A Review on Seismic Issues and Remedies in High-Rise Structures

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ABSTRACT

The increase in population in urban areas have popularised high rise structures, as a means of accommodating more people in a limited area. The major concerns in the designing and construction of high-rise structures are the safety aspects against wind and earthquake forces, as the collapse of the structure can lead to a disaster. The seismic zoning map of India shows that a large area of India is prone to earthquakes. The growing use of high strength and lightweight materials in high-rise structures makes them more flexible and lightly damped, thereby making these structures more sensitive to dynamic excitations. Presence of irregularities, setbacks, open ground story, weak and soft storeys, also increases the seismic vulnerability of high-rise structures. Vertical ground shaking can be of significant concern in terms of amplification of acceleration along the height of the building, and also, achieving vertical isolation had been challenging as the gravitational load must be sustained by the isolation system. Quasi-Zero stiffness system was found to be effective in vertical isolation of structures. Installing damping devices at optimal locations, base isolation systems, and suitable seismic retrofitting strategies can enhance the seismic performance of structures. This paper reviews the various factors that lead to seismic issues in high-rise structures such as size, shape, configuration, structural aspects, and material properties. The appropriate remedies to address the seismic issues are also reviewed.

Keywords: High-Rise Structures, Seismic Issues, Vertical Isolation, Damping Devices, Seismic Retrofitting.

1 INTRODUCTION

The Indian subcontinent has experienced some of the most severe earthquakes ever occurred. Himalayas is one of the most active tectonic belts of the world. It is also one of the rare sites of active continent-continent collision. Seismic zoning identifies regions of similar probable intensity of ground motion in a country and provides a base to take adequate measures to ensure seismic resistant construction. The seismic zoning map of India shows that a large area of the country is prone to earthquakes. Seismic zone IV and zone V includes some of the most populated regions of the country, including Delhi (Agarwal and Shrikhande, 2014). High rise structures have become popular as a means to accommodate more people in a limited area. Since high rise structures are susceptible to vibration, seismic forces assume significance in the design of these structures. The building layout and structural system become important aspects which defines the seismic performance of high-rise structures. This paper provides a review on the various seismic issues in high rise structures and the current practices to remedy them.

2 LOADS ACTING ON HIGH-RISE STRUCTURES

According to the Council on Tall Buildings and Urban Habitat (CTBUH), there is no absolute definition of tall buildings. A building with 14 or more stories, or height more than 50m or 165 feet is generally considered as a

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threshold for a tall building, while heights of more than 300m is regarded as Supertall buildings and 600m as Mega-tall buildings.

A tall building may be considered as a cantilever with fixed end on the ground. Loads that should be considered in the designing of tall buildings other than self-weight and imposed loads are mainly wind loads and seismic forces. Wind forces acts on the exposed faces and inclined roof surfaces and can lead to bending of the structure. Wind effects reduces the pressure on the windward side and increases the pressure on the leeward side of the foundation. Earthquakes causes shaking of the ground leading to motion at the base of a building resting on the ground. Earthquake forces are completely random in all directions and can be resolved into three mutually perpendicular directions, in which the horizontal direction is taken to be the most prominent direction of motion. Seismic events will result in additional lateral forces in the structure. Poulos, (2016) states that and additional forces on the foundation system are induced by kinematic forces and moments by action of ground movements.

3 STRUCTURAL SYSTEMS

The structural systems used in high-rise structures can be braced-frame systems, rigid-frame frame systems, wall-frame systems, shear wall systems, core and outrigger systems, and tubular systems. Rigid-frame structures are generally used for buildings up to 25 storeys, shear wall structures for up to 35 storeys, wall frame structures for up to 50 storeys, outrigger braced structures for 40 to 70 storeys, and tubular structures for even higher stories (Smith and Coull, 1991). The foundations of high-rise structures need to support very heavy vertical and lateral loads, overturning moments, and pile foundations, piled raft foundations, and compensated piled raft foundations are generally adopted.

4 SEISMIC ISSUES OF HIGH-RISE BUILDINGS

Seismic loads are introduced in structures in the event of earthquakes. This is of much concern for structures located in seismic zones with higher intensity of ground shaking. The catastrophic earthquakes of the past and their lethal hazards had created a considerable interest among professionals and researchers associated with civil engineering in studies regarding earthquake engineering and safety issues during different earthquakes of varying magnitudes. Many studies have been done in areas of seismic analysis of buildings with different structural configurations, shapes, the behaviour of individual structural and non-structural members, foundation requirements, and even on soil properties of the site during earthquakes, and also regarding different strategies and techniques that can be adopted in structures to improve the seismic performance to ensure enhanced seismic stability.

