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ISSN: 2178-7727

DYNAMIC PRESSURE ON A FLOATING PLATFORM DUE TO SURFACE WAVES

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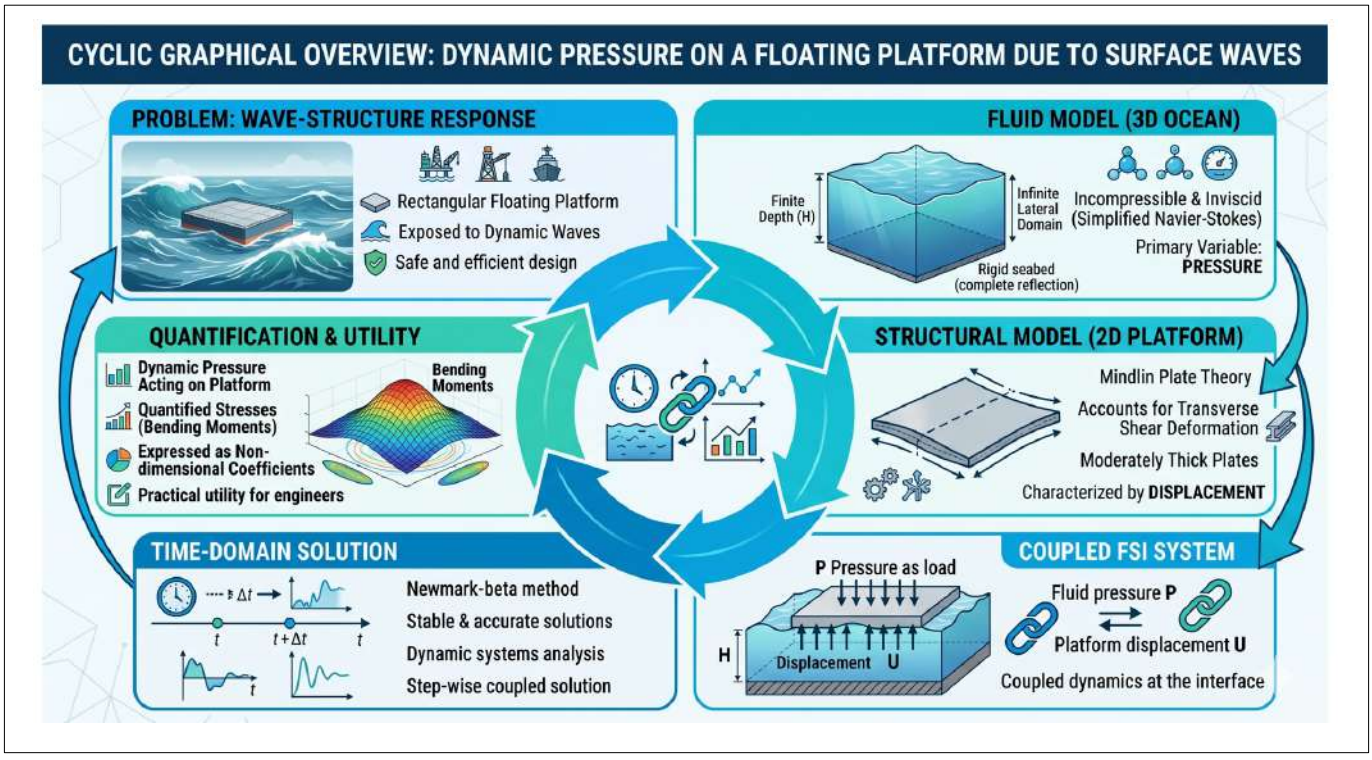
Graphical Abstract



Highlights

- Examines the rectangular floating platforms' responses to dynamic wave actions using a coupled fluid-structure interaction model.
- The structural model uses Mindlin plate theory to accurately account for transverse shear deformations of moderately thick plates.
- Models the 3D fluid domain using simplified Navier-Stokes equations, assuming incompressible and inviscid flows on a rigid seabed.
- The time-dependent coupled equations are solved using Newmark-beta methods to ensure stable and accurate dynamic system solutions.

- Evaluates dynamic pressure and quantifies induced stresses as non-dimensional bending moment coefficients to aid efficient design.

