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Dolphin Structures Health Monitoring: A Case Study in Hai Phong, Vietnam

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ABSTRACT

The safety and durability of port structures are essential for ensuring uninterrupted maritime operations, particularly for dolphins used in berthing and mooring. This paper focuses on assessing a deteriorated dolphin structure in Hai Phong province, Vietnam, aiming to evaluate its current technical condition and structural integrity. The study adopts a multi-stage methodology combining visual inspection, dynamic response measurement, and numerical analysis. Field surveys documented extensive cracking, spalling, and material degradation in the pile system and cap, indicating significant structural damage. Vibration monitoring was conducted using accelerometers to record dynamic responses under vessel impact, and the results were analyzed through frequency-domain techniques. A finite element model was developed to simulate structural behavior and to compare calculated natural frequencies with field measurements. The findings revealed a significant reduction in load-bearing capacity, classifying the dolphin as severely degraded under international standards. The study demonstrates the effectiveness of integrating on-site inspection, vibration testing, and numerical modelling to provide a comprehensive evaluation framework for port structure health assessment.

1 Introduction

The durability and reliability of maritime infrastructure are fundamental to the sustainability of port operations worldwide. Among various port structures, dolphin-independent offshore structures used for berthing and mooring play a crucial role in ensuring safe docking, transferring berthing energy, and protecting quays from excessive impact. Despite their importance, dolphins are often overlooked in research compared to jetties, piers, or offshore platforms. However, these structures are highly exposed to harsh marine environments, cyclic berthing forces, and long-term material deterioration, which can compromise their serviceability and safety if not adequately assessed and maintained [1, 2].

Over the past decades, significant progress has been made in the inspection and monitoring of marine and offshore structures. Early research focused on condition assessment using visual inspection, non-destructive evaluation, and conventional damage detection techniques [3, 4]. With advances in sensor technology and structural health monitoring

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(SHM), researchers increasingly adopted dynamic response methods, particularly vibration analysis, as sensitive indicators of stiffness degradation and structural damage [5, 6]. Changes in natural frequencies, mode shapes, and damping ratios have been correlated with progressive deterioration in offshore and civil structures [7]. These methods are advantageous because they allow for global assessment and continuous monitoring under operational conditions [8, 9].

Nevertheless, several critical limitations in the literature remain. First, while vibration-based monitoring has been successfully applied to bridges, towers, and offshore platforms, its application to mooring dolphins remains scarce [10, 11]. Most prior studies treat dolphins as secondary elements within larger port systems, neglecting their unique geometry, pile–soil interaction, and failure mechanisms. Second, most practical assessments rely heavily on visual inspections, which are often subjective, labor-intensive, and unable to accurately quantify damage severity [12]. Although valuable, such methods cannot capture reductions in structural stiffness or predict remaining service life. Third, there is still a lack of integrated approaches that combine field vibration measurements with numerical modelling to validate and quantify structural health indices. This integration is essential to move beyond qualitative descriptions toward robust, quantitative diagnostics [13].

Another significant gap lies in regional representation. Much of the published work on port structure health monitoring originates from Europe, North America, or Japan, where research facilities and maintenance budgets are more advanced [14]. By contrast, studies addressing ageing marine infrastructure in Southeast Asia, particularly Vietnam, remain very limited, despite these countries experiencing rapid port expansion to support economic growth. Although several studies have been conducted, they primarily focus on condition assessment and the proposal of upgrading or reinforcement solutions for existing structures [15–17]. The scarcity of localized studies hampers the ability of port authorities to adopt evidence-based maintenance strategies that reflect real environmental and operational conditions. This underlines the importance of conducting case-specific investigations in developing contexts, where deterioration often progresses faster due to tropical climates, limited maintenance resources, and heavy vessel usage [18].

In addition to these gaps, there is growing recognition that dolphins are critical to port resilience in the era of larger vessels. With the continuous increase in ship sizes, berthing energies have reached unprecedented levels, placing higher demands on fender systems and supporting structures [2, 3]. Dolphin failures or underperformance can result in severe operational disruptions, costly repairs, and safety hazards. Consequently, the development of effective assessment frameworks for dolphins is not only a technical necessity but also a socio-economic imperative.

