Six-Degree-of-Freedom Motion Response Analysis of a SPAR-Type Floating Nuclear Power Plant in Halmahera Waters: A Conceptual Study Based on ANSYS-AQWA

Muh. Asyhari Ramadhan, Muh. Hadid Kaharuddin, A. Muh. Ikram, Fuad Mahfud Assidiq

Department of Ocean Engineering, Faculty of Engineering, Hasanuddin University
Email: asyhariramadhan17@gmail.com

Abstract

Reliable electricity supply for the archipelagic regions of Eastern Indonesia motivates the assessment of floating nuclear power plants (FNPPs) as low-carbon baseload sources. This study revises and expands a conceptual motion-response assessment of a 250 MWe spar-type FNPP proposed for Halmahera waters. The model base consists of a 45 m diameter cylindrical structure, a total height of 73 m, a draft of 48.5 m, a modeled water depth of 150 m, and a nine-line spread-mooring system. Hydrodynamic behavior is evaluated in the frequency domain using a six-degree-of-freedom framework and the ANSYS-AQWA outputs available from the original study. Regular-wave responses are interpreted through response amplitude operators (RAOs), while irregular-wave behavior is assessed through response spectra and stochastic amplitudes. Directional patterns are physically consistent: maximum surge is 1.825 m at 0° wave heading, maximum sway is 1.825 m at 90°, heave is 0.226 m for all headings, maximum roll is 0.532° at 90°, and maximum pitch is 0.532° at 0°. All responses remain below the adopted screening criteria of 12 m for surge/sway, 1.3 m for heave, and 45° for roll/pitch. Nevertheless, satisfying these thresholds demonstrates only preliminary hydrodynamic feasibility and does not constitute a nuclear safety case. Site-specific metocean validation, mooring-line tension and one-line-damaged analyses, nonlinear time-domain simulations, tsunami assessment, and qualification of safety-related equipment are required before advancing the concept to a technical pre-feasibility stage.

Keywords: ANSYS-AQWA, floating nuclear power plant, Halmahera, mooring, motion response, RAO, SPAR

INTRODUCTION

Indonesia faces different electricity challenges in major load centers and remote island regions. Halmahera's geographic characteristics, settlement distribution, industrial growth, and public-service needs require a supply that is not only sufficient in energy but also frequency-stable and continuously available. Statistical publications for Central Halmahera provide an initial basis for understanding the geographic, social, and economic conditions of the study area [1], while national data indicate that per-capita electricity consumption continues to increase, requiring supply readiness and grid strengthening [2]. In this context, modular power plants that can be centrally constructed, transported to a site, and connected to an island grid are relevant topics for phased analysis.

Small Modular Reactors (SMRs) offer more flexible power ranges and configurations than conventional nuclear power plants (NPPs) with very large capacities. The IAEA technology catalogue shows the development of various SMR designs for electricity, process heat, hydrogen, and desalination applications [3]. The IAEA study on floating nuclear power plants also emphasizes that the use of offshore platforms may enable shipyard fabrication, centralized quality control, and energy supply for remote regions, while introducing cross-cutting issues involving nuclear safety, maritime safety, security, safeguards, transportation, and institutional responsibilities [4]. Therefore, a floating nuclear power plant (FNPP) cannot be treated merely as a conventional offshore platform or as a land-based nuclear installation simply relocated to sea.

The Offshore Floating Nuclear Plant (OFNP) concept developed by Buongiorno et al. combines light-water reactor technology with a deep-water platform to reduce exposure to seismic hazards and provide a large ultimate heat sink [5]. MIT hydrodynamic studies of the OFNP configuration indicate that hull form, draft, mass distribution, and the mooring system govern heave, pitch, and responses under storm conditions [6]. More recent research has also developed structural analyses of floating nuclear power plants using ANSYS hydrodynamic modules, including frequency-domain responses and load transfer to structural models [7]. Meanwhile, studies of cylindrical platforms with multi-point mooring show that wave direction and mooring-line configuration significantly affect motion responses and tension characteristics [8]. These findings position six-degree-of-freedom motion analysis as an initial check before assessing the safety of reactor systems, electrical systems, and offshore operation.

The initial manuscript presented a conceptual SPAR-type design, RAO curves, response spectra, and

Lisensi Creative Commons Atribusi 4.0 Internasional.

stochastic amplitudes for four incident-wave directions. However, several issues require correction to ensure scientific interpretability: the site depth is stated as approximately 100 m in one section but 150 m in the mooring model; the general distance to the island of less than 30 km differs from the 1.44 km export-cable length; translational and rotational RAO units are not correctly distinguished in the plots; the source and status of the motion criteria are not explained; and the conclusion that the design is "safe" is not separated from preliminary hydrodynamic feasibility. In this revision, 150 m is used as the model basis because it is consistent with the mooring configuration, while 1.44 km is treated as an assumed cable length for the detailed concept rather than as a representation of all site-selection criteria.

The objectives of this study are to: (1) transparently restate the design basis and numerical assumptions; (2) explain the formulation of six-degree-of-freedom motion response, RAOs, and response spectra; (3) interpret the ANSYS-AQWA results for surge, sway, heave, roll, pitch, and yaw; (4) assess response ratios against the adopted screening criteria; and (5) identify further analysis requirements for mooring, metocean conditions, tsunamis, power cables, and qualification of nuclear equipment. The scope is a conceptual study based on available data and simulation outputs. No new simulation, physical model testing, or independent verification of the original ANSYS model file was performed.

THEORETICAL BACKGROUND

SPAR-Type Floating Nuclear Power Plant Concept

A SPAR platform has a cylindrical main body, a large draft, and a relatively small waterplane area. This configuration provides high hydrostatic stiffness against roll and pitch and places most of the submerged volume below the wave-affected surface. For an FNPP, motion stability is relevant to coolant behavior, liquid levels, rotating equipment, cable connections, personnel access, and emergency procedures. Although an offshore concept may reduce some land-site hazards, site evaluation must still follow a graded approach that covers natural and human-induced external events [9]. Meteorological and hydrological hazards should be characterized using site data and uncertainty, rather than a single wave-height and wave-period pair [10]. Seismic hazards, seabed deformation, submarine landslides, and tsunami sources must also be considered in site assessment [11].

Floating nuclear power plants belong to the family of transportable nuclear power plants and therefore raise questions concerning jurisdiction, licensing, ownership, fuel transportation, waste management, physical security, and inter-agency emergency response [12]. In Indonesia, the 3S pre-licensing consultation process, covering safety, security, and safeguards, has begun to be used as an initial mechanism for prospective NPP developers [13]. Hydrodynamic design should therefore be developed alongside the licensing framework, rather than waiting until the platform structure has been fully defined.

Six-Degree-of-Freedom Equations of Motion

The motion of a floating platform is represented by three translations—surge (x-direction), sway (y-direction), and heave (z-direction)—and three rotations—roll, pitch, and yaw. In linear frequency-domain analysis, the equations of motion can be written as:

$$[-\omega^2(M + A(\omega)) + i\omega B(\omega) + C]\xi(\omega) = F_{exc(\omega)} \quad (1)$$

Where M is the structural mass and moment-of-inertia matrix, A(ω) is the added-mass matrix, B(ω) is the radiation-damping matrix, C is the hydrostatic stiffness matrix plus the linearized mooring contribution, ξ(ω) is the complex motion-amplitude vector, and Fexc(ω) is the wave-excitation force vector. This formulation is a general foundation of floating-structure hydrodynamics [19]–[22] and is used in potential-flow-based software such as ANSYS-AQWA [23].

