Assessment of Base Isolation Effectiveness Using Response Spectrum Analysis in Simplified Structural Models

[1]**Akash Jeeyaldas Khanchandani**, [2]**Pranesh B. Murnal**

[1]Post-Graduate Student, Applied Mechanics Department, Government College of Engineering, Aurangabad, India
[2]Retired Professor, Applied Mechanics Department, Government College of Engineering, Aurangabad, India

Abstract - **Earthquakes pose a significant threat due to their unpredictability and destructive impact. Structural resilience against seismic forces has been extensively researched, with base isolation emerging as a widely adopted technique. This study evaluates the effectiveness of seismic isolation in buildings with varying heights and lateral dimensions. Using High Damping Rubber Bearings (HDRB), 27 structural models with different height-to-depth ratios and story counts (5 to 15) are analysed in SAP2000 through Response Spectrum Analysis. Key seismic parameters—including natural time period, base shear, storey displacement, and joint acceleration—are compared between base-isolated and fixed-base structures. The findings provide insights into the influence of building geometry on isolation efficiency, contributing to improved seismic design strategies.**

Keywords: Seismic Isolation, Base Isolation, High Damping Rubber Bearing (HDRB), Structural Dynamics, Response Spectrum Analysis, SAP2000, Seismic Resilience, Natural Time Period, Base Shear.

I. Introduction

Base isolation provides an alternative approach by incorporating a flexible layer at the foundation, reducing the transfer of seismic forces to the superstructure. This technique increases the natural time period of the structure and lowers horizontal acceleration, thereby mitigating earthquake effects. A well-designed base isolation system must ensure flexibility to extend the structural time period, damping to dissipate seismic energy, and sufficient load-bearing capacity to support the structure without compromising stability.

One of the most widely used base isolation systems is the High Damping Rubber Bearing (HDRB), which combines flexibility with energy dissipation capabilities. By installing HDRBs at the foundation, the superstructure remains relatively undisturbed during seismic activity, reducing damage and improving overall seismic resilience. However, the effectiveness of base isolation is influenced by factors such as the lateral dimensions of the structure and the number of stories, which affect the natural time period and overall behaviour of the system.

This study evaluates the performance of base isolation for structures with varying heights and lateral dimensions. Using SAP2000, a series of models with different height-to-depth ratios and story counts (ranging from 5 to 15 stories) are analyzed through Response Spectrum Analysis. This study is inspired by H. Toopchi-Nezhad's Key seismic parameters—including natural time period, base shear, storey displacement, and joint acceleration—are examined and compared between base-isolated and fixed-base structures. The findings contribute to a deeper understanding of how base isolation performs across different structural configurations, offering insights into optimizing seismic design for enhanced safety and performance.[3]

The theoretical basis of seismic isolation as a means to decouple ground motion effects has been extensively discussed in earlier studies [2], forming a key foundation for this research.

II. Structural Design Considerations

The design of steel-reinforced elastomeric bearings requires a balanced approach to compressive, shear, and rotational stiffness. The shape factor, calculated as the plan area divided by the perimeter's free-to-bulge area, influences compressive and rotational stiffness while leaving translational stiffness unaffected. The bearing's elastomeric strain and steel reinforcement stress must be controlled by adjusting the elastomer layer thickness and form factor. Key design constraints include fatigue, stability, delamination, yield, and rupture of the steel, along with stiffness and geometric restrictions of the elastomer.

The design methodology for High Damping Rubber Bearings (HDRBs) adopted in this study is informed by the comprehensive frameworks provided by Naeim and Kelly [4] and Kelly [5]. These works outline essential considerations for isolator configuration, including vertical and horizontal stiffness, damping behaviour, and load-bearing capacity, ensuring that the seismic isolators modelled in this study conform to practical and theoretical standards of performance.

