The 2025 World Congress on
Advances in Structural Engineering and Mechanics (ASEM25)
BEXCO, Busan, Korea, August 11-14, 2025

Analytical study on seismic isolated structure to improve seismic performance of AI data centers

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ABSTRACT

AI data centers are rapidly expanding to meet global data processing demands and are critical infrastructure in the Fourth Industrial Revolution. These facilities concentrate high-density servers and essential systems, making seismic resilience vital. Traditional seismic design focuses on life safety but often allows damage to internal equipment, which is unacceptable for operations. Thus, active seismic isolation systems are essential to ensure operational continuity.
This study conducts an analytical investigation of base-isolated foundation systems for superstructures. This study confirms that the base-isolated system such as LBR can significantly reduce seismic forces transmitted to superstructures by decoupling ground motion from the upper structure. These findings support the use of LRB as an effective and practical seismic isolation strategy in engineering design, particularly for critical infrastructure where seismic resilience is essential. The outcomes contribute to seismic isolation guidelines suited to domestic conditions.

1. INTRODUCTION

Artificial Intelligence (AI), a core enabler of the Fourth Industrial Revolution, necessitates ultra-high-speed data processing and storage capabilities. Consequently, the deployment of large-scale AI data centers is rapidly accelerating. These data centers serve as computational backbones for AI training and inference across various sectors, including government, finance, manufacturing, defense, and healthcare, and are

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intrinsically linked to national security and digital sovereignty.

Given their operational nature, AI data centers accommodate thousands to tens of thousands of high-density server units, resulting in substantial power consumption and concentrated heat generation. This necessitates an exceptionally high degree of system reliability and uninterrupted maintenance. Accordingly, ensuring structural resilience against external hazards—particularly seismic events—has become a critical factor in safeguarding AI infrastructure.

Unlike conventional data centers, AI data centers are characterized by a high density of high-performance GPU servers and exhibit the following distinctive features. Firstly, high heat and power are required. High-performance computing hardware such as GPUs and TPUs generate significant thermal loads, necessitating advanced cooling systems and highly reliable power delivery infrastructure. Secondly, continuous and steady operation is essential. AI data centers must support uninterrupted services for latency-sensitive inference tasks and large-scale model training workloads, where downtime is unacceptable. Additionally, flexible scalability is also required. With the increasing demand for AI workloads, rapid scalability and seamless integration of equipment are necessary to ensure distributed and responsive infrastructure (Mishra 2024, Chandrakumara 2025). Therefore, AI data centers are subject to substantially greater combined structural and infrastructural vulnerabilities than conventional office facilities, thereby necessitating the incorporation of proactive, disaster-resilient design strategies at the initial planning stage.

Although the Korean Peninsula had long been considered a region of relatively low seismic activity, the 2016 Gyeongju earthquake (M 5.8) and the 2017 Pohang earthquake (M 5.4) brought renewed attention to the presence and seismic potential of active inland faults. These events underscored the growing importance of seismic preparedness, particularly in densely developed areas with critical infrastructure. Notably, the Pohang earthquake resulted in significant damage to buildings with pilotis structures, highlighting the need for thorough pre-assessment of seismic safety based on structural configuration and system type (Eom et al., 2019).

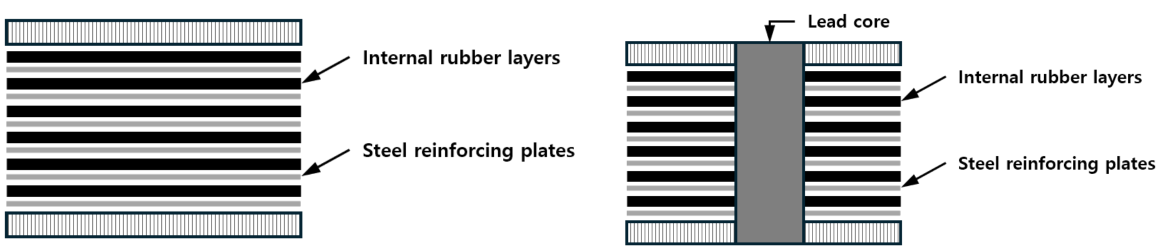
This study investigates the application of base isolation systems—one of the most advanced forms of seismic design—by considering the mechanical and functional characteristics specific to AI data centers using numerical analysis. The concept of base-isolated structural systems was first examined, and a representative cross-section was selected to perform numerical simulations using a two-dimensional finite difference method, with the goal of analyzing the dynamic response of the entire soil–structure system, including the base isolation layer, under seismic loading.

