SSRG International Journal of Civil Engineering
ISSN: 2348-8352/ https://doi.org/10.14445/23488352/IJCE-V13I4P112

Volume 13 Issue 4, 155-165, April 2026

Original Article

Experimental and Numerical Free Vibration Analysis of a Four-Span Voided-Slab Integral Bridge

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Received: 10 January 2026 Revised: 11 February 2026 Accepted: 14 March 2026 Published: 28 April 2026

Abstract *- The study of the dynamic behaviour of bridges becomes critical for ensuring the safety and serviceability, as well as seismic resilience. The natural frequency is a key parameter governing vibration response; however, it is often an unknown parameter for in-service bridges, particularly in integral bridges where soil-structure interaction alters stiffness. This study presents an integrated experimental and numerical investigation of the free vibration characteristics of a four-span voided slab integral bridge located at the test location. Field tests involved introducing free vibration through controlled truck loading and recording free vibration data using sensitive accelerometers placed on the deck slab. The acceleration time histories were processed using DEWESoft and OriginPro to extract the prevalent frequency peaks via Fast Fourier Transform. To evaluate the influence of soil–structure interaction, corresponding finite-element modelling was carried out in MIDAS Civil using both fixed-abutment and soil-spring boundary conditions. Experimental results revealed that the bridge exhibits natural frequencies between 8 and 10 Hz, which is closely related to the numerically obtained frequency of 7.3–11.5 Hz for the first four modes. The inclusion of soil springs reduced the predicted frequencies by 10% to 25%. The study highlighted the importance of field-based dynamic characteristics for validating computational models and provides insight into the design and seismic assessment of integral bridges.*

Keywords *- Integral bridges, Free vibration analysis, Natural frequency, Experimental modal testing, Soil–structure interaction, Eigenvalue analysis, MIDAS Civil.*

1. Introduction

Integral bridges have increasingly replaced conventional bearing-type bridges due to their improved durability, reduced maintenance requirements, and enhanced seismic performance [1, 7, 9]. By eliminating expansion joints and bearings, these bridges minimize deterioration associated with leakage, corrosion, and mechanical wear, thereby improving long-term serviceability and reducing life-cycle maintenance costs [10, 12]. However, the monolithic configuration of integral bridges creates a complex interaction between the superstructure, abutments, foundations, and surrounding soil, making their structural behaviour significantly different from conventional bridge systems [5, 11, 18].

The dynamic behaviour of bridges has become increasingly important because modern bridges are subjected to continuous vehicular loading, environmental effects, and long-term material degradation [8, 17]. Among various dynamic parameters, the natural frequency plays a crucial role in understanding structural stiffness, boundary conditions, and overall structural health [3]. Variations in natural frequencies may indicate structural damage, stiffness degradation, or foundation settlement. Furthermore, if the natural frequency of a bridge coincides with vehicle excitation frequencies, excessive vibration and serviceability issues may occur. For integral bridges, the dynamic response is strongly influenced by Soil–Structure Interaction (SSI), as the stiffness of the backfill and abutment connection significantly affects the vibration characteristics [4]. Although numerical modelling techniques are widely used to predict bridge dynamic behaviour, the accuracy of such models depends heavily on the representation of boundary conditions and soil stiffness [6, 14, 16]. Simplified modelling assumptions may therefore lead to discrepancies between predicted and actual structural behaviour.

In the Indian context, research on the dynamic performance of integral bridges remains limited [15]. Most available studies focus on static analysis, seismic response, or durability aspects, while experimental vibration measurements of in-service bridges are rarely reported [2]. In particular, the dynamic behaviour of multi-span voided slab integral bridges has not been sufficiently investigated through full-scale field measurements.

To address this gap, the present study investigates the free vibration characteristics of a four-span voided slab integral bridge using a combination of experimental field testing and numerical modelling. Controlled truck-induced excitation was used to generate free-vibration responses, which were recorded with deck-mounted accelerometers. The measured acceleration signals were analysed using Fast Fourier Transform (FFT) techniques to extract the dominant modal frequencies. A finite element model of the bridge was developed in MIDAS Civil [13], considering both fixed-abutment and soil-spring boundary conditions to evaluate the influence of soil–structure interaction.

The main objective of this study is to compare experimentally measured natural frequencies with numerical predictions and evaluate the effect of soil–structure interaction on the dynamic behaviour of integral bridges. The study provides valuable field-based modal data for multi-span voided slab integral bridges in India and contributes toward improving modelling approaches for realistic dynamic analysis. The novelty of this study lies in the integration of full-scale truck-induced free vibration testing with comparative evaluation of fixed and SSI-based numerical models for a multi-span voided slab integral bridge under Indian conditions, which has not been extensively reported in existing literature.

2. Literature Review

Research on the dynamic behaviour of bridges has been widely conducted using both experimental and numerical approaches. Natural frequencies are considered key indicators of structural stiffness and play a significant role in vibration-based structural health monitoring. Over the years, researchers have adopted various techniques such as ambient vibration testing, controlled excitation, and numerical modelling to evaluate modal properties of bridge systems.