III. Elastomer Material Properties

Natural rubber, commonly used in bearing pads, exhibits linear viscoelastic behaviour and can sustain significant deformations. It is defined using a strain energy function based on material constants like compression modulus and shear modulus. The primary properties considered for the elastomeric rubber pad include stiffness, bulk modulus, Poisson's ratio, linear thermal expansion coefficient, relaxation modulus, and dynamic modulus with loss tangent.

IV. Seismic Isolation and Structural Modelling

Seismic isolation aims to increase a building's fundamental time period [6], reducing the impact of ground motion. The fundamental period (T) is given by:

$$T = \frac{0.09h}{\sqrt{d}}$$

Where h is the building height and d is the lateral dimension. This study evaluates the effectiveness of base isolation for structures modelled with varying **h/√d ratio** ratios (3, 5, 7, 9, 11, 13, and 15) using response spectrum analysis. Structural models were developed for buildings with 5 to 15 stories, ensuring practical lateral dimensions ($\geq$ 9m).

The h/√d ratio is a widely accepted empirical parameter to estimate the fundamental time period of fixed-base buildings, especially in Indian seismic codes (e.g., IS 1893:2016). It indicates how building geometry influences dynamic response. As the height (h) increases or the lateral dimension (d) decreases, the resulting time period becomes longer. Therefore, tall and slender buildings have longer natural periods, whereas short and wide buildings have shorter periods.

In this study, the h/√d ratio serves as a representative of fixed-base time periods, allowing us to examine how geometric configurations affect the efficacy of base isolation.

On the other hand, base-isolated structures are designed with a target time period of 2 seconds, which is significantly higher than typical fixed-base structures. This intentional increase ensures separation from ground motion frequencies and maximizes isolation benefits.

It is crucial to highlight that base isolation is only effective when a significant shift in time period occurs. If the fixed-base structure already has a time period close to or exceeding 2 seconds, base isolation may offer minimal benefit. This emphasizes the importance of time period separation, and the h/√d ratio is a key parameter to evaluate whether such separation—and thus effective isolation—is achievable.

Thus, in this study, the h/√d ratio not only reflects geometric variability but also acts as a controlling parameter in determining the viability and effectiveness of seismic isolation.

V. Research Design and Model Selection

A total of 27 structural models were analysed using SAP2000 software. The response spectrum analysis considered both fixed-base and base-isolated structures. The study extracted natural time periods, base shear, top acceleration, and displacement. For base-isolated structures, isolators were designed for vertical stiffness (Kv) and horizontal stiffness (Kh)[5], using the following formulas:

$$K_V = \frac{(D.L + L.L)}{g} \times \left(\frac{2\pi}{T}\right)^2$$

$$K_H = \frac{K_v \times E_c}{G}$$

Where *D.L* and *L.L* are dead and live loads, *g* is gravity (9.81 m/s²), *T* is the design time period (2 sec)[1], and *G* is the shear modulus (0.620).

Isolators were modelled and installed at base nodes in SAP2000, allowing comparison between fixed and isolated structures.

VI. Response Spectrum Analysis

Response spectrum analysis was used to evaluate the seismic performance of the models. This method considers the dynamic response of structures under seismic loading by representing the peak response of a single-degree-of-freedom system subjected to earthquake ground motion. The response spectrum method enables an effective assessment of base shear, displacement, and acceleration for both fixed-base and base-isolated structures. By comparing the spectral responses, the study determines the effectiveness of base isolators in reducing seismic impact. The natural time period shift due to base isolation is a key parameter in evaluating seismic performance and structural stability.

VII. Data Collection and Analysis

SAP2000 was used for analytical modelling, providing reliable data on structural performance parameters. Response spectrum analysis extracted key values, such as time period, base shear, top displacement, and acceleration.

VIII. Results and Discussion

The seismic response of a structure depends on its mass, stiffness, and damping. Fixed-base buildings rely on controlled yielding to withstand major earthquakes, whereas base isolation enhances flexibility, reducing seismic forces and damage. This study evaluates base isolation effectiveness using Laminated Rubber Bearings (LRB) across varying H/√d ratios, which influence the fundamental time period (T = 0.09h/√d, per IS 1893). A target time period of 2 seconds is set to minimize acceleration. Response spectrum analysis compares fixed and isolated structures in terms of displacement, acceleration, and base shear. Results show that base isolation significantly reduces seismic demand, improving structural resilience.

