
QSEERB: a real-time smart sensor platform for quantitative seismic monitoring of buildings

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ABSTRACT

Enhancing the seismic resilience of buildings requires continuous, data-driven evaluation of structural performance that can directly support post-earthquake decision-making. This paper presents the development and implementation of the QSEERB (Quantitative Shaking Evaluation for Earthquake-Resistant Buildings) platform, an integrated smart-sensor system combined with a quantitative seismic-response framework, EQXIL (Earthquake Quantitative Intensity Level).

QSEERB integrates compact tri-axial MEMS accelerometers with high-frequency sampling at 100 Hz, mini-PC-based processing units, and automated algorithms for real-time signal conditioning and seismic-intensity evaluation. Recorded acceleration data are transformed into interpretable shaking-intensity indices, including the Seismic Intensity Level (SIL) and MMI, together with response parameters derived using the Newmark- β integration method. The SIL framework provides a simplified and user-friendly measure of floor-level shaking severity that is independent of structural models and regional seismic design codes, while EQXIL extends conventional intensity measures by quantifying both instantaneous and cumulative response intensity.

System performance is evaluated through numerical simulations and case studies of two buildings on the Nihon University campus: Building No. 55 (an eight-storey reinforced concrete structure) and Building No. 70 (a large-scale multi-storey complex). Ground motion recorded during the 2011 Great East Japan Earthquake at station FKS018 is applied at the base of each model, and floor-level responses are used to compute real-time SIL values using an expanding time-window strategy. Results demonstrate improved sensitivity to localized structural response and practical capability for real-time monitoring, early warning, and post-earthquake inspection support.

The study highlights the potential of QSEERB and EQXIL to bridge the gap between seismic monitoring, performance-based design, and resilient building operation.

1 INTRODUCTION

Seismic Intensity Level (SIL) is a practical and intuitive metric for classifying the severity of earthquake-induced ground and structural motion. Unlike conventional structural response measures such as displacement or inter-storey drift, which depend on specific building properties and analytical models, SIL provides a universal representation of shaking intensity that can be readily interpreted by engineers, decision-makers, and non-expert users. Derived from intensity-based frameworks such as the Japan Meteorological Agency (JMA) seismic intensity scale (JMA 2025), SIL translates complex accelerometric records into a single, easily understandable index, thereby facilitating rapid post-earthquake assessment and decision-making.

The ability to relate measured seismic motion to human perception, structural response, and potential damage states is essential for improving disaster preparedness, emergency response, and post-event inspection strategies in seismically active regions (Egatama et al., 2024A-B, Gan 2022). While traditional seismic intensity measures are effective for regional hazard communication, their application to building-specific performance evaluation remains limited. This limitation highlights the need for quantitative intensity frameworks that can bridge the gap between measured motion, structural response, and actionable information for building operation and safety assessment (Gan 2022, Wariyatno et al., 2021).

Recent advances in embedded sensing technologies and smart monitoring systems have enabled real-time, data-driven evaluation of building response during earthquakes. Low-cost Micro-Electro-Mechanical Systems (MEMS)-based inertial sensors, integrated with embedded processing platforms and custom signal-processing pipelines, allow continuous high-frequency monitoring of floor-level vibrations. Real-time filtering, frequency-domain shaping, and vector magnitude analysis tailored to intensity-based metrics such as SIL provide robust and noise-resilient measurements suitable for operational environments. These developments form the technological foundation of modern structural health monitoring systems aimed at rapid seismic assessment, early warning, and disaster risk mitigation.

In this context, this study presents the development and implementation of the QSEERB (Quantitative Shaking Evaluation for Earthquake-Resistant Buildings) platform, an integrated smart-sensor system combined with the EQXIL (Earthquake Quantitative Intensity Level) framework. Unlike conventional acceleration-based monitoring approaches that emphasize peak ground response metrics or offline analysis, the proposed QSEERB platform provides an integrated framework for both real-time and post-event computation of SIL and related intensity indices from measured acceleration data, together with quantitative evaluation of instantaneous and cumulative response intensity. The system is validated through time-history dynamic analyses of two buildings on the Nihon University campus using ground motion records from the 2011 Great East Japan Earthquake. The objective is to demonstrate the capability of the proposed platform to capture floor-level shaking intensity in real time and to provide meaningful quantitative information to support post-earthquake inspection, early warning, and resilient building operation (Nouchi et al., 2023).