2. SEISMIC ISOLATION SYSTEM

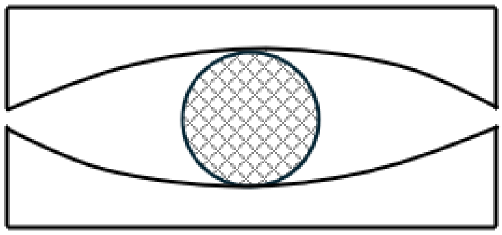
In general, seismic design strategies can be grouped into two broad approaches: (1) increasing the strength of the structure, and (2) enhancing its ductility. Strengthening a structure enables it to remain stable during earthquakes up to the design level; however, it often results in oversize members that raise construction costs and may still allow sudden brittle failure, leading to severe loss of life. Conversely, improving ductility allows structural components to dissipate seismic energy through controlled plastic deformation, thereby reducing the effective earthquake forces transmitted to the members. This approach, however, makes post-earthquake repair and retrofitting difficult and expensive. Therefore, the seismic isolation system was developed to efficiently overcome the drawbacks of conventional seismic design approaches. A seismic isolation system protects the structure by concentrating on seismic energy within specially designed isolation devices, thereby reducing the transmission of ground vibration to the superstructure. While the initial construction cost of an isolation system is generally higher than that of conventional seismic-resistant structures, it offers the advantage of preventing or minimizing plastic deformation of structural members. This not only simplifies post-earthquake repair and retrofitting but also reduces associated costs. Moreover, by effectively decoupling the structure from ground vibrations, isolation systems provide superior protection for sensitive equipment and systems housed within the building or structure

The core component of a seismic isolation system is the seismic isolation device. Since earthquake forces are primarily applied in the horizontal direction, isolation devices must possess high vertical stiffness to support the self-weight of the structure, while allowing large horizontal displacements through flexibility in the lateral direction. By inserting these devices between the structure’s foundation and the ground, the structure can be effectively decoupled from the horizontal ground motion during an earthquake. This configuration lowers the fundamental frequency of the isolated structure compared to that of a fixed-base system, ensuring that seismic deformation is concentrated within the isolation system’s first mode, while the superstructure behaves nearly as a rigid body.

Such seismic isolation devices can be broadly classified according to their constituent materials and mechanisms of action into laminated rubber bearings(LBRs), and resilient frictional base isolator (R-FBI). The laminated rubber bearings (LRBs) system primarily uses vibration-isolating rubber as the core material, combined with steel plates to ensure vertical stiffness. In some cases, lead rubber bearings (LRBs with lead core) are used by inserting a lead plug at the center of the cross-section to enhance initial stiffness and energy dissipation capacity. The R-FBI (Rubber-Friction Bearing Isolator) system incorporates a sliding plate within the laminated rubber layers, allowing for larger horizontal displacements compared to the conventional LRBs. As a result, it can further reduce dynamic loads induced by earthquakes. Spherical sliding bearings is the typical device of R-FBI. An overview of these types is illustrated in the following diagram.



(a) Laminated rubber bearing (b) Lead rubber bearing (LBR)



(c) Spherical sliding bearing
Fig. 1 Types of seismic isolation devices

Among these, the most widely used seismic isolation device is the lead rubber bearing (LRB). The LRB integrates vertical load-bearing capacity, horizontal flexibility, and damping performance into a single unit. By combining the restoring force and ductility of rubber with the energy absorption capacity of the lead core (hysteretic damping), it offers the advantage of effectively responding to earthquakes of varying magnitudes. Therefore, it is particularly suitable for structures where the stability of internal equipment and operational continuity are critical (Lee, 1995).

3. NUMERICAL MODELING

3.1 Modeling Conditions

In this study, the seismic isolation performance of the most widely used Lead Rubber Bearing (LRB) was evaluated through numerical analysis. For this purpose, two-dimensional dynamic analyses were conducted using FLAC2D, a general-purpose geotechnical simulation software. The target structure was selected to represent a typical foundation system, consisting of a footing embedded 2 meters into the ground, and a pile foundation installed beneath the footing. The substructure and the superstructure pedestal were isolated using LRBs. To simulate the initial stress conditions of the ground, a static analysis was first conducted considering the self-weight of the soil and foundation structure. Subsequently, dynamic analysis was performed. The two-dimensional numerical analysis was carried out using the finite difference method, and quiet boundaries were applied to minimize the reflection of waves at the model boundaries. A summary of the numerical modeling conditions is presented in the following table.