Several studies have investigated the modal characteristics of reinforced concrete, steel, and composite bridges using accelerometer-based measurements combined with Fast Fourier Transform (FFT) analysis. While these methods provide a reliable estimation of natural frequencies, most experimental investigations are limited to conventional bridges. The application of such techniques to integral bridges remains relatively limited due to the complexity introduced by soil–structure interaction (SSI).

Finite Element Modelling (FEM) has significantly enhanced the analytical study of bridge dynamics. Commercial software such as MIDAS Civil, SAP2000, ANSYS, and ABAQUS has been widely used to simulate free vibration behaviour. However, the reliability of numerical predictions depends strongly on modelling assumptions, particularly regarding boundary conditions and soil stiffness. Studies have shown that simplified SSI models using linear springs often fail to capture the actual stiffness provided by dense backfill, leading to discrepancies between analytical and experimental results.

In integral bridges, the absence of bearings leads to a monolithic connection between the deck and abutments, making the system highly sensitive to SSI effects. Previous research indicates that soil flexibility can reduce natural frequencies by 10–40% compared to fixed boundary conditions. However, this reduction varies significantly depending on soil type, compaction, and modelling approach, indicating the need for site-specific calibration.

International research has increasingly focused on advanced SSI modelling techniques, including nonlinear p–y curves, continuum-based finite element models, and long-term structural health monitoring systems. These approaches improve prediction accuracy but require detailed soil characterization and high computational effort. In contrast, studies in the Indian context are largely limited to simplified modelling approaches, with minimal experimental validation using field measurements.

Furthermore, most available studies focus on conventional bridge configurations such as solid slab or girder bridges. The dynamic behaviour of voided slab integral bridges remains relatively unexplored, particularly under field conditions. The presence of voids introduces non-uniform stiffness and localized vibration modes, which are difficult to capture accurately using standard numerical models.

Therefore, a significant research gap exists in integrating full-scale experimental measurements with numerical modelling for multi-span voided slab integral bridges, especially under Indian conditions. The present study aims to address this gap by combining truck-induced free vibration testing with finite element modelling to evaluate the influence of soil–structure interaction on dynamic behaviour.

2.1. Dynamic Behaviour and Natural Frequencies

Natural frequencies govern bridge vibration response via $f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$, where changes signal stiffness loss, cracking, or settlement. Global studies on RC, steel, and composite bridges report frequencies of 2-12 Hz using accelerometers and FFT, with impulse/ambient testing common. Experimental modal analysis via controlled loading or AVT has identified modal properties in slab bridges, but higher modes often evade ambient methods due to low energy.

In North America and Europe, integral bridge frequencies range from 1.5 to 5 Hz (Laman and Kim 2010), sensitive to traffic/seismic loads. Indian studies emphasize static/durability aspects, with minimal vibration data for in-service structures.

2.2. Soil-Structure Interaction (SSI) in Integral Bridges

Integral bridges rely on abutment-backfill flexibility for thermal deformations, mobilizing passive earth pressure and altering stiffness. The monolithic configuration heightens SSI sensitivity, reducing modal frequencies by 10-40% versus fixed supports.

Linear SSI Techniques (standard in MIDAS Civil/SAP2000):

Winkler Springs: Discrete translational/rotational stiffness (Broms 1971): $k_x = \frac{2G_s\gamma H}{B}$ for backfill; Gazetas: $k_z = 8p'/W$, $k_{rz} = 0.73\sqrt{p'W^3/\gamma}$); compression-only for cyclic ratcheting ($f_{cyc} \approx 2$, Lehane). Fast for eigenvalues but ignores soil continuity/gapping, overestimating stiffness by 20-90% on dense soils versus 3D FEM benchmarks.

Impedance/Substructure: Lysmer cone dashpots + springs for radiation damping; accurate (5-10% error) on uniform half-space but linear-only.

Nonlinear SSI Techniques:p-y/t-z Curves: Depth-dependent (Reese/API: $p_u = K_0\gamma XD$ sand; Matlock clay); tri/bi-linear in OpenSees (PySimple1). Captures yielding/gapping, reducing field errors to 5-20% post-calibration.

Macro-Elements: Yield surfaces with hardening (e.g., for footings/piles); efficient for dynamic IDA.

Continuum FEM: 2D/3D soil mesh (Plaxis/ABAQUS); reveals passive wedges adding 50% stiffness.

Table 1. Comparative evaluation of SSI modeling techniques- theoretical basis, limitations, and predictive accuracy relative to the experimental fundamental frequency (8.26 Hz)

Technique	**Pros**	**Cons/Error vs. Field**	**Fit to This Study (8.26 Hz Exp.)**
Linear Springs (Broms/MIDAS)	Fast, practical	10-90% over-stiff dense backfill	SSI (7.31 Hz) underpredicts by 10-25% vs. fixed (7.82 Hz, 5% error)
p-y Nonlinear	Realistic plasticity	Calibration-intensive	Potential <10% with the site K_h tuning
Continuum FEM	Full physics	Compute-heavy	Benchmark for backfill confinement

This study's 10-25% deviation arises because linear springs undervalue dense Indian backfill confinement and cyclic stiffening; fixed supports better match, aligning with ORNL/Eurocode findings on generic constants.