Fig. 1 illustrates the relationship between the **h/√d ratio** (X-axis) and **Base Shear reduction ratio** (Y-axis) for structures with 5 to 15 stories. The reduction ratio increases with **h/√d**, with a sharp rise observed beyond **h/√d = 7** and **stories >11**. A response reduction factor above **0.35** suggests that base isolation is effective for **h/√d ≤ 9** and **stories ≤ 11**. Beyond this, the reduction ratio stabilizes, indicating minimal influence of story height on base shear reduction for a given **h/√d ratio**.
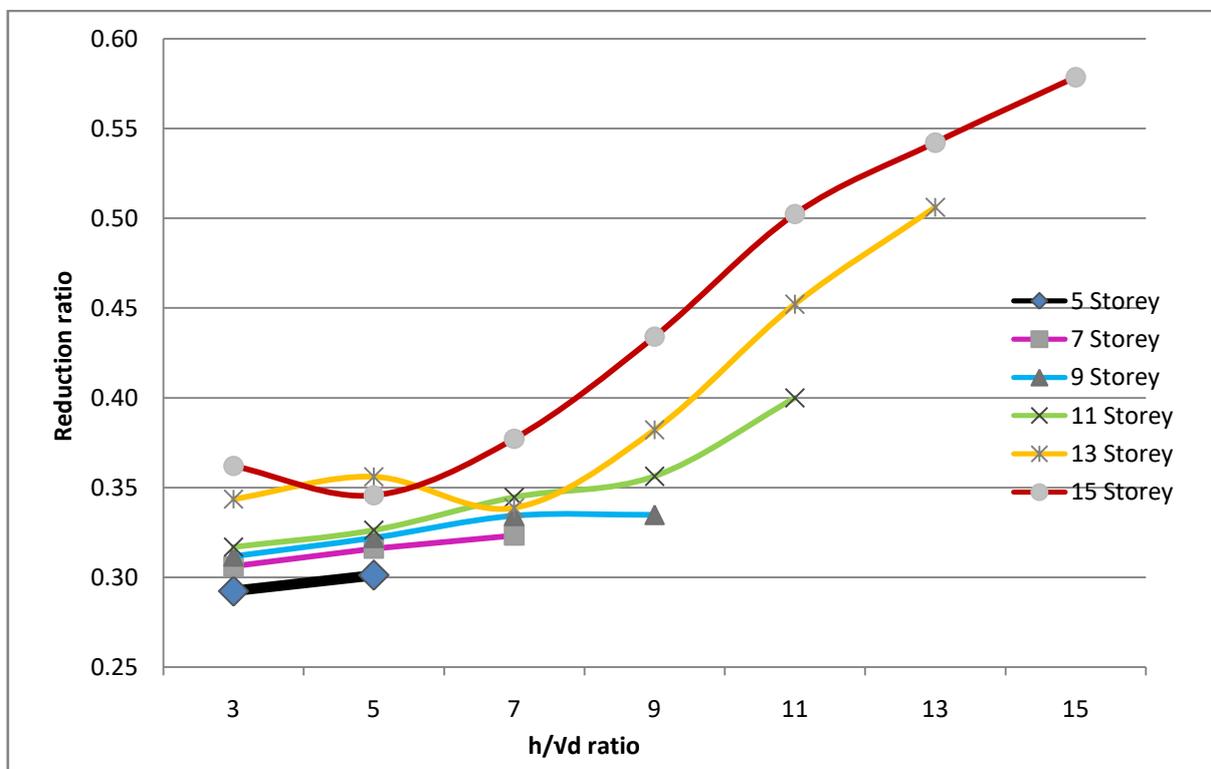