4.1 Architectural Features

The behaviour of buildings in the event of an earthquake is greatly influenced by its size, shape, and configuration aspects. The damages to structures during past earthquakes around the world provided an idea of the configurations that will remain stable during an earthquake, and also configurations that must be avoided (Duggal, 2007).

i. Size of Buildings: During earthquakes, buildings with one dimension much larger or smaller than the other two, generally do not perform well.
ii. Horizontal Layout: Buildings with simple plan shape and configuration generally perform well during earthquakes, where as those with re-entrant corners or other complicated shapes may suffer damage.

iii. Vertical layout: Earthquake forces developed at different floors need to be brought to the ground by the shortest possible path. Deviations or discontinuities in this path leads to poor seismic performance of the structure. Some of the common examples for causes in vertical irregularities in buildings are: setbacks, unusually tall storeys, weak or flexible storeys, hanging or floating columns, discontinuing structural members, and also slopy ground.

iv. Adjacency of Buildings: The presence of two buildings close to each other can lead to pounding between the structures due to horizontal vibrations. The impact of this collision can be severe with increase in building height, and when the heights of the buildings do not match, the roof of the shorter building may pound at the mid-height of the column of the taller one, which is even more severe.

4.2 Irregularities

Irregularities leads to a discontinuity or deviation in the path to transfer the seismic forces generated at different floors in the structure. Buildings with lesser number of columns or walls in a storey, or unusually storey heights tend to damage or even get collapsed with damage initiating in that storey. Similarly, buildings constructed on slopy sites and hilly terrains may have columns with unequal heights along the slope, that may lead to the twisting and damaging of shorter columns. Buildings in which columns are not reaching the foundation also have discontinuous load transfer path. Also, in some buildings, concrete walls are constructed to transfer to the seismic forces to the foundation, and if these walls stop at some intermediate storeys and are not going to the ground, the structure is susceptible to be damaged during earthquakes. Many studies have been performed on buildings with irregularities about the behaviour of buildings, effects of various irregularities etc. Among the four types of irregularities: mass, stiffness, strength, and combined strength and stiffness, the effect of mass irregularity is the smallest, then stiffness irregularity, then strength irregularity, and then, the combined effect of strength and stiffness irregularity. Chintanapakdee and Chopra (2004) studied the seismic response of vertically irregular frames by Response History Analysis (RHA) and Modal Pushover Analysis (MPA). It was understood that, all the three irregularities: strength, stiffness, and combined strength and stiffness, influences the height wise variation of story drifts, and the combined effect of strength and stiffness irregularity was found to have the maximum effect. Also, the effects of strength irregularity were found to be larger than stiffness irregularity.

4.3 Asymmetry and Setback

Buildings with asymmetry in plan and structure causes a sudden jump in the seismic forces at the discontinuity, eventually resulting in poor performance of structures during earthquakes. Lavan and Wilkinson (2016) presented an analysis-redesign type approach for efficient seismic design of three dimensional (3D) asymmetric and setback RC frame buildings for drift and strain limitation with the aim to get an efficient design satisfying the inter story drift and strain limits. The behaviour of irregular and asymmetric structures are generally characterised by high concentration of local deformation demands at the locations of irregularity, and also in their peripheries.

4.4 Open Ground Story

Open Ground Story (OGS) buildings are buildings in which the ground storey is intended primarily to serve as a space for parking. The ground story columns do not have walls in between them. They are also referred to as buildings on stilts. An OGS building with columns alone in the ground story, while both columns and walls in the upper storeys have two specific aspects **(**EQ Tips, IIT Kanpur**)**:

i. It is comparatively flexible in the ground storey: The relative horizontal displacement in the ground storey is much more than the storeys above.
ii. It is comparatively weaker in the ground storey: The earthquake force that can be carried by the ground storey is much smaller than that could be carried by the storeys above.