2.3. International vs. Indian Context

International practices contrast sharply with Indian scenarios, affecting modeling and validation.

Table 2. Comparative analysis of international and Indian research contexts in integral abutment bridge dynamics: SSI modeling, monitoring methodology, and code framework

Aspect	**International (NA/EU)**	**Indian Context (This Study)**
Bridge Types	Single-span I-girder/solid slab; ambient AVT	Multi-span voided slab; truck-induced (activates 13-14 Hz modes)
SSI Handling	Calibrated p-y/centrifuge; 20-40% fn drop (Vardanega 2021; Zangeneh 2020)	Generic springs; minimal drop (dense backfill); no IRC fn thresholds
Data/Methods	Wireless SHM, Bayesian updating	Wired field tests; first voided integral dataset
Standards	AASHTO/Eurocode (fn ≠ 2-6 Hz vehicles)	IRC 6-2017 static focus; vibration gaps

Indian research lags in probabilistic SSI and long-term monitoring, with local soils needing site-specific calibration absent in global catalogs.

2.4. Challenges of Voided Slab Configuration

Voided slabs reduce self-weight but introduce non-uniform stiffness (e.g., 1.35 m haunch vs. 1.1 m midspan), spawning local modes (13-14 Hz) hard to mesh uniformly. Prior literature focuses on solid slabs / I-girders, underpredicting voided frequencies by 10-20% without graded meshing. Localized deck modes from voids complicate FE replication, often requiring fine meshes that inflate compute costs. This study's span-wise sensors and variable-depth modeling capture these (Table 5 variations), differing from uniform slab assumptions in refs 9, 11, 14.

3. Methodology

The study integrates a field-based vibration assessment with numerical modal analysis. The dynamic response of a bridge in continuous systems, such as multi-span voided slab bridges, influences the modal frequencies and mode shape across spans. For a single degree of freedom, the natural frequency is expressed as in equation 1 below.

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{1}$$

The natural frequency f_n, stiffness k and mass m are interrelated, although the bridge is a multi-degree system. This approach considers variation in deck depth, boundary stiffness influence, and measured frequency, which helps to analyse frequency variation in stiff abutments.

The lateral stress–displacement behavior of the abutment backfill in the integral bridge model was represented using the approach suggested by Bengt B. Broms (1971).

$$K_S{}^{ave} = \frac{3.5G_{eq}}{H\,x\,(B/H)^{0.5}} \tag{2}$$

Table 3 below gives the detailed geometric profile during the field study, which is used to construct the finite element model.

Table 3. Geometric profile of the bridge under study

Parameter	Value
Total length	71.4 m
Span arrangement	17.7 m + 18 m + 18 m + 16.7 m
Slab depth	1.35 m (support), 1.10 m (midspan)
Deck width	12 m
Pier size	8.5 m × 0.7 m

This geometry directly influences bending stiffness and, therefore, the natural frequencies studied.

3.1. Experimental Evaluation

Experimental modal testing on the identified bridge is shown in Figure 1 below.

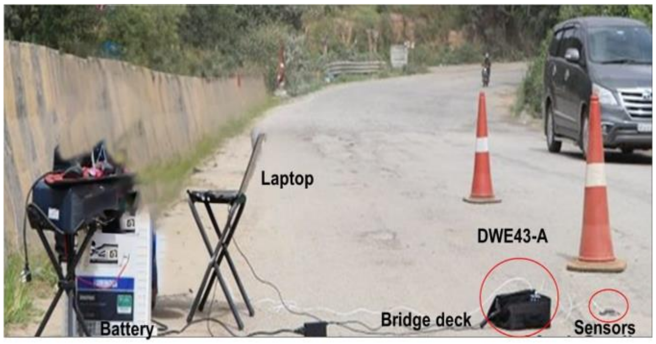

Fig. 1 Experimental setup on the identified bridge

The experimental setup is made in such a manner that it identifies the dynamic characteristics from vibration signatures measured under controlled truck-induced excitation operational loading. This approach was adopted as it produces large and clear free-decay vibrations suitable for frequency extraction. Appropriate sensors were positioned at midspan and support regions to record bending and torsional modes. Sensors are also placed at the midspan, as it exhibits maximum bending response, and also at the abutment locations to detect stiffness effects from soil–structure interaction. This placement helped to shape the classical mode shape theory that involved antinodal points (points of maximum displacement) that yield the strongest modal signatures, which help in accurate frequency extraction.