Figure 1: h/√d ratio vs Base Shear per unit mass Reduction ratio

Fig. 2 illustrates the relationship between the h/√d ratio (X-axis) and Acceleration reduction ratio (Y-axis) for structures with 5 to 15 stories. The reduction ratio decreases from h/√d = 5 to 7, then increases for higher h/√d ratios. For h/√d = 3, acceleration reduction ranges from 17% to 24%, decreasing slightly to 16%–20% at h/√d = 7. However, beyond h/√d = 9, the reduction ratio rises sharply, diminishing the effectiveness of base isolation. The isolation remains effective up to h/√d = 9 and stories ≤ 13, with no significant variation in reduction ratio for h/√d ≤ 11 stories.
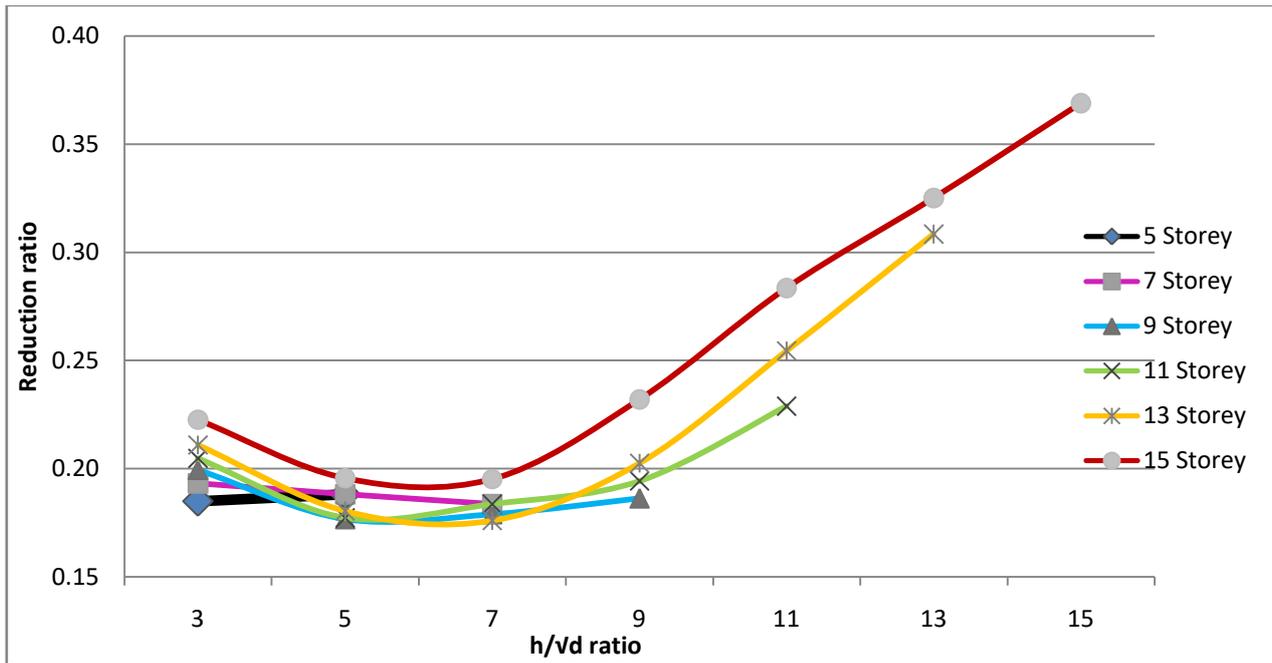
Figure 2: h/√d ratio vs Top Acceleration Reduction ratio

