SEISMIC RISK ASSESSMENT AND MITIGATIOS FOR WIND TURBINE INSTALLATION JACK-UP: A CASE STUDY

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ABSTRACT

A comprehensive seismic risk assessment and mitigation study has been performed for the development of a major offshore wind farm in Taiwan. The wind farm site is situated in a highly seismic area and liquefiable top soils. Mitigations of the anticipated seismic risk during foundation and wind turbine installations using a wind turbine installation jack-up had been a major challenge for the planning and installation campaign of the wind farm. In the absence of industry guidelines for jack-up seismic assessment for a wind farm development, the project stakeholders developed a holistic engineering approach involving numerical seismic soil-structure interaction simulations, quantitative risk assessment and monitoring of the actual seismic risk exposure. The paper described the detailed process and challenges in mitigating the seismic risk for the successful installation campaign.

KEY WORDS: Seismic soil-structure interaction, numerical modelling, liquefaction, fully-coupled analysis, wind turbine installation jack-up, quantitative risk assessment

1. INTRODUCTION

Jack-up deployment in a high seismicity area requires a comprehensive seismic risk assessment and mitigation study to demonstrate the capability of the unit to sustain seismic actions, in addition to the operating conditions, without progressive collapse of the structure. It is essential that the integrity and global stability of the jack-up unit is assessed for any excessive structural stresses, significant settlement and/or differential settlement that may occur from cyclic loading on the foundation soil and the dynamic responses of the jack-up unit. Displacements of the jack-up unit (total and relative) induced by the seismic events can also be problematic with respect to the nearby structures.

Seismic events exert cyclic loading on the foundation soils that support the jack-up unit. This cyclic loading can result in the accumulation of excess pore-water pressure and a reduction in the soil strength and stiffness. In coarse-grained soils such as sands, soil liquefaction can occur causing a complete loss of soil strength and stiffness to sustain any loading. In medium dense to very dense non-cohesive soils, cyclic mobility can occur which may not affect the soil strength significantly, but the soil stiffness can be reduced significantly over a certain strain range. Seismic-induced cyclic mobility or liquefaction of the foundation soil can therefore have significant implications for the stability of a jack-up unit.

Given the complexity and diverse operating conditions of a wind turbine installation jack-up unit, site-specific seismic analyses will be cost prohibitive. The existing standards for offshore structures installations in seismic regions, e.g., ISO 19905-1 [1] and ISO 19001-2 [2], do not provide a specific guidance for jack-up seismic risk assessment involving a large number of sites within a single installation campaign. In addition, most seismic studies for jack-up reported in the public domain were focused on site-specific assessments for an operation at a single location. An example of seismic assessment of an offshore wind farm jack-up at a wind farm is described by Hofstede et al. [3].

This paper discusses the process and challenges of the seismic risk assessment and mitigation study implemented for a jack-up unit operating in an OWF project located off the west coast of Taiwan. Seismic soil-structure interaction analysis (SSSIA) is performed using a full 3D dynamic non-linear finite element modelling using a target earthquake. In the following section, key aspects related to the seismic risk assessment and mitigation study undertaken for this case study OWF project are discussed and highlighted including geotechnical site conditions and seismic characteristics of the project site, geotechnical modelling of jack-up response under seismic loading, detailed structural modelling and quantitative risk assessment, among others.

2. GEOTECHNICAL SOIL CHARACTERISTICS AND SITE CATEGORISATIONS

The subject offshore wind farm (OWF) is located approximately 50km west of Taiwan coastline within the Taiwan strait. The proposed project comprises a total of 111 Wind Turbine Generator (WTG) locations to be installed by a wind turbine installation jack-up, namely Seajacks Scylla, a four-legged GustoMSC NG-14000X design class. The water depth across the jacking locations varies from 27.5m to 45.5m with average water depth of 38.0m.

The soil investigation campaign consists of soil sampling boreholes and continuous cone penetration tests (CPT). The cone penetration test was performed at each of the WTG locations. The sampling boreholes and CPT probes were advanced to a maximum depth of 20m to 120m depth while majority of the boreholes were terminated at 20m to 40m depth. The soil samples taken were subjected to standard and advanced soil laboratory tests such as anisotropic triaxial tests, monotonic and cyclic direct simple shear tests, resonant column tests, and bender element tests.

The subsoil conditions across the offshore wind farm areas generally consist of alternating layers of sands, clays and silts to the final borehole termination depth. The top-soil conditions generally comprise loose to medium dense sand overlying silts. The underlying soils are generally of alternating layers of medium dense to dense sands, stiff to hard clays and silts. For a consistent classification of soil stratigraphy across the wind farm area, six geotechnical soil units (GSU), denoted as GSU I to GSU VI, were proposed and identified by Fugro in the static geotechnical interpretative report. The identification of the GSU is based on various parameters estimated from CPTs such as net cone resistance q_{net}, normalized pore pore pressure ratio B_q, soil behaviour type index I_c and inferred fines content.

Geotechnical site characterization was performed by a consultant to develop a generalized soil model for the entire offshore wind farm. The generalized soil model was developed for strain rate effects, cyclic strength degradation, excess pore water pressure accumulation under cyclic loads, small strain stiffness parameters and generalized monotonic stress-strain relationship. It was then used as the basis for soil constitutive model calibration adopted in the numerical modelling of SSSIA carried out for the entire OWF.

Owing to the significant number of WTG locations and to have a more targeted and efficient SSIA across the OWF area, site categorisation was performed by grouping several WTG locations with similar characteristics and soil profile trends into individual categories. Net cone resistance q_{net} profiles were used as a basis for categorisation through grouping of similar q_{net} profiles from various WTG locations. The process was first done using visual inspection and then followed by a detailed analysis to evaluate the characteristic of q_{net} profiles using detailed CPT interpretation and statistical analysis. Examples of such site categorization are shown in Figure 1.