Table 1. Summary of numerical modeling conditions

Analysis conditions	Description
Method	Finite Difference Method (FDM)
Procedure	- Static: Initial stress condition of the model - Dynamic: Applying seismic load
Model	- Ground: Mohr-Coulomb model - Structural element: Elastic model
Boundary conditions	- Static: Fixed boundary (sides and bottom) - Dynamic: Quiet boundary (sides only)
Input motion	Artificial earthquake wave, Seismic Design Category I (Collapse Prevention Level)

An artificial earthquake ground motion, generated to reflect both short- and long-period spectral characteristics, was selected as the input motion for the dynamic analysis. The time history of the applied ground motion is summarized in the following Fig. 2. The ground profile for the representative section comprised an upper alluvial soil layer and a lower soft rock layer. The analysis cross-section including the ground conditions, geometry, dimensions, and the detailed view of the foundation area are shown in Fig. 3.

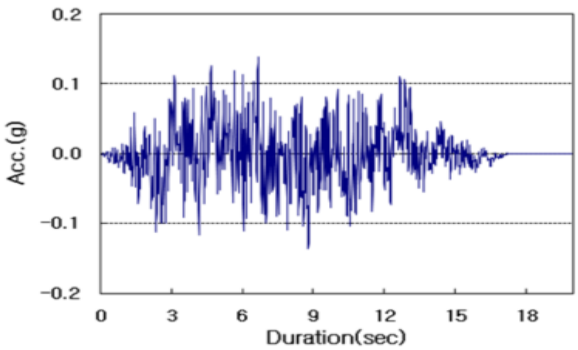
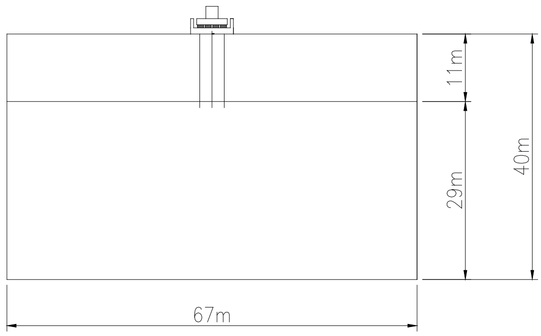
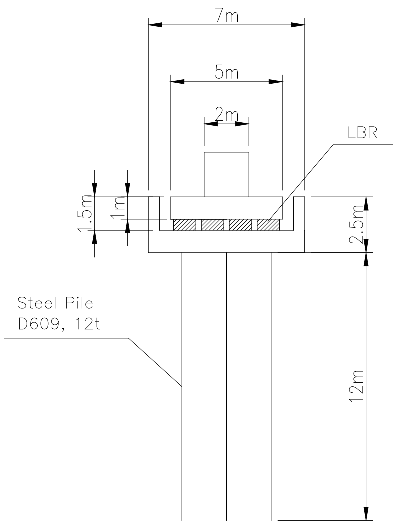


Fig. 2 Time history of the input wave



(a) Overview of analysis model



(b) Detailed view of the foundation

Fig. 3 Analysis cross-section

The pile type consists of three steel pipe piles (SPS 400), each with a diameter of 609 mm. The allowable compressive stresses are 140 MPa under static loading and 210 MPa under dynamic loading. The pile length is 12 meters, and it is assumed to be embedded into the underlying soft rock layer.
The seismic isolator, Lead Rubber Bearing (LRB), was modeled using the Support Element, one of the structural elements provided in the FLAC program. The Support Element is a structural element that transmits forces between mesh zones via elastic springs based on a user-defined force-displacement relationship. In particular, it is highly effective for idealizing the anisotropic resistance characteristics of real structural components such as seismic isolators, supporting members, and connecting elements. The Support Element is a one-dimensional structural component that transfers force based on the relative displacement between two nodes. Therefore, the force-deformation behavior of the support element is defined as an input parameter, and the user-defined force-displacement relationship is provided in the form of a table for numerical analysis. In this study, a typical force-displacement relationship of a lead rubber bearing (LRB) was assumed and applied as shown in Fig. 4.

