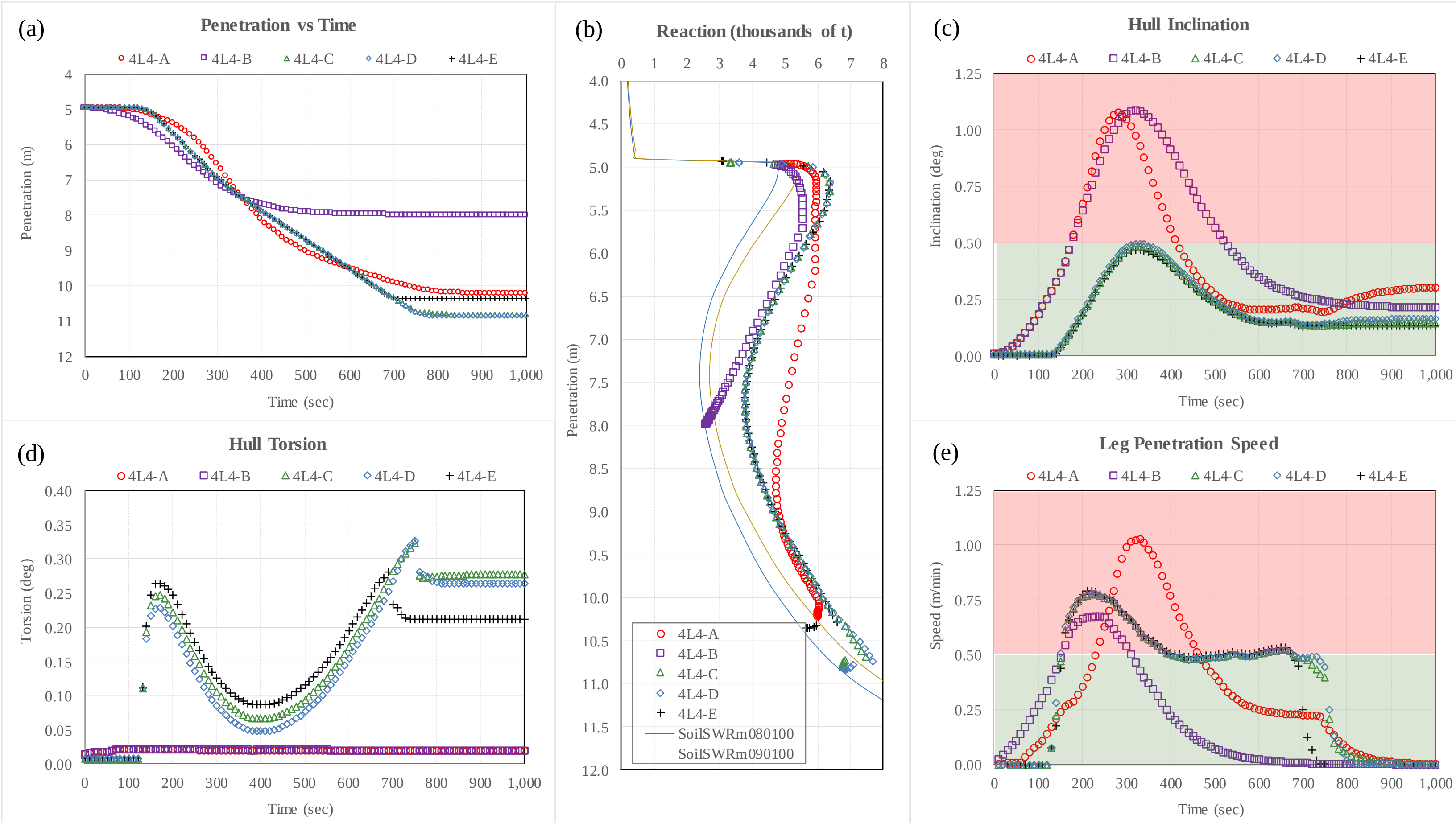
Simulation	Intent
3L2-A	*Single Leg Preloading* of Forward Leg, at *Difficult Site 2*, Starting at 2m Airgap
3L2-H	Same as 3L2-A, but Increase Water Depth by 20m to 75m.
3L2-I	Same as 3L2-A, but Reduce Water Depth by 20m to 35m.

Figure 9 – Comparison of Critical Leg Results for Simulations 3L2-A + 3L2-H and 3L2-I (Effect of Water Depth)