To address the aforementioned gaps, this paper presents a comprehensive assessment of a deteriorated dolphin structure in Northern Vietnam. The novelty of this work lies in its multi-stage methodology, which integrates: (1) Detailed condition survey, documenting cracks, spalling, and material loss; (2) Dynamic response measurements, capturing natural frequencies during actual vessel berthing; (3) Finite element modelling (FEM), used to simulate structural behaviour and validate field measurements.

By correlating field test data with numerical predictions, the study establishes a quantitative health index for the dolphin, benchmarked against international standards. This integrated framework reduces subjectivity, enables more precise evaluation of residual capacity, and provides a replicable approach for similar port structures in resource-constrained regions.

2 Case Study and Methodology

2.1 Case study

The investigated structure presented in this paper is located in Hai Phong, Vietnam. The structural characteristics are as follows: the dolphin is designed as a mooring and berthing structure for vessels of up to 2500 DWT. The foundation consists of a high-pile cap system with the cap supported by reinforced concrete square piles. The reinforced concrete (RC) cap has a hexagonal plan with overall dimensions of 4.6×4.4 m and a height of 2.15 m.

The pile foundation consists of eight RC piles of 40×40 cm. The outer row of piles is inclined toward the river with a slope of 1:6, while the inner row is inclined 1:6 toward the bank. The front face of the dolphin is fitted with a fender panel. Additionally, the structure is equipped with one 50-ton bollard and alamda fender type 3000L. Plan and cross-section drawings of the structure are shown in Fig. 1.

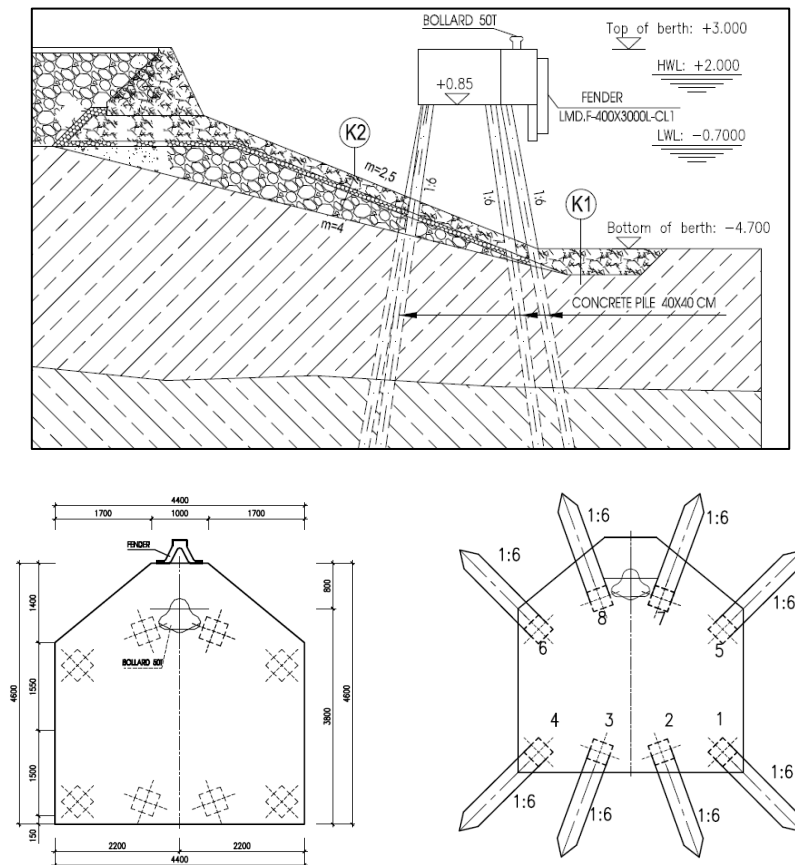


Fig. 1 –Designed dolphin structure

Currently, the dolphin remains in service for daily berthing and mooring operations. However, after years of operation, signs of deterioration have been observed, particularly severe cracking and spalling of piles. Fig. 2 illustrates the overall condition of the structure.



