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Effect of types of input motions on the response of jacket structure

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ABSTRACT: The dynamic response of jacket structures with pin-pile foundations is highly sensitive to seismic input characteristics, including frequency content, amplitude, duration and waveform shape. This study comparatively evaluates how distinct input motion types govern coupled structural and soil behaviour under axial and combined axial–lateral loading using centrifuge modelling. Motions with dominant energy near the structural natural frequency induce pronounced resonance amplification, increasing tower-top acceleration and phase lag between base and top, whereas higher-frequency inputs promote modal interaction, redistribute stress demand and reduce soil–structure synchronisation. When lateral loading is introduced, these input-dependent mechanisms intensify, producing greater base moment demand, rotation and asymmetric deformation. Differences in waveform and frequency content also lead to distinct soil response patterns; strong 1 Hz sinusoidal excitation accelerates cyclic stiffness degradation through excess pore pressure accumulation, reducing effective stress and shaft friction and resulting in progressive pile settlement, effects that are further amplified under combined loading due to additional shear mobilisation. Spectral analysis confirms that variations in input motion type systematically modify effective stiffness and energy dissipation through soil–structure interaction. The findings demonstrate that the seismic performance of jacket foundations embedded in a saturated granular deposit is controlled by the specific frequency characteristics of the imposed motion, establishing input motion type as the governing parameter for amplification, rotation and settlement within a serviceability framework.

1 INTRODUCTION

Jacket Jacket substructures are widely adopted for offshore wind turbines in intermediate to deep waters where monopiles become impractical. Their open truss configuration provides favourable global stiffness and efficient load transfer; however, the reliance on multiple slender members and pin-piled foundations increases sensitivity to dynamic loading. In seismic regions, offshore wind turbines are subjected to combined aerodynamic, hydrodynamic, and inertial demands, with the tall, flexible tower–RNA system amplifying low-frequency excitation. Unlike conventional oil and gas jackets, which are typically heavier and governed by ultimate limit state requirements, wind turbine jackets must satisfy stringent serviceability criteria to maintain rotor–nacelle alignment and ensure uninterrupted operation. Accurate assessment of seismic response is therefore essential, as even moderate rotations or cumulative settlements may impair long-term operability, reduce power generation efficiency and increase maintenance demand. Serviceability thus becomes the governing design consideration for jacket-supported offshore wind turbines in seismic environments. However, full-scale field observations under earthquake loading remain scarce, limiting direct insight into soil–structure interaction mechanisms.

To address this limitation, centrifuge modelling provides a controlled means of reproducing soil–structure interaction under realistic stress conditions, enabling direct evaluation of foundation and structural performance during seismic excitation. Within this framework, the characteristics of the imposed input motion become critical, since frequency content, duration and waveform shape govern structural amplification, phase behaviour and soil degradation. The present study reports centrifuge tests on jacket structures supported by pin-pile foundations, conducted to comparatively investigate the influence of distinct seismic input motions under axial and combined lateral loading conditions, with particular emphasis on serviceability-driven response mechanisms.

2 JACKET MODEL DESIGN

2.1 Design concept

The centrifuge model of the jacket structure was developed to replicate the dynamic behaviour of an in-field offshore wind turbine foundation system. A reduced-scale space-frame jacket with pin-pile foundations was constructed, with geometry and material properties defined to tune the overall dynamic characteristics, with particular attention to the natural frequency, so that they matched those of the reference jacket structure. This alignment preserved dynamic similarity, delivering a realistic seismic response that enabled the meaningful reproduction of resonance effects, soil–structure interaction mechanisms, and serviceability-related deformations in the centrifuge environment. The overall configuration of the jacket model and foundation system is illustrated in *Figure 1*.