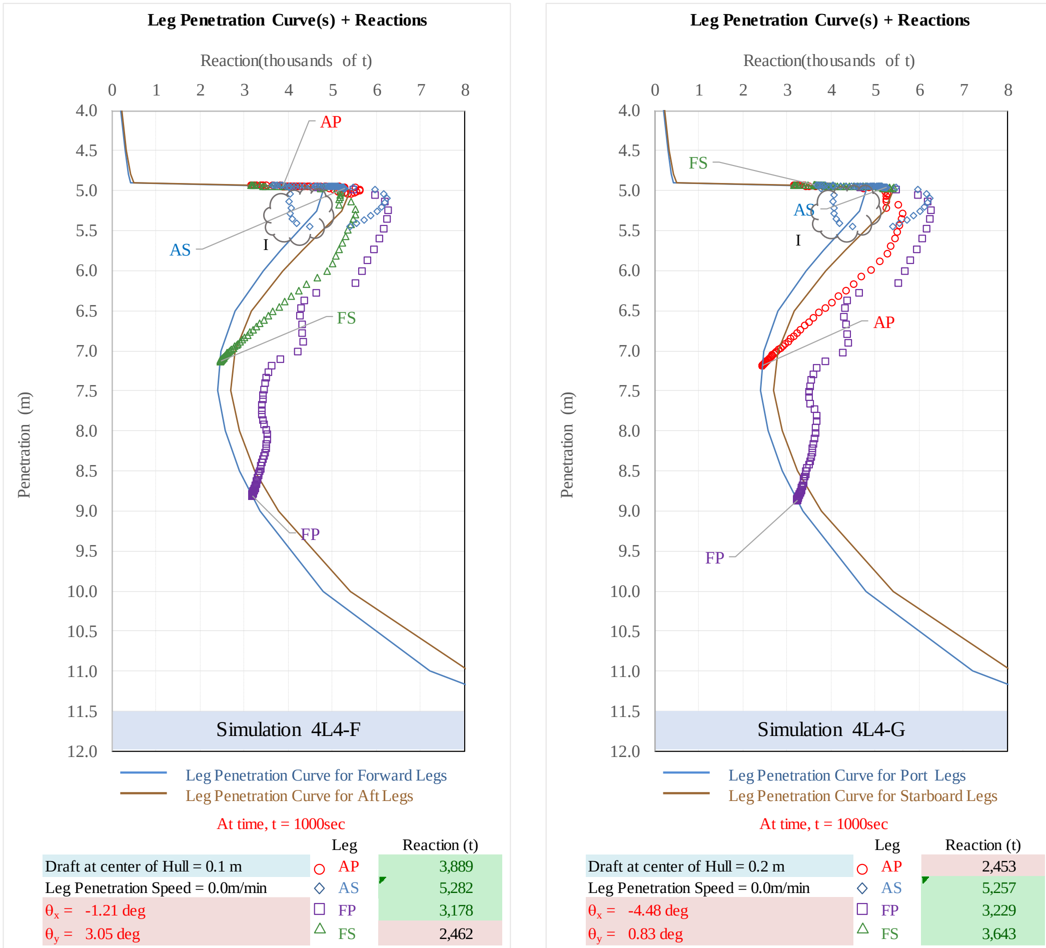
Simulation	Intent
4L3-A	*Active Leg Preloading* of AP/FS Legs at *Difficult Site* 2, Starting at 1m Airgap.
4L3-B	Similar to 4L3-A, but with 4,000t of Preload Water.
4L3-C	Similar to 4L3-B, but Starting at 0.3m Draft (i.e., *Active Leg Driving*).

Figure 10 – Comparison of Critical Leg Results for Simulations 4L3-A to 4L3-C (Effect of Using Preload Water)



Simulation	Intent
4L4-A	*Jack Hull Up* at *Difficult Site 3* , Without Paying Attention to Soil or Behavior Until Reaching 0.5m Airgap.
4L4-B	Same as 4L4-A, but Stop Jacking Once *Hull Inclination* Reaches 0.5deg.
4L4-C	*Active leg predriving* of AS/FP Legs from 1.9m Draft, After Having Reached 1.1m Draft. Stop when *Hull inclination* =0.5deg
4L4-D	Same as 4L4-C, but with 1,000t Extra Cargo Weight (or Having Added 1,000t of Preload Water).
4L4-E	Same as 4L4-C, but with 1,000t Less Cargo Weight.

Figure 11 – Comparison of Critical Leg Results for Simulations 4L4-A to 4L4-E (*Predriving* vs "Just" *Jacking Hull Up*)