2 QSEERB PLATFORM ARCHITECTURE AND QUANTITATIVE EVALUATION FRAMEWORK

2.1 Hardware and system implementation

Figure 1 illustrates the overall architecture of the QSEERB (Quantitative Shaking Evaluation for Earthquake-Resistant Buildings) platform, which integrates sensing, processing, and quantitative intensity evaluation into a unified real-time monitoring system (Sakai et al., 2025). The platform is designed to capture floor-level seismic response and transform measured motion into interpretable intensity metrics for operational decision-making. At the sensing layer, compact tri-axial MEMS-based accelerometers continuously record acceleration data at a sampling rate of 100 Hz, providing high-resolution measurements of structural vibration during seismic events. The sensor outputs are transmitted to a mini-PC-based embedded processing unit implemented

on a Windows operating system. This processing unit serves as the core of the QSEERB platform, enabling on-site real-time computation without reliance on external servers. Within the embedded unit, automated algorithms perform signal conditioning, intensity evaluation, and response quantification. The processed data are converted into quantitative seismic intensity indices, including the Seismic Intensity Level (SIL), together with response-based parameters required for the EQXIL (Earthquake Quantitative Intensity Level) framework. Results are visualized through a smart monitoring interface that displays real-time SIL classifications, acceleration waveforms, and logged response histories. This integrated hardware–software configuration enables scalable deployment of the QSEERB platform for continuous seismic monitoring and rapid post-earthquake assessment.

The MEMS accelerometers used in the QSEERB platform have noise levels on the order of 1 mg and measurement ranges of several g. Considering the filtering and sustained acceleration conditions embedded in the JMA SIL formulation, very small noise-dominated signals typically result in SIL values close to zero, while the available dynamic range is sufficient to capture typical building floor accelerations without sensor saturation.

In the present implementation, the MEMS sensor unit is installed indoors and mounted directly to the floor surface using industrial-grade double-sided adhesive tape within a rigid enclosure. Because the monitored floor slab is substantially more massive and stiffer than the lightweight sensor package, the attachment method is considered sufficient for practical measurement of floor-level structural response provided that firm surface contact is maintained. The indoor installation environment also helps minimize external disturbances, while subsequent signal-conditioning procedures are applied to reduce the influence of measurement noise.