Kaushik et al. (2009) proposed some strengthening options based on nonlinear analysis for masonry infilled RC frames with OGS. In the OGS frame considered, majority of the lateral deformations were at the first story due to absence of infills in first story, and heavy mass on upper stories. The strengthening options of providing additional columns and lateral buttresses in the open story were found to be effective in improving the lateral strength and ductility. When diagonal bracing was adopted, a sharp reduction in lateral strength was noted after the failure of second story infills even though an increase in lateral strength and stiffness was initially observed. Likewise, in the case of fully infilled frames, a sharp reduction in lateral strength was noticed after the failure of first story infills. Saravanan et al. (2017) studied on the dynamic testing of OGS structure and in-situ evaluation of Displacement Demand Magnifier (DDM) to quantify the vulnerability of OGS, and variations of DDM with respect to the stiffness ratio between OGS and infilled story. DDM is the ratio between the bottom storey displacement demands of an OGS frame and a frame of equally distributed stiffness.

4.5 Vertical Ground Shaking

Vertical ground shaking may be of great concern in terms of amplification of acceleration along the height of the building, as that can cause considerable damages to non-structural elements. Also, achieving vertical isolation had been challenging as the gravitational load must be sustained by the bearing. Ryan and Dao (2015) studied on the influence of vertical ground shaking on the horizontal response of seismically isolated buildings with friction bearings. It was observed that, the structure remained elastic, and the floor accelerations recorded were nearly lower than the peak ground acceleration (PGA) always. Zhou et al. (2019) studied analytical and numerical investigation of quasi-zero stiffness (QZS) vertical isolation system, and proposed a novel nonlinear isolation system designed for buildings, to isolate vibrations in the vertical direction. The system is characterised by QZS obtained by the combination of linear springs in parallel with disk springs having nonlinear stiffness, including a region with negative stiffness. The results revealed that, for QZS isolated model, vertical response of bottom floors was slightly larger, while that of the upper floors were suppressed. The schematic representation of the QZS system is shown in figure 1.

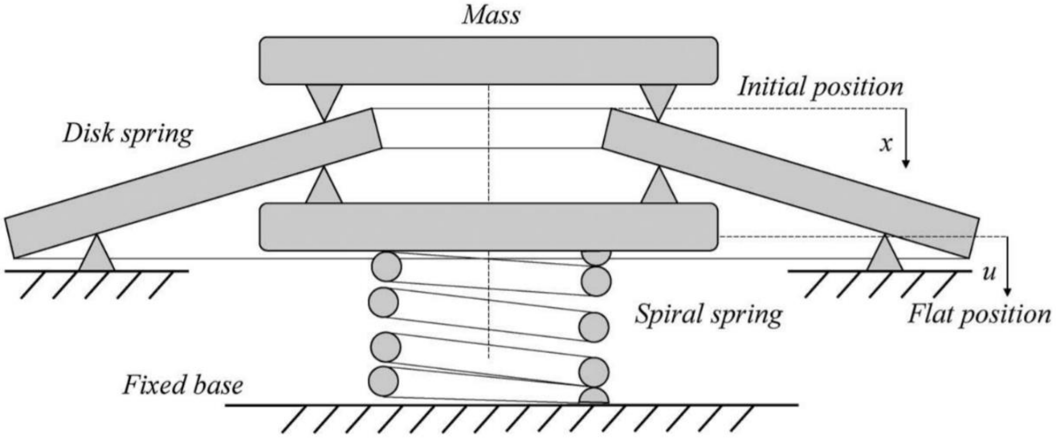

Figure 1. Schematic representation of the QZS system. (source: Zhou et al., 2019)

5 REMEDIES TO VARIOUS SEISMIC ISSUES

The main objective of seismic resistant design is to ensure the safety of the occupants during an event of earthquake. Construction of earthquake-proof structures is not in the interest of engineers as such structures will be too robust and expensive, but instead to make structures earthquake-resistant such that, they may get severely damaged, but do not collapse during earthquakes. The structure can be safeguarded against the ill effects of earthquakes either by strengthening the structural components or by reducing the seismic demand. Installation of damping devices, base isolators and active control systems are some of the common methods employed to reduce the seismic response in structures.