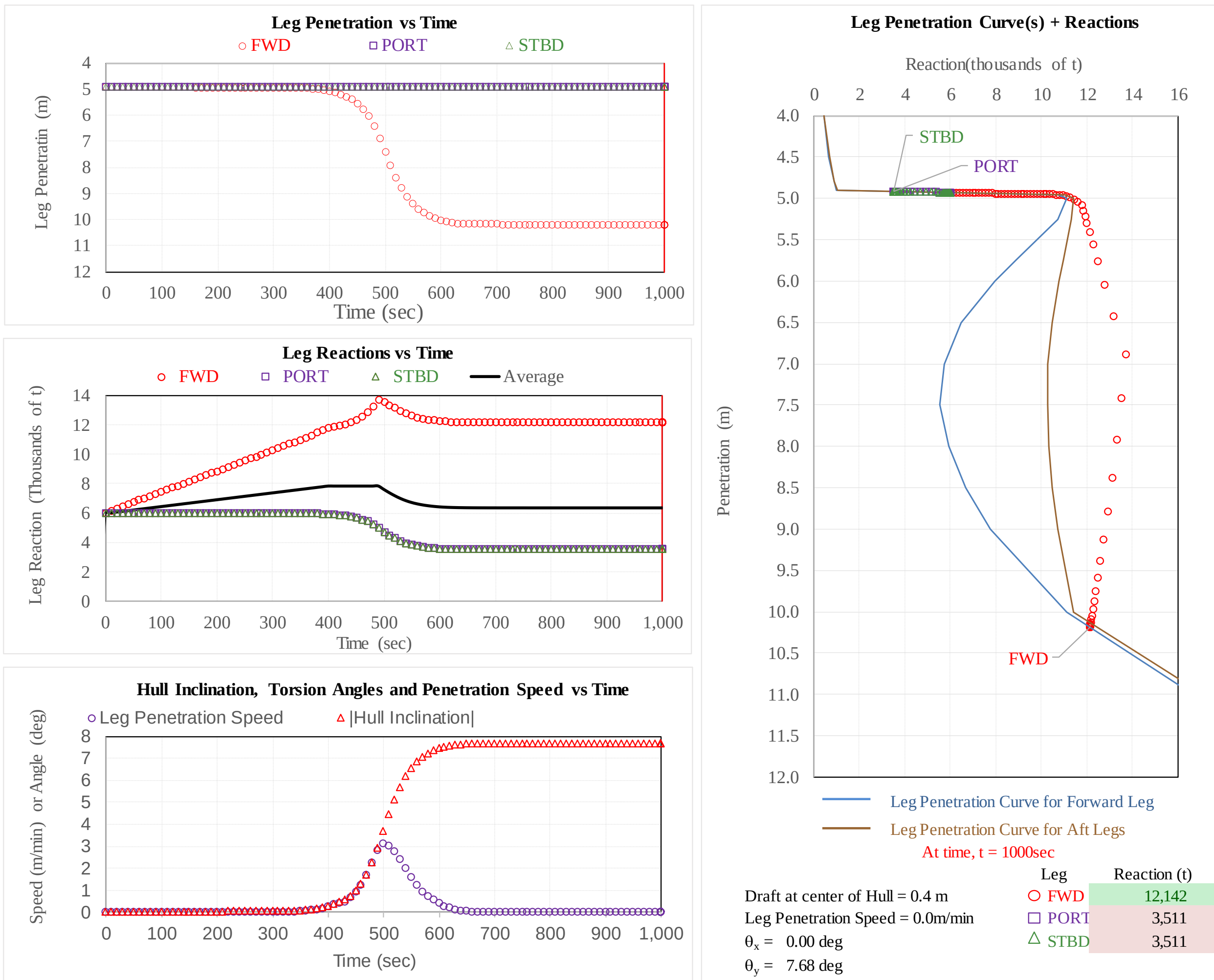


Simulation	Intent
4L4-F	Same as 4L4-A, but Having Come in Very Light, Hull was Jacked Up out of the Water, *Leg Preloading* of the AS/FP Leg Starts.
4L4-G	Same as 4L4-F, but rotate the jackup 90 Degrees.

Figure 12 – Comparison of Critical Leg Results for Simulations 4L4-F and 4L4-G (*Preloading w/o Predriven Legs in Difficult Site 3*)

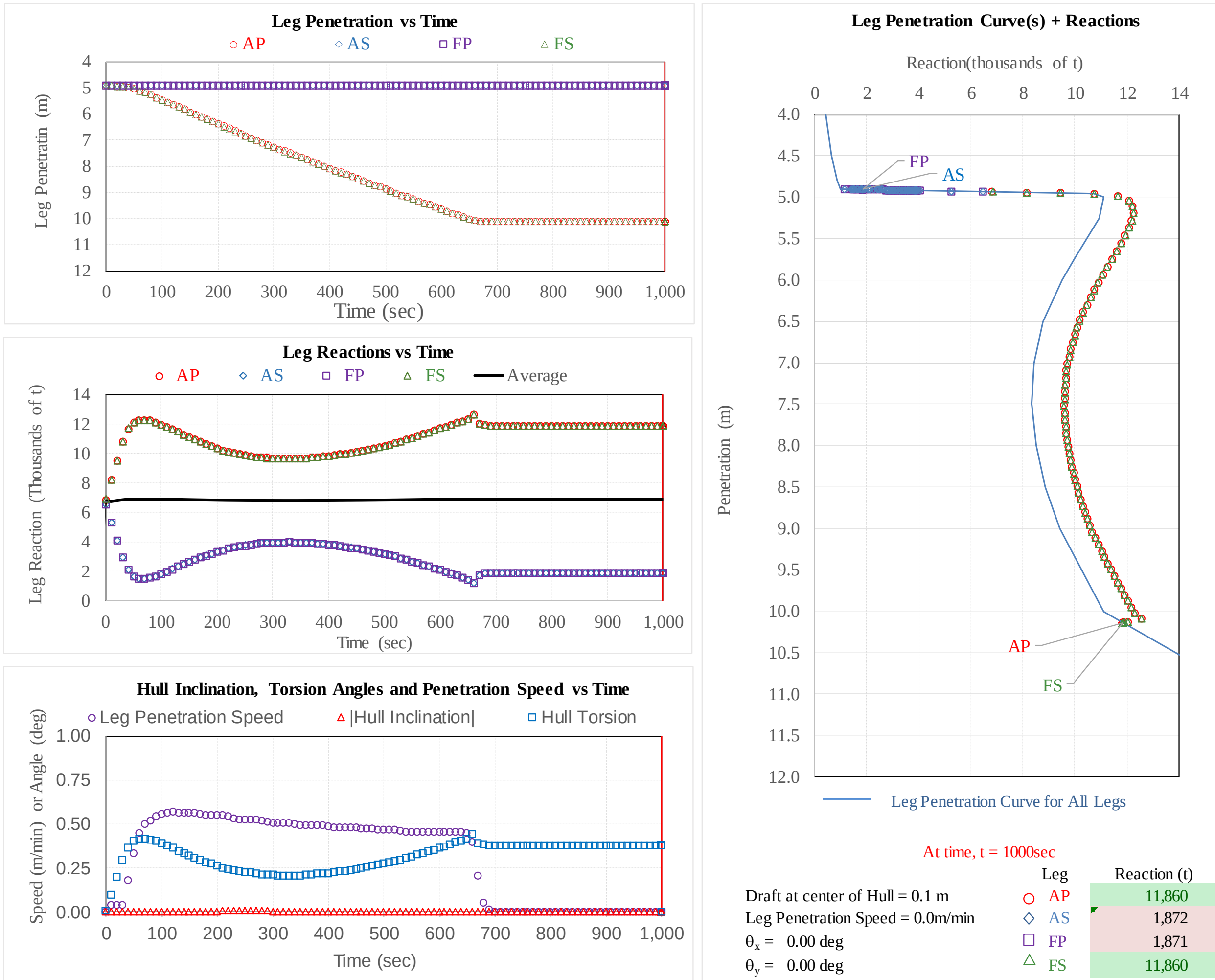
	Reaction (t)				Penetration (m)				Rot_x (deg)	Rot_y (deg)	Leg Penetration Speed (m/min)				Hull Torsion (deg)
	FWD	PORT	STBD		FWD	PORT	STBD				FWD	PORT	STBD		
Max	12,623	6,000	6,000		4.14	2.99	2.99		0.00	1.74	0.10	0.00	0.00		N/A
t_{ass} (sec)	900	0	0		1,000	0	0		180	990	340	-340	-340		N/A

Figure 13 – Simulation 3L1-B Results (*Single Leg Preloading* of Forward Leg in Good Soil, Ignoring Excessive *Hull Inclination*)