Fig. 2– Overall view of the dolphin structure

2.2 Methodology

The technical assessment of the structure was conducted through a comprehensive three-stage process: detailed site investigation, dynamic response measurement, and numerical analysis.

First, a detailed investigation was performed to identify the location and severity of structural deterioration. This involved a systematic inspection of cracks and damage using visual observation, photographic documentation, and physical measurements. For reinforced concrete (RC) members, specific crack patterns, lengths, and widths were precisely

quantified using measuring tapes and specialized crack-width gauges. Following the field survey, dynamic response measurements were collected to evaluate structural behavior under ambient and forced vibrations.

Finally, a numerical analysis was executed to evaluate the overall structural integrity. A high-fidelity finite element model was developed in SAP2000, with loading conditions applied in accordance with the original design assumptions. The simulation results were then reviewed and correlated with the field measurement data. This correlation process facilitated the calculation of a comprehensive technical condition index for the dolphin, providing a quantitative basis for determining its current safety and serviceability levels.

3 Results and Discussion

3.1 Detailed inspection results

The inspection results conducted by the assessment unit revealed that the dolphin structure had suffered severe damage, especially in the pile system, as shown in Fig. 3. All piles exhibited cracking and spalling within approximately 1 m below the cap bottom. The entire concrete portion of the pile heads within this zone had fractured. Numerous horizontal and diagonal cracks ranging from 2–10 mm widths were observed. Large concrete fragments detached, with the most significant piece measuring 40×20 cm at a pile corner. The concrete surface was honeycombed, and hammer testing indicated debonding and loss of integrity. The piles showed bending and a tendency to fracture about 60 cm below the cap bottom.



Fig. 3–Current state of dolphin piles

The current status of the cap is shown in Fig. 4. The cap maintained its designed geometry and dimensions; however, a visual inspection indicated that the RC concrete was subjected to chemical attack and surface degradation. Multiple areas of spalling were observed, especially on the river-facing side. Several edges were broken off.



Fig. 4–Current state of dolphin cap

3.2 Vibration Measurement

3.2.1 Measurement principle and method

To capture the dynamic behavior of the dolphin structure, two measurement points were strategically established: Point 1 was aligned parallel to the riverbank, while Point 2 was oriented in the perpendicular direction. The instrumentation suite comprised accelerometers and displacement sensors, which were securely fixed to the structural cap and interfaced with a centralized controller and computer system for real-time data acquisition.

Dynamic excitation was generated by the berthing operations of vessels with a displacement ranging from 1,000 to 2,000 tons. The resulting vibration signals were processed and analyzed using the Fast Fourier Transform (FFT) method to identify the spectral characteristics of the structure. The comprehensive layout of the vibration test is illustrated in Fig. 5, while representative photographs of the field measurement process are provided in Fig. 6.

