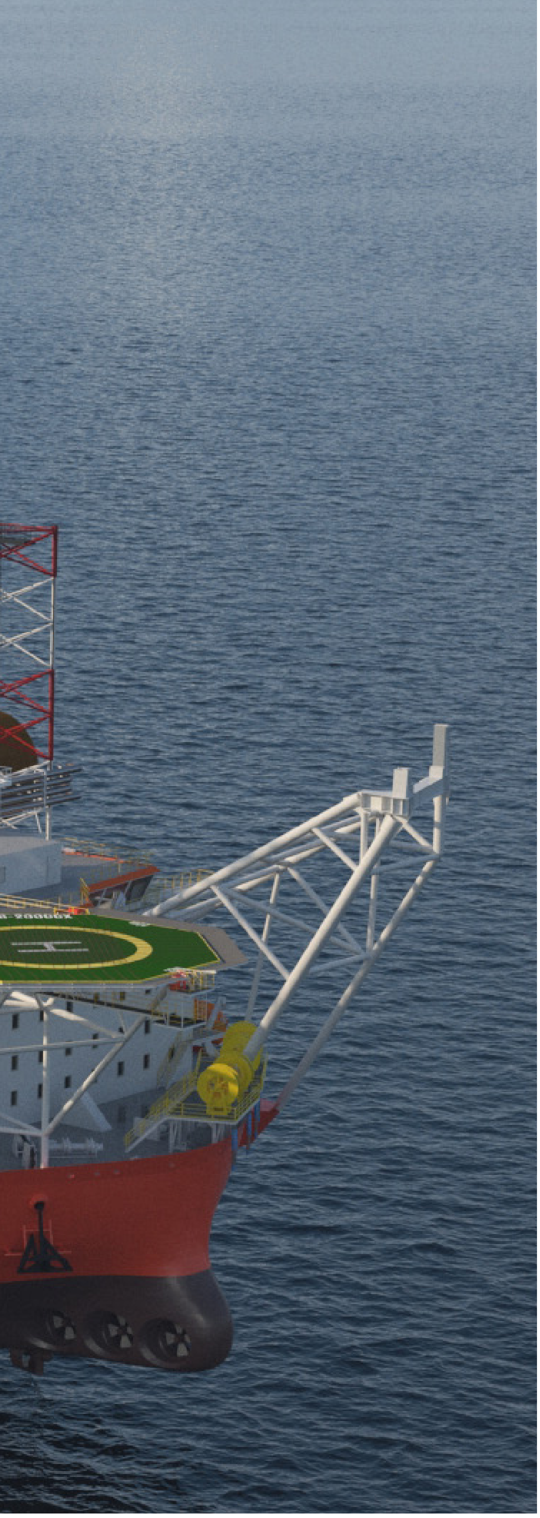
Rethinking load cases for large monopile installation

As monopile diameters surpass 10 metres, the lowering phase can generate structural demands comparable to and in some cases exceeding survival conditions. Coupled dynamic interaction between the suspended pile and the supporting jack-up is emerging as a governing design consideration for offshore wind installation.



Monopiles are getting bigger. Diameters above 10 metres and weights over 2,000 tonnes are now common in offshore wind projects, with designs moving toward 12 to 15 metres and more than 2,500 tonnes.

That growth does more than challenge fabrication yards and transport logistics. It changes how installation behaves structurally.

For jack-up vessels, lowering a monopile from air into water has traditionally been viewed as an operational step, limited mainly by crane capacity. Detailed analysis shows that this phase can instead govern the structural demand of the jack-up. In certain components, installation loads can approach and in some cases, exceed those associated with extreme survival conditions.

The driver is not heavier lifting alone. It is the dynamic interaction between the suspended monopile and the supporting jack-up.

A suspended structure, not suspended cargo

Monopile installation from a jack-up follows a well-established sequence. The vessel transits to the site, elevates, preloads its legs and achieves operational air gap. The gripper is deployed. The monopile is lifted from the deck, upended, guided into the gripper and then lowered into the water column until it reaches the seabed.

The most demanding condition occurs when the full weight of the monopile is suspended from the crane and laterally restrained by the gripper, as it enters the water and progresses through partial submersion.

In this configuration, the monopile cannot be treated as passive cargo. It behaves as a large diameter structure exposed to wave and current loading. As submersion increases, wave forces rise rapidly. With the full weight hanging from the crane and lateral restraint provided at the gripper, the monopile places considerable additional demand on the hull and legs.

Because the monopile is both heavy and hydrodynamically active, its movements begin to influence the jack-up and the vessel's motions feed back into the pile. The flexibility of the hull and legs allows this interaction to develop. Rather than acting independently, the vessel and monopile respond together as a coupled system.

As monopile dimensions increase, the hydrodynamic loads acting on the pile during this phase become more significant. For piles with large diameters, forces induced by waves on the monopile can be several times higher than those acting on the slender jack-up legs. This means the monopile, rather than the vessel, becomes the dominant source of horizontal loading.

A representative case study

To better understand these effects, a recent study by GustoMSC examined the lowering of a large monopile from a modern four-legged jack-up of the Cadeler A-Class type. The monopile diameter ranged between 10 and 12 metres, with a weight between 1,500 and 2,500 tonnes. Water depth was 40 metres, with shallow spudcan penetration in uniform sand.

The study focused on the lowering phase, from initial water entry to increasing submersion depth. A range of realistic wave periods, directions and moderate sea states typical of installation limits were assessed. Multiple simulations were carried out for each condition to capture variability in vessel and monopile response. The results were processed statistically to identify representative high-load cases.