Abstract

Floating platforms serve a wide range of strategic and functional purposes, including offshore infrastructure for industrial operations and oil exploration, as well as civic applications such as floating airstrips and recreational parks. They are also critical in defence sectors, particularly for naval bases and mobile support systems. Given their exposure to dynamic environmental forces, especially wave action, understanding their structural response is essential for safe and efficient design. In this study, the behaviour of a rectangular floating platform is examined under hydrodynamic loading. The platform is assumed to float on an infinitely extended fluid domain with finite depth, which reflects realistic ocean conditions where lateral boundaries have negligible influence but depth remains a governing factor. The problem is treated as a coupled fluid–structure interaction system, where the fluid domain is modelled in three dimensions using pressure as the primary nodal variable, while the platform is represented as a two-dimensional structural element characterized by displacement. To accurately capture the mechanics, the platform behaviour is modelled using Mindlin plate theory, which accounts for transverse shear deformation and is suitable for moderately thick plates. The fluid motion is governed by the Navier–Stokes equations, simplified under the assumptions of incompressibility and inviscid flow to focus on dominant pressure effects. The base of the fluid domain is considered perfectly rigid, ensuring complete wave reflection without energy dissipation—an assumption that helps isolate the impact of wave-structure interaction. The resulting time-dependent coupled equations are solved using Newmark-beta method, which provides stable and accurate solutions for dynamic systems. Dynamic pressure acting on the platform is evaluated, and the additional stresses induced by wave action are quantified in terms of bending moments. These are further expressed as non-dimensional coefficients, offering practical utility for engineers to estimate bending responses efficiently in design applications.

Keywords: Floating Platforms, Hydrodynamic Loading, Lateral Boundaries, Mindlin Plate Theory, Navier–Stokes Equations.

1. Introduction

Accelerated growth in industrial and environmental activities, social and cultural intermixing of nations has put a lot of stress on creation of offshore platforms and there is continuous study on the subject to provide a safe place in the ocean (Wang et al. 2008; Ahmadi et al. 2025). Fluid-structure interaction between a floating plate and the fluid has been studied by several investigators mainly to account for the dynamic pressure developed on the plate during excitation due to wave. Significant contribution has been made to observe the effects of different parameters such as geometry of the fluid domain (Bendahmane et al. 2021), nature of excitation, material properties of the plate and boundary conditions of the free surface on the dynamic pressure developed on the plate. Many a times, analytical methods become difficult because of the irregular geometry of the

fluid-structure interface and the reservoir boundary. So, finite element method (FEM) is preferred by many as a suitable numerical technique for analysis of these interaction problems. Liu and Sakai (1996) have developed a numerical method to analyze the dynamic responses of large-scale floating structures to waves. The numerical approach proposed in this study simulates the interaction of waves and flexible floating structure by employing BEM for evaluating the fluid motion and FEM for calculating the deformation of floating structure (Jafari-Talookolaei and Lasemi-Imani, 2015). The unknown time-dependent boundary conditions on the free surface and the interface have been evaluated by a time-stepping procedure. Kyoung et al. (2005) developed a numerical method (FEM) for solving the fluid region where the sea-bottom geometry was not flat. For various sea-bottom topographies, the decrease of hydro-elastic responses was observed in variable sea-bottom at the rear part. It was concluded that the sea-bottom effects should be considered when the VLFS was constructed in the coastal area. Pani and Bhattacharyya (2007) solved the coupled problem of fluid–structure interaction of a lock-gate in a rigid dam with the reservoir in a decoupled manner by analyzing the gate and the fluid domain independently.

Finite element technique is adopted for the solution of this interaction problem and an iterative convergence procedure was followed to maintain the equilibrium and compatibility of the fluid–structure interface (Pani and Bhattacharyya. 2009; Bauri and Sarkar, 2022). Effect of excitation frequency, aspect ratio and thickness of the gate on dynamic pressure have been investigated. Xia et al. (2008) presented a model to study the hydro-elastic response of a mat-type VLFS under the action of a solitary wave, or a frontal Tsunami wave within the scope of linear beam theory for the structure and the nonlinear, Level I Green–Naghdi (GN) theory for the fluid. The beam equation and the GN equations are coupled through the kinematic and dynamic boundary conditions to obtain a new set of modified GN equations. (Kumar Singh and Agarwal, 2026) These equations represent long-wave motion beneath an elastic plate. A set of jump conditions those were necessary for the continuity (or the matching) of the solutions in the open water region and that under the structure had been derived through the use of the postulated conservation laws of mass, momentum, and mechanical energy. The resulting governing equations, subjected to the boundary and jump conditions, were solved by the finite-difference method in the time domain (Singh et al. 2019; Das, A 2026).

Numerous studies have investigated fluid flow around submerged structures (Bauri and Sarkar, 2022). However, these works predominantly focus on flow characteristics alone. In contrast, the fluid dynamic behaviour associated with floating bodies remains comparatively underexplored and warrants comprehensive investigation. In most of the cases, velocity potential has been used as nodal variable with their inherent merits and demerits. In few cases, mostly in which the relative displacement of the fluid with respect to the structure is small but interaction is substantial, pressure as the nodal variable has been used advantageously (Singh and Agarwal, 2023). However, the structure is always modeled with displacement as the nodal variable. Here, a solution technique to determine the dynamic pressure on the floating platform due to a surface wave is developed and the

effect of the flexibility of the platform and frequency of the wave on dynamic pressure are investigated.