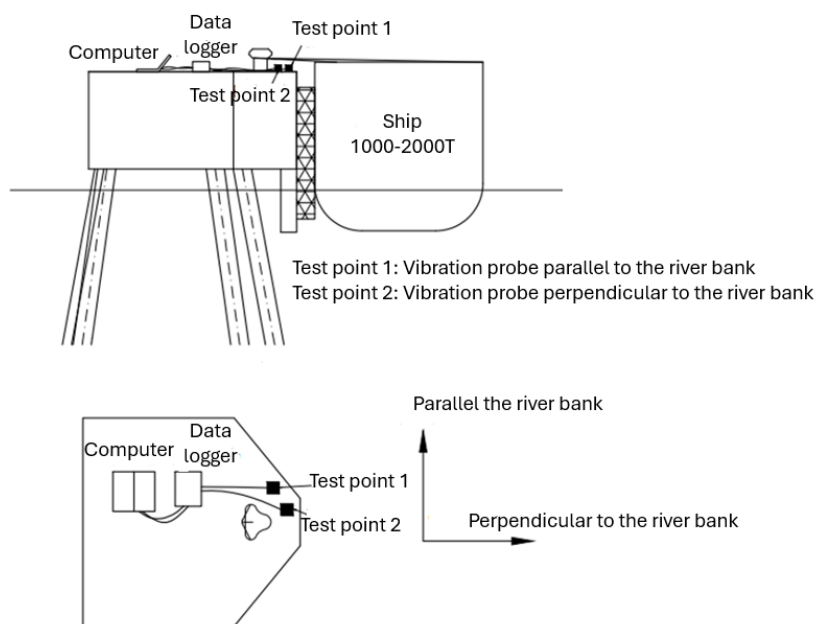


Fig. 5–Layout diagram of vibration measurement



Fig. 6–Field measurement implementation

3.2.2 Measurement results

The natural frequencies were identified using peak-picking and phase-angle criteria. Due to significant excitation forces, nonlinear behaviors were observed; consequently, both primary and secondary peaks were accounted for where necessary. The experimental procedure involved two barge-to-dolphin impact tests, the results of which were subsequently

averaged. Dynamic acceleration responses, initially recorded in the time domain, were transformed into frequency spectra via the Fast Fourier Transform (FFT). Figures 7 and 8 present the results for tests 1 and 2 in the direction parallel to the riverbank, while Figures 9 and 10 illustrate the corresponding data for the perpendicular direction.

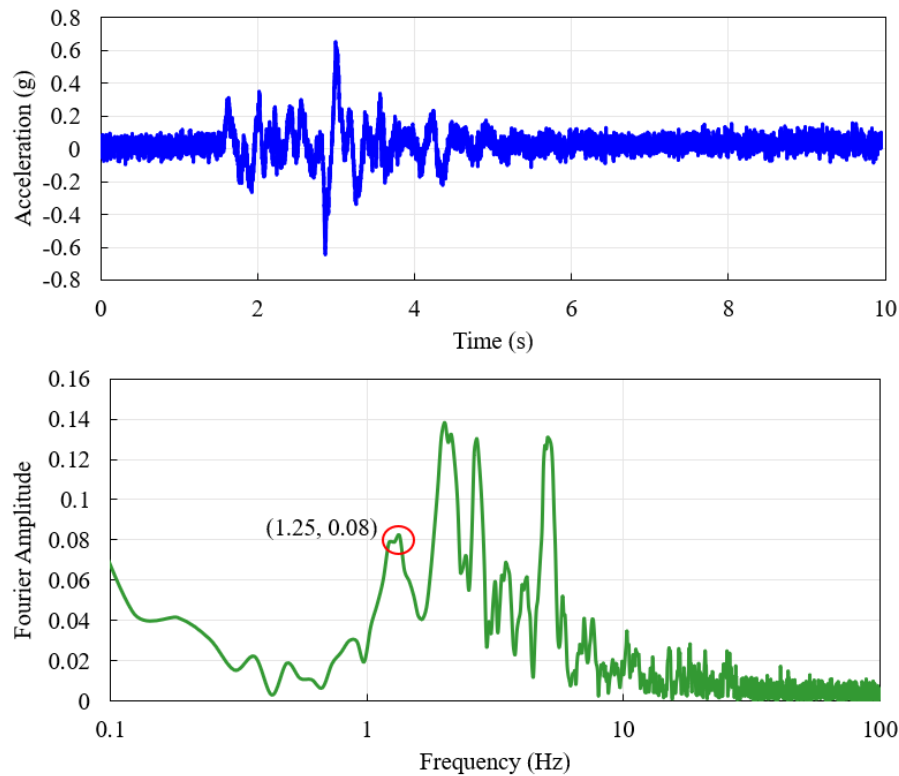


Fig. 7– Acceleration response parallel to the riverbank (Test 1)