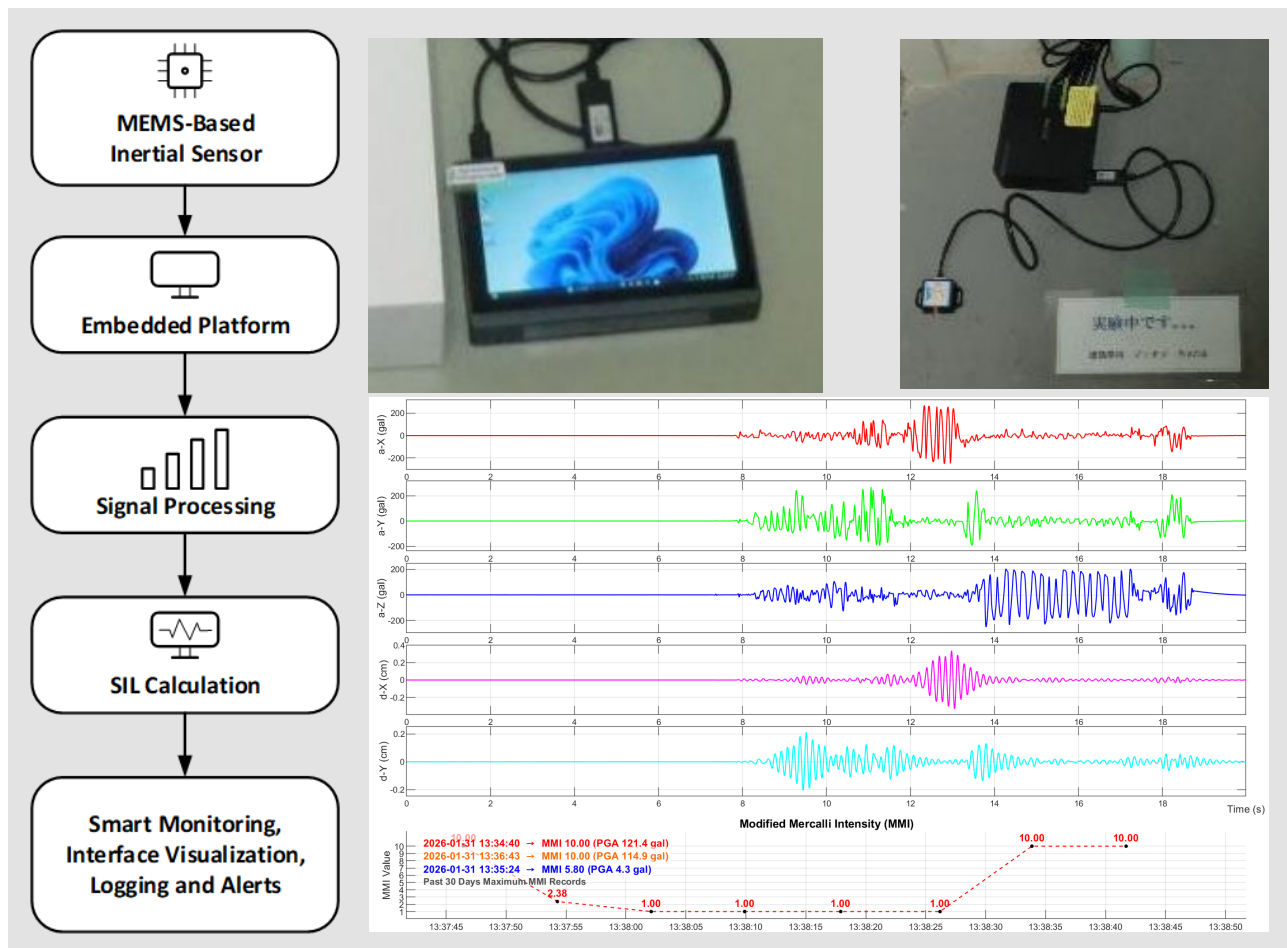


Figure 1: Architecture of the QSEERB smart seismic monitoring platform

2.2 Signal processing and quantitative intensity evaluation

The quantitative evaluation capability of the QSEERB platform is governed by a custom signal-processing pipeline designed to transform raw acceleration measurements into meaningful seismic intensity metrics in real time. Initially, several time-domain pre-processing steps are applied to the recorded tri-axial acceleration signals to improve signal quality prior to intensity evaluation. These include removal of constant bias (offset correction), high-pass filtering to suppress low-frequency drift, and moving-average smoothing to reduce high-frequency noise. High-pass filtering combined with moving-average smoothing is employed to enhance signal quality while preserving the essential characteristics of earthquake-induced motion. A short moving-average window is applied during time-domain pre-processing to suppress high-frequency noise. The window size is defined relative to the sampling rate and can be adjusted depending on monitoring requirements. This smoothing operation is distinct from the SIL evaluation window used in the intensity calculation. In the present implementation, SIL values are evaluated over a 30-s window and updated at 5-s intervals to capture sustained seismic shaking characteristics while maintaining near-real-time monitoring capability.

Following time-domain conditioning, frequency-domain shaping is performed using a Fast Fourier Transform (FFT)-based procedure. Band-pass filtering within the range of 0.1–20 Hz is applied to isolate the dominant frequency components associated with structural response in low- to mid-rise buildings. This frequency range reflects the typical dynamic characteristics of building systems relevant to performance-based seismic evaluation.