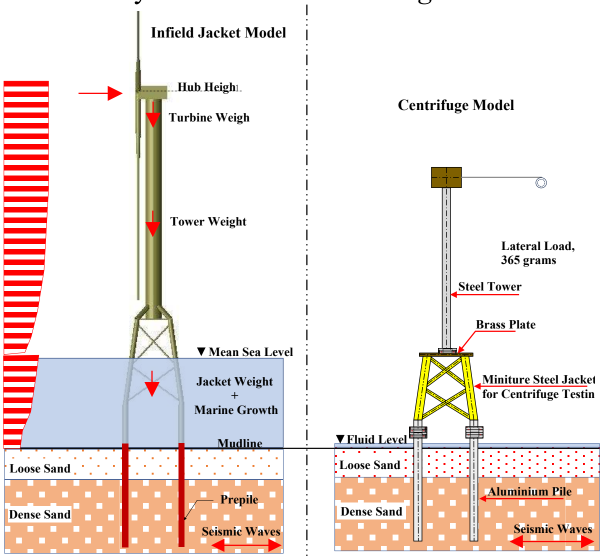

Figure 1. Model Design Concept

2.2 Centrifuge Model

The centrifuge experiments were carried out in an equivalent shear beam (ESB) container filled with HN31 Hostun sand, prepared in two layers with a loose upper deposit overlying a deep, dense layer in saturated condition, as illustrated in *Figure 2*. The required relative densities were achieved through sand pluviation using the automatic sand hopper (Madabhushi, Houghton and Haigh, 2006), with values of approximately 46 % ± 3 % in the loose layer and 85 % ± 5 % in the dense layer. All tests were performed at 60g using the Turner beam centrifuge at the Schofield Centre, University of Cambridge, allowing model dimensions in to be interpreted at prototype scale through established scaling relations (Schofield, 1980; Madabhushi, 2014).

Figure 2. Centrifuge Model - Testing Layout and Arrangement.

The instrumentation consisted of piezoelectric accelerometers positioned at various depths to record soil response, complemented by miniature pore pressure transducers to monitor the development of excess pore pressure. The structural response was measured using MEMS accelerometers fixed at the tower base and top, while settlements were recorded with LVDTs aligned in the direction of shaking. A lateral load system was incorporated into the loading tower, using a pneumatic piston that could be activated during flight to apply a controlled horizontal load in addition to axial loading, thereby enabling evaluation of combined load conditions. The details of the jacket model and its scaled properties are summarised in Table 1.

Table 1. Centrifuge Model Details.

Parameters	**Infield Jacket[1]**	**Centrifuge Model[2]**	**Equivalent Prototype[3]**
Water Depth	20 m	30 mm	1.8 m
Turbine mass	475 MT	2.0 kg	432 MT
Tower mass	325 MT	0.545 kg	117.72 MT
Tower height	90 m	0.55 m	33 m
Natural frequency	0.276 Hz	0.271 Hz	0.289 Hz
OTM (Overturning Moment)	320 MNm	Stat=120.2Nm Dyn=223Nm	Stat=10.5MNm Dyn=19 MNm
Pile diameter	2300 mm	22 mm	1.32 m
Pile length	40 m	320 mm	19.2 m
Pile-flexural stiffness, kNm^2	60×10^6	0.260	3.4×10^6

Note:
1 Values correspond to the actual full-scale field measurements.
2 Values correspond to the physical model measurements used in the centrifuge experiment.
3 Values correspond to prototype-equivalent quantities obtained through centrifuge scaling for testing conducted at 60g, using established scaling relations (Schofield, 1980; Madabhushi, 2014).

The design aimed to capture the essential characteristics of the prototype system in scaled form. Based on these properties, the natural frequency was calculated at 0.271 Hz, which is close to the in-field jacket value of 0.276 Hz, confirming that the intended dynamic similarity was achieved.

The corresponding measured frequency from the centrifuge tests is presented in the following section.

2.3 Earthquake Input Motions

Earthquake motions of varying characteristics were applied to investigate the seismic response of the jacket structure. The series commenced with EQ1, a sine sweep used to characterise the dynamic properties and confirm the fundamental frequency. EQ2 introduced the Imperial Valley record, representing a realistic earthquake scenario for benchmarking purposes. Subsequent tests employed sinusoidal inputs of increasing intensity: EQ3 as a moderate 1 Hz excitation, EQ4 as a stronger motion, and EQ5 as a very strong input. All motions were applied at the base of the ESB container to replicate bedrock acceleration, with lateral load conditions adjusted as required during shaking. The details of the input motions are summarised in Table 2.

Table 2. Earthquake Input Motions.

EQ's Parameters	Lateral Load	Input accl, g
EQ1 Sine sweep	No	0.022
EQ2 Imperial Valley	Yes	0.012
EQ3 Moderate - Sinusoidal	Yes	0.160
EQ4 Strong Excitation	No	0.270
EQ5 Very Strong Excitation	Yes	0.350

2.4 Frequency Characteristics of Input Motions

The acceleration time histories and corresponding Fourier amplitude spectra for all five earthquake inputs are presented in *Figure 3*. These plots illustrate how each motion differs in terms of frequency content and amplitude, forming the basis for evaluating the effects of narrowband and broadband excitation on the jacket response. EQ1, a sine sweep input, gradually increases in frequency with low amplitude and is primarily used to identify the fundamental frequency of the jacket system. Its spectrum extends continuously up to about 4 Hz, representing a swept-frequency excitation rather than a fixed-frequency narrowband or a broadband earthquake. The Imperial Valley motion (EQ2) shows irregular acceleration pulses and multiple peaks of varying amplitude, with its energy distributed across the entire frequency range, classifying it as a *broadband excitation*.