3. SEISMIC CHARACTERISTICS AND SELECTION OF ANALYSIS MOTIONS

Taiwan’s seismotectonic setting is formed of active tectonic structures along the plate boundary, and include both the subduction plate interface and intraplate zones associated with the Manila and Rykuyu trenches, shallow crustal thrust faults and active folds associated with the collision’s accretionary prism complex, and normal faults along the China continental shelf margin and the margins of the basin surrounding Taipei and the Ilan Plain. The thrust faults mapped across Taiwan are seismically active and produce both surface fault rupture hazards and strong ground shaking hazards. The west side of Taiwan is characterized by an extensive fold and thrust belt, and is where the 1999 moment magnitude M_w 7.7 Chi Chi earthquake occurred approximately 100km ESE of the wind farm site.

A Probabilistic Seismic Hazard Analysis (PSHA) was conducted for the project site by a consultant and uniform hazard response spectra for various return periods were derived. Seven sets of recorded ground motion time histories, each set comprising two horizontal components and one vertical component, were selected and processed to be compatible with the target response spectra. The ground motion selection was based on project specific parameters as determined from the seismic hazard deaggregation such as earthquake magnitude and site-to-source distance, duration of shaking and frequency content. Fault rupture mechanism and site conditions were also taken into consideration in the selection process. Seven sets of spectral-matched earthquake ground motion time histories at outcrop were provided for various return periods of 475, 650, 1,000 and 3,800 years.

4. INITIAL SCREENING OF LIQEUFACTION RISKS

Initial screening of liquefaction potential assuming free-field condition was carried out by a consultant and DNV using a simplified procedure as described in Idriss & Boulanger [4]. Two approaches were used in the initial screening assessment, namely the simplified procedure and an advanced procedure using excess pore pressure (EPP) accumulation S-N curves. In the first approach, the potential of liquefaction using the simplified method is evaluated by comparing the seismic demand on the soil (cyclic stress ratio, CSR) with the capacity of the soil to resist liquefaction (cyclic resistance ratio) using correlations with CPT. The applicability of the method is usually limited to a depth of approximately 25m from which the case history data was used to develop the procedure. Moreover, the applicability of this method to silty soils as encountered at the project site may leave uncertainty to the predicted liquefaction potential. The second approach was adopted by using the cyclic shear stress time histories obtained from a site response analysis (SRA) in combination with the excess pore pressure accumulation procedure as interpreted from the cyclic laboratory tests. This advanced analysis is more elaborate and has a rigorous theoretical basis with accumulation of seismic-induced EPP explicitly calculated from the results of SRA and interpreted cyclic laboratory tests.

The results of the simplified method show that at 650-year return period earthquake the top seabed soils is potentially liquifiable and at some locations the potential liquefiable layers extend to within the upper 18m. The deeper sands were assessed to be largely not liquefiable though some of the soil layers showed a marginal safety factor against liquefaction where cyclic mobility in terms of vertical displacements could be accumulated. The analysis using the advanced procedure suggests contradictory results compared to the simplified method. The simplified method predicted that liquefaction may occur for some parts of the soil column but the advanced method did not predict any liquefaction potential for the entire soil column under the same return period events. In conclusion, the simplified method has a tendency to over-predict liquefaction hazard especially for lower return period. Although the advanced method is deemed to be more reliable, it is however limited to the free-field condition and does not consider the effect of high bearing pressures resulting from loaded spudcans, and the dynamic interaction response of a jack-up unit as the foundation soil undergoes cyclic degradation during seismic shaking.

5. INSTALLATION CHALLENGES

The initial screening of free-field liquefaction potential performed for the wind farm using the simplified method predicted liquefaction hazards for 650-year return period events. This is in view of the sandy nature of the seabed soils and the relatively high seismic accelerations at the sites. Although the simplified and advanced methods yielded comparable results at low return periods, discrepancy between the two approaches was observed with increasing return periods. This leaves uncertainty as to whether the sites could be considered safe for elevated operations of a wind turbine installation jack-up. On the other hand, due to the required crane outreach, a hull-in-water operation, which could mitigate the soil liquefaction risk, was not considered feasible as it would hinder the blades installation. Furthermore, at some WTG locations relatively deep spudcan penetrations were predicted which necessitated a more careful installation planning to ensure a good utilization of weather windows and minimize the risk of waiting on weather at WTG locations.

The installation plan had been impacted by the pandemic while the vessel had to leave for the next charter at the end of the year. The installation of a total of 79 WTGs was commenced at end of March 2022 and needed to be completed in an 8-month period.

6. OVERVIEW OF SEISMIC RISK ASSESSMENT AND MITIGATIONS

A return period of 1,000 years was selected as the initial target threshold earthquake return period for jacking operations at the WTG locations and the marshaling port. The most onerous ground motion was initially selected from seven sets of earthquake ground motions supplied for the study based on their Arias intensity. Arias intensity indicates a measure of earthquake intensity level or the released energy (in m/s) and is proportional to the square of the acceleration time history. Figure 2 illustrates the Arias intensity levels for all the seven earthquake ground motions for 1,000 years return-period. The selected most onerous ground motion was also verified using free-field site response analysis and 3D SSSIA sensitivity analysis. The input ground motion with 0.288g horizontal peak ground acceleration is shown in Figure 3.