The response amplitude operator (RAO) is the transfer function between response amplitude and wave amplitude. For translational motions, the RAO is expressed in m/m, whereas rotational-motion RAOs are expressed in rad/m or deg/m. Accordingly, the "deg/m" labels on the surge, sway, and heave curves in the initial manuscript should be regarded as labeling errors; these three responses are translational. Mathematically:

Lisensi Creative Commons Atribusi 4.0 Internasional.

$$RAO_{j(\omega,\beta)} = \frac{|\xi_{j(\omega,\beta)}|}{\zeta_a} \quad (2)$$

Where ζa is the regular-wave amplitude, j denotes the motion mode, and β is the incident-wave direction. An RAO peak indicates the frequency range with the greatest amplification and should be compared with the dominant wave-spectrum frequency and the system's natural frequencies.

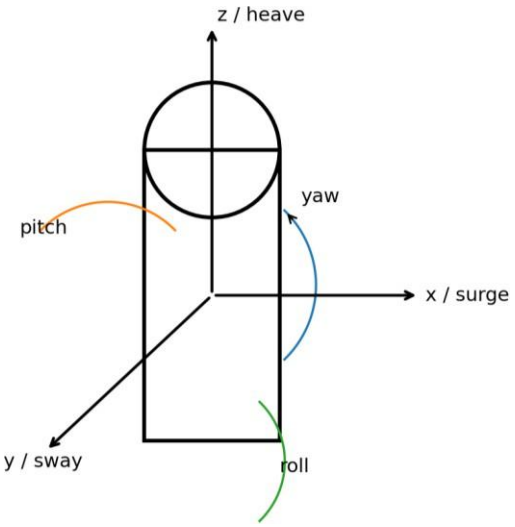


Figure 1. Six-degree-of-freedom coordinate system for the SPAR-type platform

Irregular-Wave Response

Actual ocean waves can be represented as a short-duration stationary random process. The JONSWAP spectrum is commonly used for developing seas and has a sharper energy peak than the Pierson–Moskowitz spectrum [24]. Assuming a linear system, the response spectrum for mode j can be obtained from:

$$S_{xj(\omega,\beta)} = |RAO_{j(\omega,\beta)}|^2 S_{\eta(\omega)} \quad (3)$$

Where Sη is the free-surface elevation spectrum. The nth-order spectral moment is defined as $mn = \int \omega^n Sx(\omega)d\omega$. The response standard deviation is $\sigma = \sqrt{m0}$, while the estimated extreme amplitude depends on duration, the effective number of peaks, spectral bandwidth, and the selected probability. Therefore, the term "most probable amplitude" must be accompanied by a definition of simulation duration and probabilistic formulation so that the result can be reproduced.

For a nuclear facility, motion values should not be evaluated only at the global-platform level. Responses must be transformed into accelerations, inclinations, relative displacements, and loads on internal structures and safety-related equipment. Nuclear-installation design principles require safety functions to remain available during design-basis events and other considered conditions [27], while operating requirements call for consistent operating limits, monitoring, testing, and maintenance programs [28].

Mooring System and Acceptance Criteria

A spread-mooring system provides horizontal restoring forces and limits platform offset. In preliminary analysis, mooring restoring stiffness can be linearized around the equilibrium position. Extreme-response assessment, however, requires a nonlinear model incorporating catenary or taut-line geometry, seabed contact, line drag, elasticity, pretension, and dynamics. Environmental conditions should be defined in accordance with metocean design-basis principles [14], while stationkeeping assessment should cover intact, damaged, accidental, and fatigue conditions under stationkeeping standards [15], DNV guidance [16], [17], and API guidance [18].

The criteria of 12 m for surge/sway, 1.3 m for heave, and 45° for roll/pitch used in the initial study are retained as screening criteria so that the comparison remains unchanged. These values are not treated as final safety limits. Final limits must be derived from mooring and cable clearances, riser or umbilical stroke where applicable, gangway capability, helideck operating limits, stability, habitability, and qualification of the reactor and equipment. The consequences of FNPP failure are greater than those for an ordinary commercial platform; therefore, reliability targets and design margins must be established by the relevant regulator and classification

Lisensi Creative Commons Atribusi 4.0 Internasional.

organization.

RESEARCH METHODOLOGY

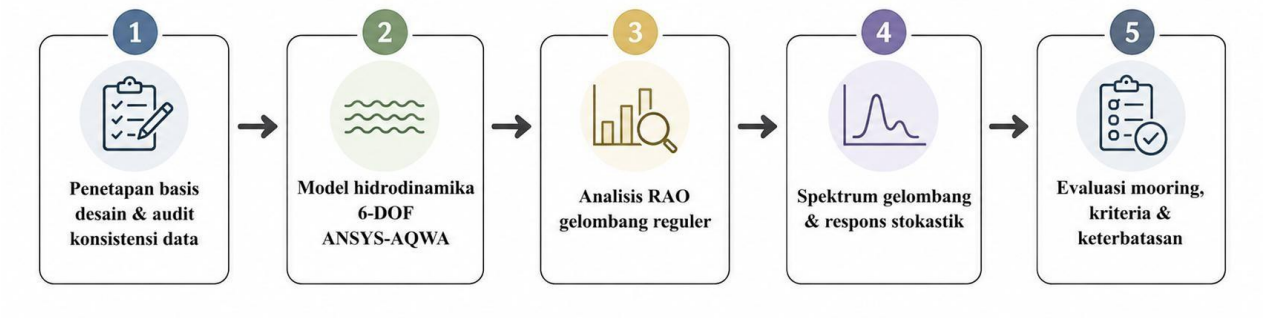


Figure 2. Workflow for revision and conceptual evaluation of floating nuclear power plant motion response

Data Basis and Scope

This study uses secondary data and simulation outputs from the initial manuscript. The main data comprise platform geometry, mooring-system characteristics, RAO curves for wave directions of 0°, 30°, 60°, and 90°, response-spectrum curves, characteristic periods, and stochastic amplitudes for the six motion modes. The available output values were not changed. The revision addresses unit consistency, methodological structure, physical interpretation, criterion assessment, and validation requirements.

Table 1. Conceptual design basis and data status

Parameter	Baseline Value	Usage Notes
Platform type	Cylindrical SPAR	Source conceptual model.
Reactor power	557 MWt / 250 MWe	Conceptual power class.
Body diameter	45 m	Used as the geometric basis.
Total height	73 m	Includes the upper structural section.
Draft	48.5 m	Basis for stability and submerged mesh generation.
Water depth	150 m	Selected to maintain consistency with the mooring model.
Minimum freeboard	15 m	Requires verification against extreme wave crest elevations.
Export cable length	±1.44 km	Conceptual route assumption; not based on a site survey.
Wave direction	0°, 30°, 60°, 90°	Quadrant symmetry analysis.
Wave condition	Hs = 1.16 m; Tp = 7.16 s	Initial study input; return period status requires verification.

Site information refers to Central Halmahera as the regional context [1]. National energy-demand information is used only to explain the relevance of power supply and is not an input to the hydrodynamic model [2]. The 250 MWe reactor is treated as a conceptual design class that requires verification against the technology catalogue and the technology owner's design documents [3]. The latest IAEA study emphasizes that FNPP deployment decisions should integrate technology, infrastructure, regulation, and the readiness of the host country [4].