2. Theoretical formulation

The coupled problem of the floating platform and the surface wave is solved in a decoupled manner by transferring the pressure from the fluid to the platform and transferring the acceleration of the platform to the fluid in a successive manner till equilibrium is obtained (Tripathy and Pani, 2013; Bauri and Sarkar, 2019; Das, A 2025 a, b, c). The formulation is divided into two parts, i.e. formulation for the fluid part and formulation for the structure (platform) part.

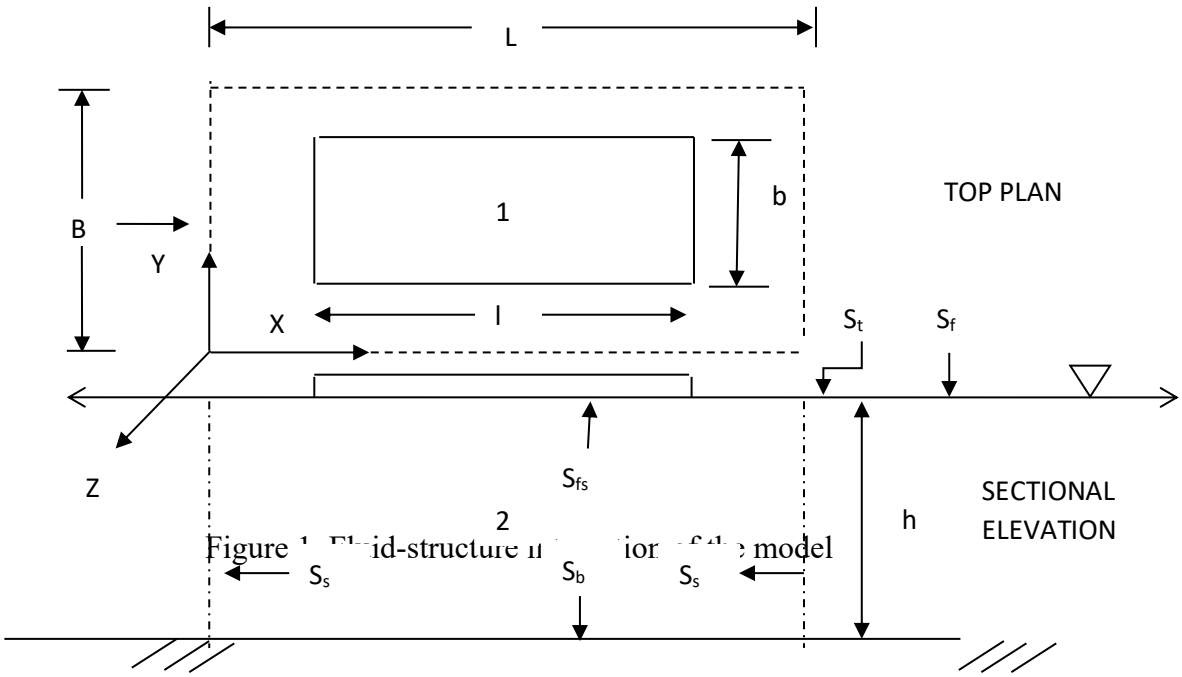


Figure 1. Fluid-structure interaction of the model

Neglecting body force and assuming the flow to be irrotational, Navier-Stokes equation may be represented as Laplace equation in pressure term form, and represented as Eq. (1):

$$\nabla^2 p(x, y, z) = 0 \qquad \text{----------} \qquad (1)$$

On the free surface, the vertical velocity u_z can be expressed as the time derivative of the surface elevation η above the static free surface and it is indicated as in Eq. (2):

$$u_z = \frac{D\eta}{Dt} = \frac{\partial \eta}{\partial t} + (U.\nabla)\eta \quad \text{----------} \qquad (2)$$

where, U is the velocity vector comprising of components u_x, u_y, u_z in the three co-ordinate directions (Singh and Pal, 2021). Using a velocity potential φ such that the derivative of the potential in any co-ordinate direction represents the velocity in that direction, Eq. (3) may be represented as

$$\frac{\partial^2 p}{\partial t^2} + (U.\nabla p) - \rho_f g \frac{\partial h}{\partial t} = 0 \qquad \text{----------} \qquad (3)$$

3. Linearized approximation of free surface

3.1 Boundary Conditions

For the problem under consideration of a floating platform (Ref. Figure 1), the following boundary conditions are adopted (Singh et al. 2024).