The controlled sinusoidal inputs EQ3–EQ5 exhibit well-defined frequency peaks, with dominant components at approximately 1 Hz and 3 Hz. EQ3 has a clearly stronger 1 Hz component, while EQ4 and EQ5 have nearly balanced amplitudes between the two peaks, indicating dual-harmonic narrowband characteristics. Overall, EQ2 represents a broadband ground motion, EQ3–EQ5 represent dual-harmonic controlled excitations, and EQ1 serves as a swept-frequency test for identifying resonance. This deliberate variation in input type enables the assessment of how frequency, bandwidth, and intensity affect the jacket's seismic amplification, modal interaction, and soil–structure coupling in subsequent analyses.

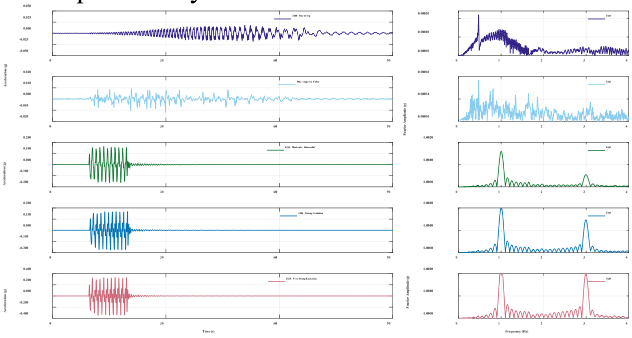

Figure 3. Time histories and Fourier amplitude spectra of input motions (EQ1–EQ5).

3 JACKET STRUCTURAL RESPONSE

3.1 Acceleration Response at Tower Top

The tower-top acceleration responses under the five input motions and their corresponding Fourier spectra are compared *in Figure 4.* In all cases, a dominant peak occurs at about 0.29 Hz, representing the fundamental frequency of the jacket–tower system. The amplitude and bandwidth of the response vary with the nature and intensity of the excitation, reflecting how different input motions influence energy transfer and dynamic coupling within the structure.

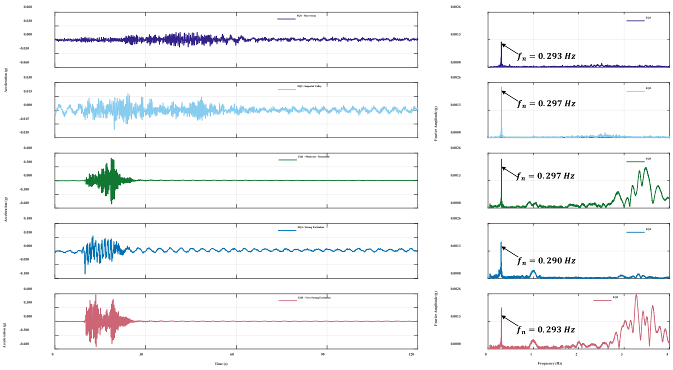

Figure 4. Acceleration Time histories and Fourier amplitude spectra of tower top response (EQ1–EQ5).

The sine-sweep excitation (EQ1) generated the strongest resonance as its frequency crossed 0.29 Hz, clearly defining the system's first-mode behaviour and confirming efficient excitation of the structural natural frequency. The Imperial Valley motion (EQ2,

≈ 0.02 g) induced a weak broadband response centred around the same frequency, showing first-mode dominance but limited energy input. The controlled sinusoidal excitation (EQ3, ≈ 0.52 g) produced a sharp resonance at 0.29 Hz with minor spectral broadening beyond 1 Hz due to nonlinear soil–structure interaction under higher acceleration levels. The strong input (EQ4, ≈ 0.08 g), applied without lateral load, yielded a narrowband and symmetric response, with a small 1 Hz feature attributed to soil-layer frequency content observed in the input spectrum. The very strong laterally biased motion (EQ5, ≈ 0.6 g) produced the highest tower-top acceleration. It maintained the same fundamental frequency but showed broader spectral dispersion and irregular energy beyond 2 Hz, which is interpreted as high-frequency soil vibration and instrumentation noise rather than structural response.