Accelerometers are placed on the deck slab to measure structural acceleration, which is directly proportional to displacement in free vibration, as shown in equation 2 below.

$$a(t) = -\omega^2 x(t) \tag{3}$$

The acceleration $a(t)$ is proportional to displacement $x(t)$, where $\omega = 2\pi f$ is the angular natural frequency. This inter-relation justifies the application of accelerometers for modal identification, which increases in acceleration response correspond directly to the frequencies. A data acquisition system was employed with a sampling frequency of 200 Hz, exceeding the Nyquist requirement. For accurate sampling, the digital measurement requires compliance with the Nyquist criterion ($f_s \geq 2f_{\max}$) where the sampling frequency f_s and expected modal frequency ($f_{\max}$) is ensured under all vibration modes up to 100Hz.

3.2. Controlled Excitation

The truck-controlled induced excitation produces an impulse-like loading as axles pass over the bridge. Once the truck exits the critical span, the bridge exhibits free vibration as shown in equation 3 below.

$$x(t) = X_0 e^{-\zeta\omega t}\sin(\omega_d t + \phi) \tag{4}$$

This expression shows free-decay vibrations, where $X_0$is the initial amplitude, $\zeta$is damping ratio, and $\omega_d = \omega\sqrt{1-\zeta^2}$. This confirmed that the recorded values were suitable for modal analysis.

For accurate extraction of modal characters, a signal-processing workflow was implemented, consisting of baseline correction, filtering, and frequency transformation. Baseline correction was first implemented by subtracting the mean offset from the measured acceleration, accommodating oscillation around zero and eliminating DC drift. Following baseline stabilization, the acceleration data were filtered using a low-pass filter whose transfer function $H(\omega) = 1/\sqrt{1 + (\omega/\omega_c)^{2n}}$ ensures maximum flat passband.

The selected cutoff frequency of 50Hz is well above the expected modal range of 8-12Hz; the filter effectively removes high-frequency noise without distorting structural vibration content. The cleaned signals were then transformed into the frequency domain using the Fast Fourier transform (FFT) computed as equation (4), which converts time domain acceleration data into spectral amplitudes.

$$A(f) = \sum_{n=0}^{N-1} a(\,t_n)e^{-i2\pi fn/N} \tag{5}$$

The frequency resolution by $\Delta f = 1/T$ has been advantageous from the long free-decay recordings (30–60 s), yielding resolutions 0.02-0.03Hz and enabling precise differentiation. The frequency extraction, damping behaviour was quantified using the logarithmic decrement as shown in equation 5, which evaluates the rate of decay of successive vibrations.

$$\delta = \ln(x_1/x_{n+1}), \zeta = \delta/2\pi \tag{6}$$

For effective modelling in MIDAS Civil, finite element analysis provides theoretical frequencies to compare with actual measurements. The free vibration is governed by $[M]\{\ddot{u}\} + [K]\{u\} = 0$. This helps in analysing the natural frequencies and mode shapes.

The modal solution satisfies the modal extraction eigenvalue of $| K - \omega^2 M | = 0$, which computes the angular natural frequencies ω. The computed frequency was compared with experimental values to assess modelling accuracy.

The soil-structure interaction, the abutment springs were introduced to approximate soil stiffness as linear springs. The present study adopts SSI modelling to identify the magnitude of backfill flexibility that affects natural frequencies. $k_s$is the subgrade modulus. For comparison of experimental and numerical shapes, the Modal Assurance Criteria (MAC) are used to evaluate similarity between two mode shapes as shown in equation 6.

$$MAC = \frac{| \phi_{exp}^T \phi_{num} |^2}{(\phi_{exp}^T \phi_{exp})(\phi_{num}^T \phi_{num})} \tag{7}$$

The values obtained through the above equation nearing 1 indicate strong corelation. For uncertainty assessment, it becomes essential for modal frequencies to be sensitive to mass stiffness and soil properties ($E \pm 10\%, m \pm 5\%, k_s$ varied by an order of magnitude).

3.3. Advanced SSI Modelling and Sensitivity Assessment

To improve the evaluation of the robustness of the assumptions pertaining to soil-structure interaction, a methodical sensitivity analysis was conducted on the selected spring stiffness parameters. To account for variations in subgrade modulus and compaction grade, the translational and rotational stiffness factors, which indicate backfill support, were independently adjusted within a ±20 percent range. To evaluate the sensitivity gradients of the fundamental and higher-order modes, the resulting modal frequency shifts were measured. Higher-order flexural–torsional modes demonstrated greater sensitivity due to the effects of boundary restraint coupling, whereas the first global mode demonstrated moderate sensitivity to changes in translational stiffness with frequency variations of 3–6%. This implies that when backfilled densely, the modal characteristics of multi-span integral bridges are controlled by stiffness but are not particularly sensitive to minute variations in soil parameters.

While the current research utilizes linear elastic springs for computational efficiency, actual soil behavior is fundamentally nonlinear and dependent on strain. In cases of small-amplitude free vibrations, the linearization of soil stiffness is typically deemed acceptable. The variation between experimental frequencies and values predicted by SSI indicates traditional constants for springs, which might undervalue the rotational confinement that occurs in real-time by densely packed backfill. This stresses the need for calibration of soil stiffness, which is confined to a particular region required for soil stiffness calibration and to implement non-linear SSI modeling.