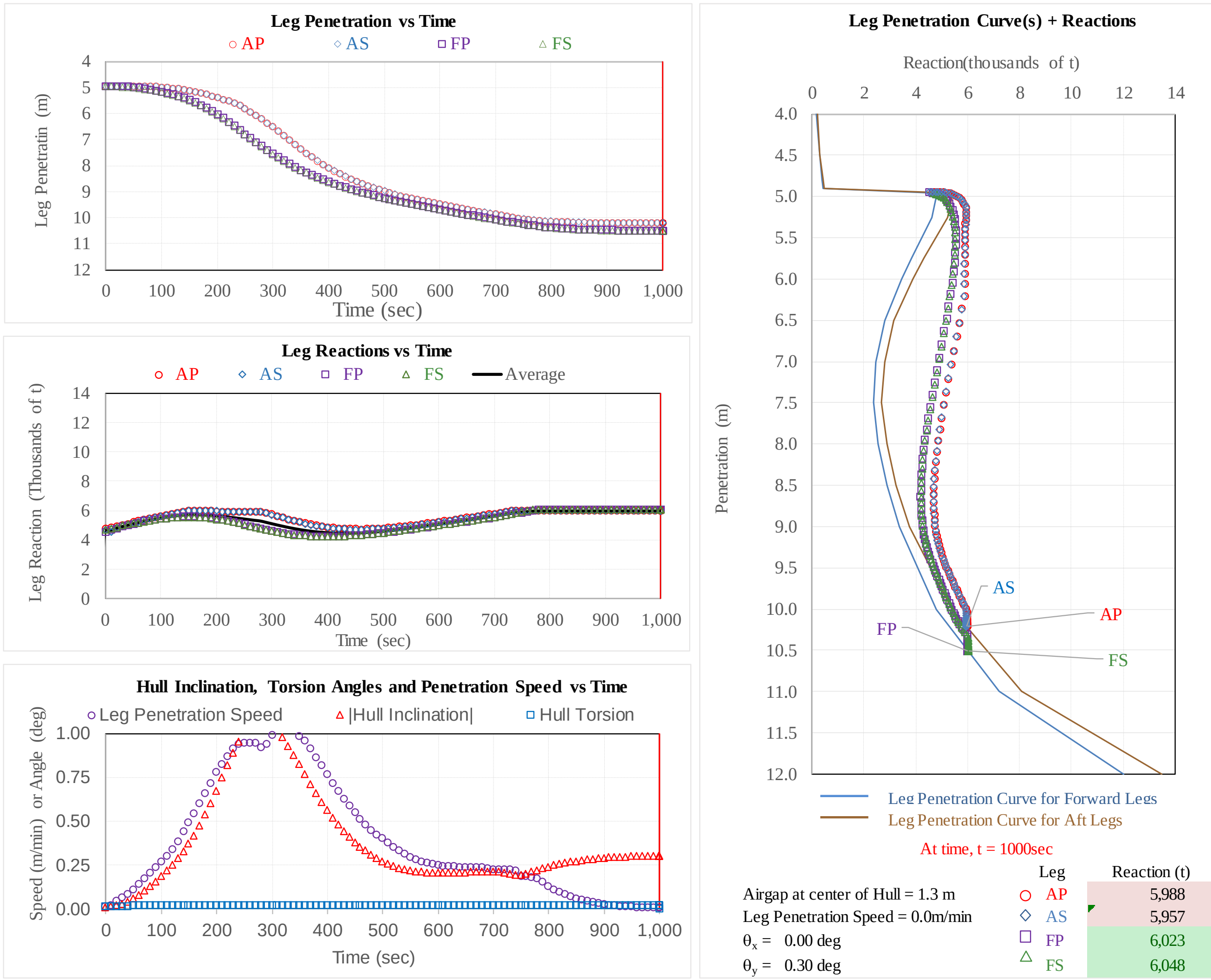
	Reaction (t)				Penetration (m)				Rot$_x$ (deg)	Rot$_y$ (deg)	Leg Penetration Speed (m/min)				Hull Torsion (deg)
	FWD	PORT	STBD		FWD	PORT	STBD				FWD	PORT	STBD		
Max	13,720	6,011	6,011		10.19	4.92	4.92		0.00	7.68	3.12	0.00	0.00		N/A
t_{ass} (sec)	490	0	0		900	10	10		240	840	500	0	0		N/A

Figure 14 – Simulation 3L2-A Results (*Single Leg Preloading* of Forward Leg in *Difficult Site 2*)