The below graph in Fig. 3 illustrates the relationship between h/√d ratios and deformation reduction ratios. For structures with fewer than 9 stories, the reduction ratio shows no clear pattern. However, for stories ≥ 9, deformation reduction sharply increases beyond h/√d = 9, indicating that base isolation is effective up to h/√d = 9.
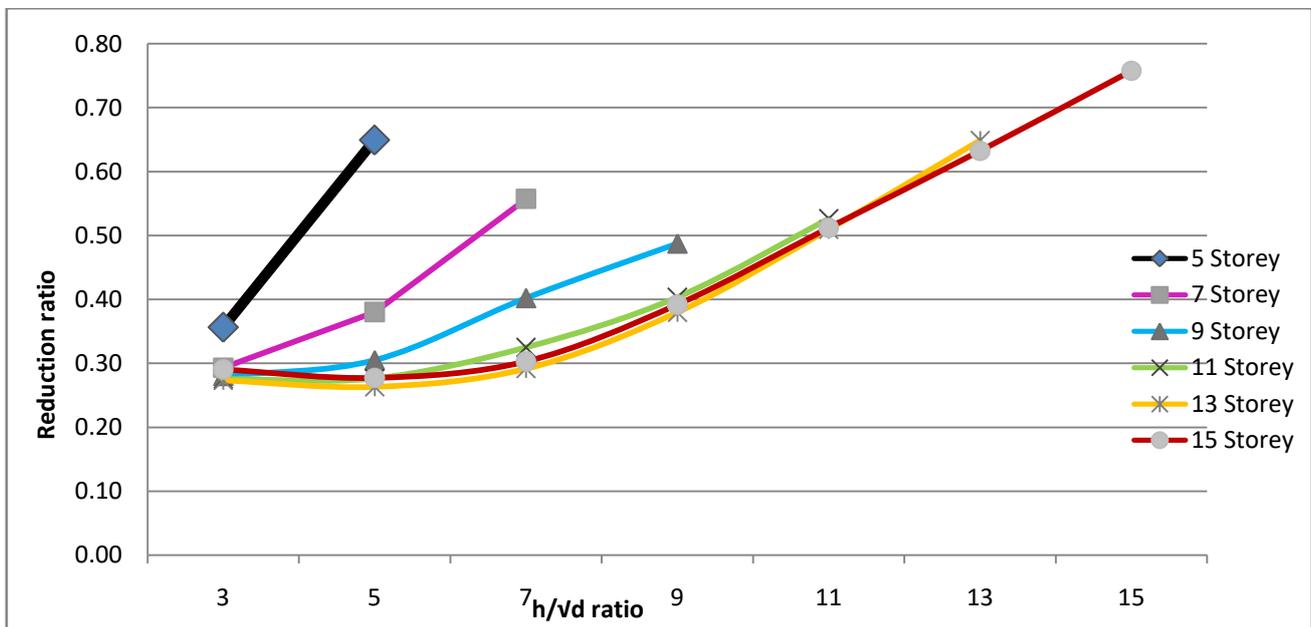