Hydrodynamic Model

The hydrodynamic model is assumed to use linear potential theory, a linear free surface, an inviscid and incompressible fluid, and small motion amplitudes. The structure is treated as a rigid body to obtain added mass, radiation damping, excitation forces, and RAOs. This framework is suitable for frequency-domain screening but is less adequate for nonlinear phenomena such as slamming, green water, dominant viscous drag, vortex-induced motion, snap loading, and extreme tsunami response. The ANSYS-AQWA documentation describes the use of diffraction/radiation panels and frequency-domain motion-response calculations for floating structures [23].

Model-quality checks that are required but could not be verified from the initial manuscript include panel-

Lisensi Creative Commons Atribusi 4.0 Internasional.

mesh convergence, center-of-gravity and center-of-buoyancy locations, mass and moments of inertia, unit consistency, waterplane area, hydrostatic stiffness, additional damping, natural frequencies, and wave-direction conventions. Because the model file was unavailable, this revision treats the plots as final outputs from the source study and does not reconstruct the curve values.

Mooring-System Model

Nine lines are arranged radially in three groups of 3 × 3. This configuration is intended to provide restoring forces for multiple incident-wave directions. Although the maximum tensile capacity is stated, the initial manuscript does not provide pretension, material type, chain and wire/polyester segment lengths, fairlead coordinates, anchor radius, anchor type, soil profile, or maximum tension from the analysis. Therefore, mooring safety cannot be concluded from motion data alone.

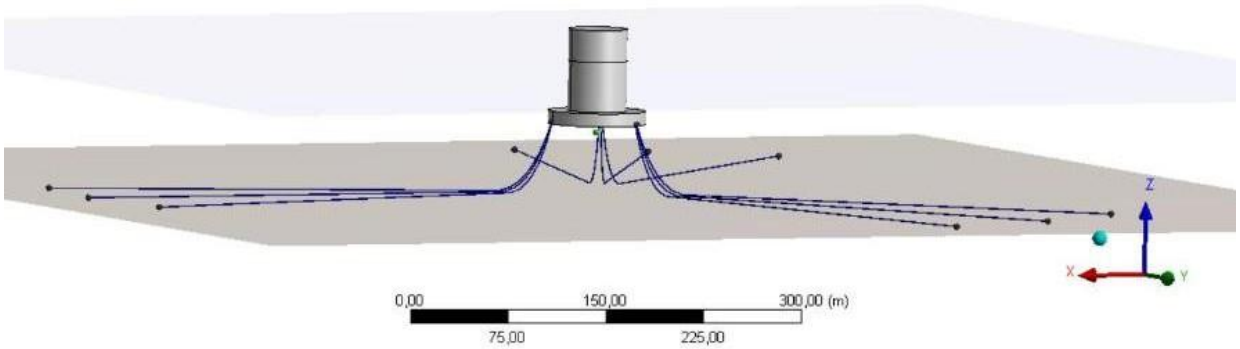


Figure 3. Conceptual platform configuration and nine-line spread-mooring system at the modeled water depth of 150 m

Further assessment should follow four condition groups: intact ultimate limit state, damaged condition after one line breaks, fatigue limit state due to long-term cycling, and accidental limit state. ISO 19901-7 provides a stationkeeping methodology for floating structures [15]. DNV-OS-E301 and DNV-RP-C205 provide frameworks for environmental combinations, tension analysis, and safety factors [16], [17], while API RP 2SK provides recommended practice for stationkeeping-system design and component checks [18].

Table 2. Mooring-line properties used in the source model

Mooring-line parameter	Value
Length of each line	420 m
Mass per unit length	370 kg/m
Equivalent cross-sectional area	0,09 m²
Axial stiffness EA	800.000 kN
Maximum tensile capacity	11.981 kN
Added-mass coefficient	1,0
Transverse drag coefficient	2,4
Equivalent diameter	0,13 m
Longitudinal drag coefficient	1,15

Analysis Cases and Evaluation Parameters

The utilization ratio is defined as $U = \frac{Rmax}{Rlim}$. A value of $U < 1$ indicates that the response is lower than the adopted criterion. However, U is not a structural safety factor and does not replace checks of hull stress, stability, anchor capacity, line tension, fatigue, or equipment functional limits. The quality of conclusions is classified into three levels. Level one comprises direct results from the source study, such as amplitudes and maximum-response directions. Level two comprises physical interpretations based on hydrodynamic theory. Level three comprises design recommendations based on standards and literature. This separation prevents additional recommendations from being mistaken for new simulation outputs.

Table 3. Analysis-case matrix

Lisensi Creative Commons Atribusi 4.0 Internasional.

Stage	Case	Main outputs
Hydrostatics	Equilibrium condition at a draft of 48.5 m	Displacement, center of buoyancy, GM, trim
Regular waves	Frekuensi 0-±2,2 rad/s; arah 0°, 30°, 60°, 90°	Six-DOF RAOs
Irregular waves	Spectrum based on source Hs and Tp	Six-DOF response spectra
Extreme statistics	Most-probable amplitude from the source study	T0, ζext for each direction
Criterion assessment	Maximum response/criterion comparison	Utilization ratio U
Design audit	Consistency and gap assessment	List of further analyses

RESULTS AND DISCUSSION

Floating Nuclear Power Plant System Configuration

The platform arrangement places the reactor and cooling pool in the lower section to reduce the center of gravity, while the turbine, condenser, control room, transformer, maintenance rooms, and helideck are located at higher elevations. This vertical mass distribution is beneficial for stability but requires an integrated assessment of the structure, containment, shielding, maintenance access, ventilation, fire protection, and segregation of safety systems. The OFNP concept emphasizes the benefits of shipyard construction and using the sea as a heat sink [5], but detailed design must prevent common-cause failures that could simultaneously affect the platform and reactor.

Figure 4. Conceptual arrangement of the main components inside a SPAR-type floating nuclear power plant platform.

The power-transmission system using a subsea cable must be designed for platform offset, bending radius, dynamic-cable fatigue, seabed protection, anchor-drag failure, and grid loss. The OFNP balance-of-plant study discusses the importance of integrating generation, transformation, and power transmission from the platform to shore [30]. In the source design, the cable length of approximately 1.44 km indicates that the platform is relatively close to shore. Consequently, navigation conflicts, port impacts, safety zones, sedimentation, and bathymetric effects are more important than for a deep-water concept located tens of kilometres offshore.

For maritime safety, the transport of fresh and spent nuclear fuel must meet requirements for packaging, protection, and vessel operations. The IMO INF Code establishes safety requirements for the carriage by sea of packaged irradiated nuclear fuel, plutonium, and high-level radioactive waste [26]. The ABS document on pathways for floating nuclear power plants emphasizes the need to integrate maritime classification with nuclear requirements and to map hazards that differ from those of ordinary ships [25].

Response to Regular Waves

The surge curve shows the largest response at wave directions of 0° and 30°, then decreases at 60° and approaches zero at 90°. This pattern is consistent with the projection of wave forces onto the model's longitudinal axis. At low frequencies, the platform and mooring system move in response to wave excitation and drift forces, resulting in relatively high translational RAOs. The response decreases as frequency increases because of inertia, radiation damping, and the hydrodynamic characteristics of the submerged body. This result is consistent with the transfer-function concept for floating platforms [19]–[21].

Lisensi Creative Commons Atribusi 4.0 Internasional.