A two-stage approach of seismic soil-structure interaction analysis (SSSIA) was adopted in the study. In the first stage, detailed modelling of the dynamic response of the foundation soil is performed using soil continuum model integrated with an equivalent bar stool model of the jack-up. An effective-stress based soil model was adopted to simulate cyclic mobility or liquefaction of the soils with strength and stiffness degradations under seismic loading. The resulting spudcan responses were used as input for the subsequent structural assessment. The structural analysis was performed with a detailed structural model using the spudcan response time history obtained from the first stage analysis. If the structural performance was found acceptable under the 1,000-year return period excitation, this return period is conservatively taken as the threshold frequency of initiating event representing the potential for catastrophic failure. Such a frequency should have been site specific and required an iterative process to derive the actual threshold. However, for convenience the same frequency of initiating event was used for all the analysis sites provided the structural acceptance criteria is met.

7. GEOTECHNICAL MODELLING OF JACK-UP RESPONSE UNDER SEISMIC LOADING

Seismic soil structure interaction analysis for this OWF project was carried out using a fully coupled three-dimensional (3D) dynamic non-linear effective stress analysis to simulate the behaviour of the foundation soils subjected to a design Abnormal Level Earthquake (ALE) ground motion. A commercial finite element software (Plaxis 3D) with dynamic feature was used for the SSSIA. The 3D model captures the complexity involved in the effect of loaded spudcans and the dynamic interaction response of a jack-up unit as the foundation soil undergoes cyclic degradation during seismic shaking. Soil cyclic response under seismic loading is modelled using an effective stress elasto-plastic UBC3D-PLM (Plaxis Liquefaction Model) [5] model which is a generalized 3D formulation of the original two-dimensional UBCSAND models [6].

Calibrations of the UBC3D-PM soil model have been performed against the generalized soil model framework proposed by Fugro for the project, particularly the generalized monotonic stress-strain curve, small-strain stiffness degradation and damping, and EPP accumulation (S-N curves). The performance of the model against advanced soil laboratory test, for instance cyclic DSS, is shown in Figure 4. The calibration process was performed for each site category and for each GSU soil layer encountered in the representative CPT profile.

A large soil domain was modelled to minimize the boundary effect of wave propagation during earthquake excitation by considering the spudcan size and the legs spacing of the jack-up unit. The free-field and compliant base boundary conditions were considered along the sides and bottom boundaries, respectively.

The design soil profile for each site category was discretized into several distinct layers based on the q_{net} profile and within the individual GSU layer up to 40m depth. A base layer was introduced with the same shear wave velocity corresponding to that assumed for the outcrop motions. The earthquake motion was applied as dynamic input at the base of the model boundary.

A jack-up structure was incorporated in the model using a bar stool comprising a simplified grillage supported by four columns representing the legs (Figure 5). Crane operating condition is expected to be more onerous than the storm survival therefore the mass characteristic associated with the shifted centre of gravity was considered resulting in non-uniform distribution of stillwater footing reactions. Calibration was first carried out for the bar stool model to ensure that the jack-up global responses matched that of the detailed structural model. The effect of predriving was incorporated in the soil continuum model by means of an influence zone beneath the spudcan with increase in soil strength and modulus according to the stillwater reaction.

Examples of the key outputs from the 3D SSSIA in terms of vertical and horizontal accelerations time history at the spudcan and hull are shown in Figure 6. Seismic-induced spudcan settlements, differential settlements, lateral displacements are shown in Figure 7. The resulting motions and settlement of the spudcans during the earthquake were then used in the subsequent stage of the detailed structural model.

8. DETAILED STRUCTURAL MODELLING

The intention of the study is to show that the jack-up unit is able to survive the design return period earthquake event without a catastrophic collapse, whilst operating at the conditions simulated in the seismic soil-structure interaction analysis. The structural assessment was performed using a 3D Abaqus finite element model to verify the overturning stability, leg strength, leg holding system strength as well as the maximum hull movement and acceleration. The model was subjected to ground motions and predicted differential settlement during the earthquake event derived in the preceding SSSIA, both applied to the spudcans. The response of the structure was assessed and checked for failure.

The assessment considers the operation (i.e., crane lifting) condition to be conservative due to the crane load slewed outboard for each assessment with the most onerous seismic condition to ensure that the results are applicable to all the WTG locations belonging to each site category, covering both the longest and shortest leg length below keel. The intention of the assessment is also to demonstrate that the frequency of occurrence of the seismic event does not exceed the target annual probability of failure.

The assessment was completed in general accordance with the ISO 19901-2 ALE approach [2]. The analysis, however, deviated from the ALE approach, using acceleration time histories with lower return periods than those prescribed in ISO 19901-2 to demonstrate that the vessel can survive a seismic event with a specified probability of occurrence. All load and resistance factors have therefore been set to unity as the present analysis represents an Abnormal Limit State (ALS) check with the objective of establishing the annual probability of failure. The outcome of the analysis forms the basis for a quantitative risk assessment as discussed in the next section.

A typical structural model and example jack-up responses are plotted in Figure 8. Results from the detailed structural modelling coupled with the SSIA demonstrates the satisfactory performance of the unit to operate within the operational range considered for all the WTG locations within the offshore wind farm for 1,000 years return period earthquake event.

9. QUANTITATIVE RISK ASSESSMENTS

Seismic risk associated with the operation of the jack-up during the installation was assessed through Quantitative Risk Assessment (QRA) in order to achieve a target annual probability of failure acceptable to all the stakeholders. It was collectively agreed that the acceptance criteria for the risk level is below the intolerable level of 10^{-3} per year and well above the target of 10^{-4} per year and is subject to demonstrating that it is ALARP, i.e., there are no practicable means of reducing the risk. The frequency of initiating event, probability of collapse and probability of exposure at the individual locations are accounted for in the risk assessment.