Overall, narrowband inputs such as the sine-sweep effectively drive resonance, while broadband natural motions like those in the Imperial Valley produce limited amplification. Stronger or laterally biased excitations lead to increased tower-top demand and a wider spectral spread. The irregular spectral content above 2 Hz is considered non-structural and excluded from interpretation. These results confirm that the type and intensity of seismic input directly govern resonance amplification, damping, and nonlinear coupling within the jacket–tower system.

3.2 Acceleration Response at Jacket Top

At the jacket level (*Figure 5*), the response reflects the coupled stiffness of the tower, jacket truss, and pin-piled foundation, rather than the independent behaviour of the jacket alone. The spectral concentration near 1 Hz arises because this combined system acts as a band-pass filter, transmitting energy most effectively in the frequency range where the tower and jacket stiffnesses interact. The flexible tower absorbs energy components below this range, while higher-frequency components are damped by the truss and soil layers, resulting in a focused response around 1 Hz.

Under the sine-sweep input (EQ1), this filtering behaviour becomes evident as energy is concentrated near 1 Hz, while the input's lower-frequency feature around 0.47 Hz produces only a minor response. The Imperial Valley motion (EQ2) generates a broadband spectrum with greater activity between 1 and 2 Hz, indicating that irregular ground motions excite a wider frequency band but do not strongly amplify resonance. For the controlled sinusoidal excitations (EQ3–EQ5), the spectral peaks align with the 1 Hz content of the input motion, confirming that the structure selectively amplifies the frequencies that coincide with its effective stiffness coupling. The no-bias case (EQ4) remains narrowband and symmetric, whereas the laterally biased, higher-intensity case (EQ5) shows increased amplitude and mild spectral broadening due to asymmetric soil–structure interaction and energy redistribution through the jacket members.

Overall, the results demonstrate that the jacket-top response is governed by the interaction between input frequency content and system stiffness rather than by an isolated structural frequency. Narrowband inputs drive a concentrated response near 1 Hz, broadband motions distribute energy across 1–2 Hz, and lateral or higher-intensity excitations amplify and widen the response band. This behaviour highlights how the type and strength of the input motion control energy transmission and dynamic demand within the integrated tower–jacket–pile system.

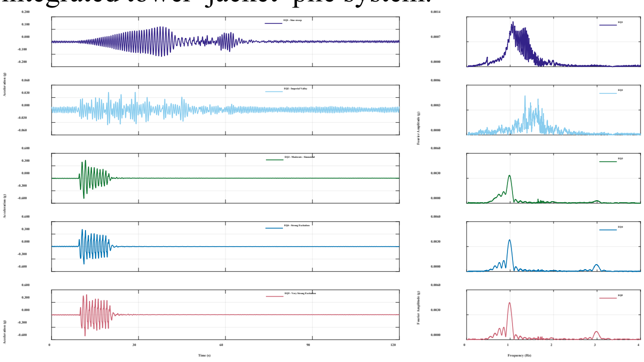

Figure 5. Acceleration Time histories and Fourier amplitude spectra of Jacket top response (EQ1–EQ5).

3.3 Response Spectra Analysis

The response spectrum analysis, as shown in Figure 6, illustrates how variations in the frequency content of the input motion influence the dynamic behaviour of the jacket structure. For EQ1, the response is dominated by input energy around 1 Hz, resulting in a clear peak at the tower base but negligible amplification at the tower top, as the excitation frequency lies well above the structural natural frequency of 0.29 Hz. A similar pattern is observed for EQ3–EQ5, where dominant input peaks occur near 1 Hz (with smaller components around 3 Hz), leading to strong base responses but limited tower-top participation due to the off-resonant nature of these inputs. In contrast, EQ2 exhibits a distinct tower-top response at 0.29 Hz, coinciding with the natural frequency of the jacket structure, confirming effective resonance between the input and the first structural mode. The presence of an additional small input peak near 2.5 Hz in EQ2 produces minimal influence on the upper response, further highlighting the selective transmission of low-frequency energy through the flexible jacket–soil system. Overall, these results demonstrate that the seismic response of the jacket structure is highly sensitive to the dominant frequency of the input motion: motions rich in low-frequency content (e.g. EQ2) effectively excite the structural mode, whereas those dominated by higher frequencies (EQ1, EQ3–EQ5) are largely attenuated through soil–structure interaction, resulting in greater motion confinement at the base and reduced amplification at the tower top.