Figure 3: h/√d ratio vs Deformation Reduction ratio

Fig. 4 shows that isolator displacement decreases as h/√d increases. While displacement remains fairly constant for h/√d ≤ 7, a steady decline is observed beyond h/√d = 11. The reduction is more pronounced for h/√d ≥ 13, with the lowest displacement at h/√d = 15 (0.029925 m for 15 stories).
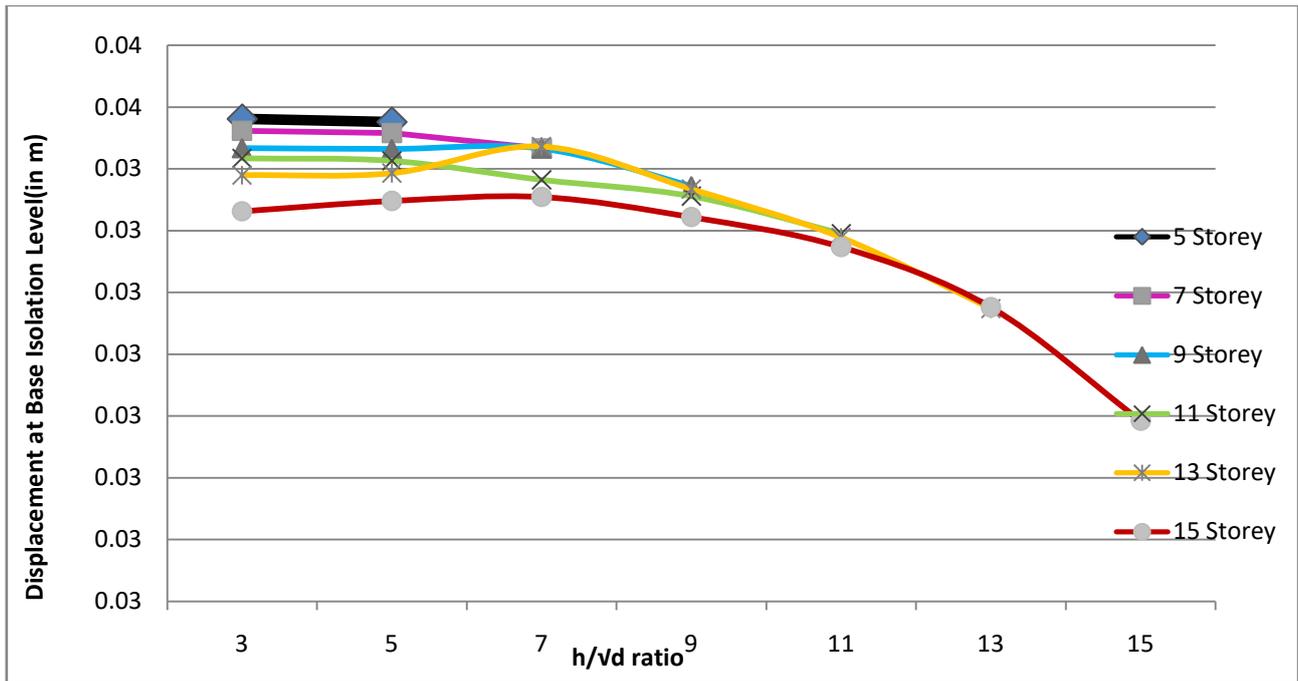
Figure 4: h/√d ratio vs Displacement at Base Isolation level