Top surface (S_f) excluding the platform area (Eq. 4):

$$\frac{\partial p}{\partial n} = \frac{\partial p}{\partial z} = -\frac{1}{g}\ddot{p} \quad \text{----------} \quad (4)$$

Fluid-structure interface (S_{fs}):

The top surface of the fluid domain over which the platform is floating (Eq. 5), the condition will be

$$\frac{\partial p}{\partial n} = -\rho_f a \quad \text{----------} \quad (5)$$

where,$p(x, y, z)$ is the pressure and $a(x, y)$ is the acceleration of the fluid-structure interface at that instant of time in the direction of the outward normal n to the interface.

Four side surfaces (S_s), the computation is carried through Eq. (6):

$$\frac{\partial p}{\partial n} = 0 \quad \text{----------} \quad (6)$$

Bottom surface (S_b), the calculation is done through Eq. (7):

$$\frac{\partial p}{\partial n} = 0 \quad \text{----------} \quad (7)$$

3.2 Finite Element Formulation

Using Galerkin's weighted residual method (Eq. 8), the weighted integral statement of Eq. (1) may be represented as

$$\sum \int_{\Omega_e} N^T (\nabla^2 p)\, d\Omega_e = 0 \quad \text{----------} \quad (8)$$

Here, $\sum$ and Ω_e refer to the summation of all the elements and one element respectively. The weak form of Eq. (8) may be written as and indicated in Eq. (9):

$$\sum \left[\int_{\Omega_e} (\nabla N^T . \nabla p) d\Omega_e - \int_{\Gamma_e} \left(N^T \frac{\partial p}{\partial n} \right) d\Gamma_e \right] = 0 \quad \text{----------} \quad (9)$$

Γ_e indicates the total boundary surface of the element.

In concise matrix form, this may be represented as (Eq. 10, 11 and 12):

$$[G]\{\ddot{p}\} = \{B\} \quad \text{----------} \quad (10)$$

in which,

$$[G] = \sum \int_{\Omega_e} (\nabla N^T . \nabla N)\, d\Omega_e \quad \text{----------} \quad (11)$$

$$\{B\} = \sum_s \int_{\Gamma_e} N^T \frac{\partial p}{\partial n} d\Gamma_e \quad \text{----------} \quad (12)$$

$\sum_s$ refers to the total boundary surface of the fluid domain. N is the shape function for the total domain (Singh et al. 2025).

The boundary term $\{B\}$ may be split into its components and is represented in Eq. (13), (14), and (15):

$$\{B\} = \{B_f\} + \{B_{fs}\} + \{B_b\} + \{B_s\} \quad \text{----------} \quad (13)$$

At the free surface $\{B_f\}, \frac{\partial p}{\partial n} = -\frac{\partial p}{\partial z} = -\frac{1}{g}\ddot{p}$ ---------- (14)

$$\{B_f\} = \sum_{S_f} \left[\int_{\Gamma_e} (N^T N) d\Gamma_e \right] \frac{\{\ddot{p}\}}{g} \quad \text{----------} \quad (15)$$

Utilizing Eq. (16) and (17), at the fluid structure interface$\{B_{fs}\}$, since $\frac{\partial p}{\partial n} = -\rho_f a$

$$\{B_{fs}\} = \rho_f [R_{fs}]\{\bar{a}\} \quad \text{---------- (16)}$$

$$\text{where, } [R_{fs}] = \sum_{S_{fs}} \int_{\Gamma_e} N^T N_s \, d\Gamma_e \quad \text{---------- (17)}$$

N_s is the shape function of the structure corresponding to nodes of the fluid-structure interface and $\{\bar{a}\}$ is the vector of nodal accelerations (Tripathy and Pani, 2014; Singh et al. 2021).

At the bottom surface of the fluid domain$\{B_b\}$and $\{B_s\}$the four sides the normal pressure gradient vanishes

Combining all these, Eq. (10) may be represented as in Eq. (18):

$$[E]\{\ddot{\bar{p}}\} + [G]\{\bar{p}\} = -\rho_f [R_{fs}]\{\bar{a}\} \quad \text{---------- (18)}$$

The terms of Eq. (18) are defined in Eq. (19), and denoted as

$$[E] = \frac{1}{g} \sum_{S_f} \left[\int_{\Gamma_e} (N^T N) \, d\Gamma_e \right] \quad \text{---------- (19)}$$

The dynamic equilibrium equation for the platform without considering the effect of damping is given as (Eq. 20):

$$[M]\left\{\ddot{\bar{W}}\right\} + [K]\{\bar{W}\} = \{\bar{F}\} \quad \text{---------- (20)}$$

where, $[M]\&[K]$are the mass and stiffness matrices of the platform and $\{\bar{W}\}\&\{\bar{F}\}$are the displacement and load vectors. The mass and stiffness matrices are formulated based on Mindlin's plate bending theory (Singh et al. 2022).