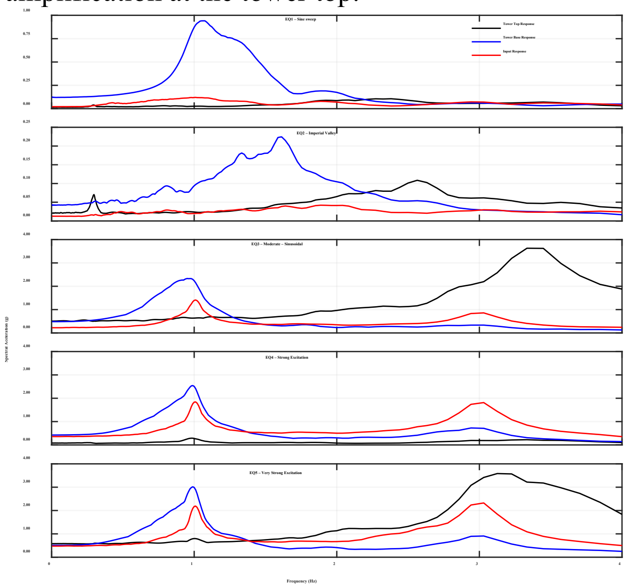

Figure 6. Response Spectrum Analysis.

3.4 Transfer Function

The transfer function, shown in *Figure 7*, clarifies how the input motion shapes the jacket's response. Amplification at the tower top is significant only when the input contains energy close to the structural natural frequency (~0.29 Hz); otherwise, the system largely transmits and amplifies motion at the base while attenuating it aloft. This is why the sine-sweep case does not produce a strong top response: the sweep passes quickly through 0.29 Hz, resulting in little buildup, whereas the Imperial Valley record sustains energy near 0.29 Hz and produces a clear top amplification (≈4.2). By contrast, energy concentrated around 1–3 Hz, common in the other records, drives significant base amplification (e.g., up to ~10 near 1 Hz in the sweep) but couples poorly to the first mode, so the tower-top transfer function stays small. Occasional features near ~2.5–3 Hz likely reflect local or higher-mode/soil effects with low participation at the tower top. Overall, the transfer functions show that the jacket behaves as a frequency-selective system: input motions rich in energy near 0.29 Hz control tower-top demand. In contrast, inputs dominated by 1–3 Hz mainly elevate base demand through soil–structure interaction without producing comparable amplification at the top. This explains the contrast across EQs and indicates that record selection and scaling for this structure should emphasise content near 0.29 Hz when assessing tower-top performance, while recognising that off-resonant inputs primarily affect foundation and base response.

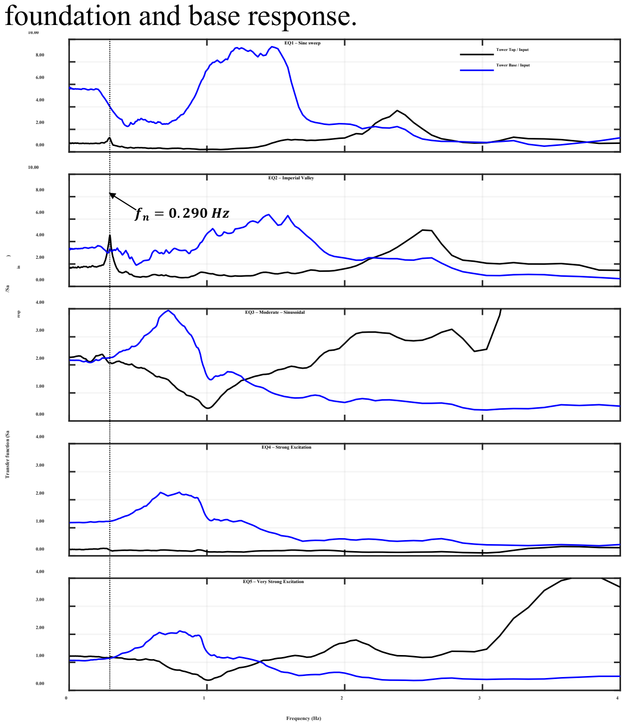

Figure 7. Transfer Function for EQ1 – EQ5

4 SOIL RESPONSE AND FOUNDATION BEHAVIOUR

Soil response under seismic shaking is governed by input frequency content and duration. Narrow-band excitation close to the jacket's natural frequency increases acceleration amplification and phase lag, and in saturated granular deposits can accelerate excess pore-pressure growth, bringing rotation and settlement nearer to serviceability limits. In contrast, broadband input distributes energy across frequencies, limiting peak amplification but allowing cumulative cycling that may still induce tilt and settlement. Interpretation therefore begins with input bandwidth and its proximity to the system frequency.