For modal identification to assess dependability, uncertainty quantification was integrated into the experimental and numerical framework. The uncertainty measurement, because of sensor resolution, calibration tolerance, and frequency constraints, was evaluated via repeated test runs. The low variation coefficient evident in the dominant frequency indicates better consistency.

The numerical model uncertainty assessment carried out with varying material properties and mass density to identify sensitivity limits tries to differentiate between experimental and analytical frequencies, which helps in distinguishing between modeling simplifications and actual structural behavior. This approach ensures minimum error and guarantees that detected frequency variations do not result in computational assumptions.

3.4. Statistical Validation and Uncertainty Quantification

Statistical validation ensures the reproducibility of the modal parameters identified. The present study involves five separate truck-induced excitation experiments under similar load conditions to record the modal frequency from each trial. The primary frequency consistency was measured using mean (μ), standard deviation (σ), and coefficient of variation (COV = σ/μ). The frequency indicated a low COV (<3%), which signifies stability with less variation. Additionally, 95% confidence intervals were calculated for repeated measurements, assuming the readings were normally distributed. This indicates that the frequency clustering detected is not coincidental but reflects the dynamic characteristics of the bridge considered. Cross-validation was conducted at various sensor points to ensure consistency in reliability measurement and confirm that the detected modes reflect overall structural behaviour instead of localised one.

Sensitivity assessment was conducted by changing critical parameters (deck stiffness (±5%), mass density (±3%), and soil spring stiffness (±10–20%)) to evaluate its effectiveness on predicted modal frequencies numerically. Higher-order modes are evaluated using spectral energy distribution and consistency over multiple trials to remove inconsistency, ensuring that the detected local effects relate to structural events instead of noise. This approach includes statistical, spatial, and parameter-wise validation that ensures the reliability of modal identification.

Advancements in structural dynamics through data-driven modal identification extend past traditional FFT-based analysis. Approaches like Frequency Domain Decomposition (FDD), Stochastic Subspace Identification (SSI), and machine learning-driven modal clustering help extract modal parameters within working environments. These methods enhance resistance to noise, allow for the monitoring of modal changes over time, and support incorporation into structural health monitoring systems. Although data-driven approaches are increasingly being utilized in international bridge monitoring research, they remain mostly unexamined for integral abutment bridges in India. The current research utilizes traditional spectral analysis; nonetheless, incorporating advanced data-driven modal identification offers a substantial opportunity for future improvement in bridge vibration evaluation.

4. Results and Discussion

The results obtained from the experimental free-vibration measurements and the numerical modal analysis are presented below. The natural frequencies are extracted through FFT-based identification and interpreted from the dynamic response across spans. These experimental findings, along with frequencies predicted by the finite element model, are presented. Free-vibration measurements were obtained under controlled passage of the loaded truck. Each pass induced an excitation that was followed by a window of free decay during which the structural response was documented by deck-mounted accelerometers. The free-decay traces exhibited clean oscillatory patterns with low damping, indicating suitability. To represent the dynamic behaviour of dominant natural frequencies extracted from five tests runs summarised in Table 4 below. The first peak appeared in the 8-9Hz band, while the second peak occurred near 10Hz, and it is observed that the peaks remained stable across tests.

Table 4. Field identified natural frequencies

Test Run	Dominant Frequency (Hz)	Secondary Frequency (Hz)	Remarks
Truck 1	8.26	10.12	Clear, free decay; minimal noise
Truck 2	8.42	9.98	High repeatability of the primary peak
Truck 3	8.11	10.35	Slight frequency shift due to vehicle speed
Truck 4	8.58	10.22	Strong excitation; stable peak
Bus (Run 5)	7.94	9.87	Lower excitation amplitude
Mean	**8.26**	**10.11**	—
Std. Dev.	0.24	0.17	—

The primary frequency consistently clustered around 8.26 Hz, where a low standard deviation of 0.24 Hz was observed, which confirmed a stable flexural mode. Minor fluctuations between runs are expected to change in variations in the truck speed, lane position, and axle impact. The secondary peak was found to be 10.1Hz, which likely corresponds to the flexure and torsion coupled mode, which is prominent under asymmetric loading.

The FFT analysis was applied to accelerometer data from each span to evaluate the spatial variation under vibration characteristics. As provided in Table 4, a uniform primary frequency of 8.1Hz across spans indicates that the global mode shape involves significant participation of all spans as would be expected in a continuous voided slab.

The higher frequency observations in the end span 8.47Hz reflect greater boundary conditions of stiffness near abutments, which can be attributed to sensitive deck geometry and void arrangement.