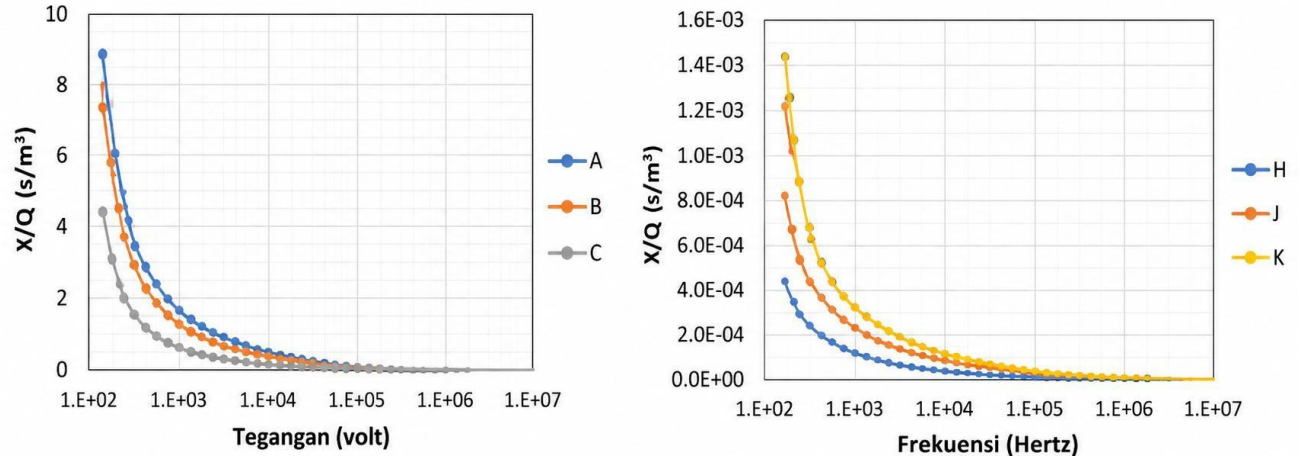


Figure 5. Surge and sway RAOs from the source model. Translational units are interpreted as m/m

Sway exhibits a complementary pattern: the response is minimum at 0° and maximum at 90°. For a cylindrical structure that is nearly axisymmetric, differences between surge and sway primarily arise from wave-direction convention, mooring configuration, mass distribution, or details of the model that are not fully symmetric. The equal maximum values of surge and sway, 1.825 m, support the interpretation that the principal directional responses are dominated by comparable load projections and mooring restoring forces.

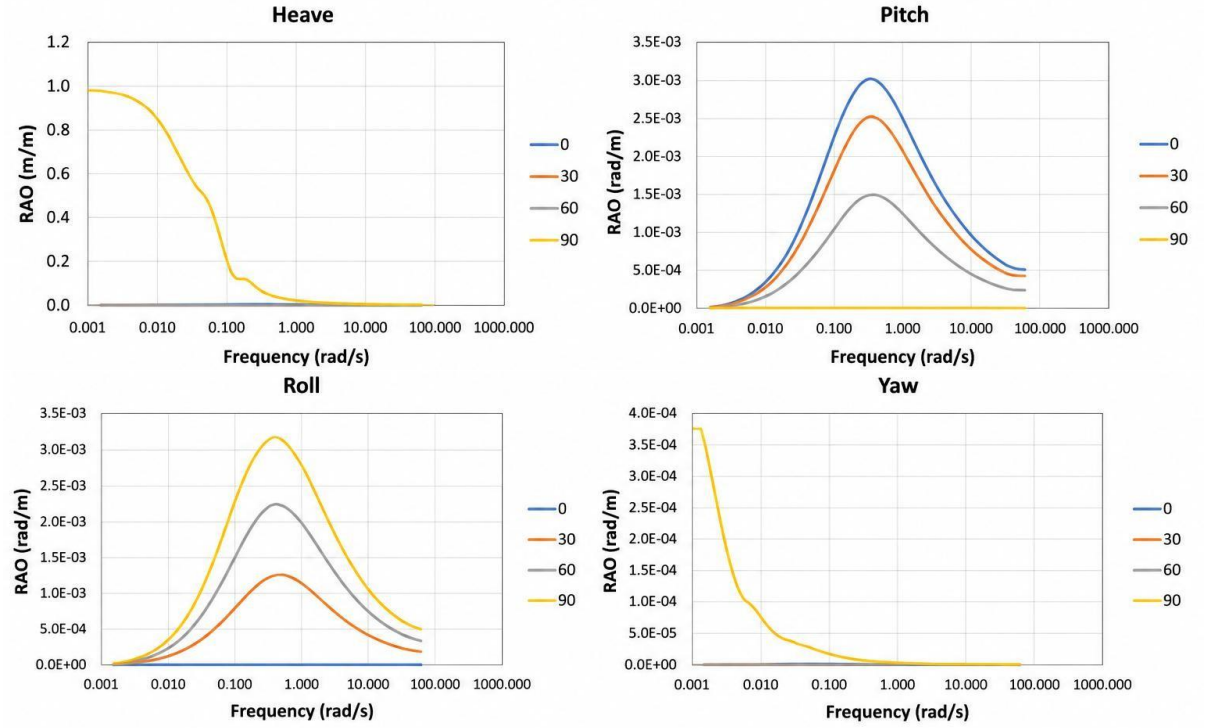


Figure 6. Heave, pitch, roll, and yaw RAOs from the source model

Low frequencies require particular attention because horizontal offset determines the required clearance from the shore, other structures, anchors, and cables. Frequency-domain analysis usually does not capture alllow-frequency drift components and catenary nonlinearities accurately. Therefore, coupled time-domain analysis remains necessary for design combinations of waves, wind, and current.

Heave is a translational response in m/m; roll, pitch, and yaw are rotational responses per unit wave amplitude. Heave is nearly identical for all directions, consistent with a cylinder that is almost symmetric about its vertical axis. Heave response is high at very low frequencies and decreases toward zero beyond approximately 1.5–2 rad/s. However, the curve does not show a sharp heave-resonance peak. This may be because the natural frequency lies outside the analysis range, numerical damping is relatively high, or the curve data have been normalized in a particular way. Hydrostatic stiffness, added mass, and natural frequency should be checked to confirm this interpretation.Maximum pitch occurs for waves at 0° and decreases toward 90°, whereas maximum roll occurs at 90° and is nearly zero at 0°. Both curves peak at approximately 1.0–1.2 rad/s, indicating rotational amplification at periods of about 5.2–6.3 s. Since the source peak wave period of 7.16 s corresponds to a frequency

Lisensi Creative Commons Atribusi 4.0 Internasional.

of approximately 0.88 rad/s, the dominant wave energy is close to the range of increased rotational response. This explains why roll and pitch response spectra require closer evaluation even though their absolute amplitudes are small.

Yaw is very small for all directions. Such low values may indicate symmetry of the body and mooring system, but they should also be checked for output rounding or inactive coupling terms. In real operation, yaw may be induced by combinations of wind direction, current, misaligned waves, mooring asymmetry, a broken line, and cable interaction. Therefore, zero yaw should not be regarded as an absolute design characteristic.