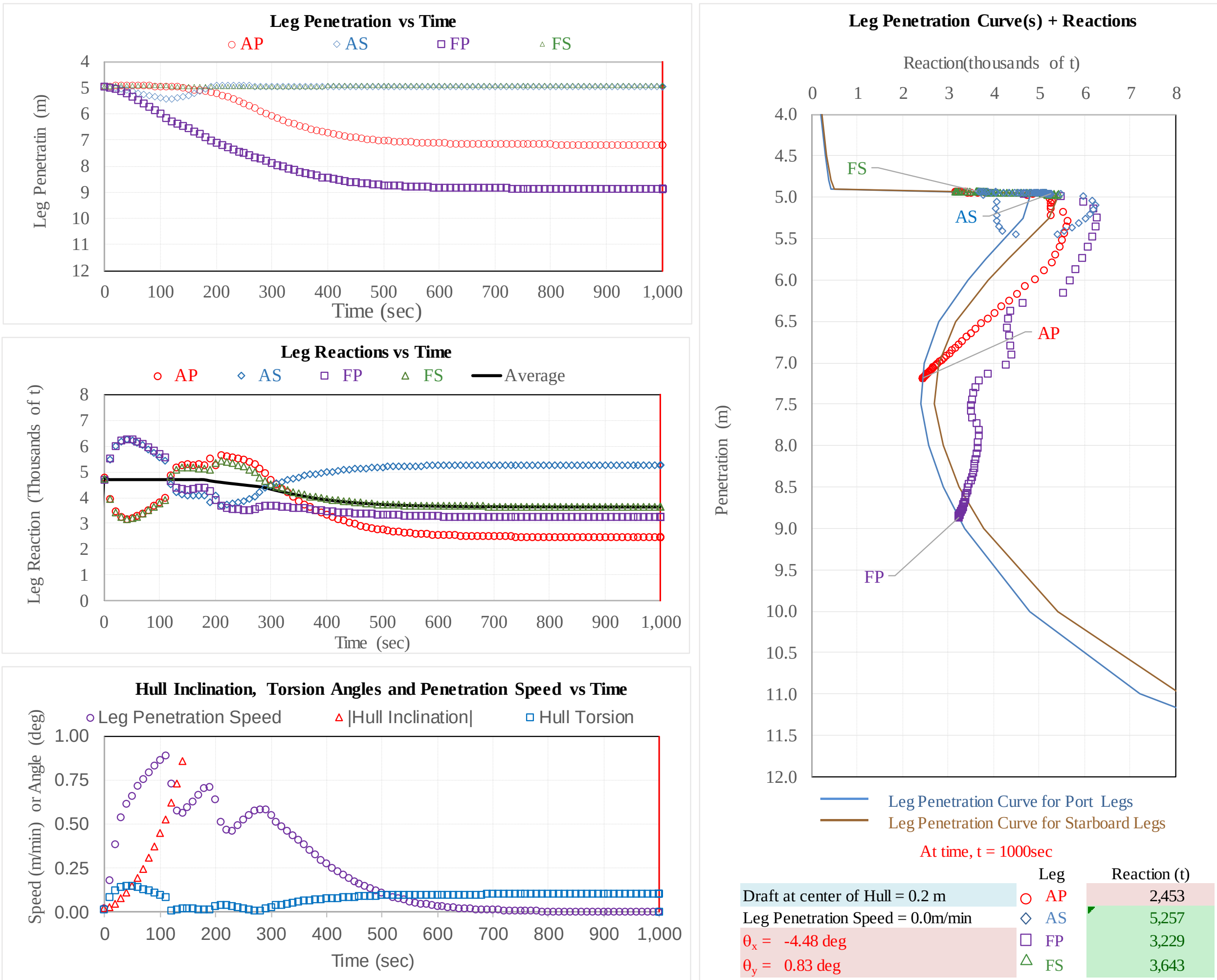
	Reaction (t)				Penetration (m)				Rot_x (deg)	Rot_y (deg)	Leg Penetration Speed (m/min)				Hull Torsion (deg)
	AP	FP	FS	AS	AP	FP	FS	AS			AP	FP	FS	AS	
Max	12,588	6,497	12,588	6,484	10.14	4.93	10.14	4.93	0.01	0.00	0.56	0.02	0.57	0.02	0.00
t_{ass} (sec)	660	0	660	0	820	0	730	0	270	270	130	670	120	670	-340

Figure 15 – Simulation 4L3-C Results (*Leg Predriving* in 0.3m Draft w/Additional Preload Water to Reach High Target Preload Reaction)



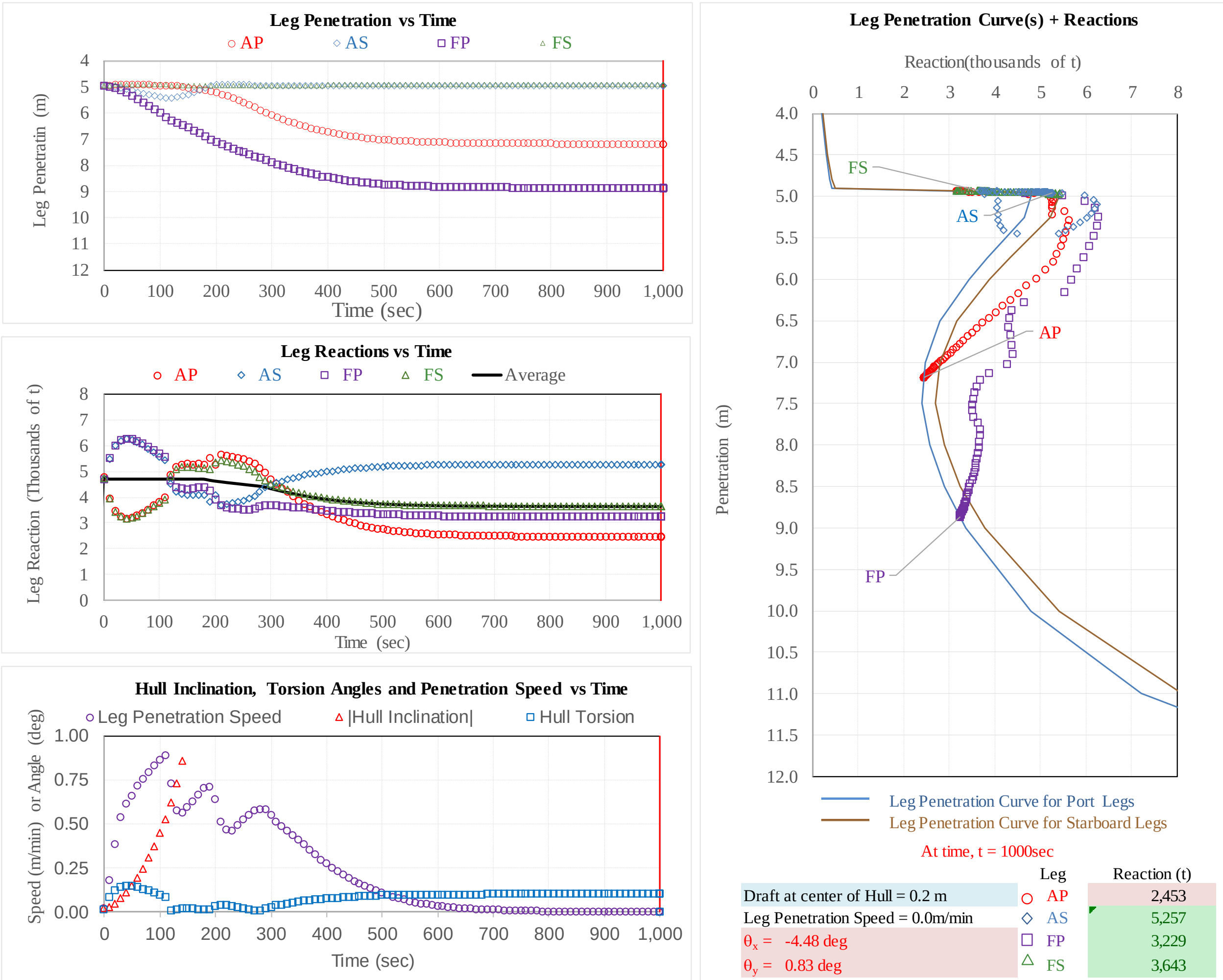
	Reaction (t)				Penetration (m)				Rot_x (deg)	Rot_y (deg)	Leg Penetration Speed (m/min)				Hull Torsion (deg)
	AP	FP	FS	AS	AP	FP	FS	AS			AP	FP	FS	AS	
Max	6,004	6,023	6,048	5,968	10.22	10.50	10.51	10.20	0.02	1.08	1.03	0.95	0.95	1.02	0.00
t_{ass} (sec)	740	1,000	1,000	160	1,000	1,000	1,000	1,000	230	280	330	260	260	330	-340