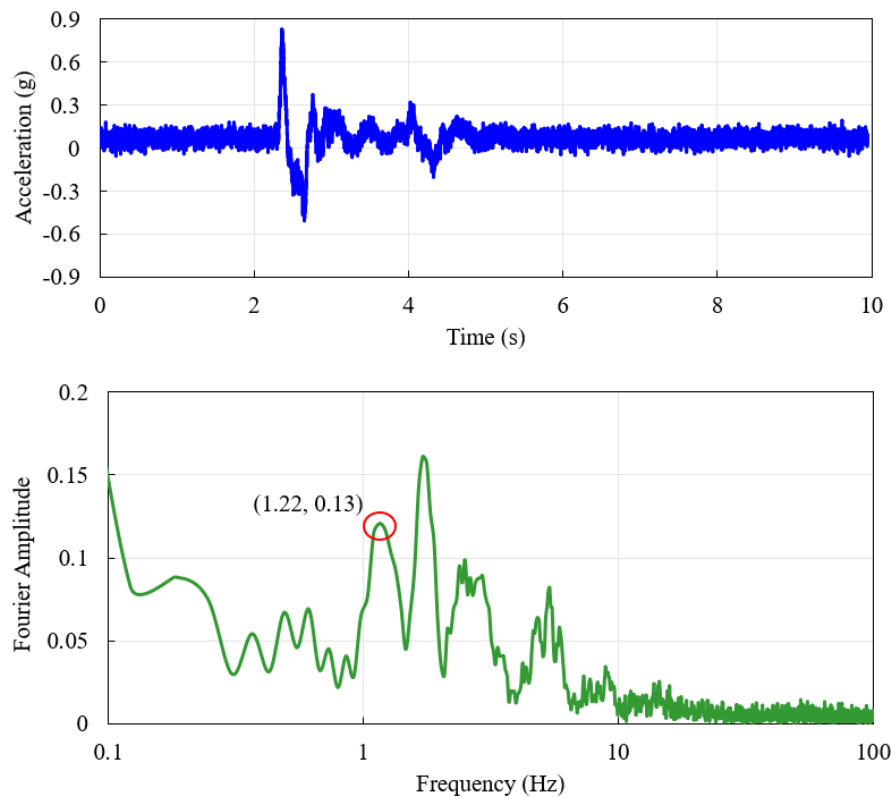


Fig. 8– Acceleration response parallel to the riverbank (Test 2)

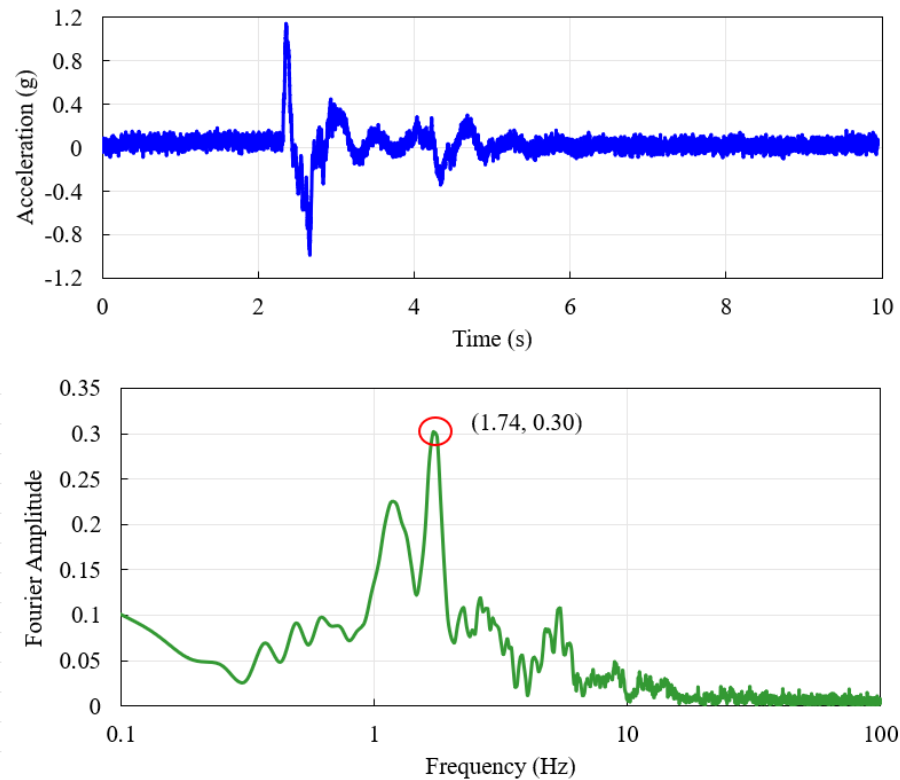


Fig. 9 – Acceleration response perpendicular to the riverbank (Test 1)

