第 I 部門 **Vibration Monitoring for Stability Assessment of Pipe Bent**

京都大学工学研究科　学生員　○Shiuan-Cheng Pai　　京都大学工学研究科　正会員　金　哲佑
株式会社日本構造分析舎　正会員　河邊　大剛，高瀬　和男
三井住友建設鉄構エンジニアリング株式会社　正会員　皆田　龍一，成田　徹也
非会員　鈴木　康宏

1. INTRODUCTION

Pipe bent is widely used in modern infrastructure construction, especially for bridges and high-rise buildings. Due to its temporary and lightweight nature, pipe bent structures are highly susceptible to external influences such as uneven weight distribution, and gradual ground deformation. These factors can introduce structural instability and increase safety risks, especially during long-term construction processes. Traditional visual inspection methods are often insufficient to detect early-stage deterioration or subtle ground settlement beneath pipe bent supports. To address this, vibration-based structural health monitoring techniques supported by system identification methods have been introduced to assess structural behavior using sensor data such as acceleration. Among various system identification methods, Stochastic Subspace Identification (SSI)[1] and a Fast Bayesian FFT (Bayesian FFT)[2], are widely applied due to their ability to extract dynamic characteristics from ambient vibrations without requiring controlled excitation. Bayes-FFT enables probabilistic estimation of modal parameters with uncertainty quantification, while SSI provides robust identification of natural frequencies, damping ratios, and mode shapes under operational conditions. By combining these two methods, it is possible to cross-validate results and improve the reliability of modal parameter interpretation. These dynamic features can then be used as indirect indicators to infer changes in ground stiffness or structural integrity. This study proposes a monitoring framework that utilizes modal parameters extracted from SSI and Bayes-FFT analyses of real-world pipe bent systems, aiming to detect hidden changes in ground conditions. The framework highlights how variations in modal frequency, damping, and mode shape configuration correlate with support boundary conditions and underlying soil stiffness.

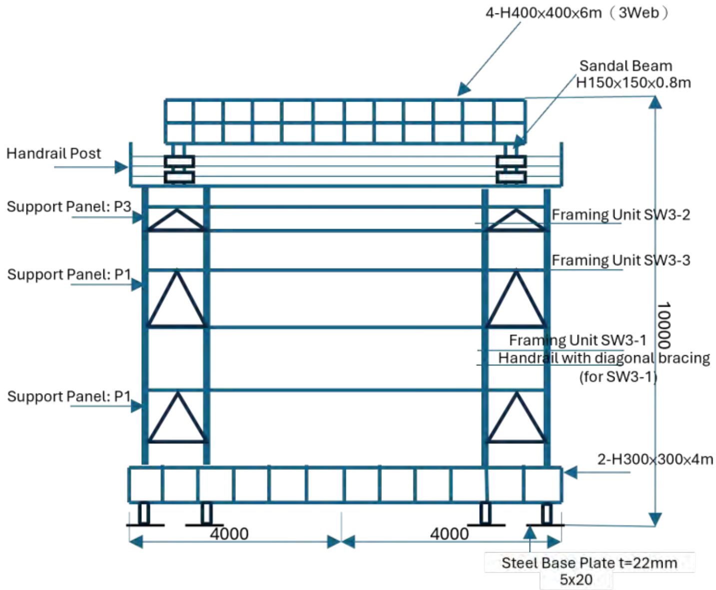

Figure 1 Overview of pipe bent setup

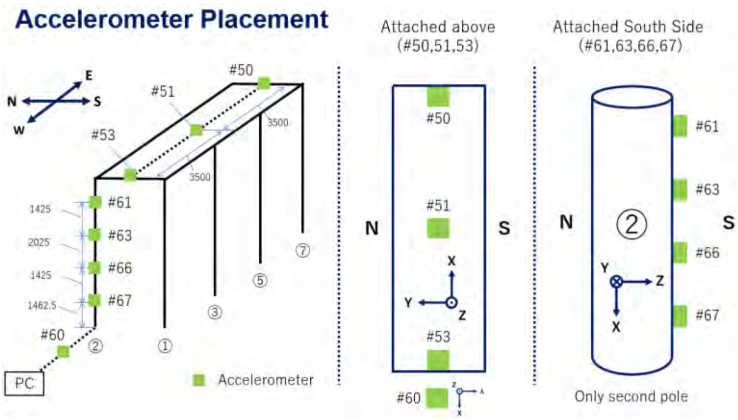

Figure 2 Sensor setup

2. FIELD EXPERIMENT AND PRELIMINARY ANALYSIS

2.1 Experimental setup

A full-scale 10-meter-high pipe bent structure was constructed using modular panels and steel H-beams shown as **Figure 1**. Eight base iron plates were placed beneath the pipe bent legs, for the substitution of