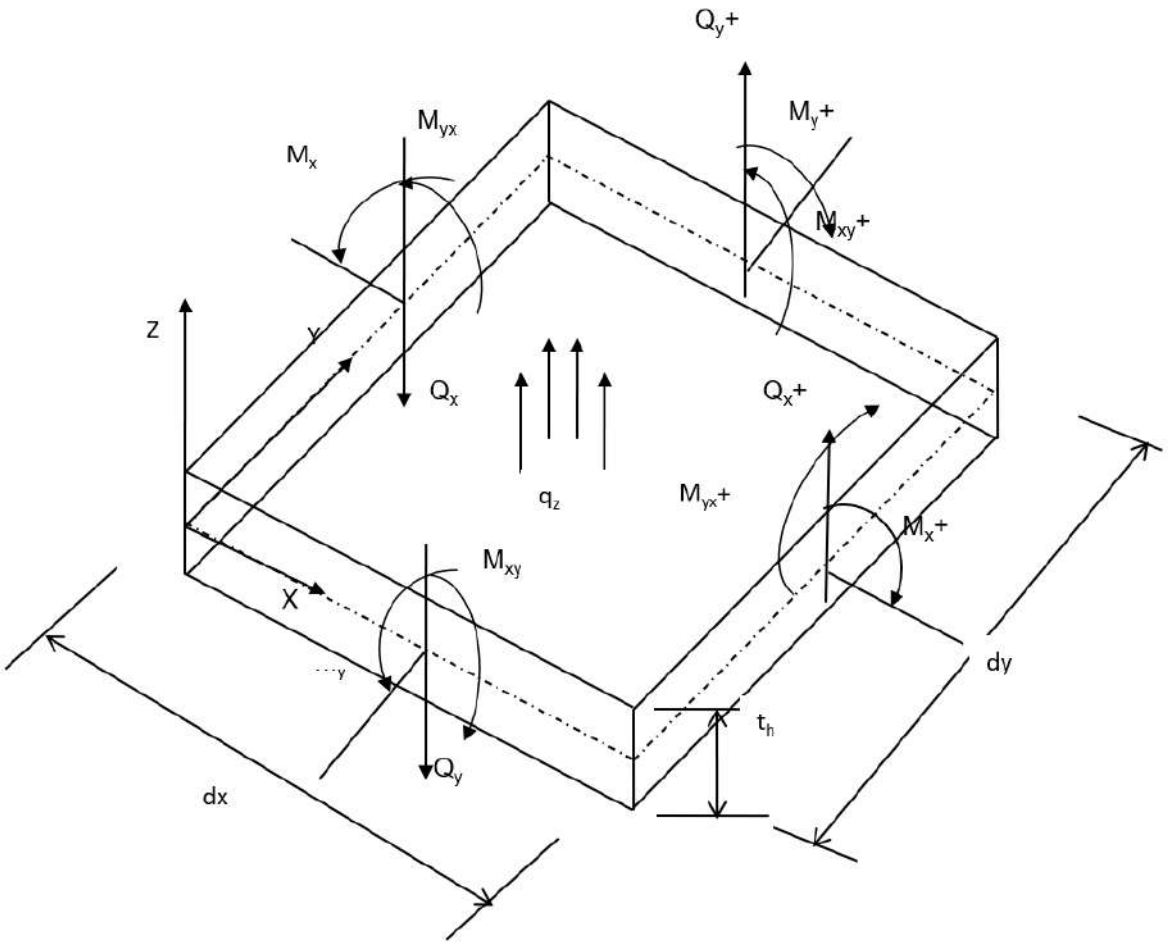


Figure 2. Plate element with external and internal forces + indicates differential increment, as $M_x += M_x + \frac{\partial M_x}{\partial x} dx$ and $M_y += M_y + \frac{\partial M_y}{\partial y} dy$

4. Results and discussion

The free surface profile is non-linear and at any instant of time it has to satisfy both kinematic and dynamic boundary conditions. However, for small rise of the surface wave, the top free surface may be approximated in a linearized form depending upon the magnitude of the surface elevation relative to the depth of the fluid domain and expanse of the platform. The dynamic pressure on the platform is studied considering the wave to be linear. The change in dynamic pressure with the change in the flexibility of the platform and change in the frequency of excitation is examined through the results of a few numerical examples.