10. MONITORING OF ACTUAL EXPOSURE DURATION AND MITIGATION MEASURES

A total of 12 WTG installation cycles were performed for this campaign. The actual exposure duration of the jack-up unit in elevated mode at the individual WTG locations were monitored. The plot of average jack-up time per cycle is presented in Figure 9. For the first two cycles, the jacked-up time was extended due to weather down time at the first WTG location. From the first several cycles, the average exposure time was found to slightly exceed the target average of 24 hours per WTG location. To anticipate further exceedance of the target exposure and obtain allowance for weather down time, additional simulations were performed for subsequent installation locations with a higher return period earthquakes to maintain the same total risk level.

11. ACTUAL JACK-UP RESPONSES UNDER SEISMIC LOADING

On 17 September 2022, an earthquake with a magnitude M_w 6.5 struck at the southeast coast of Taiwan, at Taitung county. The second earthquake with a larger magnitude M_w 7.2 then struck in the same area on the following day, roughly 17 hours after the first one, followed by several smaller aftershocks. The earthquake epicenter is approximately 170km southwest of the jack-up location and at the depth of 7.3km at the Taiwan's main island.

When the major earthquakes struck on two consecutive days, the jack-up unit was operating at two WTG locations at 24m airgap. The jack-up crane was about to lift tower gripper when the first event occurred. The personnel were evacuated from the jacket and the crane was made safe. During the M_w 6.4 earthquake, the leg load was found to fluctuate approximately 400 tonnes. A larger fluctuation of 700 tonnes was observed when the M_w 7.2 earthquake occurred on the following day. This is approximately 60% of the anticipated leg load increase for the design earthquake. The vessel list/trim were fluctuating less than $\pm 1^{\circ}$. In both events, the vessel height remained constant indicating no spudcan settlement induced by the earthquakes. Throughout the multiple aftershocks preceding the main earthquakes, the recorded change in the leg loads was insignificant.

12. SUMMARY

A holistic engineering approach has been performed to quantify and mitigate seismic risks during operation of offshore wind farm jack-up. In the present study, various analyses have been performed using a time-domain approach with a fully coupled, dynamic, non-linear, and effective-stress based model to allow realistic simulations of soil structure interactions under seismic loading. The adoption of such an advanced approach enables better quantification of cyclic mobility and/or liquefaction risks to jack-up and overcomes the apparent over-conservatism associated with the use of simplified method for free-field.

13. ACKNOWLEDGEMENT

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14. REFERENCE

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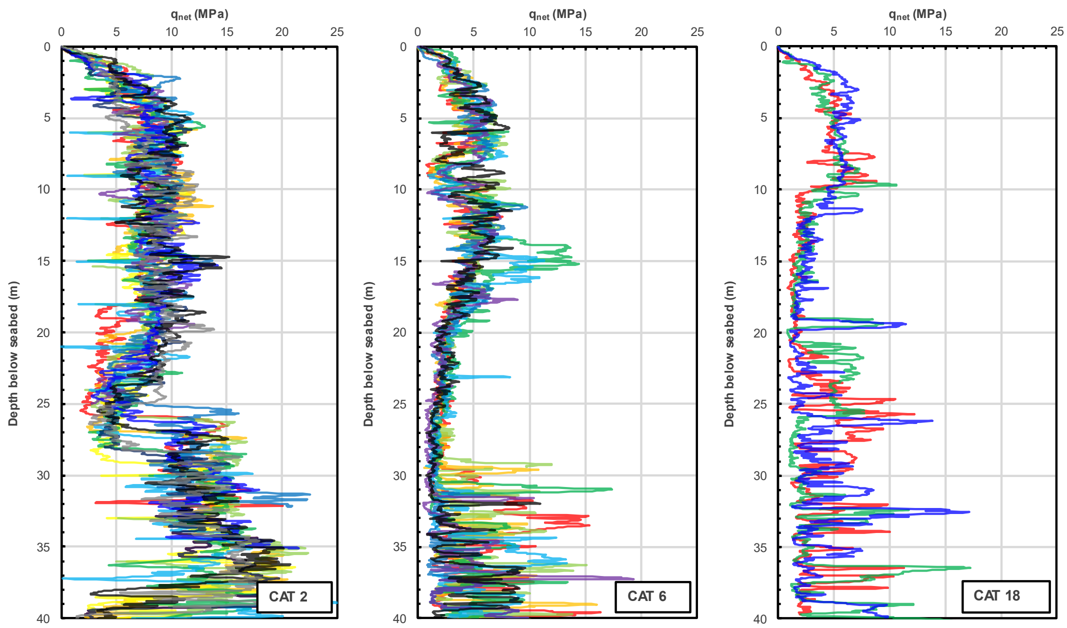


Figure 1 Example of site categorization carried out for the offshore wind farm based on q_{net} profiles