5.1 Damping Devices and Isolation Systems

5.1.1 Damping Devices

Application of Seismic Dampers is a technique to control the impact of seismic forces on structure thereby preventing or reducing damage to the structure. The dampers absorb a part of the seismic energy and helps in energy dissipation in the structure when it is transmitted through them during earthquakes, thus damping the motion of the structure and protecting it. Fu and Jonson (2011) proposed the applications of distributed mass damper (DMD) systems for structural and environmental controls in buildings, and proposed external shading fins as mass dampers to control the structural movements, and also control the energy consumptions of the building by adjusting the fins. It was observed that, the resulting DMD system significantly reduces the structural motions during the earthquakes. Also, mass dampers were found to be more effective when they are placed on the top of the structure. Even though, the damper masses distributed in the DMD system and the concentrated damper mass is comparable, a near optimal DMD systems outperforms a single tuned mass damper system. Li et al. (2011) studied the dynamic behaviour of Taipei 101 tower by field measurements and numerical analysis. The dynamic response of a structure is very much influenced by the amount of damping in each mode, and its relevance is increasing as modern buildings are taller and more flexible. Fu and Zhang (2016) studied the integration of double skin facades and mass dampers for structural safety and energy efficiency. The double skin facade system comprises of two heavy glass layers. Air flow between these layers aid in ventilation. It also protects and insulates the building. Both passive and active structural control strategies are employed in the study. In passive control strategies, the damper parameters were optimised to reduce interstory drifts. In the active control systems, actuators will be employed to control the movements of the double skin facade. Li and Cui (2017) described a novel design approach of a nonlinear TMD with duffing stiffness and studied the control performance of a TMD when nonlinear behaviour caused by nonlinear spring stiffness is taken into consideration in practise. It was observed that, the nonlinear effect of TMDs designed using linear approach degrades the control performance. The effect of damping was analysed and it was noticed that, the resonance amplitude increases with increase in the damping ratio.

5.1.2 Base isolation

Base isolation (BI) systems is an effective method to protect structures during earthquakes. In this method, isolation systems are installed beneath structures to lengthen their fundamental period towards the low acceleration region of the response or design spectrum. This significantly reduces the base shear and horizontal acceleration demands on the structure. The basic principle of BI is that, the movement of the ground will not be transmitted to the superstructure thus modifying the response of the building. Thus, large force due to shaking of the ground will not be transmitted to the building. Sayani and Ryan (2009) proposed a comparative evaluation of base-isolated and fixed-base buildings using a comprehensive response index and investigated the possibility of allowing the super structures of isolated buildings to respond inelastically with deformation ductilities comparable to those of fixed base buildings. Results of the RHA shows that the force reduction factors in base isolated buildings are smaller than in fixed buildings for comparable ductility, and super structure design forces can be even reduced considerably for isolated buildings. Isolated buildings show better seismic performance with respect to superstructure deformation and total acceleration demands, at the same super structure ductility. Kuang et al., (2015) analysed the performance of BI systems during seismic events. The performance of the BI Christchurch Women's Hospital (CWH), New Zealand was analysed during the series of Canterbury Earthquakes. The study realised that, the CWH building behaved as a fixed base structure and not as an isolated structure during the seismic events, even though it has been designed with methods and techniques proved in other cases. The observed behaviour could be due to improper design of the bearing, or construction. Also, the CWH building was directly connected to the adjacent Christchurch General Hospital, which may have led to changes in lower story motion behavior during major seismic waves. Peng et al., (2020) performed shake table test of seismic isolated structures with sliding hydromagnetic bearings and analysed its effectiveness for seismic mitigation. The study states that, sliding hydromagnetic bearings are more suitable for seismic mitigation of floor accelerations and inter-story drifts for far-field earthquakes than near-fault earthquakes. Also, the BI structure with sliding hydromagnetic bearings was found to exhibit a satisfactory seismic mitigation of horizontal torsions during both far-field and near-fault earthquakes.

5.1.3 Tuned Mass Damper and Base Isolation

Base Isolation (BI) and Tuned Mass Damper (TMD) are two widely used strategies to reduce the vibration of structures. Both these techniques may be associated with the concept of discontinuity, considered as a sudden variation of stiffness within a structure. In BI, the stiffness of the isolation layer is generally lower than that of the super structure, so that it offers the possibility of a seismic energy deflection due to low values of participating factor for higher modes, beyond increasing the fundamental period of vibration. In TMD, a disconnection is introduced between the main super structure to be protected and a supplementary vibrating mass. Fabrizio et al., (2019) introduced a unique 2 degree-of-freedom (2-DOF) model to describe the behavior of multi-degree-of-freedom (m-DOF), in which a system discontinuity, like the case of a TMD or BI may be applied, thereby improving the performance of the structure by means of a disconnection. The 2-DOF model proved to be a simplified prototype version of the M-DOF system. The schematic representation of a discontinuity as a TMD and BI is shown in figure 2.