Fig. 5 clearly shows this trend, highlighting that the effectiveness of base isolation is more prominent in shorter, broader buildings where the isolation introduces a significant shift in dynamic properties. Therefore, the h/√d ratio is not only a geometric descriptor but also a critical parameter in evaluating the performance and efficiency of base isolation in structural seismic design. The variation in natural time periods for both fixed-base and isolated-base models with increasing h/√d ratio is presented. As shown in the graph, the fixed-base time period increases notably from approximately 0.61 seconds at h/√d = 3 to 1.16 seconds at h/√d = 15. This indicates that taller and more slender buildings tend to have a naturally longer fundamental period. On the other hand, the isolated-base structures are designed for a time period close to 2 seconds, and the analysis shows that they remain consistent with slight increases—from 1.98 seconds at h/√d = 3 to 2.28 seconds at h/√d = 15. This consistency is crucial, as it ensures that the base isolation provides a controlled dynamic behaviour across all structural configurations.
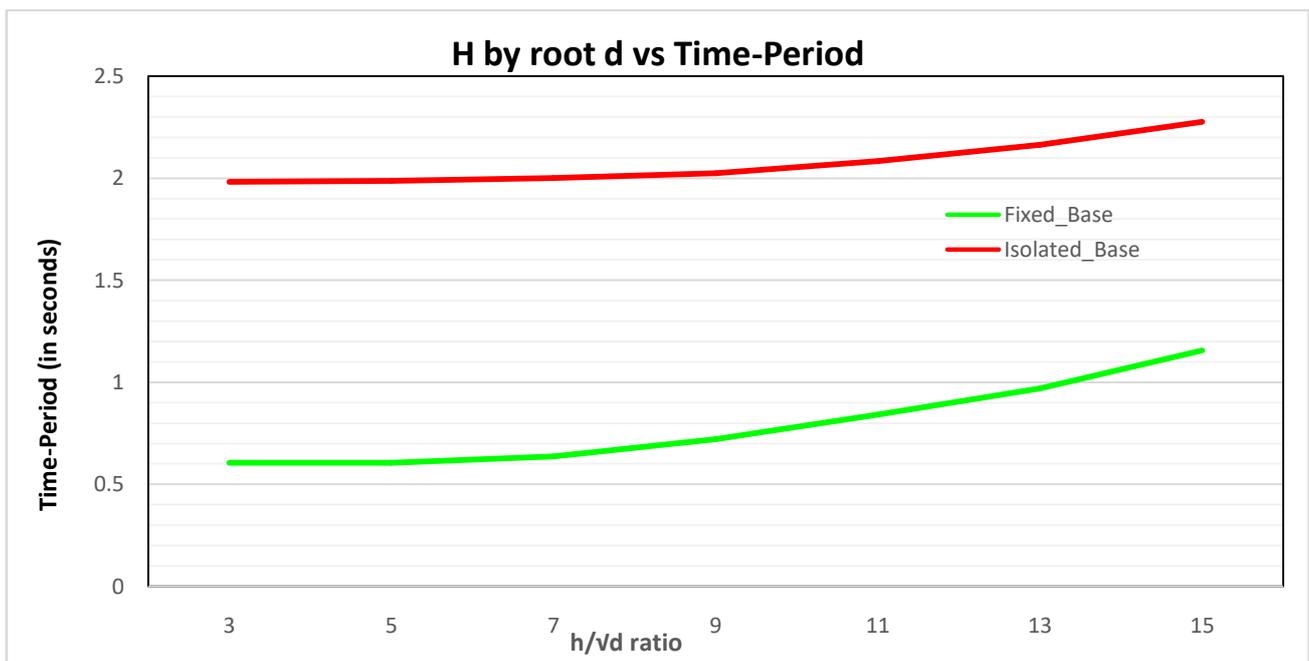

Figure 5: h/√d ratio vs Time-Period

8.1 Effect of base isolation on h/√d ratios

a) Base Shear Reduction:

- The Base Shear Reduction Ratio increases with an increase in the h/√d ratio.
- A sharp increase in reduction is observed beyond h/√d = 7 and for buildings with more than 11 stories.
- A Response Reduction Factor (RRF) of 3 is typically used for non-ductile fixed-base buildings, which corresponds to a reduction factor of 0.33. The study shows that for h/√d > 7, the reduction factor surpasses 0.35, indicating improved effectiveness of base isolation.
- However, beyond h/√d = 9, there is no significant further reduction in base shear, regardless of the number of stories.

b) Acceleration Reduction:

- The Acceleration Reduction Ratio shows an initial decrease between h/√d = 5 to 7, indicating that base isolation becomes less effective within this range.
- However, for h/√d ≥ 9, the reduction ratio starts to increase exponentially, reducing the overall effectiveness of base isolation in controlling acceleration.
- For structures with h/√d = 3, the acceleration reduction ratio ranges between 17% to 24%, while for h/√d = 7, this range drops to 16% to 20%.
- Beyond h/√d = 9, acceleration reduction becomes inconsistent, making base isolation less effective for taller buildings.

c) Deformation Reduction:

- Deformation reduction does not follow a clear pattern for buildings below 9 stories, meaning base isolation does not significantly affect deformations in shorter structures.
- However, for buildings taller than 9 stories, deformation reduction sharply increases beyond h/√d = 9, confirming that base isolation remains effective within this range.

d) Isolator Displacement:

- The displacement at the isolator decreases as h/√d increases.
- For h/√d = 3, displacement reduces from 0.0348 m (5 stories) to 0.0333 m (15 stories).
- For h/√d = 5, displacement remains stable at around 0.0347 m, but for h/√d = 7, displacement is nearly constant for 7 to 9 stories, before decreasing for taller buildings.
- For h/√d ≥ 11, displacement values steadily decrease from 0.0329 m (11 stories) to 0.0327 m (15 stories).