Figure 16 – Simulation 4L4-A Results (*Jacking Hull Up* Through at *Difficult Site*, Without Paying Attention Soil or Behavior)



	Reaction (t)				Penetration (m)				Rot_x (deg)	Rot_y (deg)	Leg Penetration Speed (m/min)				Hull Torsion (deg)
	AP	FP	FS	AS	AP	FP	FS	AS			AP	FP	FS	AS	
Max	5,629	6,268	5,426	6,242	7.18	8.86	4.97	5.44	4.48	1.00	0.58	0.89	0.06	0.36	0.00
t_{ass} (sec)	210	40	210	40	1,000	1,000	230	120	1,000	230	280	110	210	50	-340

Figure 17 – Simulation 4L4-F Results (*Leg Preloading* w/o having done *Leg Predriving* in *Difficult Site 3*)



	Reaction (t)				Penetration (m)				Rot_x (deg)	Rot_y (deg)	Leg Penetration Speed (m/min)				Hull Torsion (deg)
	AP	FP	FS	AS	AP	FP	FS	AS			AP	FP	FS	AS	
Max	5,629	6,268	5,426	6,242	7.18	8.86	4.97	5.44	4.48	1.00	0.58	0.89	0.06	0.36	0.00
t_{ass} (sec)	210	40	210	40	1,000	1,000	230	120	1,000	230	280	110	210	50	-340

Figure 18 – Simulation 4L4-G Results (*Leg Preloading* w/o having done *Leg Predriving* in *Difficult Site 3* w/Hull Rotated 90 degrees)

TABLES

Parameter	3-legged jackup	4-legged jackup
Hull Length (m)	70.0	90.0
Hull Breadth (m)	70.0	56.2
Hull Depth (m)	15.0	15.0
Longitudinal Leg Spacing (LLS)	39.0	56.0
Transverse Leg Spacing (TLS)	45.0	39.0
Heave Hydrostatic Stiffness (t/m)	3,891	5,188
Elevated Weight (t)	18,000	24,000
Stillwater Leg Reaction (t)	6,000	6,000

Table 1 – Basic Properties used for 3- and 4-Legged Models

Set	Simulation	Intent
1	3L1-A	*Simultaneous Preloading* at *Good Site*, Starting at 1m Airgap.
	3L1-B	*Single Leg Preloading* of Forward Leg on "Good Soil" (Ignoring Excessive *Hull Inclination*).
	3L1-C	*Single Leg Preloading* of Forward Leg on "Good Soil" (Correcting Excessive *Hull Inclination* - Once).
	4L1-A	*Active Leg Preloading* of AP/FS Legs at *Good Site*, Starting at 1m Airgap.
	4L1-B	*Passive Leg Preloading* of AP/FS Legs on "Good Soil"
	4L1-C	Same as 4L1-A, but with Reduced Stiffness of Hull Members by Factor of 2.
2	3L2-A	*Single Leg Preloading* of Forward Leg, at *Difficult Site 2*, Starting at 2m Airgap
	3L2-B	Same as 3L2-A, but Damping=500KN/(m/s).
	3L2-C	Same as 3L2-A, but Damping=2,500KN/(m/s).
	3L2-D	Same as 3L2-A, but Ignore the Effect of Buoyancy.
	3L2-E	Same as 3L2-A, but Rotate Jackup 180 Degrees.
	3L2-F	Same as 3L2-E, but Perform *Single Leg Preloading* on Port Leg.
	3L2-G	Same as 3L2-A, but Perform *Simultaneous Preloading*.
	3L2-H	Same as 3L2-A, but Increase Water Depth by 20m to 75m.
	3L2-I	Same as 3L2-A, but Reduce Water Depth by 20m to 35m.
3	4L3-A	*Active Leg Preloading* of AP/FS Legs at *Difficult Site* 2, Starting at 1m Airgap.
	4L3-B	Similar to 4L3-A, but with 4,000t of Preload Water.
	4L3-C	Similar to 4L3-B, but Starting at 0.3m Draft (i.e., *Active Leg Driving*).
4	4L4-A	*Jack Hull Up* at *Difficult Site 3*, Without Paying Attention to Soil or Behavior Until Reaching 0.5m Airgap.
	4L4-B	Same as 4L4-A, but Stop Jacking Once *Hull Inclination* Reaches 0.5deg.
	4L4-C	*Active leg predriving* of AS/FP Legs from 1.9m Draft, After Having Reached 1.1m Draft. Stop when *Hull inclination* =0.5deg
	4L4-D	Same as 4L4-C, but with 1,000t Extra Cargo Weight (or Having Added 1,000t of Preload Water).
	4L4-E	Same as 4L4-C, but with 1,000t Less Cargo Weight.
	4L4-F	Same as 4L4-A, but Having Come in Very Light, Hull was Jacked Up out of the Water, *Leg Preloading* of the AS/FP Leg Starts.
	4L4-G	Same as 4L4-F, but rotate the jackup 90 Degrees.