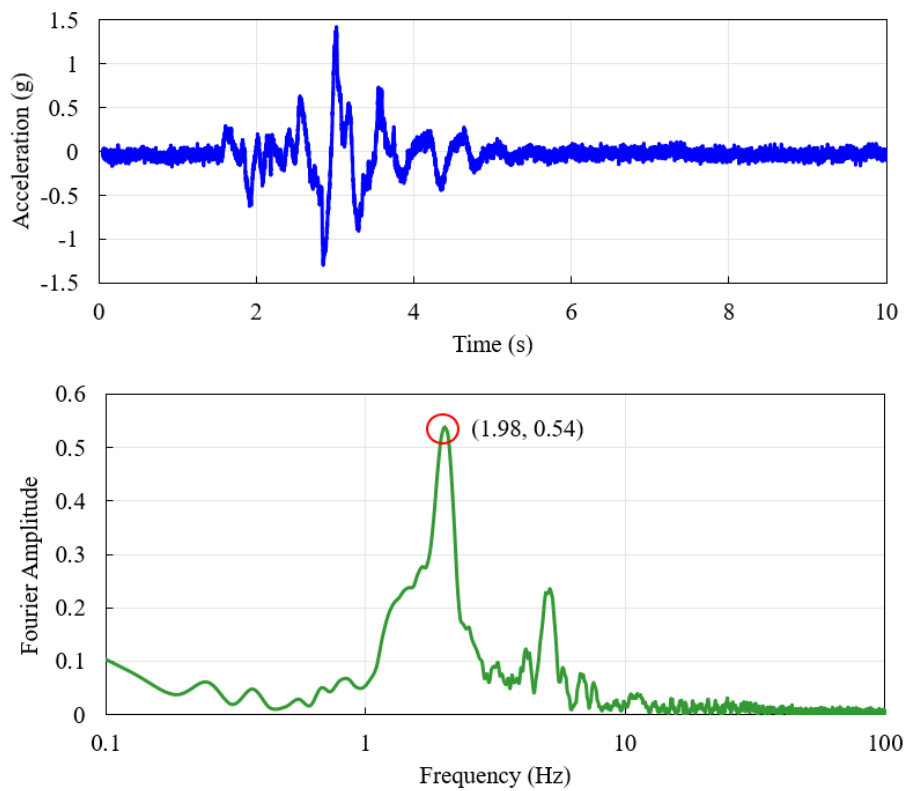


Fig. 10– Acceleration response perpendicular to the riverbank (Test 2)

The table below summarizes the natural frequencies (in both parallel and perpendicular directions to the riverbank) determined from field vibration test results.

Table 1 - Natural frequencies determined from the analysis of field measurement results

Vibration Direction	Natural Frequency (Hz)	Average Result (Hz)
Parallel to the riverbank	Test 1: 1.25	1.23
	Test 2: 1.22	
Perpendicular to the riverbank	Test 1: 1.74	1.86
	Test 2: 1.98	

3.3 Numerical modelling and structural assessment

3.3.1 Numerical modelling

Finite Element Analysis (FEA) was conducted in SAP2000. Piles were modelled using frame elements, while the cap was modelled with solid components. Excitation was simulated by the impact force of a 1500-ton vessel. Soil–pile interaction was represented by an assumed fixed connection with embedment depth calculated per TCVN 10304:2014 [19].

$$\Delta = \frac{2}{\sqrt[5]{\frac{BK}{EI}}}$$

Where:

- Δ : Embedment depth, measured from the riverbed to the calculated fixity point (m);
- B: Equivalent width of the pile, determined as follows:
 - When $D \geq 0.8$ m, then $B = D + 1$ (m);
 - When $D < 0.8$ m, then $B = 1.5D + 0.5$ (m);
- E: Elastic modulus of pile material (kPa);
- I: Moment of inertia of the pile cross-section (m⁴);
- K: Proportional coefficient depending on soil type, which can be taken from Table A1 of TCVN 10304:2014.