The model included the structural behaviour of the jack-up, the crane and gripper arrangement, the suspended monopile and the relevant static and hydrodynamic loads. The emphasis was placed on horizontal motions and the forces transferred to the legs and foundations.

Why static loads already dominate the baseline

Before dynamic amplification is considered, static loads are substantial. The elevated weight of the jack-up accounts for the majority of the vertical reaction at the leg foundations. In addition, transferring the monopile from deck storage to the gripper introduces a significant increase in vertical load. In the analysed case, this transfer represented roughly 30% of the total vertical load at the most heavily loaded leg, while the elevated weight accounted for approximately 60%.

Hull flexibility plays an important role. Crane pedestal moments deform the hull and redistribute vertical loads unevenly across the four legs, increasing demand on the aft legs.

These static effects establish a high baseline load condition. Dynamic effects develop on top of an already demanding state.

Where loads peak and why it matters

As the monopile is lowered and more of its length enters the water, the behaviour of the system changes. The jack-up and the suspended pile do not respond in the same way at every stage of submersion.

The highest dynamic loads were consistently observed when the monopile was submerged by roughly 10 to 15 metres. At this stage, a significant portion of the pile is exposed to wave action, while the full weight remains suspended from the crane and restrained by the gripper. The pile attracts substantial hydrodynamic force while still being strongly connected to the vessel.

Under certain wave periods, the motions of the monopile and the jack-up reinforce one another. When this occurs, forces in the legs and at the foundation level increase noticeably.

In the analysed case, bending moments at the lower guide reached values up to approximately 20% higher than those associated with 50-year North Sea survival conditions, even though the sea state itself was moderate. Installation conditions can therefore govern specific structural components.

Beyond around 20 metres of submersion, the interaction gradually reduced as the monopile became more compliant. The most critical range was therefore during partial submersion, not at full depth.

The influence of wave direction

Wave direction proved to be a decisive factor. Loads varied considerably depending on how waves approached the vessel, particularly in relation to the crane and gripper position.

Certain headings consistently produced higher forces because they excited motion about the gripper location more effectively. In practical terms, vessel orientation during lifting can significantly influence structural demand.

This reinforces the importance of project-specific assessments that evaluate multiple wave headings rather than relying on a limited set of environmental assumptions.

Foundation reactions and bearing capacity

Vertical and horizontal reactions at the most loaded leg foundation were evaluated using combined load checks in accordance with ISO 19905-1.

Maximum representative load combinations were assessed against the bearing capacity envelope. The results showed that the most heavily loaded leg approached the design envelope during partial submersion conditions, in the same 10 to 15 m range.

The governing combinations were driven by the interaction between high static vertical loads and significant lateral hydrodynamic forces transmitted from the monopile. While crane lifting contributes heavily to the vertical load, the lateral forces from the monopile were equally important in pushing the load point toward the envelope boundary.

Foundation safety during installation therefore depends as much on the behaviour of the lifted monopile as on the jack-up itself.

The importance of coupling

A key conclusion from the study is that simplified, uncoupled models can underestimate demand during monopile lowering.

If the monopile is treated purely as a suspended weight, its hydrodynamic inertia and interaction with jack-up flexibility are not fully captured. This becomes particularly relevant in conditions prone to resonance, where moderate waves can produce amplified responses.

The simulations assumed fixed submersions for 30-minute intervals, which is conservative compared to continuous lowering in practice. However, operational pauses and interruptions can occur, making this approach reasonable for assessment. More refined time-varying analyses may offer further insight, provided operational uncertainties are properly considered.

Wind Ally: engineered to transport five monopiles of up to 12 m diameter per trip, showcasing the complex integration of the crane, jacking system, and Huisman foundation handling equipment required for safe and efficient installation

Implications for practice

As monopiles continue to grow in diameter and mass, these effects will become more pronounced. Larger diameters increase hydrodynamic forces and greater mass alters the response of the combined system. The partial submersion phase therefore becomes increasingly sensitive to dynamic amplification.

Current standards address jack-up site-specific assessment and monopile installation separately. They do not explicitly cover the dynamic interaction between a suspended monopile and the supporting jack-up.

For piles with large diameters, several practical considerations follow:

- Perform coupled dynamic analyses during lowering.
- Evaluate multiple wave headings.
- Assess how the response changes with submersion depth.
- Consider hull flexibility during crane operations.
- Check combined vertical and horizontal foundation loads.

In some cases, installation may become the governing load case for specific structural components.

A foundation on a monumental scale: 37 ft (11.3 m) wide at the seabed, supporting the next generation of 12 MW offshore wind turbines at Ocean Wind 1

Lowering as the governing load case

Lowering a modern monopile through the splash zone may only take minutes, but it represents one of the most demanding phases of offshore wind construction. As foundation sizes increase, the interaction between monopile, waves and jack-up vessels becomes stronger and more complex.

The vessel is elevated, crane loads deform the hull and leg reactions are unevenly distributed. At the same time, a large hydrodynamically active body is suspended and restrained asymmetrically. As submersion increases, the interaction between the monopile and jack-up evolves continuously.

For modern large monopiles, this phase cannot be treated as routine. Dynamic interaction can significantly increase structural demand and, in some cases, it becomes the critical condition for key components.

Recognising this coupled behaviour and incorporating it into installation assessments is essential for ensuring safe and reliable operations. For GustoMSC, this represents a natural extension of jack-up engineering into the evolving demands of offshore wind installation.

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