Table 2 – Description of Simulation Sets

Simulation	Max Leg Penetration (m)	Max Leg Reaction Reaction (t)	Peak Leg Run Speed (m/min)	Peak Hull Torsion (deg)	Peak Hull Inclination (deg)	Leg Run Duration (sec)	Punch Through Duration (sec)	Apparent Punch Through Speed (m/min)
3L1-A	4.1	11,892	0.1	N/A	0.4	0	0	N/A
3L1-B	4.1	12,623	0.1	N/A	1.7	0	0	N/A
3L1-C	4.1	12,262	0.1	N/A	1.0	0	0	N/A
4L1-A	4.1	12,099	0.3	0.53	0.1	0	0	N/A
4L1-B	4.1	11,803	0.1	0.50	0.1	0	0	N/A
4L1-C	4.1	11,972	0.3	0.62	0.1	0	0	N/A
3L2-A	10.2	13,720	3.1	N/A	7.7	160	160	1.97
3L2-B	10.2	13,695	9.1	N/A	7.7	80	80	3.95
3L2-C	10.2	13,725	1.9	N/A	7.7	240	210	1.62
3L2-D	11.1	17,840	3.5	N/A	9.0	170	170	2.18
3L2-E	10.1	13,725	1.3	N/A	7.6	260	260	1.20
3L2-F	10.2	13,680	3.1	N/A	6.6	160	160	1.97
3L2-G	10.7	15,139	3.6	N/A	8.4	150	150	2.32
3L2-H	10.6	14,629	3.5	N/A	8.3	160	160	2.13
3L2-I	9.8	12,992	2.8	N/A	7.2	160	160	1.84
4L3-A	10.0	11,858	0.8	0.46	0.0	180	0	N/A
4L3-B	10.1	12,476	0.5	0.43	0.0	0	0	N/A
4L3-C	10.1	12,588	0.6	0.44	0.0	260	0	N/A
4L4-A	10.5	6,048	1.0	0.02	1.1	310	240	1.39
4L4-B	8.0	5,967	0.7	0.02	1.1	160	140	1.30
4L4-C	10.4	7,020	0.7	0.28	0.6	450	120	2.75
4L4-D	10.8	7,904	0.8	0.33	0.5	560	0	N/A
4L4-E	10.4	6,797	0.8	0.28	0.5	530	0	N/A
4L4-F	8.8	6,268	0.9	0.15	3.1	220	140	1.65
4L4-G	8.9	6,268	0.9	0.15	4.5	260	180	1.30

e for the Critical Leg, defined as the leg with the highest leg penetration speed.

Table 3 – Summary of Key Results

APPENDIX

This Appendix is included to compare the estimated hull torsion values for Sim4L-1D with those from a structural analysis of a representative hull and to compare the variation of deck stresses levels from preloading the 4-legged jackup using *Leg preloading* on the FP and AS legs vs only using preload water (as would be done on 3-legged jackups).

The structural analyses were carried out using ANSYS (Ref 17). The model is intentionally a very simple representation of a rectangular hull, having double symmetry and supported at four (4) points on the bottom of the hull at the location of the legs. Leg spacing, hull length and width are as indicated in Table 1. All models start with the 24,000t weight used in the OrcaFlex Sim4L-A simulation (which assumes negligible weight from the legs). For these analyses, hull depth was assumed to be 8m and a uniform steel plate thickness of 3/4in (20mm) was used.

Weights are modelled as line vertical loads acting at the intersection of the bulkheads and the bottom plating. The model has no stiffeners nor any local reinforcement - anywhere. The ¾" plate thickness was chosen so as to produce hull sagging deflections in the order of 2 inches (~50mm) when all legs have equal reactions of 6,000t.

A total of six (6) cases were considered, as outlined below.

1. Uniform hull weight of 24,000t, with all reactions set at 6,000t (i.e., no preloading)
2. Uniform hull weight of 24,000t, with 11,500t reactions on the AS/FP legs and 500t on the other two legs (i.e., simulating the traditional *Leg preloading* by 4-legged jackups)
3. Uniform hull weight of 46,000t, with 11,500t reactions (i.e., simulating the simultaneous preloading using preload water)
4. Uniform hull weight of 24,000t, plus 11,000t weight uniformly applied in the vicinity of the forward legs (i.e., simulating preloading of the two forward legs using preload water)
5. Uniform hull weight of 24,000t, plus 11,000t weight uniformly applied in the vicinity of the port legs (i.e., simulating preloading of the two port legs using preload water)
6. Uniform hull weight of 24,000t, plus 5,500t weight uniformly applied in the vicinity of the FP leg (i.e., *Single-Leg preloading* of the FP leg using preload water)

Results for Case 1

Figure A-1 shows the *Hull Deformations* and main deck stresses prior to performing any preloading. As can be seen, The relative deformation between the leg locations and the center of the hull is ~1.8in = 4.5cm. Peak stresses (near the leg locations) are seen to be ~12.3ksi. At the center of the deck, stresses peak at ~6ksi.