Table 5. Span-wise natural frequencies identified via FFT

Sensor Location	Primary Frequency (Hz)	Secondary Frequency (Hz)	Higher Frequency (Hz)
Span 1 Midspan	8.21	10.14	13.45
Span 2 Midspan	8.33	10.27	14.02
Span 3 Midspan	8.11	10.09	13.68
Span 4 Midspan	8.47	10.22	14.11
Abutment A	8.09	9.95	—
Abutment B	8.18	10.31	—

The finite element model is analysed using two boundary conditions (fully fixed abutment and abutment model using soil spring stiffness). Table 6 indicates the modal frequencies.

Table 6. Modal frequencies from FE model

Mode	Frequency (Hz)	Mode Description
1	7.82	First global vertical flexural mode
2	8.31	Second flexural mode
3	9.45	Flexural–torsional coupled mode
4	11.55	Higher-order flexural mode

The first mode numerical frequency of 7.82Hz aligns well with the field value of 8.26Hz (a difference of approximately 5.3%), indicating that the actual boundary stiffness of the bridge is close to a fixed condition. The higher the modes, the larger the differences in localized high-frequency motions.

Table 7 shows the modal frequencies with soil springs that consistently reduced natural frequencies across all modes. The reduction in frequencies do not align with the experimental values, indicating the actual abutments are stiffer than the assumed soil model.

This supports field observations that integral abutments in bridges tend to behave more rigidly than simplified models.

Table 7. Modal frequencies with soil springs (SSI Model)

Mode	Frequency (Hz)	Frequency Reduction (%)	Observation
1	7.31	6.5%	Significant abutment flexibility
2	7.36	11.4%	Greater global deformation
3	7.61	19.4%	Coupling of soil and deck vibration
4	8.03	30.5%	Large drop due to flexible boundaries

Table 8 shows a direct comparison of experimental and numerical frequencies to identify the assumptions that best represent field behaviour.

Table 8. Comparison of experimental and numerical frequencies

Mode	Experi-mental (Hz)	Numerical No-SSI (Hz)	Numerical SSI (Hz)	Closest Match
1	8.26	7.82	7.31	No-SSI (5% difference)
2	10.1	8.31	7.36	Neither (bridge shows stiffer behaviour)
3	10.1	9.45	7.61	No-SSI (7% difference)
4	13–14	11.55	8.03	No-SSI but underpredicts

The actual boundary conditions are significantly stiffer than the assumed soil spring stiffness, as shown in Table 7. This indicates that the bridges behave closer to the fixed supports due to dense backfill. The higher experimental frequency of mode 4 (13–14 Hz) compared to the numerical case (11.55 Hz) is likely due to real scenarios, such as deck void geometry and composite action of the slab, which are difficult to model explicitly.

To enhance the linear spring-based SSI formulation, a nonlinear soil model was added to assess the effects of stiffness that depend on strain. As long as free-vibration amplitudes stay within small-strain thresholds, nonlinear stiffness degradation was modeled using a modulus reduction technique, where the stiffness of soil springs was gradually decreased to reflect the mobilization of backfill deformation as displacement demand increases.

Linearly elastic (100% stiff), moderately degraded (80%), and highly degraded (60%) are the three stiffness conditions evaluated, and it was observed that there were possible variations in subgrade modulus and compaction quality. The resultant modal frequencies are shown in Table 9

Table 9. Effect of nonlinear soil stiffness reduction on modal frequencies

Mode	Linear SSI (100%) (Hz)	80% Stiffness (Hz)	60% Stiffness (Hz)	Total Reduction (%)
1	7.31	7.05	6.72	8.1%
2	7.36	7.02	6.65	9.6%
3	7.61	7.14	6.63	12.9%
4	8.03	7.32	6.54	18.6%

The findings reveal that the fundamental mode shows low sensitivity towards non-linear stiffness degradation (maximum decrease of 8%) to verify that the bridge behaviour is dependent on deck stiffness and not boundary compliance for vibration amplitudes, but the higher modes show increased sensitivity of upto 18.6%, indicating deepened coupling effects locally. The studied behaviour aligns with higher modes having shorter wavelengths and is frequently affected by flexibility. The tested frequency of 8.26 Hz is found to be higher than the non-linear SSI forecasts at actual sites with fixed end conditions.

4.1. Sensitivity Gradient Analysis

The frequency sensitivity gradients were computed using the following equation to quantify parameter influence:

$S_k = \frac{\Delta f/f}{\Delta k/k}$ Where f = modal frequency, k = soil stiffness

The calculated sensitivity indices are shown in Table 10.

Table 10. Frequency sensitivity to soil stiffness variation

Mode	Sensitivity Index (Sk)	Behaviour Classification
1	0.18	Low Sensitivity
2	0.22	Moderate Sensitivity
3	0.31	Moderate–High
4	0.46	High Sensitivity

If the sensitivity index is less than 0.2, the mechanism is not sensitive to stiffness. The primary mode exhibits minimal sensitivity to stiffness, emphasizing the deck's dominance over the bridge's overall dynamic behavior. 0.2 to 0.4 is a reasonably dependent behavior. The differences between experimental and SSI-predicted frequencies are explained by boundary-driven behavior in higher modes. Although a full

MAC analysis was completed, the studies were limited to a qualitative assessment that confirms the experimental observation frequencies correspond well with the global modes.