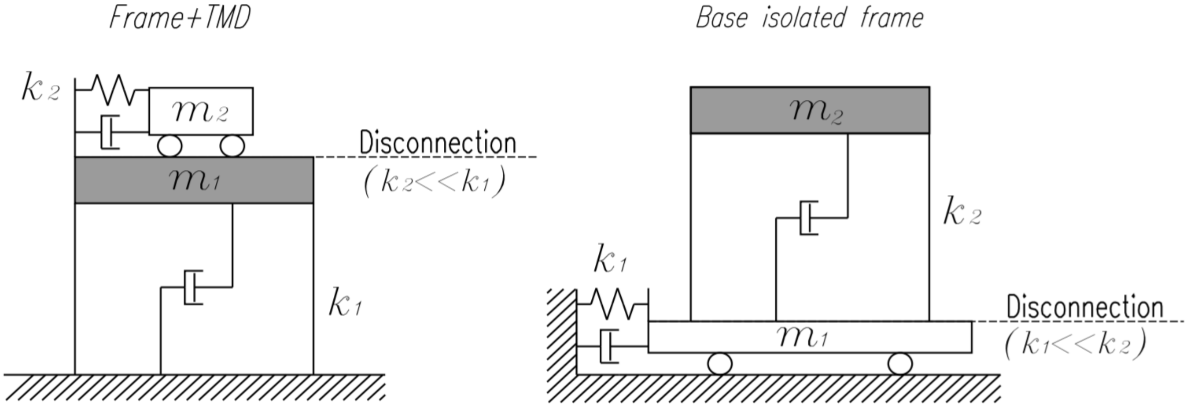

Figure 2. Schematic representation of a TMD and BI. (source: Fabrizio et al., 2019)

5.1.4 Semi-active control using Fuzzy Logic

A semiactive control system can produce a large force just by dynamically changing parameters like stiffness and damping coefficient of the control device. Fuzzy logic controller is employed to describe a complex mapping relationship between a set of inputs and outputs, and make use of this to analyse and control the behavior of structural systems. In fuzzy logic control systems, measured responses and disturbances are used as inputs, while the control command is provided as the output. Bharadwaj and Datta (2016) proposed a methodology for semiactive control of building frames using multiple semiactive hydraulic dampers (SHDs) controlled by fuzzy logic. It was observed that, there is an optimum combination of damping coefficients of the dampers installed in different floors, maximum damping coefficient, and the allowable damper force to be used. The semi active control scheme was found to provide better control than purely passive case.

5.2 Sliding Base Systems

The sliding base (SB) system strategy adopts a sliding interface between the base of the superstructure and the foundation. This is an effective and economic method for providing safety against earthquakes. Hu et al., (2020) studied on the maximum response of superstructure with sliding base systems under three-component earthquake excitation, which is of great importance in the design of sliding base structures. The superstructure response was affected by the local site conditions. The response obtained was much large for sites located on soft soils, and the dependency on the local site conditions was found to decrease with an increase in the normalized PGA.

5.3 Seismic Retrofitting

Seismic retrofitting aims to ensure the stability of an existing structure to prevent its collapse during an earthquake. The necessity of seismic retrofitting of structures arises mainly in two situations:

i. The structure is at present earthquake vulnerable and threat of being exposed to earthquake persists, but have not yet experienced a severe earthquake, and
ii. The building has already suffered minor damages due to an earthquake. Seismic retrofitting proves to be a cost-effective alternative for a majority of the structures that have been damaged during minor earthquakes, rather than demolition of the structure.

Javidan and Kim (2019) studied on Seismic Retrofit of Soft First Story Structures using Rotational Friction Dampers. The main advantage of the damper developed was to achieve much larger rotations at the friction faces than compared with conventional friction dampers, and also, for same lateral drift, greater energy dissipation because of the amplification mechanism. The energy dissipation capacity of the damper was appreciably increased by designing its geometry in such a way that its rotation was maximized for a given lateral drift of the structure. The retrofit system could be effectively applied to reduce the inter story drift ratios of a structure and prevent its collapse. The schematic representation of a rotational friction damper is shown in figure 3(a) and installation in a building in figure 3(b).