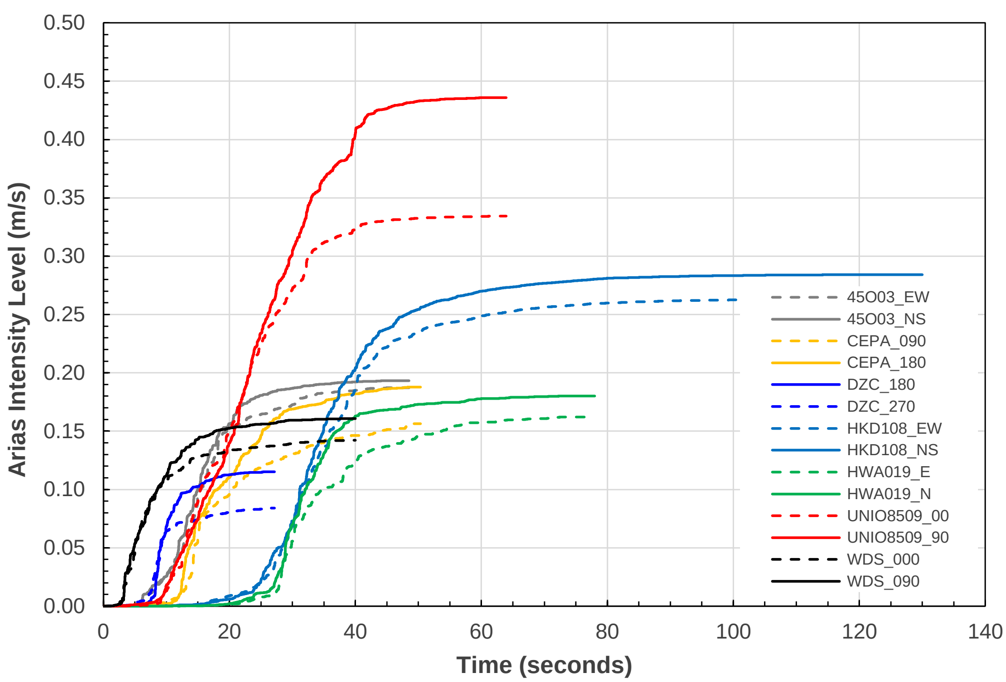


Figure 2 Arias intensity of design ground motions for 1,000-year return period

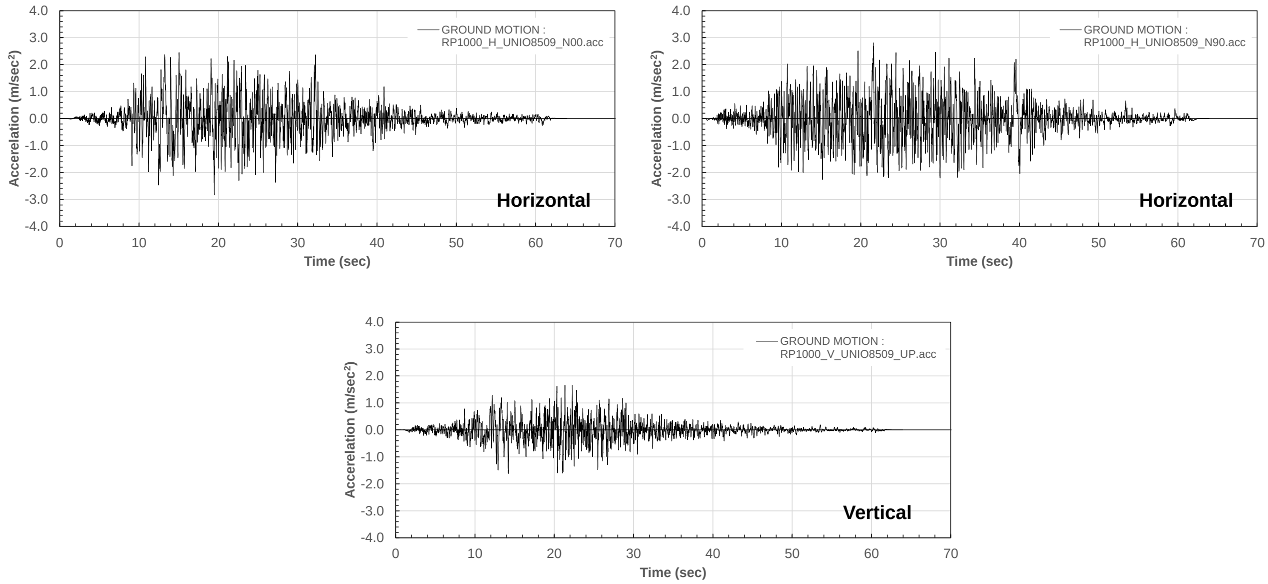


Figure 3 Selected outcrop ground motion used in seismic soil-structure interaction analysis