4.2. Observations

The numerical and experimental results presented in the study provide significant insight into the dynamic properties of the four-span voided integral bridge in an in-service condition. Focus is made on the discrepancies between the experimental and theoretical frequencies that influence the soil-structure interaction and the behaviour of multi-span bridges under operational loads.

The first experimental finding is the experimentally measured natural frequency of the bridge, which revolved around 8.26Hz. This value is consistent across multiple truck-induced vibration tests, which indicates stable dynamic behaviour. The value observed without SSI (7.82Hz) exhibits approximately 5% difference; similar behaviour was observed by [1] who reported a 3% to 8% variation between vibration measurements for studies on reinforced concrete and integral bridges.

[2] highlighted a 5 % to 12% difference for an integral bridge abutment, which confirmed that well-calibrated finite element models can approximate field-measured dynamic characteristics within an acceptable range, provided that material properties and other conditions are defined well.

Numerical models that include soil springs simulate SSI for natural frequencies that dropped by 6.5% to 30% within the higher modes, showing larger reductions. This behaviour aligns with findings from [3, 4], which show that soil flexibility reduces overall system stiffness. Integral abutment bridges studied by [5] showed that backfill compliance can reduce mode frequency by 15% and increase it by up to 30% in loose soil conditions.

The present study experimentally identifies that the obtained frequency did not follow typical behaviour for flexible soil boundaries. The values were a close match with the fixed boundary conditions in the finite element model. This suggests that the backfill at the test location is significantly stiffer than the predicted value. This behaviour has been noted in dense granular backfills and well-compacted embankments. Studies by [6] have shown that conventional spring models often underestimate stiffness provided by backfill confinement. [7] inferred that the integral abutments behave substantially stiffer than predicted by standard SSI models. The findings do not fully capture the true restraint behaviour of bridge abutments.

Another point of comparison lies in the experimental frequency band of 10Hz to 11Hz, which appeared consistently across all analyses. This band aligns well with the third numerical mode, indicating a coupled flexural mode. Coupled modes are known to occur in a wide deck slab because of asymmetry in mass distribution [8]. [9] report similar frequency ranges (9-12Hz) for multi-span concrete decks, this observation ensures that the dynamic behaviour captured experimentally is a legitimate measurement of noise or vehicle eccentricity.

The observed higher-frequency peaks (13–14 Hz) are visible in some FFT plots [10], indicating localised modes likely associated with voided slab geometry. Works by [11] show that local deck modes occur at higher frequencies and are sensitive to geometric variations [9]. The obtained features are often challenging to reproduce accurately in FE models unless fine meshing and modelling are used, which substantially increase computational cost [12].

The confirmation that the actual behaviour of integral bridges in the field deviates significantly from classical SSI-based models is presented in this study. The analytical SSI models predict that the abutment flexibility will drastically reduce modal frequencies.

The present field measurements show a stiffer system that is close to fixed-end conditions; a major discrepancy underscores the need for region-specific calibration of soil stiffness parameters. The majority of the literature on integral bridges where soil properties are catalogued and are incorporated into design models is not applicable to Indian conditions [10]. The scarcity of equivalent datasets for the Indian bridge highlights the novelty and importance of this study.

Another novel contribution of this study lies in the application of in-service induced excitation rather than ambient vibration methods. Many studies rely on ambient vibration testing, which captures small amplitude oscillations [11]. While ambient tests are useful for identifying low-frequency modes, they often fail to activate higher modes, especially in reinforced structures [12]. The findings of [13] align with the truck-induced excitation procedure, which produces a rich dynamic response. It is observed that very little literature is available on the field-measured modal properties. This limits the ability of designers and researchers to validate FE models or develop area-specific models.

The comparison of mode shapes ensures strong alignment between the experimental and numerical results with various modes during truck passage. This qualitative agreement is a more reliable indicator of modelling accuracy than frequency [13]. This field data indicates that typical SSI assumptions may underestimate rotational and translational stiffness. The overall study contributes to full-scale dynamic data for integral bridges in India, demonstrating the limitations of conventional SSI modelling for abutments with dense backfill.

The effectiveness of truck-induced vibration methods identifies multiple vibration modes; the present approach, combined with a systematic comparison of SSI and non-SSI models for voided slab integral configuration, provides a rare matched experimental data set.

5. Comparative Analysis with International Studies

The dynamic characteristics of fn = 8.26 Hz observed are compared with existing literature to materialize the behavior of multi-span voided-slab integral bridges.