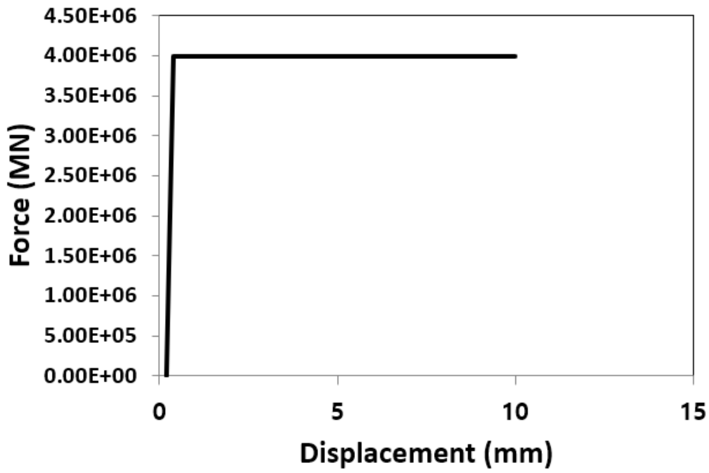


Fig.4 Force-displacement relationship of Support Element

Table 2 describes the material parameters of the ground.

Table 2. Input material parameters

Parameters	Young's modulus (MPa)	Unit weight (kN/m^3)	Cohesion (kPa)	Frictional angle (deg)	Poisson's ratio
Soil	50	19	20	30	0.30
Soft rock	1,000	22	300	33	0.28

3.2 Analysis Results

A dynamic numerical analysis was conducted using the two-dimensional finite difference method for the foundation system equipped with the LRB seismic isolator. Displacement and acceleration time histories were extracted at key locations to compare the dynamic responses above and below the seismic isolator. The selected monitoring locations for dynamic response analysis are summarized in Table 3 and the locations are also described in Fig. 5.

Table 3. Monitoring positions

Position	Location
1	Top of the superstructure above the foundation
2	Top of the upper foundation isolated by the LRB
3	Bottom of the upper foundation isolated by the LRB
4	Top of the lower foundation isolated by the LRB
5	Bottom of the lower foundation isolated by the LRB

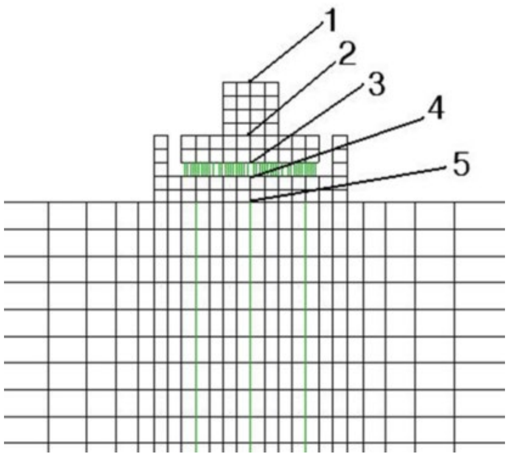


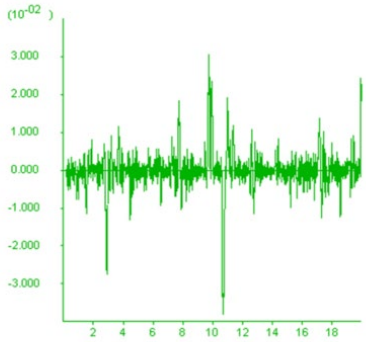
Fig. 5 Locations of the monitoring points

According to the numerical analysis results, the maximum horizontal displacement and maximum acceleration at each monitoring point are summarized in Table 4, and the displacement time histories are presented in Fig. 6.

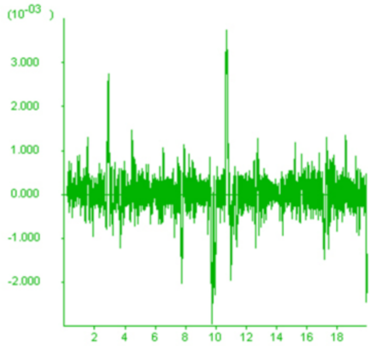
Table 4. Maximum responses

Positions	Max. horizontal displacement (mm)	Max. acceleration (g)
1	38.4	0.113
2	37.5	0.112
3	24.4	0.112
4	69.8	0.125
5	69.6	0.122