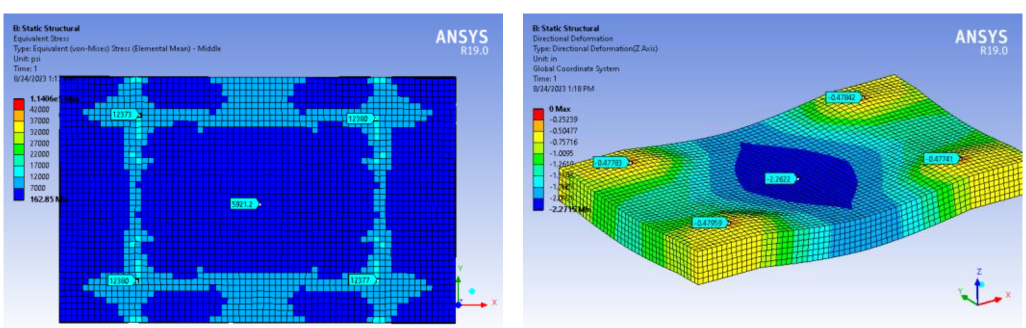


Figure A-1 – Main Deck Stress and Deformation Plots for Case 1

Results for Case 2

Figure A-2 shows the *Hull Deformations* and main deck stresses for the case simulating *Leg preloading* of the AP/FS legs. As can be seen, when the diagonally-opposite *Leg Preloading* is taking place, the difference in *Hull Elevation* at the preloading legs and the other legs is ~9.2in (0.24m). Given the leg spacing of 39m x 56m, the horizontal distance between diagonally-opposite legs is 68.45m. Therefore, the calculated torsion angle is τ = ATan[(0.24m)/(68.45m/2)] = 0.40 degrees. This value compares well with the 0.51-degree peak torsion angle shown in Table 2, at least suggesting that the chosen stiffness values to represent the hull grillage are adequate for the simulations.

Comparing stresses from Cases 1 and 2, it can be seen that *Leg preloading* of the diagonally-opposite legs increased stresses from ~12ksi to ~38ksi (ignoring the two local peak values that exceed 42ksi seen in Figure A-2).

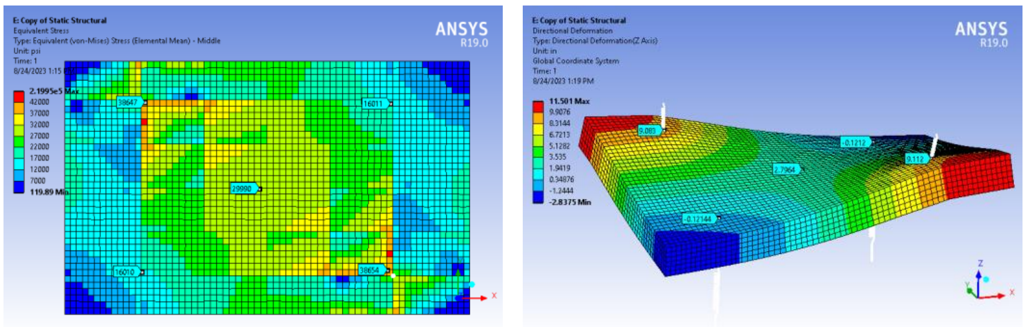


Figure A-2 – Main Deck Stress and Deformation Plots for Case 2

Results for Cases 3-6

Figure A-3 shows the main deck stresses for the cases simulating *Leg preloading* using preload water. As can be seen, when preloading simultaneously, the stresses almost double w.r.t. the stresses prior to preloading, peaking at ~24ksi. Peak stresses for the other cases are at that same ~24ksi level.

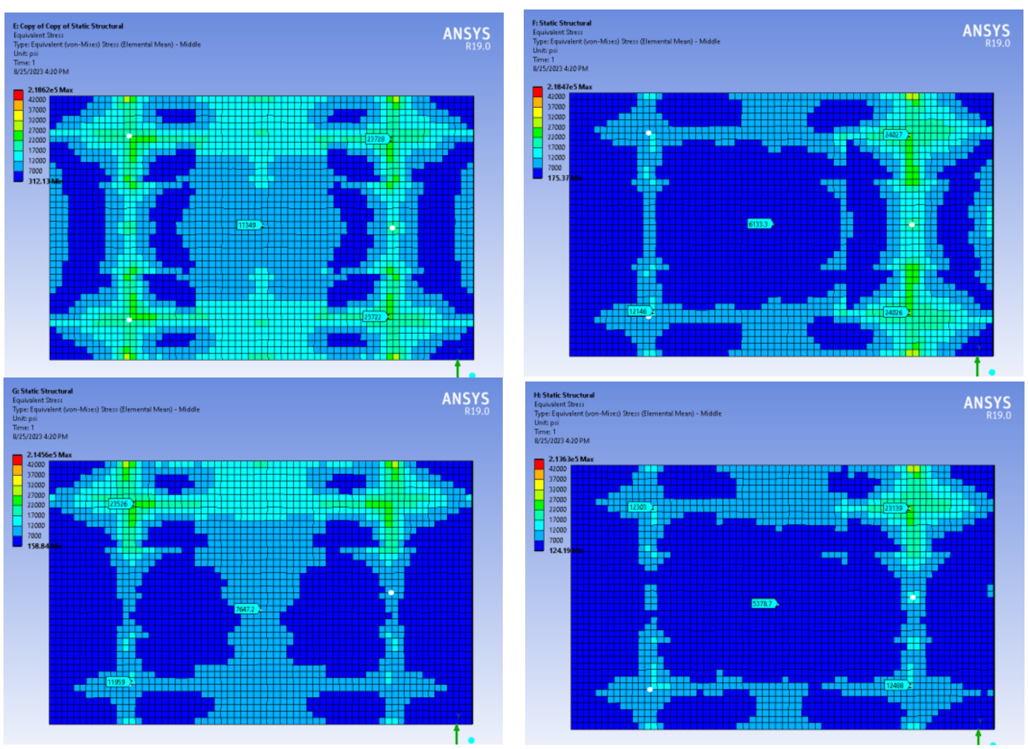


Figure A-3 – Case 2 Main Deck Stress for Cases 3 to 6