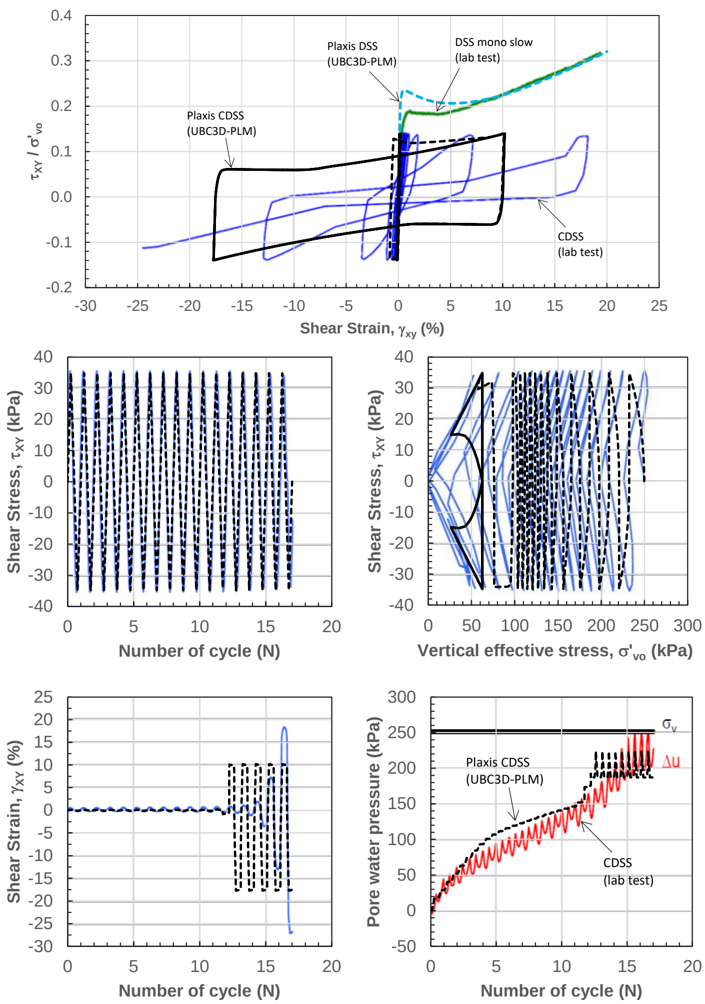


Figure 4 Calibration of soil element test using UBCSAND model