The 3D model of the dolphin structure is presented in Fig. 11. The natural frequency results of the vibration mode in the direction parallel and perpendicular to the riverbank are illustrated in Figs. 12 and 13, respectively.

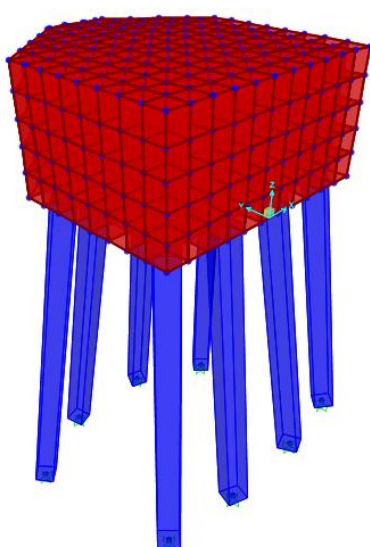


Fig.11 - Numerical model for structural analysis

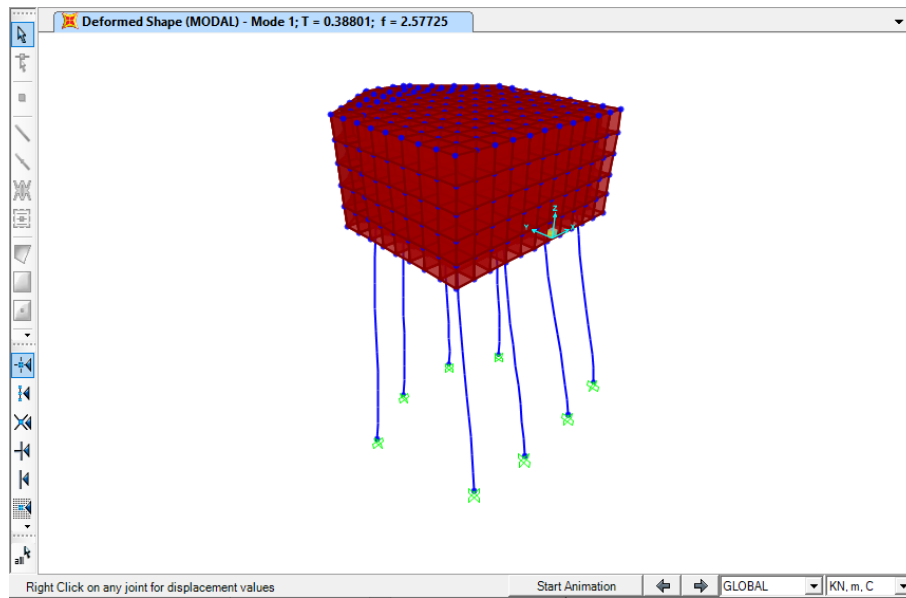


Fig.12 - Natural frequency: Longitudinal mode (parallel to riverbank)