The size of the platform considered for investigation is 10 m long, 3 m wide and 0.01 m thick. To demonstrate the effect of flexibility of the platform, different size and thickness of the platform are considered and mentioned in the appropriate places. The material properties of the platform and the fluid are considered as:

Density (ρ_p) of the material of the platform = 942.00 Kg / m^3

Young's modulus (E_s) of the material of the platform = 2.0 x 10^5 N / mm^2
Shear modulus (G_s) of the material of the platform = 0.76 x 10^5 N / mm^2
Poisson's ratio (ν) of the material of the platform = 0.3
Density (ρ_f) of the fluid = 1000.0 kg/m^3

The authenticity of the technique and the computer code developed is established by comparing the deformed shape of the platform with that of a platform available in the literature. A rectangular platform of 10 m * 3 m and thickness of 20 mm having mass density of 942 Kg/m^3 is considered to compare the results and it is found that the results (Figure. 3) match rationally except at the beginning. The time period of the wave is considered to be 1.2 second and time interval of calculation is considered to be $1/100^{th}$ of it. The difference in amplitudes of deformation in the beginning may be due to difference in approach. The present investigation is made using finite element method for both the fluid and the structure whereas Liu and Sakai (1996) used BE method for fluid and finite element method for the structure.

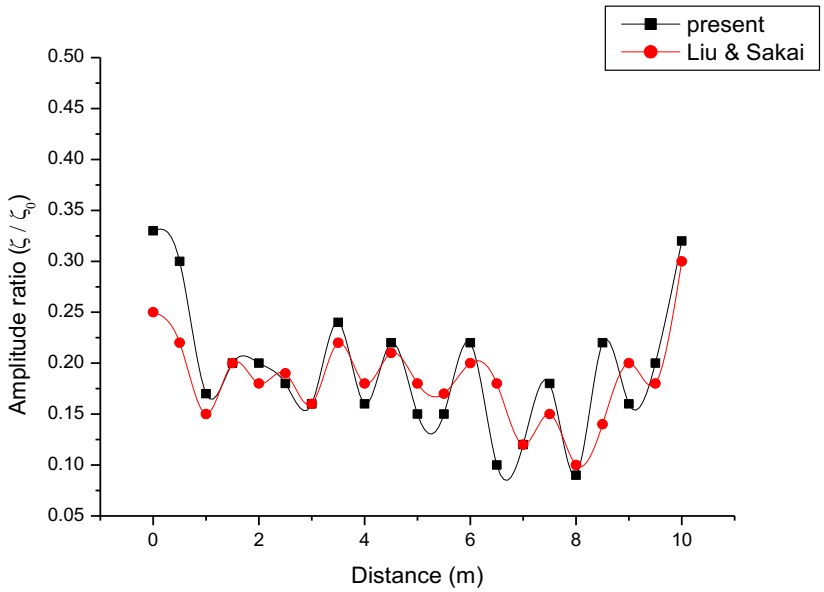


Figure 3. Ratio of amplitude of the platform with amplitude of wave at time t = T/4

The effect of the flexibility of the platform on dynamic pressure is studied by observing the change in dynamic pressure for different thicknesses of the platform keeping length and width constant. As observed, from (Figure 4), the pressure remains almost unaffected with change in thickness of the platform. However, if the width and length of the platform are increased (Figure 5), there is a change in the pressure exerted on the platform. The dynamic pressure reduces marginally with increase in width or the flexibility.

As observed, when the platform width increases from 3m to 5 m, there is a decrease of 11.2% in the dynamic pressure at the midpoint of the platform at time t = T/4, where T is the time period of the wave. This happens mainly because there is no vertical restraint at the two opposite edges in the direction of wave and the edges are free to move over the fluid. The other two edges perpendicular to the wave direction have no restraint (Bauri, K. P, 2022; Kostikov et al. 2024).

The pressure developed is due to the bending of the platform only and therefore a more flexible platform provides less restraint against deformation and consequently pressure becomes less. The thinner the platform, the deformation is more. In spite of the lower value of the dynamic pressure the effect of the dynamic pressure is crucial as the pressure changes its sign very quickly that may lead to fatigue of the material in the long run.