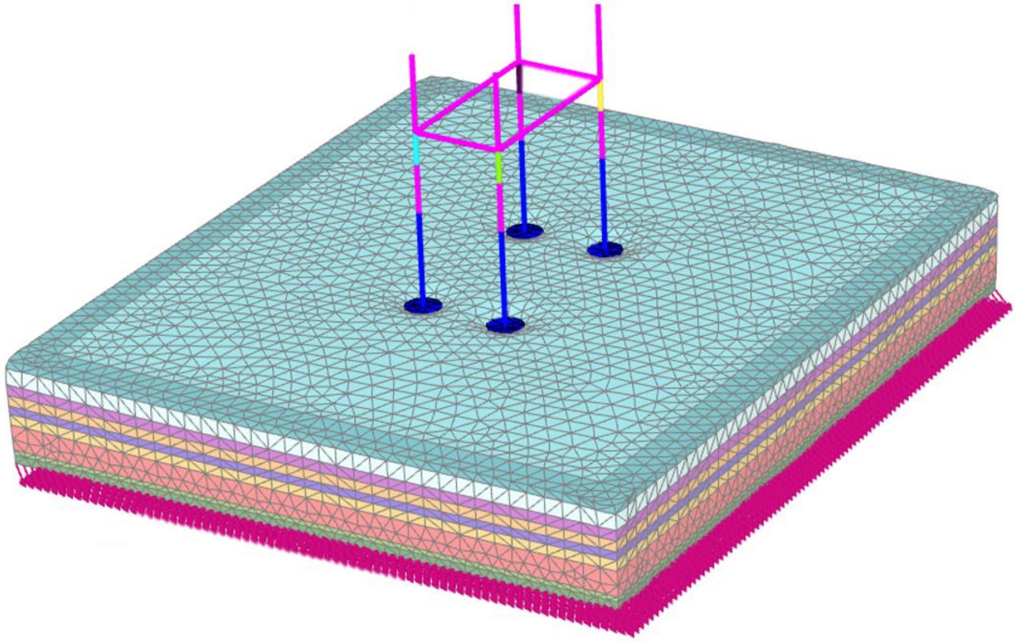
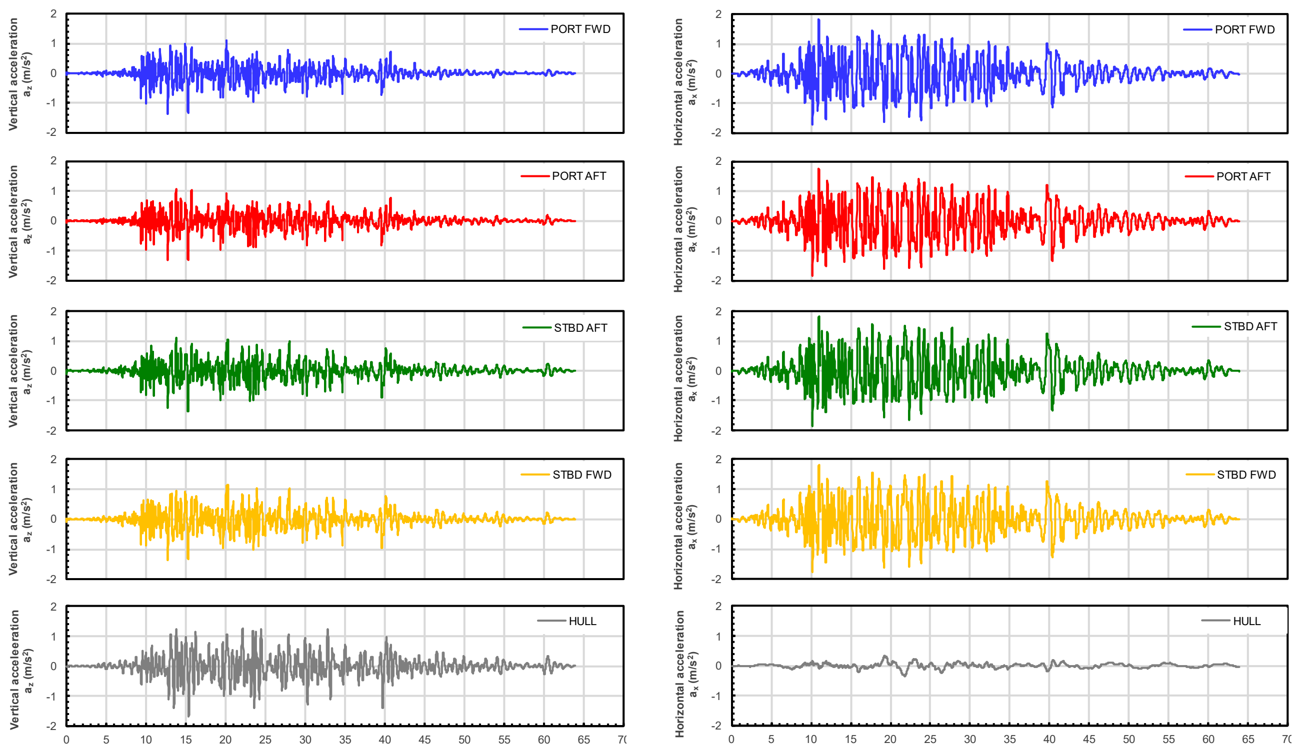
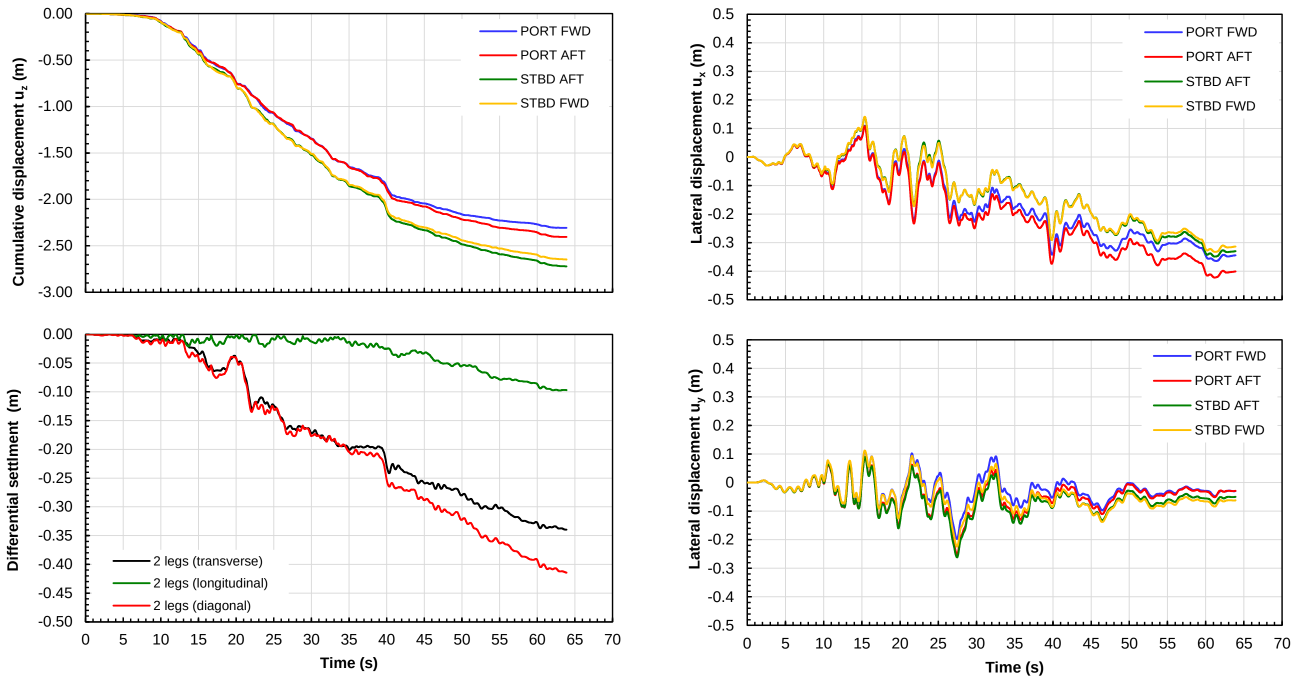