Table 4. Summary of RAO interpretation for the six motion modes

Mode	Dominant response direction	Critical frequency range	Design interpretation
Surge	0°-30°	Low frequency	Control of longitudinal offset and cable
Sway	60°-90°	Low frequency	Control of transverse offset and clearance
Heave	Nearly direction-independent	< 1,5 rad/s	Check vertical motion and accelerations
Roll	60°-90°	±1,0-1,2 rad/s	Beam waves and transverse stability
Pitch	0°-30°	±1,0-1,2 rad/s	Head waves and vertical equipment
Yaw	Very small	< 0,5 rad/s	Verify coupling and damaged mooring

Response to Irregular Waves

The surge and sway spectra peak at approximately 0.8–1.0 rad/s. Surge is dominant at 0°, whereas sway is dominant at 90°. This pattern results from multiplying the squared RAO by the wave spectrum, as expressed in Equation (3).

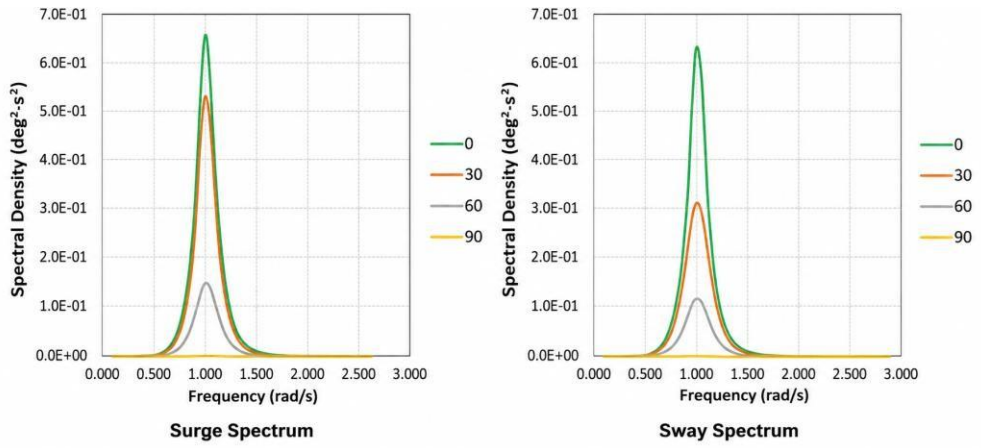


Figure 7. Surge and sway response spectra for four incident-wave directions

Because the response peaks are close to the wave-spectrum frequency, small changes in Tp or spectral shape can meaningfully alter the amplitudes. The inputs Hs = 1.16 m and Tp = 7.16 s must therefore be verified using hindcasts, buoy measurements, satellite data, and site-specific extreme analysis in accordance with ISO 19901-1 [14] and the IAEA guidance on hydrological hazards [10].

A narrow spectral peak indicates a limited response bandwidth. However, without frequency resolution, spectral-moment values, sea-state duration, and a peak-enhancement factor, the extreme-response estimate cannot be reproduced. In the next stage, the model should report m0, m2, zero-upcrossing period, significant amplitude, expected maximum for durations of 1 h and 3 h, and the selected quantile.

Lisensi Creative Commons Atribusi 4.0 Internasional.

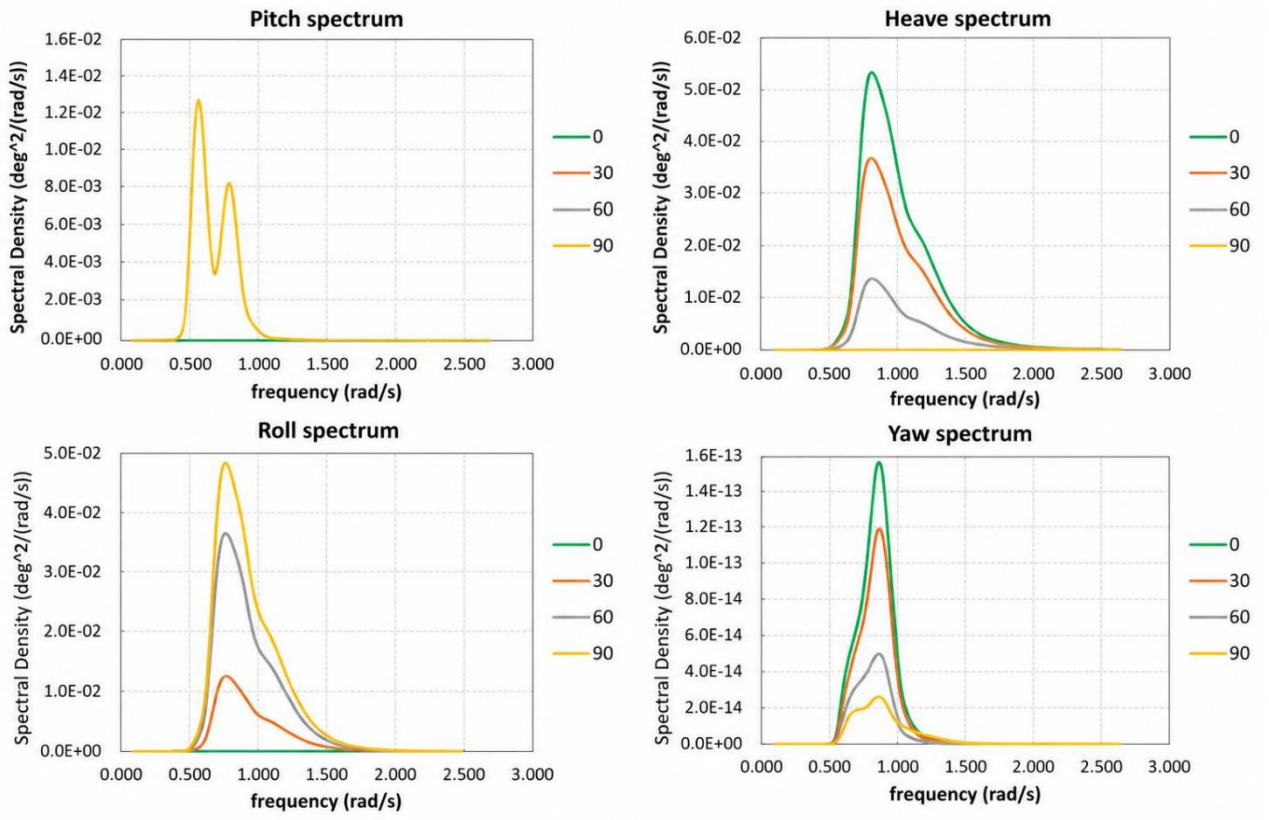


Figure 8. Pitch, heave, roll, and yaw response spectra from the source model

The pitch spectrum in the source figure has two peaks at approximately 0.6 and 0.9 rad/s. Two peaks may arise from interaction between the wave-spectrum shape and the RAO, or from coupling between modes. Because the regular-wave pitch RAO shows one main peak, the model should be audited to ensure that graph labels and motion modes have not been interchanged. In the source figure, the captions for Graphs 9 and 10 are also not fully consistent with the curve shapes. This revision follows the labels shown in the figure but identifies verification of the output file as necessary.

The heave spectrum is highest at 0° and decreases in other directions, although the heave RAO is almost identical for all directions. This inconsistency may arise from directional spectra, coupling, or plotting-order errors. This is an important audit finding: the conclusion that heave is direction-independent should not be drawn from one group of plots before the numerical data have been checked.

The roll spectrum is dominant at 90° and 60°, consistent with the RAO. The yaw spectrum is on the order of 10^{-13} to 10^{-14}, far smaller than those of the other modes. This may indicate very little energy transfer to yaw, but values approaching machine precision may also indicate perfect symmetry or a degree of freedom that receives no numerical excitation. Sensitivity tests using asymmetric wave directions, such as 15°, 45°, and 75°, and misaligned wind-wave-current combinations are required.