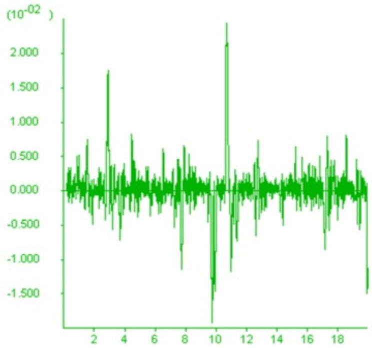
The foundation is divided into upper and lower parts by the seismic isolator. According to the analysis results, the temporal distribution of maximum horizontal displacement exhibits significantly different behaviors between the upper and lower foundations. The upper foundation (Monitoring Points 1, 2, and 3) shows a typical rigid-body vibration pattern, with a maximum displacement of 38.4 mm. In contrast, the lower foundation (Monitoring Points 4 and 5) exhibits a vibration pattern similar to that of the ground motion, with a maximum displacement of 69.8 mm, which represents an approximately 81% increase compared to the displacement above the seismic isolator. In the figure, the xaxis represents duration(second), and the y-axis represents response displacement (meter).



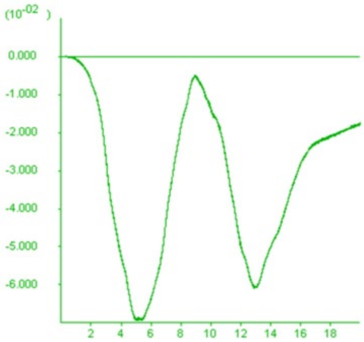
(a) Position 1



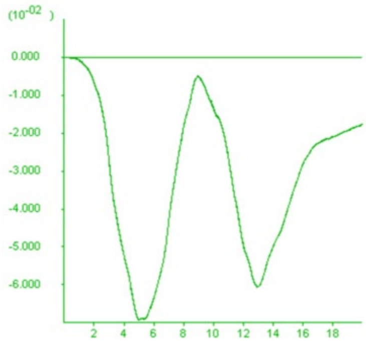
(b) Position 2



(c) Position 3



(d) Position 4



(e) Position 5

Fig. 6 Displacement estimation results

To evaluate the performance of the seismic isolator, the displacements at the upper and lower boundaries of the isolator (Monitoring Points 3 and 4) were compared, as summarized in Fig. 7.

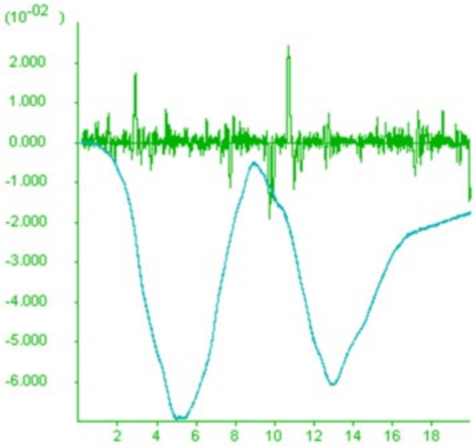


Fig. 7 Comparison of displacement response near the isolator

As shown in the comparison results (Fig. 7), the maximum displacement of the upper foundation isolated by the seismic isolator was calculated to be 24.4 mm, while that of the lower foundation was 69.8 mm, confirming an approximate 65% reduction in displacement.

4. CONCLUSIONS

In this study, a two-dimensional dynamic numerical analysis was performed using FLAC2D to evaluate the seismic performance of a foundation system equipped with a lead rubber bearing (LRB) as the seismic isolator. The input ground motion was an artificial earthquake wave that appropriately reflected both short- and long-period characteristics. The foundation structure was idealized into upper and lower parts separated by the LRB, and a series of monitoring points were installed to assess the dynamic response at key locations.

The analysis results demonstrated a clear difference in the seismic behavior of the upper and lower foundations. The upper foundation exhibited rigid-body type motion, whereas the lower foundation, which is directly influenced by the ground motion. This corresponds to a displacement reduction of approximately 65% due to the presence of the LRB. In addition, the acceleration response was significantly reduced above the isolator, confirming the effectiveness of the LRB in filtering high-frequency components of seismic waves.

The force-displacement behavior of the LRB was modeled using FLAC's Support Element, with nonlinear hysteretic characteristics approximated via a user-defined table. The simulation results not only validated the LRB's role in reducing structural response but also demonstrated the applicability of the support element for isolator modeling in dynamic analysis.

Overall, the study confirms that LRBs can significantly reduce seismic forces transmitted to superstructures by decoupling ground motion from the upper structure. These findings support the use of LRBs as an effective and practical seismic isolation strategy in engineering design, particularly for critical infrastructure where seismic resilience is essential.

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