Figure 5 Numerical model of seismic soil structure interaction analysis using Plaxis 3D Dynamics



a) Vertical acceleration   b) Horizontal (x-direction) acceleration

Figure 6 Vertical and horizontal (x-direction) acceleration time histories at spudcans and hull



a) Cumulative settlement and differential settlement

b) Lateral displacement (x- and y- directions)

Figure 7 Seismic-induced spudcan vertical and horizontal displacements

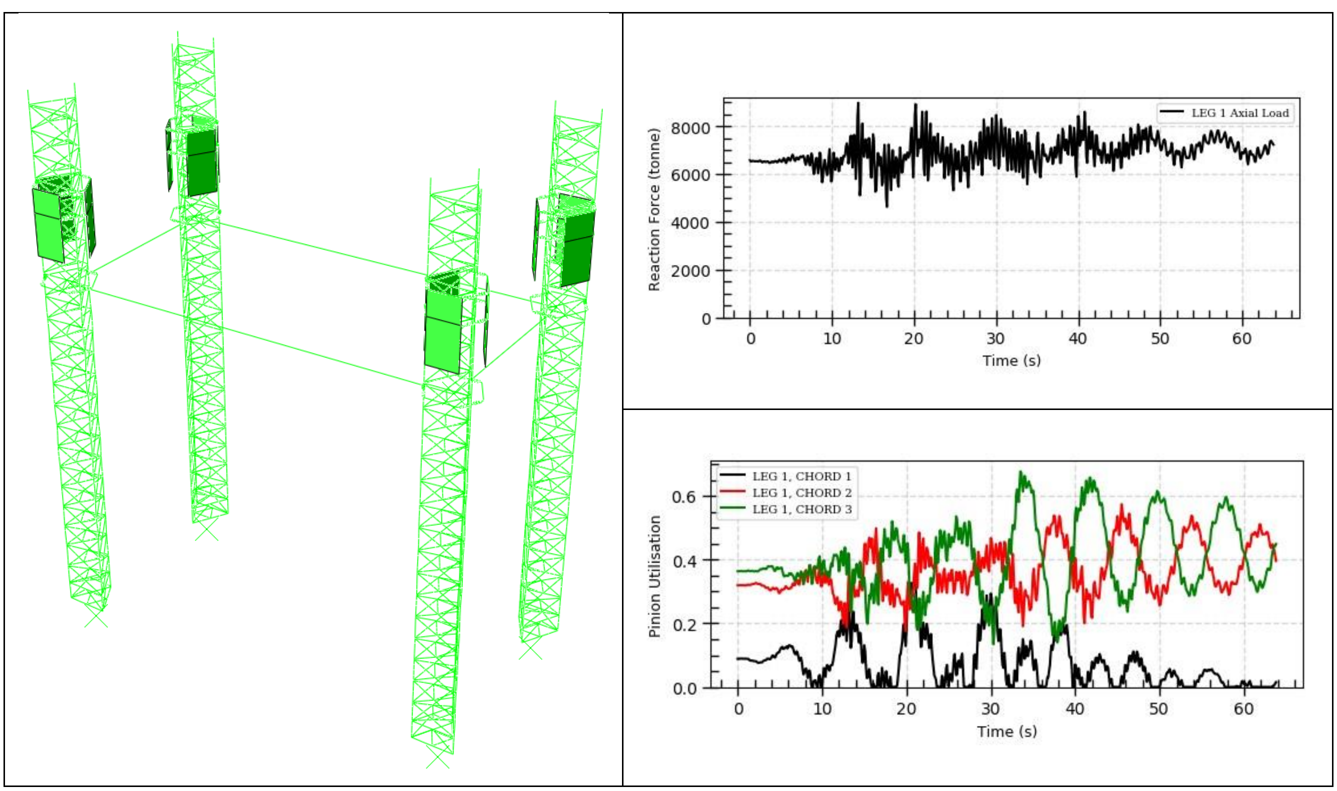


Figure 8 Detailed structural model and example jack-up responses during earthquake

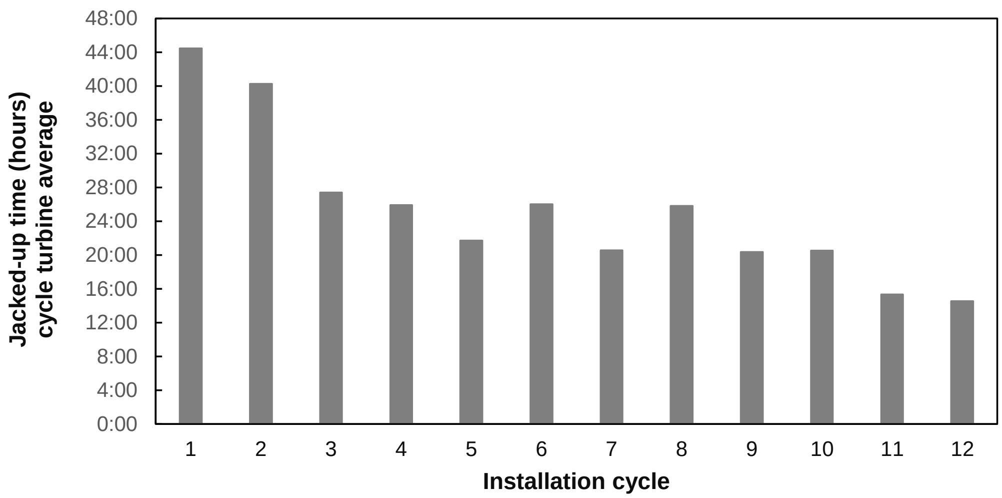


Figure 9 Monitoring of actual exposure time

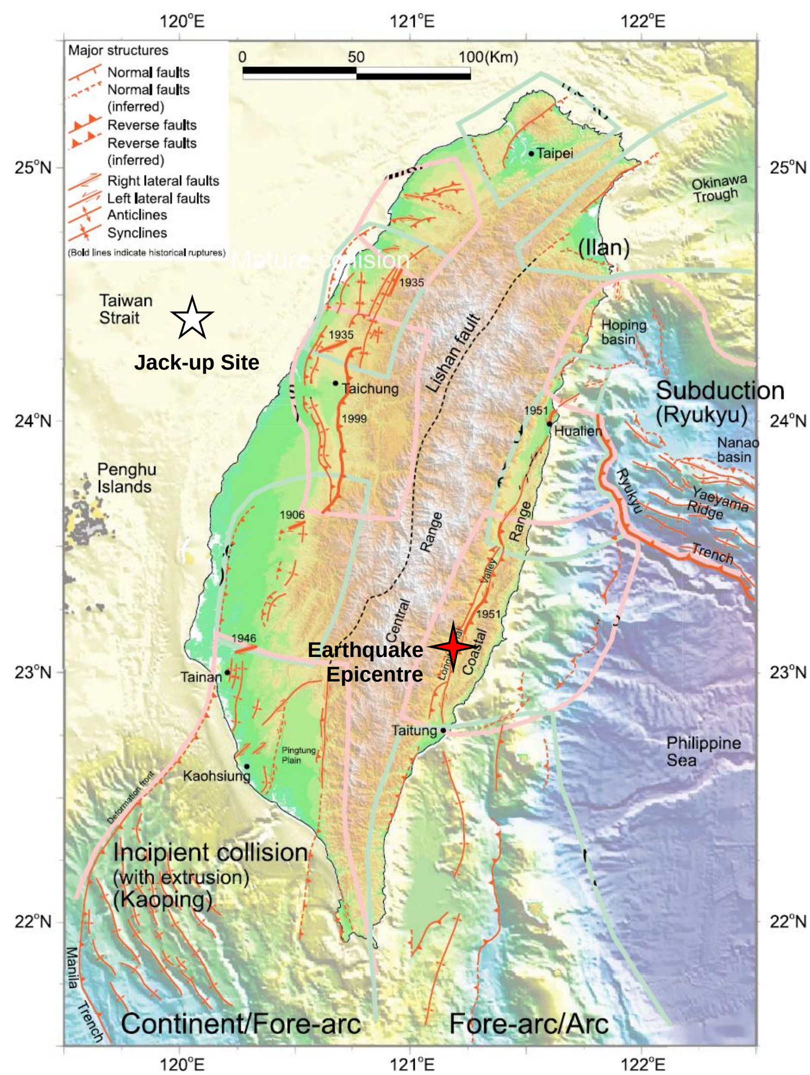


Figure 10 Location of earthquake occurred on 17 September 2022