Stochastic Amplitudes and Criterion Ratios

The maximum horizontal translational amplitude of 1.825 m is symmetric between surge at 0° and sway at 90°. Heave remains constant at 0.226 m. The maximum rotational response is only 0.532° for both pitch at 0° and roll at 90°. These directional relationships are consistent with head-sea and beam-sea excitation in the platform coordinate system. Similar sensitivity of a cylindrical configuration to environmental direction and mooring arrangement has been reported in a multi-point-moored FNPP study [8].

The T0 periods for surge and sway are approximately 7.2 s, 8.635 s for heave, and 6.234 s for roll and pitch. Their proximity to Tp = 7.16 s indicates that wave energy may interact directly with the principal motion modes. The final analysis should vary spectral parameters over a period range of 5–10 s to evaluate resonance sensitivity rather than relying on a single sea state.

Lisensi Creative Commons Atribusi 4.0 Internasional.

Table 5. Summary of most-probable amplitudes from the source study

Mode	Direction (°)	T0 (s)	Extreme amplitude	Screening criteria	Status
Surge	0 / 30 / 60 / 90	7,243 / 7,243 / 7,243 / 6,958	1,825 / 1,580 / 0,912 / 0,000 m	12 m	Meets criterion
Sway	0 / 30 / 60 / 90	7,583 / 7,243 / 7,243 / 7,243	0,000 / 0,912 / 1,580 / 1,825 m	12 m	Meets criterion
Heave	0 / 30 / 60 / 90	8,635 (all direction)	0,226 m (all direction)	1,3 m	Meets criterion
Roll	0 / 30 / 60 / 90	7,540 / 6,234 / 6,234 / 6,234	0,000 / 0,266 / 0,461 / 0,532°	45°	Meets criterion
Pitch	0 / 30 / 60 / 90	6,234 / 6,234 / 6,234 / 6,723	0,532 / 0,461 / 0,266 / 0,000°	45°	Meets criterion
Yaw	0 / 30 / 60 / 90	7,844 / 7,753 / 8,065 / 7,629	0.000° (rounded)	Not established	Not assessed

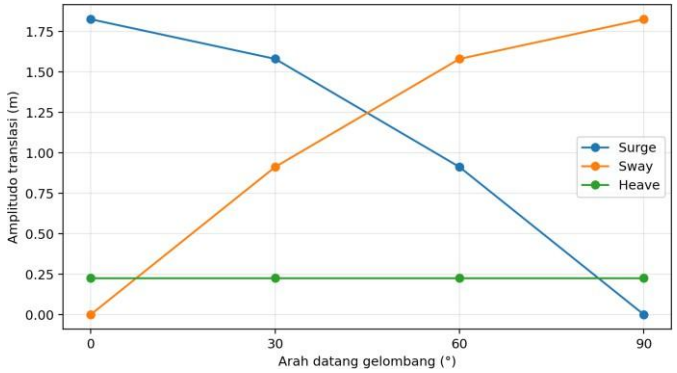


Figure 9. Variation in maximum translational amplitude with wave direction

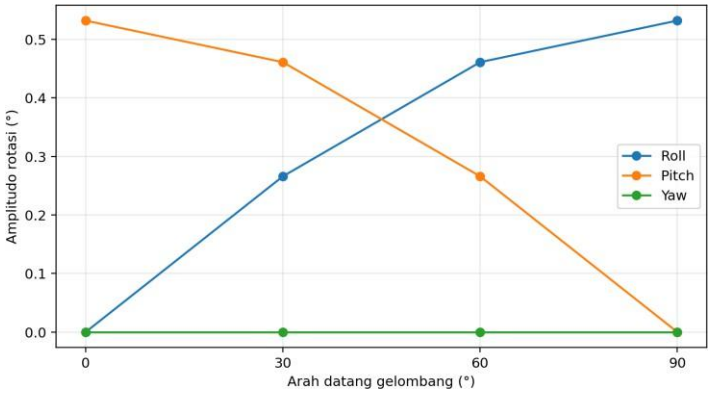


Figure 10. Variation in maximum rotational amplitude with wave direction

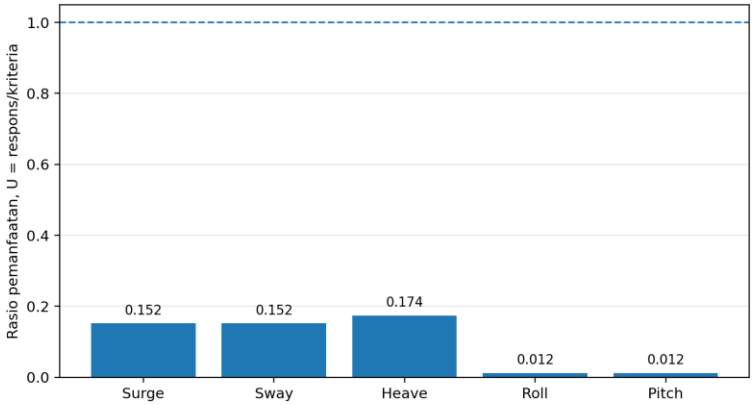


Figure 11. Maximum-response ratios relative to the adopted screening criteria

Lisensi Creative Commons Atribusi 4.0 Internasional.

Table 6. Evaluation of motion utilization ratios

Mode	Maximum response	Criterion	Ratio U	Margin relative to criterion
Surge	1,825 m	12 m	0,152	84,8%
Sway	1,825 m	12 m	0,152	84,8%
Heave	0,226 m	1,3 m	0,174	82,6%
Roll	0,532°	45°	0,012	98,8%
Pitch	0,532°	45°	0,012	98,8%

Heave has the largest ratio, U = 0.174, followed by surge and sway at 0.152. Roll and pitch are only about 0.012 relative to the 45° limit. Mathematically, all ratios are below one. However, a roll/pitch limit of 45° is too large to serve as an operating limit for nuclear equipment, personnel, turbines, and the helideck. This value is more appropriately viewed as a global screening limit than an acceptance criterion. Operational criteria are likely to be on the order of a few degrees or less, depending on system function and acceleration response.

In addition to amplitude, motion acceleration must be calculated. For harmonic motion, maximum acceleration is proportional to $\omega^2\xi$. Consequently, a small response amplitude at a higher frequency may still produce acceleration relevant to equipment. Qualification of safety-related equipment must link offshore-motion demand to the capacity of internal structures, supports, piping, and active components [27], [28].

Implications for Mooring and Cable Design

A horizontal offset of 1.825 m appears small compared with a line length of 420 m, but mooring assessment cannot be based on this geometric ratio. Line tension is affected by pretension, catenary configuration, submerged weight, anchor uplift, axial stiffness, drag, dynamic amplification, and low-frequency drift. The stated capacity of 11,981 kN must be compared with the maximum dynamic tension in each line, including load redistribution after one line fails. Without tension data, mooring utilization remains unknown.

A water depth of 150 m and line length of 420 m give a length-to-depth ratio of 2.8. This ratio may support a catenary or semi-taut configuration, although the actual type is not specified. Soft seabed conditions at the site require assessment of anchor holding capacity, cyclic degradation, creep, and possible trenching. Geotechnical investigation should establish stratigraphy, undrained shear strength, unit weight, consolidation, and cyclic parameters before selecting an anchor type.