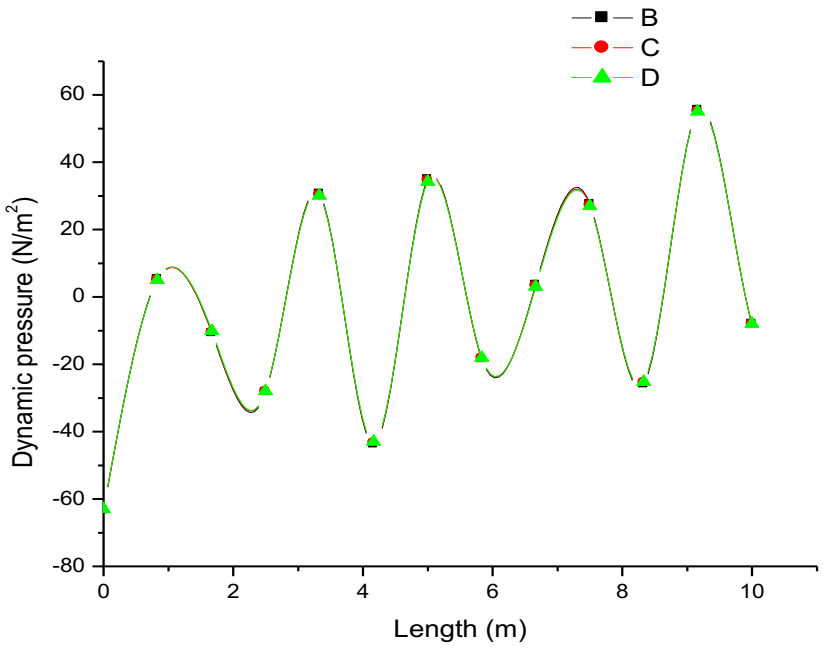


Figure 4. Pressure on the midline of the platform for different thickness of the platform

The depth of the fluid domain below the platform has a significant role in modifying the dynamic pressure developed on the platform (Figure 6). As depth increases, the dynamic pressure (Figure 7) decreases. The decrease of the pressure with increase in depth is because the pressure wave generated from beneath the platform is dissipated more as the depth increases (Bauri and Sarkar, 2020; Alazard et al. 2025).

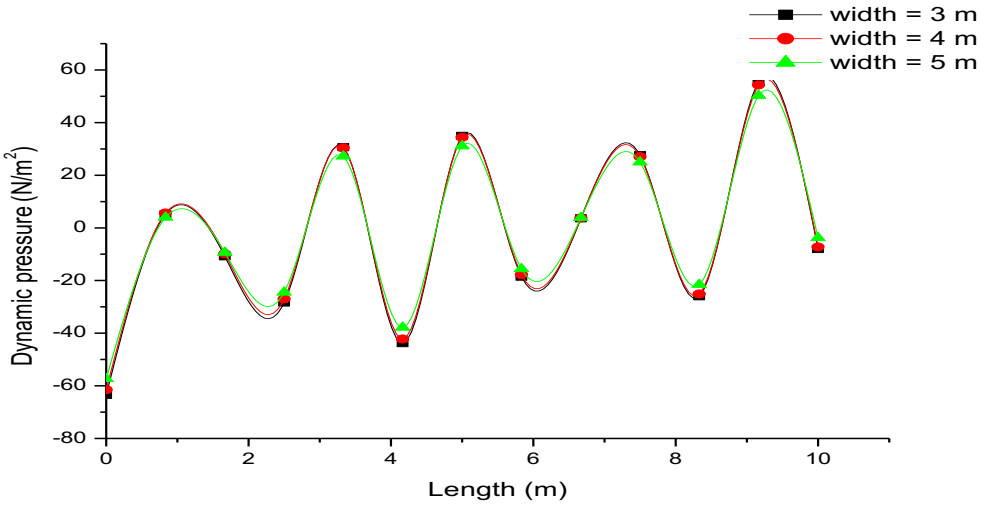


Figure 5. Dynamic pressure on the midline of the platform for different width of the Platform at time t=T/4