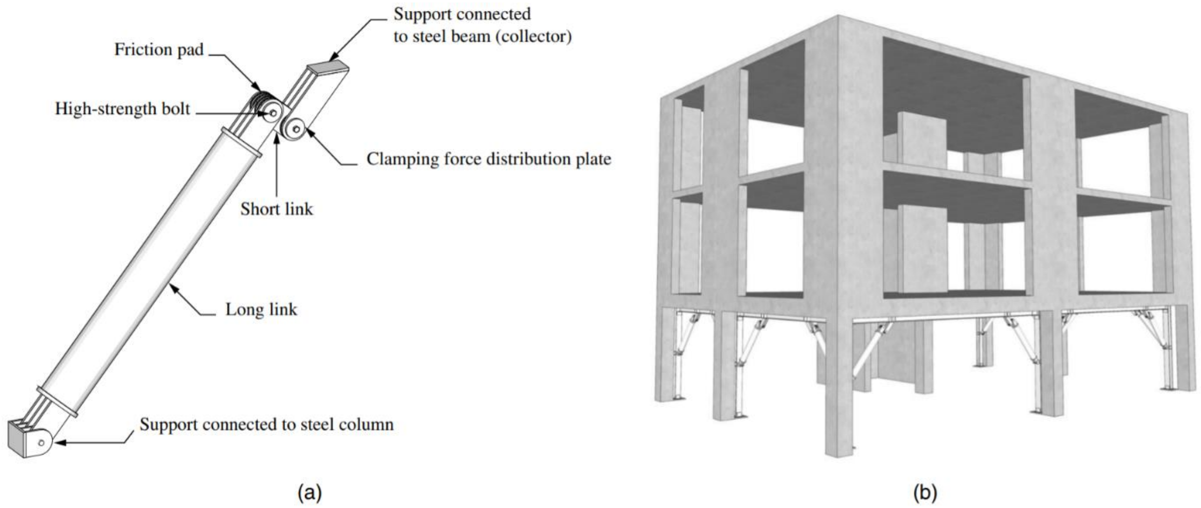

Figure 3 (a) Schematic representation of a rotational friction damper and (b) installation in a building (source: Javidan and Kim, 2019).

Apostolakis (2020) proposed an evolutionary computational framework for the seismic design of regular and irregular three-dimensional multi story structures that has hierarchical multiscale multi brace architectures. The responses of the optimal designs resulted in more uniform distribution of drifts, thus ductility demand, and also much uniform distribution of floor accelerations.

6 DISCUSSIONS AND CONCLUSIONS

It could be observed from the reviews that, high-rise structures are vulnerable to earthquakes, and the performance of structures during earthquakes depends on a large number of aspects such as architectural features, structural aspects, site conditions, materials used in construction and their properties. Buildings with one dimension much larger than the others, presence of irregularities (in mass, strength or stiffness), asymmetry, setbacks, open ground story, and structures constructed on soft and loose soil, shows poor performance during earthquakes. The seismic forces generated at different floor levels during the event of an earthquake needs to be brought down to the earth, and any discontinues in this path can lead to damages in the structure at the level of discontinuity. The seismic performance of structures can be enhanced by adopting relevant strategies such as: proper engineered construction practises, following simple plan and avoiding structural irregularities and setbacks. Application of damping devices and base isolation systems improves the safety of structures during seismic events. Sliding base systems are not suitable for very tall structures, and also for buildings constructed on soft soil. Seismic retrofitting approaches are suitable to enhance the seismic performance of structures under threat of collapse due to an earthquake or those that suffered minor damages during past earthquakes. It could be stated that:

i. The ductility of the members and building as a whole should be increased to improve its seismic performance.
ii. The effects of the responses of seismic forces were showing a general trend of increasing on moving up the storeys.
iii. Vertical ground shaking may be of great concern in terms of amplification of acceleration along the height of the building. Quasi-Zero stiffness system was found to be effective in vertical isolation of structures.

iv. The semi active control scheme was found to provide better control than purely passive case.

v. An optimal DMD system is more effective in improving seismic performance than a single mass damper.

OGS buildings are inherently poor systems with a sudden drop in stiffness and strength in the ground story, and have consistently shown poor performance during past earthquakes all over the world. The seismic response of OGS high-rise structures with various types and combinations of damping devices and isolation systems has to be further explored in the future in order to improve its seismic performance.

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