The subsea power cable experiences relative motion between the platform and touchdown point. The design should account for a lazy-wave or other configuration, bend stiffeners, buoyancy modules, protection, wave-induced fatigue, and interaction with the mooring system. Cable failure could cause loss of offsite power or a reactor trip. Grid redundancy, emergency power, black-start capability, and disconnect/reconnect procedures should therefore be incorporated from the conceptual-design stage.

Implications for Nuclear Safety, Site Selection, and Operations

Nuclear safety cannot be established from platform motion alone. Site assessment must identify all credible external hazards and their combinations. SSR-1 requires site characterization and evaluation of compatibility between hazards and the installation design [9]. Meteorological and hydrological guidance covers coastal flooding, waves, storm surge, and related phenomena [10], while seismic hazards and tsunami sources require geological and seismotectonic models [11]. An input of Hs = 1.16 m is insufficient to represent all these hazards.

A tsunami differs physically from wind-generated waves: its wavelength is extremely long, its period is long, and it can produce significant currents and water-level changes in nearshore waters. A linear diffraction model with an ordinary wave spectrum does not automatically represent a tsunami. The analysis should combine a regional tsunami-propagation model, nearshore transformation, currents around the platform, mooring loads, water-depth changes, debris impact, and anchor-failure scenarios.

National regulatory readiness is also part of feasibility. BAPETEN's pre-licensing activities indicate that an initial consultation mechanism is available [13], and its performance report records the development of the national NPP oversight infrastructure [29]. For an FNPP, coordination should extend to maritime regulators, port authorities, the Indonesian Navy, the National Search and Rescue Agency (Basarnas), the Ministry of Transportation, the Ministry of Energy and Mineral Resources, local government, and power-system operators. Responsibilities among the nuclear operator, platform owner, marine operator, and grid provider must be defined before detailed design.

Transport of nuclear materials and waste requires plans for ports, security escorts, protected areas, inspections, emergency response, and public communication. The IAEA emphasizes that FNPP deployment

Lisensi Creative Commons Atribusi 4.0 Internasional.

requires lifecycle arrangements covering fabrication, transportation, operation, refuelling, maintenance, and decommissioning [4]. The INF Code regulates the sea transport of certain radioactive cargoes [26], while cross-border and cross-jurisdictional legal and institutional issues are discussed in IAEA NG-T-3.5 [12].

Comparison with Previous Studies

Compared with the MIT concept, the model in this study is closer to shore and has dimensions associated with a 250 MWe reactor. This increases the relevance of a short export cable and logistics but also intensifies interaction with nearshore hazards, human activities, and emergency-planning requirements. The low motion responses support the conceptual feasibility of the SPAR form, consistent with OFNP hydrodynamic findings [6].

Table 7. Position of the present study relative to previous studies

Study	Subject/method	Relevant findings	Position of the present study
Buongiorno et al. [5]	SPAR-type OFNP concept	Reactor-platform integration and safety concept	Conceptual platform basis
Strother [6]	Hydrodynamics of two OFNP models	Adequate heave and pitch performance	SPAR response comparison
Cui et al. [7]	ANSYS frequency/time-domain	Transfer of marine loads to containment	Basis for the ANSYS workflow
Liu et al. [8]	Cylindrical FNPP with multi-point mooring	Environmental direction and mooring affect response	Directional-motion comparison
This study	Reinterpretasi output ANSYS-AQWA Halmahera	pectra, stochastic motion, audit gap	Site screening and further recommendations

The study by Cui et al. demonstrates the importance of linking hydrodynamic outputs to stress analyses of containment and supports [7]. The present study has not yet performed this step. Liu et al. show the need to compare several mooring configurations and combined wind-wave-current conditions [8]. The nine-line model in this study still needs to be tested against alternative layouts, pretension variations, and line-failure cases.

Study Limitations

These limitations mean that the results should be interpreted as conceptual screening. The defensible statement is that, for the model and wave conditions used, motion responses remain below the screening criteria. The available data do not support claims that the design is safe under all environmental conditions, ready for construction, or compliant with nuclear requirements.

Table 8. Main limitations and corrective actions

Limitation	Impact on conclusions	Required improvement
ANSYS model file unavailable.	Mesh, mass, damping, and boundary conditions cannot be audited.	Provide the model, solver settings, and convergence study.
Metocean data restricted to a single sea state.	Unrepresentative of operational, extreme, and joint probability conditions.	Long-term hindcast data, field measurements, and extreme value analysis.
Absence of wind/current coupled response.	Offset and tension may be underestimated.	Coupled time-domain analysis under misaligned environments.
Lack of mooring tension output.	Line and anchor capacities cannot be evaluated.	Intact, damaged, fatigue, and Accidental Limit State (ALS) checks.
Motion criteria not derived from functional requirements.	The “safe” status is too general.	Functional acceptance criteria and equipment qualification.
Absence of tsunami/seismic seabed modeling.	North Maluku-specific hazards are not covered.	Probabilistic/deterministic hazard assessment.
Lack of experimental validation.	Model uncertainties remain unknown.	Basin model testing and benchmarking.

Lisensi Creative Commons Atribusi 4.0 Internasional.

Limitation	Impact on conclusions	Required improvement
Lack of experimental validation	Risk of misinterpreting modes and units	Export numerical data and use a standard plotting template

DESIGN DEVELOPMENT RECOMMENDATIONS

The first stage is to establish a traceable site design basis. High-resolution bathymetry, waves, wind, currents, tides, storm surge, earthquakes, tsunamis, geotechnical conditions, corrosion, marine growth, vessel traffic, and coastal activities should be compiled. Metocean analysis should define operational, extreme, and abnormal conditions, including joint probabilities and directional distributions, in accordance with ISO 19901-1 [14] and DNV-RP-C205 [16].

The second stage is to update the hydrodynamic model. Mesh convergence, mass properties, damping, natural periods, and hydrostatic stability should be verified. Wave cases should cover directions at 15° or 22.5° intervals, variations in Hs–Tp, directional spreading, and heading misalignment. Nonlinear time-domain analysis should include mooring, drag, current, wind, second-order wave drift, and transient line failure. Benchmarking can be conducted against fundamental theory [19]–[22], the AQWA manual [23], and experimental results or OFNP publications [6].

The third stage is to develop a classifiable mooring and anchor design. Each line should be defined by material, segments, corrosion allowance, pretension, minimum breaking load (MBL), fatigue curve, connectors, fairleads, and anchors. Intact, one-line-damaged, accidental, and fatigue checks should follow ISO 19901-7 [15], DNV-OS-E301 [17], and API RP 2SK [18]. The layout should consider exclusion zones, cable corridors, the possibility of dragging anchors from other vessels, and inspection access.

The fourth stage is to connect motion response to the nuclear island. Six-degree-of-freedom time histories should be converted into acceleration response spectra or load histories for the containment foundation, supports, piping, turbine, electrical cabinets, batteries, spent-fuel pool, and emergency systems. Acceptance criteria should then be derived from the ability to maintain safety functions under SSR-2/1 [27] and the operation and testing programme under SSR-2/2 [28].

The fifth stage is to establish a licensing and deployment roadmap. Business ownership, jurisdictional boundaries, security responsibilities, refuelling strategy, fuel and waste transportation, emergency-planning zones, decommissioning, liability, and public engagement should be defined. The IAEA FNPP report [4], the legal study on transportable nuclear power plants [12], BAPETEN's pre-licensing mechanism [13], and the national oversight framework [29] can serve as starting points.