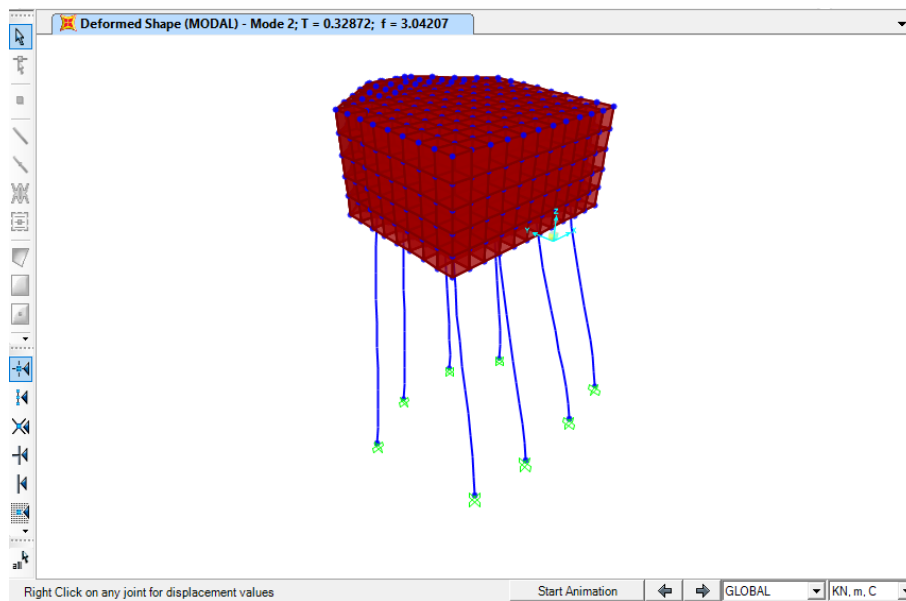


Fig.13 - Natural frequency: Transverse mode (perpendicular to riverbank)

Table 2 - Design natural frequencies (numerical model)

Vibration Direction	Natural Frequency (Hz)
Parallel to the riverbank	2.57
Perpendicular to the riverbank	3.04

3.3.2 Technical Condition Index Evaluation

The structural health index was calculated as:

$$\kappa = \frac{\text{Measured frequency}}{\text{Design frequency}}$$

Classification of the structural condition of the dolphin according to Japanese standards [20] .

Table 3 - Evaluation index of measurement results according to Japanese standards

Health Index (κ)	Evaluation Level	Structural Condition
$\kappa \leq 0.70$	A	A1 Danger may occur under extreme external loads; strengthening or repair is required.
$0.70 < \kappa \leq 0.85$		A2 Continuous monitoring of the decrease in natural frequency is required.
$0.85 < \kappa \leq 1.00$	B	At present, almost no problem is observed.
$1.00 < \kappa$	S	At present, the structure is completely sound.

Calculated results of the structural condition index of the dolphin:

Table 4 - Technical health index of the dolphin structure

Vibration Direction	Measured Natural Frequency (Hz)	Design Natural Frequency (numerical model), Hz	Health index	Level
Parallel to the riverbank	1.23	2.57	$\kappa = 0.48$	A1
Perpendicular to the riverbank	1.86	3.04	$\kappa = 0.61$	A1

According to Japanese standards, Grade A1 indicates a dangerous condition under extreme external loads, requiring urgent strengthening or redesign.

4 Conclusions

The comprehensive assessment of the dolphin structure was systematically conducted based on two primary performance indicators: (i) structural integrity, derived from detailed visual and physical inspections, and (ii) load-bearing capacity, evaluated through a correlation between in-situ vibration measurements and calibrated numerical modeling. Based on the empirical evidence and analytical results, the following conclusions are drawn:

1. Severe Material Degradation: All foundation piles exhibited critical structural failures, characterized by severe cracking and crushing at the pile heads within a 1.2-meter zone below the cap. Significant distress was observed, with crack widths reaching 1.0 cm and extensive concrete spalling (up to 50 × 30 cm) that exposed primary reinforcement bars. Notably, a consistent fracture pattern was identified in the majority of piles at a depth of approximately 0.6 m below the cap interface.

2. Component Deterioration: Both the piles and the structural cap demonstrated advanced stages of deterioration. The river-facing surface of the cap, in particular, showed widespread spalling, indicating significant environmental and operational impact on the concrete integrity.

3. Structural Health Index (κ): The calculated technical condition indices for the dolphin were $\kappa = 0.48$ in the longitudinal (parallel) direction and $\kappa = 0.61$ in the transverse (perpendicular) direction. Both values fall significantly below the safety threshold of 0.7. According to the relevant Japanese standards for port facilities, the structure is classified as Grade A1, the lowest possible bearing capacity level. This classification indicates that the dolphin is in imminent danger and lacks the structural reserve to withstand extreme operational or environmental loads.

4. The investigation confirms that the structure is in a state of terminal deterioration and no longer meets the safety requirements for continued operation. Immediate intervention is mandatory; the structure must undergo extensive strengthening, comprehensive repair, or complete replacement to mitigate the risk of catastrophic failure.

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