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Contact address: Kyotodaigaku Katsura, Nishikyo-Ku, Kyoto, 615-8246, Japan, Tel: +81-75-383-3421

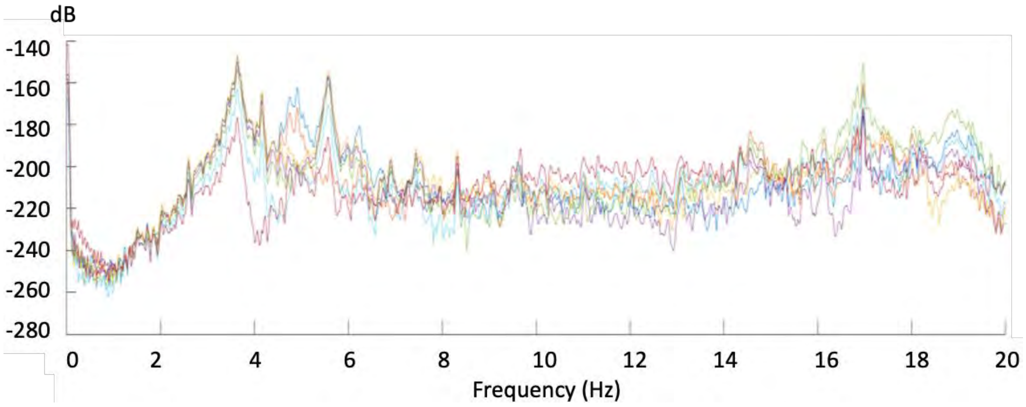

Figure 3 Result of PSD (ambient vibration)

rubber plates to simulate weak ground condition. **Figure 2** shows the location and numbers of accelerometers, strain gauges and inclinometer we installed. These setups were used for dynamic field testing and vibration monitoring.

2.2 Preliminary results

The pipe bent was subjected to a series of excitation tests including manual input, rope-based, and lifting-based methods. Ambient vibration data were also recorded under free vibration. A power spectral density curve from the ambient vibration is shown in **Figure 3**. To simulate ground variability, rubber pads were selectively installed beneath pipe bent legs and replaced with steel plates. Each condition was tested with and without an 8-tf vertical load, and the procedures were repeated for multiple configurations.

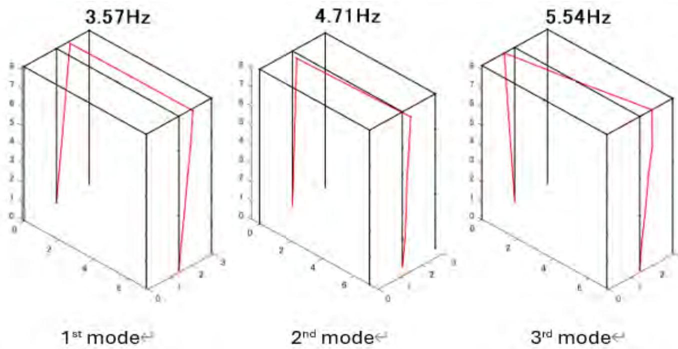

Figure 4 Mode shape model

Three primary structural modes were identified from ambient vibration data using Power Spectral Density (PSD), Stochastic Subspace Identification (SSI), and Bayesian FFT methods. The extracted modal frequencies—3.57 Hz, 4.71 Hz, and 5.54 Hz—correspond to the first weak-axis bending mode and two subsequent torsional modes. The resulting mode shapes reveal that the pipe bent exhibits pronounced torsional responses even under low-energy ambience excitation, highlighting its sensitivity to asymmetrical stiffness and boundary constraints. These quantified modal parameters, including mode shape vectors and natural frequencies, provide valuable insight into structural behavior and can serve as reliable indicators for assessing support and ground condition changes during construction.

3. FUTUREWORK

While traditional SHM applications focus on detecting damage within the structure, this study extends the concept using dynamic response of pipe bent as a proxy for detecting changes in the underlying ground condition. Through controlled experiments that simulate soil softness using rubber pad supports, we create labeled datasets representing varying ground stiffness configurations. These datasets serve as the foundation for applying Modalstiff Fourier Neural Operator (MS-FNO)[3) to learn the mapping between physical response features and ground condition labels. This approach offers a novel perspective on integrating SHM techniques for both structural and substructural health inference.

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