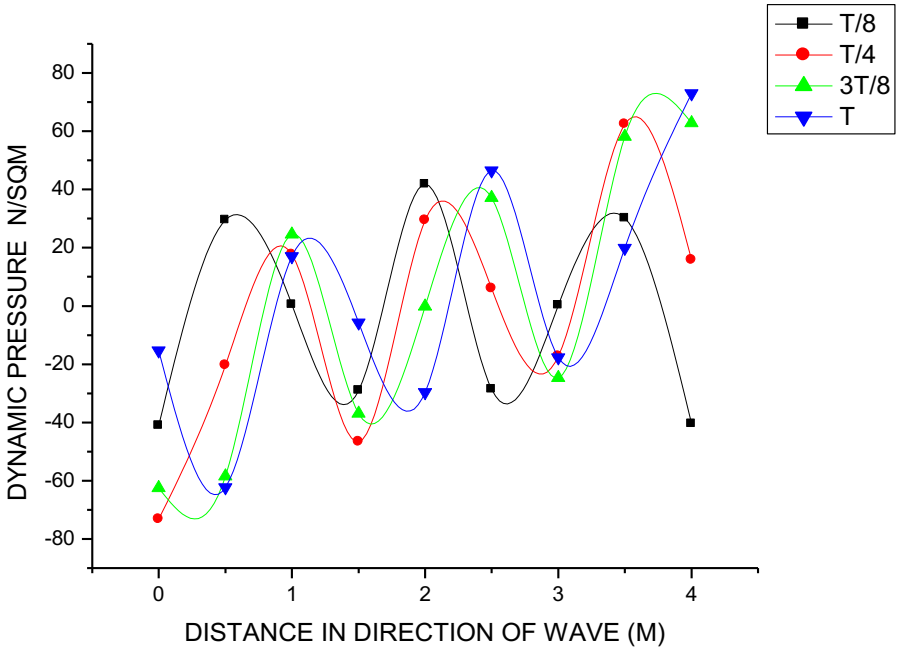


Figure 6. Dynamic pressure on the platform at various time intervals

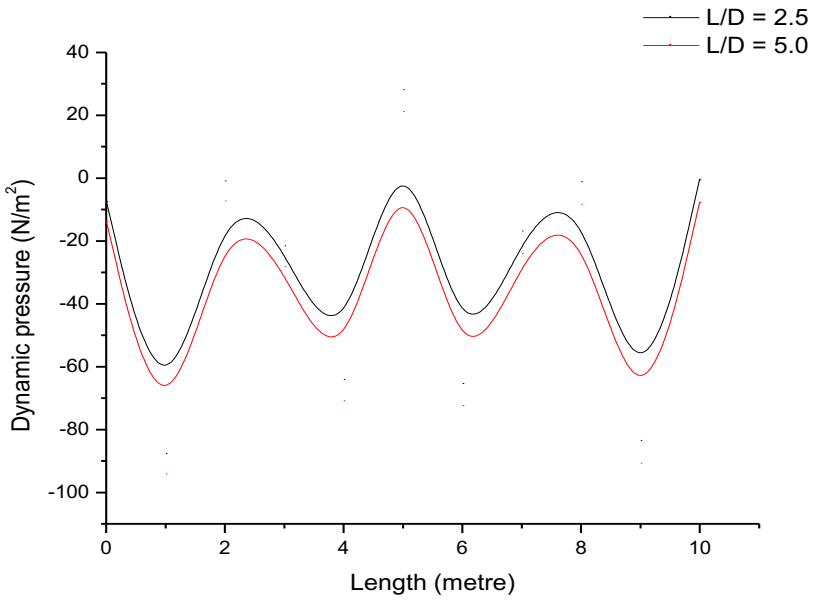


Figure 7. Effect of depth of fluid domain on dynamic pressure

5. Conclusion

The dynamic pressure acting on a platform is strongly influenced by its structural characteristics and the surrounding fluid conditions, and it differs significantly between rigid and flexible systems. A rigid platform tends to transmit the full effect of fluid-induced forces directly, resulting in comparatively higher dynamic pressures. In contrast, as the flexibility of the platform increases, it allows for greater deformation and energy absorption. This structural compliance dissipates part of the incoming energy through motion, thereby reducing the effective dynamic pressure experienced by the surface. In essence, flexibility introduces a buffering mechanism that moderates fluid–structure interaction.

The frequency of external excitation is another critical factor. As the excitation frequency increases, the dynamic pressure on the platform also rises. This occurs because higher frequencies lead to more rapid oscillations in the fluid, which in turn generate stronger inertial forces. When the excitation frequency approaches the natural frequency of the platform, resonance effects may further amplify the response, causing a noticeable increase in pressure intensity.

Fluid depth also plays a key role in determining pressure distribution. With an increase in the depth of the fluid domain, the dynamic pressure on the platform generally decreases. This reduction can be attributed to the greater volume available for wave energy dispersion, which diminishes the intensity of pressure fluctuations at the platform level. However, beyond a certain threshold—specifically when the fluid depth exceeds approximately 1.5 times the platform length—the influence of depth becomes negligible. At this stage, the system effectively behaves as if it were in an infinitely deep fluid domain, where additional depth does not significantly alter wave characteristics or pressure response.

Overall, these relationships highlight the importance of considering structural flexibility, excitation frequency, and fluid depth in the design and analysis of platforms subjected to dynamic fluid loading.

Acknowledgement

We would like to express our sincere gratitude to C.V. Raman Global University (CGU), and IGIT, Sarang, Dhenkanal, Odisha, India, for his valuable assistance in conducting this innovative work. Their expertise and support were instrumental in the successful execution of the test and obtaining accurate data for our study. The author is grateful to three anonymous reviewers for their critical comments on early version of the manuscript which helped improve its presentation and clarity. We would also like to extend our appreciation to Miss Rani-Prativa Das, Ruchika Square, Bhubaneswar, for her efforts in arranging the helpful assistance for the test. Her contribution to providing the necessary equipment and ensuring its proper functioning greatly facilitated our research work.

Credit Author Contribution Statement

Dr. Bhagirathi Tripathy: Writing-review and editing, Writing-original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization; Dr. P. K. Pani: Writing-review and editing, Writing-original draft, Visualization, Validation, Supervision; Dr. Abhijeet Das: Validation, Writing-review and editing, Dr. Krishna Pada Bauri: Supervision.

Funding

No funding is available

Declaration of Competing Interest

The author declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Clinical Manuscript No: Not Applicable

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