4.1 Soil response

Soil response to seismic shaking is governed primarily by input bandwidth and proximity to the system frequency. Narrow-band excitation near the jacket's fundamental frequency promotes acceleration amplification and clearer phase lag, while in saturated granular deposits it accelerates excess pore-pressure growth, increasing rotation and settlement demand towards serviceability limits. In contrast, broadband input distributes energy across frequencies, reducing peak amplification but allowing cumulative cycling that can still drive tilt and settlement. Interpretation therefore begins with bandwidth and frequency proximity.

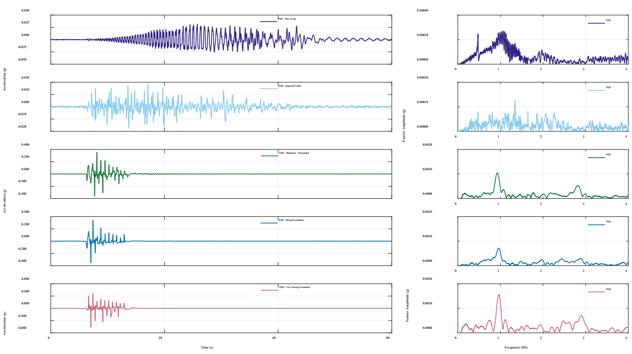

Figure 8. Acceleration Response at 2m below Soil Level

The acceleration response at 2 m below the soil level shown in Figure 8 is governed primarily by input bandwidth and lateral loading condition. In EQ1, the sine sweep traverses transmissible bands, producing a clear peak at 0.47 Hz and a secondary component near 1 Hz where the soil column efficiently transmits energy. In EQ2, energy is broadly distributed and does not persist near a single band, preventing formation of a distinct peak and resulting in low-contrast time and frequency responses. For the short sinusoidal motions (EQ3 to EQ5), acceleration initially rises due to rapid inertial mobilisation around the piles, followed by attenuation as frictional dissipation at the pile–soil interface and radiation damping progressively reduce amplitudes. Under lateral load (EQ3 and EQ5), enhanced interface confinement improves kinematic compatibility and sustains transmission in the ~1 Hz band, limiting peak escalation and maintaining waveform symmetry. Without lateral load (EQ4), reduced confinement allows intermittent separation during tensile phases and re-contact in compression, introducing directional stiffness and accelerating attenuation, which produces asymmetric response. In the frequency domain, the sinusoidal cases exhibit a secondary component near the structural frequency, although dominant energy remains concentrated around 1 Hz. Spectral density is consistently higher with lateral loading and lower without it, reflecting reduced energy retention in that band due to partial decoupling during cyclic reversals. Collectively, these mechanisms demonstrate how input-motion type and loading state regulate acceleration magnitude, symmetry and spectral distribution, thereby governing the jacket's dynamic response within serviceability limits.

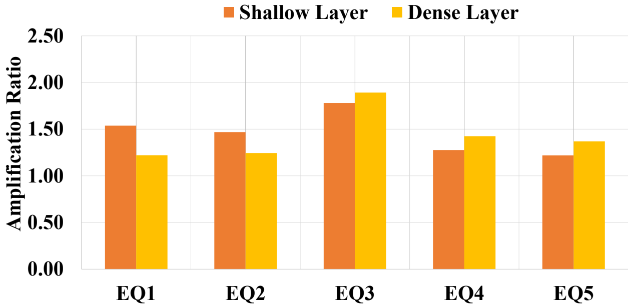

Figure 9. Soil Amplification Ratio

Amplification factors support these trends and are shown in *Figure 9*. Narrow-band excitation near 1 Hz aligns with the transmissible band, so energy resides longer and amplification increases, most clearly near the dense interface where impedance contrast and the short travel path favour transmission. The sweep and the broadband record spread energy and spend little time near resonance, so amplification is lower, especially at depth. Lateral loading stabilises pile–soil contact and improves cycle-to-cycle continuity, which sustains the 1 Hz content and raises amplification compared with the no-lateral case. Increasing the sinusoidal drive increases strain-dependent losses, shortens the effective residence near 1 Hz, and reduces amplification. Together, these points show how input-motion type and loading state control soil amplification and, in turn, the acceleration demand that shapes the jacket's response.