The filtered three-axis acceleration components are then combined into a single scalar response using vector magnitude calculation, forming a continuous SIL time history. SIL values are computed using an expanding time-window strategy to balance computational efficiency with temporal stability, enabling real-time intensity classification during ongoing seismic events. The expanding time-window strategy may introduce slight conservatism during the early stage of seismic excitation because the calculation is based only on the portion of the response record available at that time. As the shaking progresses and additional data are accumulated, the computed SIL values progressively converge toward those obtained from the complete response history. This approach therefore represents a practical balance between responsiveness and robustness for near-real-time seismic intensity monitoring. These SIL outputs constitute the primary intensity input to the EQXIL framework, which further quantifies both instantaneous and cumulative response intensity. Through this process, the QSEERB platform provides a direct link between measured seismic motion, quantitative intensity evaluation, and actionable information for early warning and post-earthquake inspection.

3 SEISMIC INTENSITY LEVEL (SIL) FORMULATION WITHIN THE QSEERB-EQXIL FRAMEWORK

One of the key advantages of the Japan Meteorological Agency's Seismic Intensity Level (SIL), compared with qualitative intensity scales such as the Modified Mercalli Intensity (MMI), is its empirically quantitative and instrument-based formulation. While MMI relies on observed damage and human perception, SIL is computed directly from recorded acceleration data, providing an objective and reproducible measure of seismic intensity suitable for real-time monitoring and automated evaluation.

Within the QSEERB platform, SIL serves as the primary instrumental intensity metric for translating measured floor-level acceleration responses into interpretable shaking-intensity classifications. The Japan Meteorological Agency defines a specific formulation for the measured SIL (m-SIL) based on the lowest maximum resultant acceleration sustained continuously over a 0.3-second duration around the peak response (Kawasumi 1943). This definition is particularly well suited to real-time implementation, as it reduces sensitivity to short-duration spikes while preserving the physical significance of sustained seismic motion. The m-SIL formulation adopted in this study is expressed as:

$$m - SIL = 2 \log_{10}(a_{03}) + 0.94 \quad (1)$$

It is important to note that, within the QSEERB–EQXIL framework, the ground-motion accelerations traditionally used in the calculation of measured SIL (m-SIL) can be replaced by acceleration responses recorded at individual floor levels of a building. This substitution enables the computation of floor-specific SIL values that directly reflect the local seismic response of the structure. By extending the SIL concept from ground motion to floor-level measurements, the QSEERB platform provides a more detailed and physically meaningful representation of seismic intensity distribution within a building, supporting refined post-earthquake assessment and operational decision-making.

4 REAL-TIME SEISMIC SIMULATION AND BUILDING CASE STUDIES

Figures 2 and 3 present the real-world photographs and corresponding finite element (FE) models of Buildings No. 55 and No. 70 located on the College of Engineering campus of Nihon University in Koriyama, Japan. These two buildings are selected as representative case studies for evaluating the real-time seismic monitoring capability of the QSEERB platform under building-specific conditions.

The photographs provide an overview of the buildings' physical characteristics, including structural form, number of storeys, and site environment. The FE models represent the analytical idealization adopted for time-history dynamic analysis and are developed to capture the essential structural features relevant to seismic response evaluation, such as floor elevations, load-resisting members, and global mass and stiffness distribution. Sensor locations corresponding to floor-level acceleration measurements are explicitly defined in the models to ensure consistency with the QSEERB monitoring configuration.