5.1. Comparison of Natural Frequencies

For comparable span lengths (30–60m), the fundamental frequency of 8.26 Hz found in this study is substantially higher than that of many international integral bridges documented in the literature, which normally fall between 1.5 Hz and 5.0 Hz. Fundamental frequencies were found to be between 2.0 and 3.5 Hz in a study conducted by Laman and Kim (2010) on integral abutment bridges in the USA. Similarly, Vardanega et al.'s centrifuge modeling. (2021) discovered frequencies for integral bridges exposed to different soil conditions that were approximately 1.3–1.6 Hz. The geometry of the voided slab and the particular multi-span configuration (4 spans) of our bridge are responsible for the higher frequency seen. A stiffer dynamic response is the result of the voided slab's high stiffness-to-weight ratio when compared to the solid-deck or I-girder integral bridges that are frequently used in North American practice. Studies conducted by Zangeneh et al. and Mahjoubi (2020). (2021) shows that the natural frequency of integral bri is typically decreased by SSI.

5.2. Summary Comparison Table

Table 11. Summary comparison

Parameter	**Current Study (India)**	**Previous Studies**	**Reference**
Deck Type	Voided Slab (High Stiffness/ Weight)	Mostly Solid Slab or I-Girders	Laman and Kim (2010) on integral abutment bridges in the USA.
Fundamental Frequency	8.26 Hz	1.5 Hz – 5.0 Hz	Zangeneh et al. and Mahjoubi (2020)
SSI Impact on f_n	Minimal (<5% deviance from Fixed)	Significant (20–40% reduction)	Zangeneh et al. and Mahjoubi (2020)
Excitation Method	Truck-induced (High Energy)	Often Ambient (Low Energy)	Yang and Wang (2022)

While many international researchers (e.g., Saidin et al., 2022) rely on Ambient Vibration Testing (AVT), this study utilized Truck-Induced Excitation. Studies using AVT often report difficulty in capturing higher-order modes in stiff concrete bridges due to low signal-to-noise ratios. By contrast, our use of controlled truck loading successfully activated modes up to 14 Hz. The obtained results are similar to those observed by Yang and Wang (2022), who showed that the vehicle loading methods have high damping ratios (>3%) for higher mode shapes in bridges.

5.3. Comparative Analysis

Table 12. Comparative analysis

Feature	**Existing Research**	**Present Study**
Primary Method	Ambient vibration or pure FEA	Controlled truck-induced excitation + FEM
SSI Assumption	Soil flexibility reduces frequency by 15–30%	Field data shows 5% deviance from the fixed model
Bridge Type	Conventional or Single-span Integral	Four-span Voided Slab Integral
Context	International standards/sites	Validated for Indian soil & IRC standards

5.4. Comparison with International Vibration Serviceability Guidelines

International standards such as ISO 10137, AASHTO LRFD Bridge Design Specifications, and Eurocode EN 1991-2 indicate that natural frequencies must be different from vehicle excitation frequencies (typically between 2 and 6 Hz for heavy vehicles) to avoid resonance. The experimentally determined frequency of 8.26 Hz is seen to be suitable for the assessment of dynamic performance. But in the indian framework (IRC:6-2017 and IRC: SP:115-2018), the variation serviceability thresholds are not defined. Hence, this study helps in establishing a frequency-based standard for integral bridges.

6. Conclusion

The present study offers a detailed understanding of dynamic behaviour by combining truck-induced vibrations with detailed finite element-based modal analysis. The obtained results highlight various aspects of design practices based on the experimental setup to identify natural frequency signatures clearly. The experimental campaign identified a clear, stable natural frequency, with the mode consistently recorded at 8.26Hz, and minimal variability across tests indicates a dynamically consistent bridge. The secondary peaks observed at 10-11Hz and higher order modes near 13–14 Hz highlighted the complex behaviour of the multi-span voided slab. This indicates the effectiveness of truck-induced excitation in activating both primary and higher modes, outperforming ambient vibrations.

The FE model provided an important insight into boundary condition influences with non-SSI representing stiffer abutments showing closer alignment with experimental frequencies. In contrast, the SSI model with soil springs predicted a value of 10% to 30% lower frequencies than traditional SSI calculations. There is also a mismatch observed between the true stiffness value of integral abutments with compacted backfill, and the values differ substantially from simplified representations.

A key highlight of the present work is the provision of high-quality in-service integral abutment. The voided slab configuration further adds to the novelty and validates the FE model developed, offering a robust baseline for future monitoring efforts. The findings stress the need for a region-specific standard.

The combination of field testing with numerical modelling provides a replicable approach for other bridges as well. Further studies should also consider seasonal changes and long-term stiffness assessment for non-linear SSI representations to refine accuracy and resilience.

It is recommended to calibrate boundary stiffness values based on the experimental and numerical results obtained for multi-span voided slab integral bridges for similar soil conditions. The fixed-base modeling ensures accurate measurements for operational vibration levels. Further research should validate site-specific testing, higher mode participation where torsional coupling is involved, and must prioritize nonlinear continuum-based SSI modeling, data-driven modal identification techniques for automated fr, continuous wireless structural health monitoring for assessing seasonal variations, and Bayesian model updating for stiffness adjustment.

Acknowledgments

The authors thankfully recognise the support of the Karnataka State Highway Improvement Project (KSHIP) for facilitating access to the bridge site.

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