4.2 Excess Pore Pressure Development

A comparative reading of the excess pore-pressure ratio r_u and input acceleration time histories for five inputs (EQ1–EQ5) in *Figure 10* shows that ground-motion character governs soil response beneath the jacket. Low-amplitude (EQ1) and broad-spectrum (EQ2) records produce only gradual r_u growth that remains well below the liquefaction criterion $r_u = 1$. The acceleration (EQ2) exhibits initial peaks that attenuate after shaking, indicating preserved strength and dependable foundation support with limited seismic vulnerability and minimal post-event interruption. In contrast, higher-amplitude inputs with concentrated spectral energy (EQ3–EQ5) drive rapid r_u escalation during shaking, with values approaching or plateauing near unity, signalling liquefaction and an abrupt loss of effective stress. The resulting stiffness reduction and increased foundation

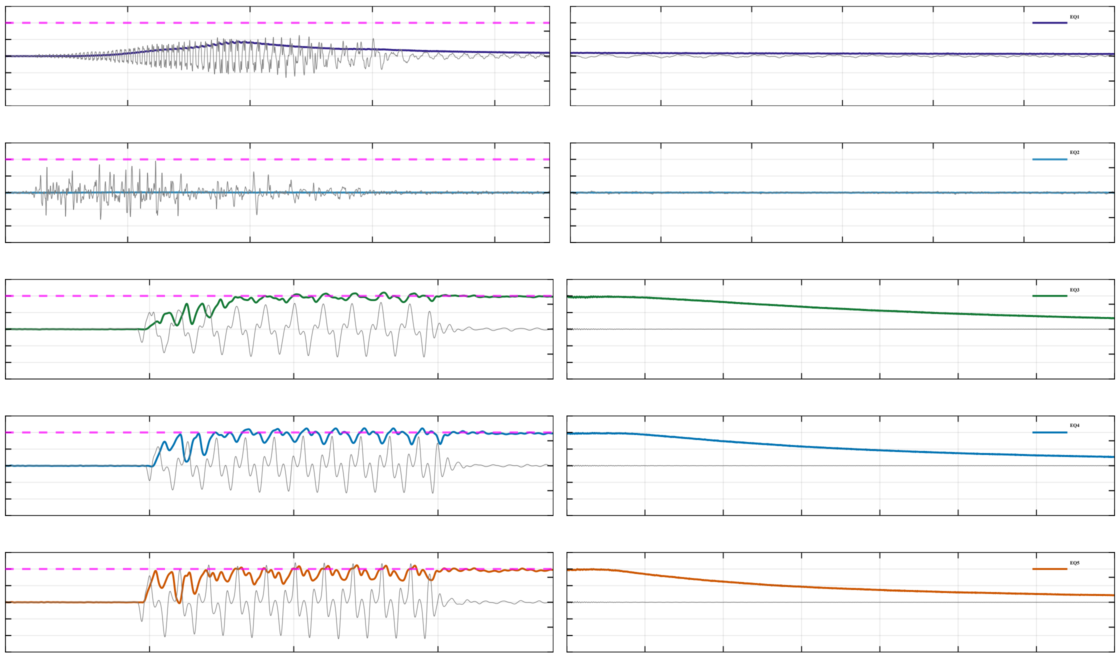

Figure 10. Soil Liquefaction at 2.5m below the soil layer with input acceleration.

compliance are evident in the decay of acceleration envelopes and the slower r_u dissipation that follows. Among these motions, EQ5 shows the most significant initial acceleration and the fastest pore-pressure accumulation, followed by EQ4 and EQ3, highlighting the dominant role of amplitude and energy concentration in triggering liquefaction. Post-shaking recovery varies systematically: EQ3 retains the highest residual (r_u~ 0.32), EQ4 is intermediate (r_u ~ 0.27), and EQ5 dissipates most quickly (r_u ~ 0.21). This ordering captures both the initial severity and the restoration of effective stress, which control serviceability criteria such as recentring capacity, settlement risk. The figure, therefore, links input-motion traits to $r_u(t)$ evolution and to the time scale of strength recovery, showing that amplitude, energy distribution, and duration not only set liquefaction potential but also shape post-event soil-structure performance.