Figure 2: Exterior views and FEM model of Buildings No. 55

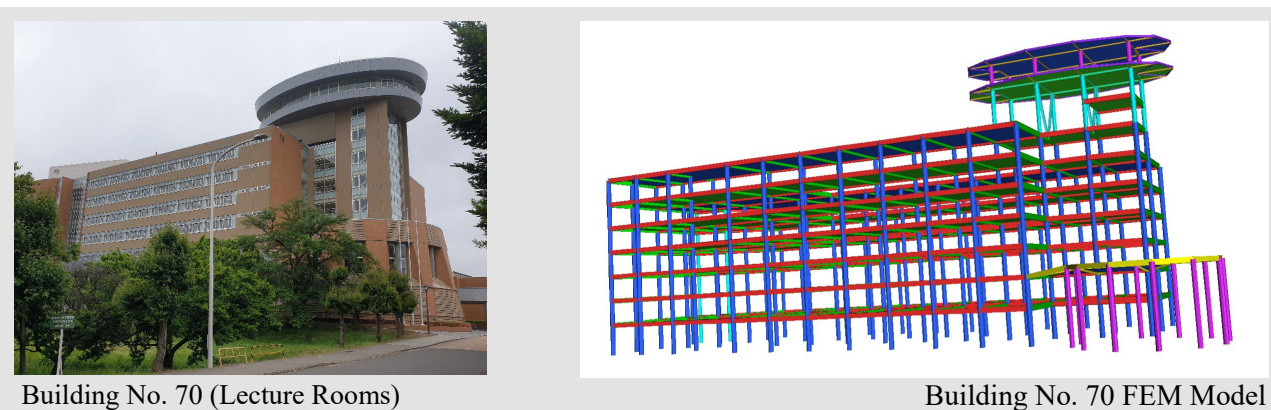


Figure 3: Exterior views and FEM model of Buildings No. 70

In both Buildings No. 55 and No. 70, sensor locations are strategically defined at three key elevations: the base (ground level), a representative intermediate floor, and the top floor. This configuration is designed to capture the variation of seismic response along the building height and to enable quantitative evaluation of floor-level seismic intensity within the QSEERB–EQXIL framework. The base sensor represents the input ground motion, while the intermediate and top sensors record the amplification and dynamic response of the structure at higher elevations.

5 SEISMIC INTENSITY (SIL) MONITORING RESULTS

The seismic simulation results for Buildings No. 55 and No. 70 provide quantitative insight into the building-specific dynamic response under the 2011 Great East Japan Earthquake ground motion. For each building, Figures 4 and 5 present the time-history results obtained from the real-time monitoring simulations implemented within the QSEERB platform.