CONCLUSION

The revised study indicates that the conceptual SPAR-type floating nuclear power plant model at a modeled water depth of 150 m exhibits hydrodynamically consistent directional response patterns. Maximum surge of 1.825 m occurs for waves at 0°, maximum sway of 1.825 m at 90°, and heave of 0.226 m for all directions. Maximum pitch is 0.532° at 0°, while maximum roll is 0.532° at 90°. Yaw is rounded to a value close to zero in the source output.

All modes for which criteria are available remain below the screening limits: the maximum utilization ratios are 0.174 for heave, 0.152 for surge/sway, and 0.012 for roll/pitch. These results indicate preliminary motion-response feasibility under the modeled wave conditions but do not demonstrate the overall safety of the structure, mooring, equipment, or reactor.

The main contributions of this revision are correction of RAO units, alignment of the depth basis, separation of assumptions from results, evaluation of directional motion, calculation of criterion ratios, and identification of design gaps. Inconsistencies between the RAO plots and heave spectrum, mode labels in some plots, and the absence of mooring-line tension data must be resolved before the results are used for design decisions.

Further development must include site-specific metocean validation for Halmahera, coupled wave-wind-current time-domain analysis, one-line-broken conditions, fatigue, anchor-soil interaction, tsunami analysis, dynamic export-cable analysis, structural load transfer, and qualification of safety-related equipment. These steps would advance the concept from academic screening to an engineering pre-feasibility study that supports the pre-licensing process.

Lisensi Creative Commons Atribusi 4.0 Internasional.

REFERENCES

[1] Badan Pusat Statistik Kabupaten Halmahera Tengah, Kabupaten Halmahera Tengah Dalam Angka 2024. Halmahera Tengah, Indonesia: BPS, 2024.
[2] Kementerian Energi dan Sumber Daya Mineral Republik Indonesia, "Konsumsi listrik masyarakat meningkat, tahun 2023 capai 1.285 kWh/kapita," Jakarta, Indonesia, Jan. 2024.
[3] International Atomic Energy Agency, Small Modular Reactors: Advances in SMR Developments 2024. Vienna, Austria: IAEA, 2024.
[4] International Atomic Energy Agency, Deployment of Floating Nuclear Power Plants: Benefits and Challenges. Vienna, Austria: IAEA, 2025.
[5] J. Buongiorno, J. Jurewicz, M. Golay, and N. Todreas, "The offshore floating nuclear plant concept," Nuclear Technology, vol. 194, no. 1, pp. 1-14, 2016, doi: 10.13182/NT15-49.
[6] M. B. Strother, "Hydrodynamic analysis of the offshore floating nuclear power plant," M.S. thesis, Massachusetts Institute of Technology, Cambridge, MA, USA, 2015.
[7] J. Cui, L. Li, M. Zhang, H. Liu, and X. Qu, "Dynamic response analysis of floating nuclear power plant containment under marine environment," in Proc. 23rd Pacific Basin Nuclear Conf., vol. 1, Singapore: Springer, 2023, pp. 543-557, doi: 10.1007/978-981-99-1023-6_53.
[8] Y. Liu et al., "Dynamic response of a multi-point mooring cylindrical floating nuclear power platform carrying a small-scale reactor," Ocean Engineering, vol. 267, art. no. 113121, 2023, doi: 10.1016/j.oceaneng.2022.113121.
[9] International Atomic Energy Agency, Site Evaluation for Nuclear Installations, IAEA Safety Standards Series No. SSR-1. Vienna, Austria: IAEA, 2019.
[10] International Atomic Energy Agency, Meteorological and Hydrological Hazards in Site Evaluation for Nuclear Installations, IAEA Safety Standards Series No. SSG-18. Vienna, Austria: IAEA, 2011.
[11] International Atomic Energy Agency, Seismic Hazards in Site Evaluation for Nuclear Installations, IAEA Safety Standards Series No. SSG-9. Vienna, Austria: IAEA, 2010.
[12] International Atomic Energy Agency, Legal and Institutional Issues of Transportable Nuclear Power Plants: A Preliminary Study, IAEA Nuclear Energy Series No. NG-T-3.5. Vienna, Austria: IAEA, 2013.
[13] Badan Pengawas Tenaga Nuklir, "Executive meeting perizinan PLTN dan perencanaan konsultasi 3S pra-perizinan," Jakarta, Indonesia, Mar. 2023.
[14] International Organization for Standardization, ISO 19901-1:2015, Petroleum and Natural Gas Industries-Specific Requirements for Offshore Structures-Part 1: Metocean Design and Operating Considerations. Geneva, Switzerland: ISO, 2015.
[15] International Organization for Standardization, ISO 19901-7:2026, Specific Requirements for Offshore Structures-Part 7: Stationkeeping Systems for Floating Offshore Structures and Mobile Offshore Units. Geneva, Switzerland: ISO, 2026.
[16] DNV, DNV-RP-C205: Environmental Conditions and Environmental Loads. Høvik, Norway: DNV, 2021.
[17] DNV, DNV-OS-E301: Position Mooring. Høvik, Norway: DNV, 2021.
[18] American Petroleum Institute, API RP 2SK: Design and Analysis of Stationkeeping Systems for Floating Structures, 4th ed. Washington, DC, USA: API, 2015.
[19] O. M. Faltinsen, Sea Loads on Ships and Offshore Structures. Cambridge, U.K.: Cambridge University Press, 1990.
[20] J. N. Newman, Marine Hydrodynamics. Cambridge, MA, USA: MIT Press, 1977.
[21] T. I. Fossen, Handbook of Marine Craft Hydrodynamics and Motion Control, 2nd ed. Hoboken, NJ, USA: Wiley, 2021.
[22] J. M. J. Journée and W. W. Massie, Offshore Hydromechanics. Delft, The Netherlands: Delft University of Technology, 2001.
[23] Ansys, Inc., Ansys AQWA Theory Manual, Release 2024 R2. Canonsburg, PA, USA: Ansys, 2024.
[24] K. Hasselmann et al., "Measurements of wind-wave growth and swell decay during the Joint North Sea Wave Project (JONSWAP)," Deutsches Hydrographisches Institut, Hamburg, Germany, Ergänzungsheft Reihe A(8), no. 12, 1973.
[25] American Bureau of Shipping, Pathways to Low Carbon: Floating Nuclear Power Plants. Houston, TX, USA: ABS, 2024.
[26] International Maritime Organization, International Code for the Safe Carriage of Packaged Irradiated Nuclear Fuel, Plutonium and High-Level Radioactive Wastes on Board Ships (INF Code). London, U.K.: IMO, 2022.

Lisensi Creative Commons Atribusi 4.0 Internasional.

[27] International Atomic Energy Agency, Safety of Nuclear Power Plants: Design, IAEA Safety Standards Series No. SSR-2/1 (Rev. 1). Vienna, Austria: IAEA, 2016.
[28] International Atomic Energy Agency, Safety of Nuclear Power Plants: Commissioning and Operation, IAEA Safety Standards Series No. SSR-2/2 (Rev. 1). Vienna, Austria: IAEA, 2016.
[29] Badan Pengawas Tenaga Nuklir, Laporan Kinerja BAPETEN Tahun 2023. Jakarta, Indonesia: BAPETEN, 2024.
[30] P. Minelli, J. Buongiorno, M. Golay, and N. Todreas, "Balance of plant and power transmission for the offshore floating nuclear plant," in Proc. 16th Int. Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-16), Chicago, IL, USA, 2015.

Lisensi Creative Commons Atribusi 4.0 Internasional.