4.3 Rotation and Tilt of the Structure

The rotational responses presented in *Figure 11* clearly demonstrate how the type of input motion governs the seismic behaviour of the jacket structure. Under weaker and more irregular excitations such as EQ1 and EQ2, the structure exhibits small rotational amplitudes not exceeding 0.25°, which decay rapidly after shaking, indicating limited structural demand and complete recovery of equilibrium. As the intensity and duration of the input motion increase, as observed in

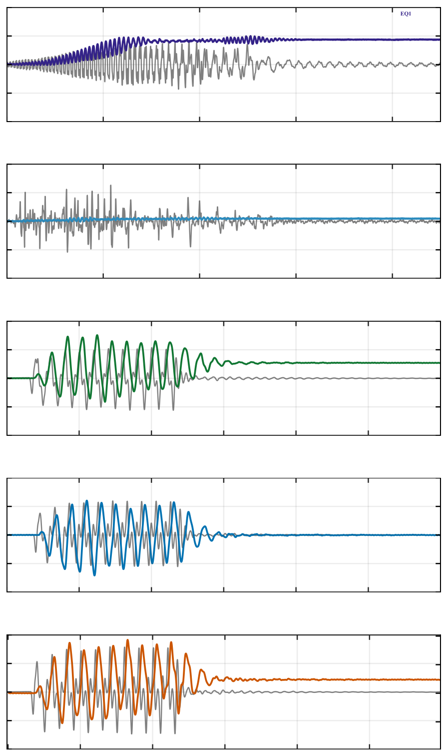

Figure 11. Structural Rotation for different input accelerations

EQ3 and EQ5, the rotational responses intensify, and the residual rotations exceed the (DNVGL-ST-0126, 2018) 0.5° limit, suggesting permanent deformation and potential serviceability concerns. In contrast, EQ4, representing the scenario without lateral load, shows transient rotations exceeding 1° during excitation but returns to nearly zero once the motion ceases, confirming that permanent tilt does not occur in the absence of sustained lateral loading. Taken together, these results from *Figure 11* confirm that the dynamic characteristics of the input motion, its amplitude, duration, and load combination, dictate both transient and residual rotational behaviour. This outcome provides the basis for understanding subsequent settlement responses, as the observed rotation patterns signify how load redistribution during and after seismic events can drive localised foundation movements and influence the overall post-earthquake stability of the jacket structure.

4.4 Settlement Behaviour

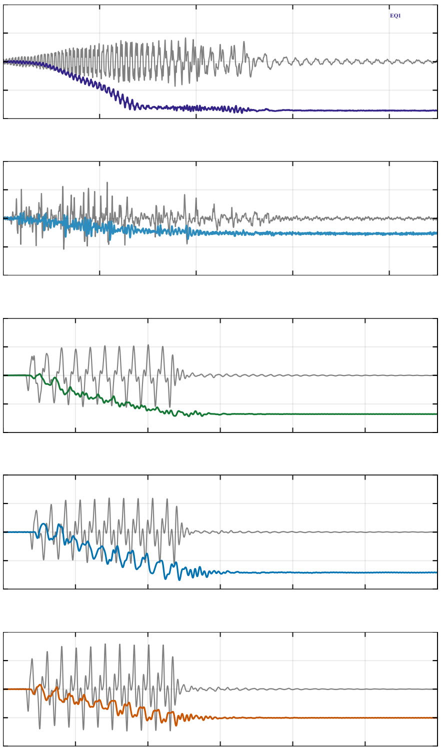

Figure 12. Structural Settlement (SLS)

The settlement response of the jacket foundation varies across the five input records and reflects differences in compaction during shaking and how quickly pore pressure dissipates afterwards (see Figure 12). Under the weaker, irregular motions of EQ1 and EQ2, vertical movements are small and stabilise soon after the main pulses, which suggests limited contractive strain in the bearing layer. In contrast, the more persistent records EQ3–EQ5 cause clear downward movement during strong shaking and leave larger permanent offsets once the motion ends. The case without lateral load (EQ4) shows a mid-range residual settlement despite large transients, indicating that loading path and static bias influence post-event compaction as much as intensity. Across the tests, final settlement aligns better with the time spent at contractive shear strains and the persistence of elevated r_u than with peak acceleration alone. This link ties input-motion character to volumetric deformation and supports serviceability checks for the jacket foundation, where acceptable performance depends on combined limits for tilt and vertical offset.

5 CONCLUSIONS

The study demonstrates that the seismic performance of the jacket–tower system, foundation, and surrounding soil is highly dependent on the type and characteristics of the input motion. Narrow-band excitations near the structural frequency produce stronger resonance and rotation, while broadband and high-intensity motions primarily drive larger settlements through cyclic compaction and pore pressure buildup. Lateral loading amplifies dynamic demand and residual effects, whereas its absence limits permanent deformation. Overall, both the transient and residual responses reveal that the combined influences of input amplitude, duration, and frequency content govern the jacket's rotational and settlement behavior, defining the key parameters for seismic serviceability evaluation.

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