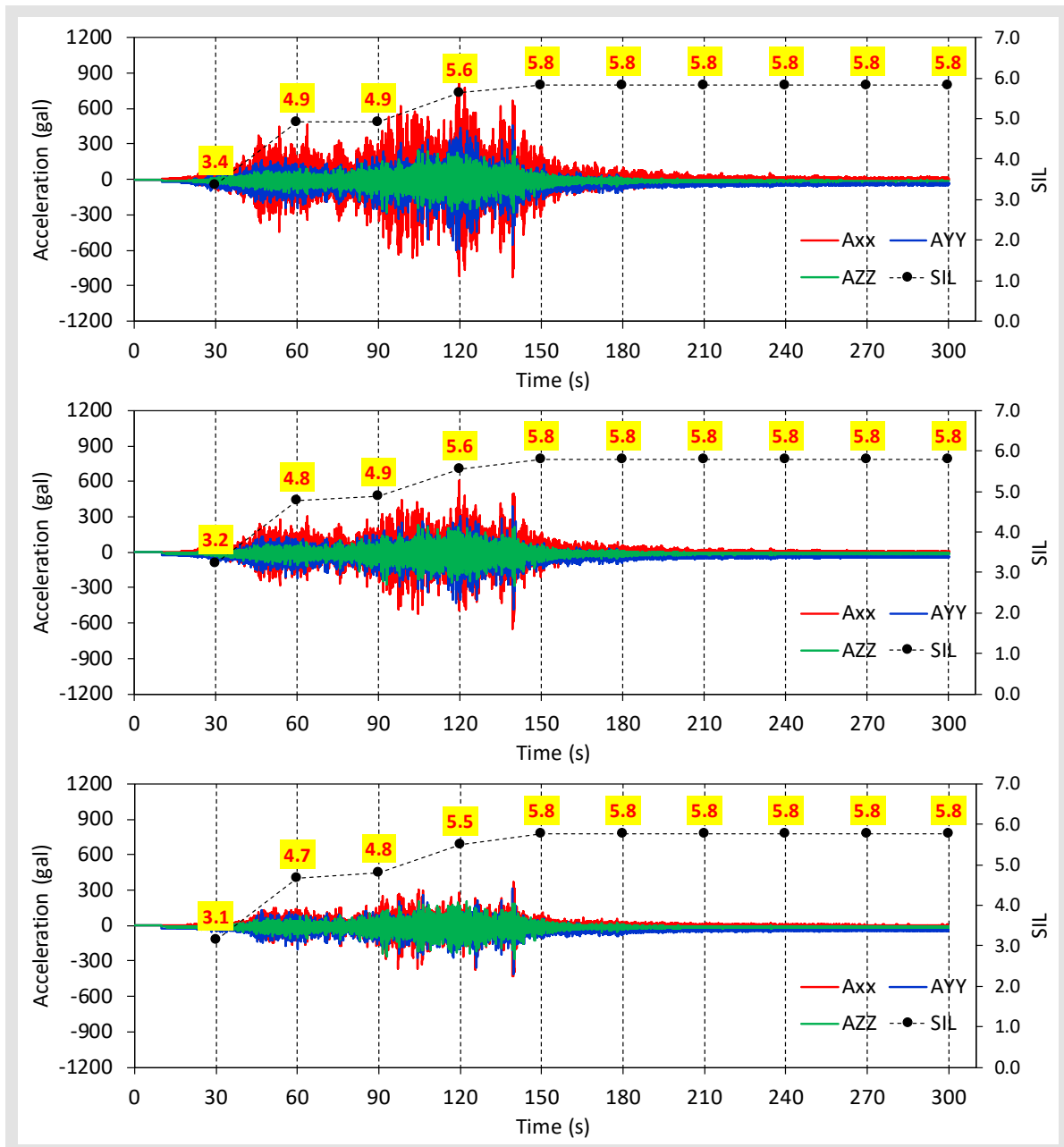


Figure 4: Seismic monitoring results (8th, 5th and 1st Floors) of Building No. 55