- The most significant reduction occurs at h/√d = 15, where displacement drops to 0.0299 m (15 stories).

e) Time Period Response:

- As shown in the graph, the fixed-base time period increases notably from approximately 0.61 seconds at h/√d = 3 to 1.16 seconds at h/√d = 15. This indicates that taller and more slender buildings tend to have a naturally longer fundamental period.
- On the other hand, the isolated-base structures are designed for a time period close to 2 seconds, and the analysis shows that they remain consistent with slight increases—from 1.98 seconds at h/√d = 3 to 2.28 seconds at h/√d = 15.
- This consistency is crucial, as it ensures that the base isolation provides a controlled dynamic behaviour across all structural configurations.

The widening gap between the fixed-base and isolated-base periods at lower h/√d ratios (e.g., 3 to 7) results in substantial time period separation, which enhances the effectiveness of base isolation. As h/√d increases, this gap narrows, and the advantage of isolation reduces because the fixed-base structure itself begins to approach a more flexible, longer-period response.

IX. Conclusions

Base Isolation is an effective technique for reducing structural response due to earthquakes. Its effectiveness primarily depends on the dynamic properties of the building and earthquake ground motion characteristics. The dynamic behaviour is influenced by geometric parameters such as building height and width, which define the h/√d ratio—a key factor in determining the time period of a fixed-base structure. Based on the analytical study conducted, the following conclusions are drawn:

- Base isolation significantly reduces seismic response parameters compared to a fixed-base structure.
- The h/√d ratio effectively represents the time period of a fixed-base building and serves as a useful parameter for evaluating base isolation effectiveness.
- Base shear and top acceleration reductions remain similar for a given h/√d ratio across buildings with up to 9 stories.
- Base isolation is most effective in reducing base shear for h/√d ratios up to 9 and building heights up to 13 stories.
- The deformation of the top story is not a reliable indicator of base isolation effectiveness.
- The h/√d ratio is an empirical parameter that estimates the natural time period of fixed-base structures, as per IS

1893:2016, and plays a crucial role in assessing dynamic behaviour based on geometric proportions.

- Therefore, the separation of time periods between fixed-base and base-isolated conditions is critical. The $h/\sqrt{d}$ ratio helps in evaluating whether such separation—and thus meaningful isolation—is achievable. For base isolation to be effective, the fixed-base time period must be significantly lower than 2 seconds. If the natural time period of a fixed-base structure is already close to 2 seconds (e.g., for tall and slender buildings), the separation is inadequate, and isolation effectiveness is compromised.

This study reinforces the significance of $h/\sqrt{d}$ ratio in seismic analysis and highlights the limitations of base isolation for very tall structures, where effectiveness begins to diminish.

REFERENCES

[1] Jangid R. S. DattaT. K., "Seismic behaviour of base-isolated buildings: a state-of-the-art review." *Proc. Instn Civ. Engrs Structs & Bldgs,* May 1995;110: p. 186-203.

[2] Constantinou M.C., "Seismic Isolation Systems: Introduction and Overview." T. T. Soong et al. (eds.), *Passive and Active Structural Vibration Control in Civil Engineering © Springer-Verlag Wien* 1994, p. 81-96.

[3] H. Toopchi-Nezhad, M. J. Tait, and R. G. Drysdale, "A novel elastomeric base isolation system for seismic mitigation of low-rise buildings." *The 14th World Conference on Earthquake Engineering, Beijing,China,* October 2008.

[4] Naeim F. and Kelly J. M., "Design of Seismic Isolated Structures: from theory to practice" *John Wiley and Sons, New York, USA* 1993.

[5] Kelly James, "Earthquake-Resistant Design with Rubber." © *Springer-Verlag London Limited 1993; First Edition*.

[6] IS 1893 (Part1) 2016, "Criteria for Earthquake Resistant Design of Structures"; *Sixth Revision*.

****