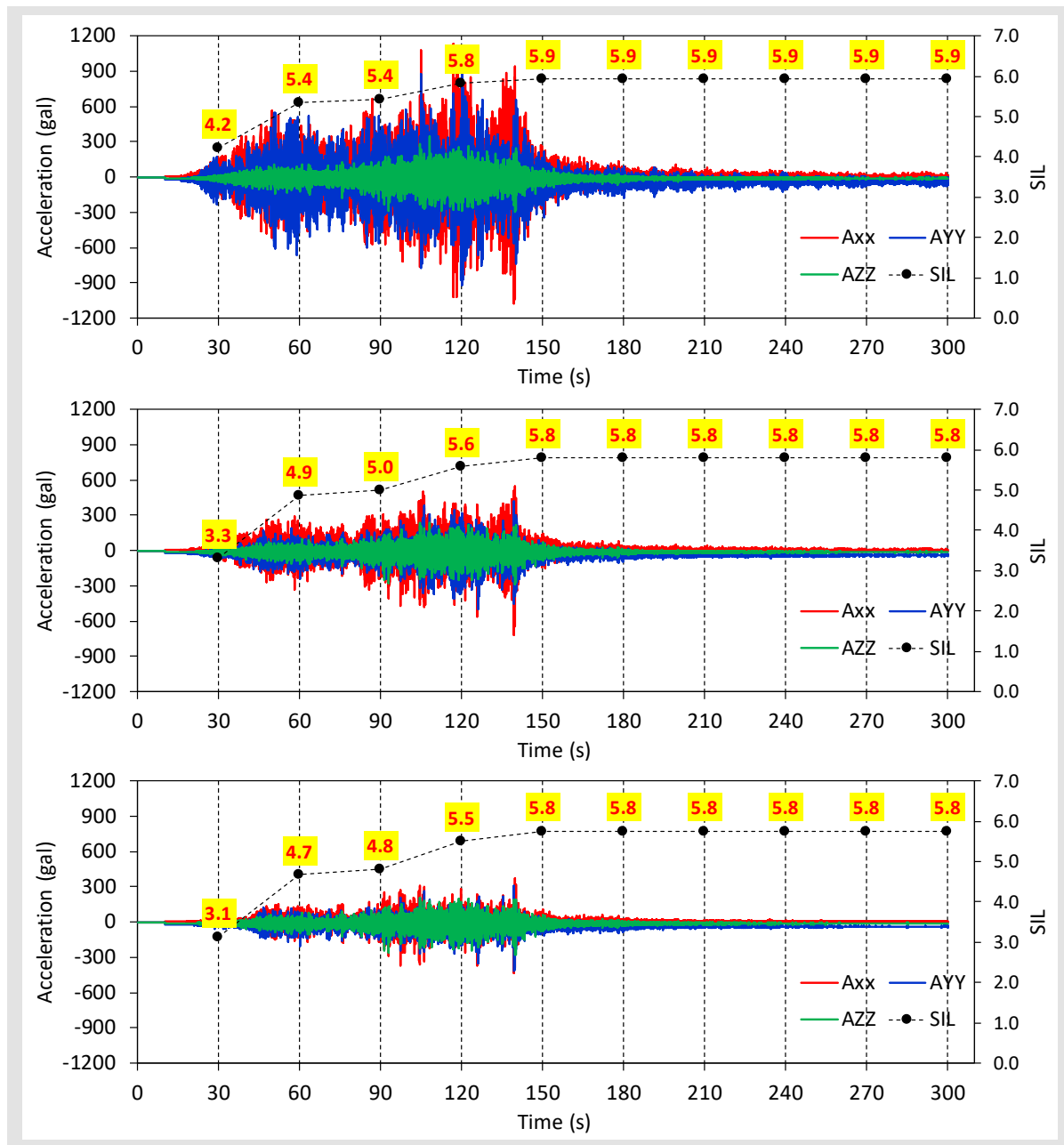


Figure 5: Seismic monitoring results (9th, 5th and 1st Floors) of Building No. 70

Figures 4 and 5 show the acceleration response time histories recorded at three representative sensor locations: the base (ground level), a middle floor, and the top floor. The acceleration responses clearly illustrate height-dependent amplification effects, with larger response amplitudes observed at higher elevations due to modal behaviour of the structures. These floor-level acceleration responses form the direct input for real-time seismic intensity evaluation.

The same figures also present the corresponding Seismic Intensity Level (SIL) time histories computed at each floor. SIL values are updated at 30-second intervals using an expanding time-window approach and accumulated over a total monitoring duration of 300 seconds, consistent with near-real-time monitoring of structural response during seismic events.

The SIL time histories illustrate the variation of seismic intensity along the height of each building as evaluated within the QSEERB platform. For both Buildings No. 55 and No. 70, higher floor levels consistently exhibit

larger SIL values, reflecting the amplification of acceleration response associated with the dynamic characteristics of multi-storey structures. This height-dependent trend is consistent with the acceleration response time histories and confirms the ability of floor-level SIL to capture structural response amplification in a quantitative manner.

6 CONCLUSIONS

This study presented the development and validation of the QSEERB (Quantitative Shaking Evaluation for Earthquake-Resistant Buildings) platform, an integrated real-time seismic monitoring system that combines smart sensing with quantitative intensity evaluation through the EQXIL framework. Using MEMS-based accelerometers, automated signal processing, and numerical simulation, the platform enables continuous assessment of floor-level seismic intensity during earthquake events.

Overall, the results highlight the effectiveness of the QSEERB–EQXIL framework in translating raw acceleration measurements into meaningful, actionable seismic intensity information. Although the present validation is limited to numerical time-history analyses of two representative buildings subjected to recorded ground motions from the 2011 Great East Japan Earthquake, the results clearly demonstrate the feasibility of the proposed framework for real-time floor-level seismic intensity monitoring. The proposed approach offers a scalable and cost-effective solution for real-time structural monitoring, early warning support, and post-earthquake inspection planning. Future work will focus on extended field deployment, integration of cumulative response evaluation within the EQXIL framework, and expansion toward networked monitoring systems for broader application in earthquake-resilient building operation.

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