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Engineering the Rocking Isolation of a Building to Withstand Wind and Seismic Actions

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Abstract

Allowing a building to rock safely has been proven to be effective in stabilising the structure and minimising damage caused to it in a severe earthquake. Pre-stressing tendon restraints can be incorporated to maintain a fixed-base condition for withstanding strong wind pressure. As the stabilising action of the prestress is surpassed when strong ground shaking is imposed, the building would cease to be fixed at the base and experience whole body rotation. Such behaviour can be engineered to take place in a safe and reliable manner whilst absorbing and dissipating energy. Although the concept of rocking isolation is well established, the engineering details is not well known. This article aims to present simplified calculations for predicting the maximum roof displacement, and the bending moment and shear forces that are developed within the rocking structure, at the instance of building starts rocking. Accuracy of estimates from the simplified calculations have been checked by comparing against results from computer simulations.

Keywords: earthquake; pre-stressing tendon restraints; whole-body rotation; rocking isolation.

1 Introduction

Building structural integrity can be severely compromised by earthquakes, especially in low-to-moderate seismicity regions where earthquakes can be frequent and intense. The dynamic loads generated by the energy release from the earthquakes can lead structures to severe damage or even collapse if the structures are not designed to resist such loads (Nitti G. et al 2021). Traditionally, earthquake designs have primarily focused on creating rigid structures fixed at the base to ensure that structures can withstand imposed loads without significant deformation. This has been achieved by using robust construction techniques. However, these construction techniques are not sufficient for strong ground motions though they are more effective in minor to moderate seismic events. The high level of stresses and strains that the structure can experience, leading to failure in extreme situations (Ghobarah A. 2001; Martin G. R. et al. 2000).

Engineers have developed various advanced construction techniques to mitigate the damage from earthquakes and to improve the resilience of buildings by base isolation and energy dissipating devices. Recently, rocking isolation has gained attention and proven to be effective in stabilising and minimising damage to structures during a severe earthquake event. This involves designing the structure to lift and rotate back and forth from its base when subjected to seismic forces. While the structure is rocking, there is a potential for sudden increase in the risk of overturning with the increase of angle of rotation. Moreover, excessive damage can be caused by the hammering on the structure at the base with the high rotation. Recent studies have introduced an innovative system using pre-stressing tendons to enhance the seismic performance of structures by allowing fully recoverable significant rotation to occur without risking overturning (Li S. et al. 2022). This development enables the structure to maintain fixed base condition for withstanding strong wind pressure while allowing whole body rotation when strong ground shaking is imposed.

Though rocking isolation, as an earthquake engineering concept, is well-established and acknowledged to have potential benefits, the specific engineering details required for its practical implementation including calculations and design principles are not well known. This article explores the concept of rocking isolation, specifically focusing on the engineering details necessary for its implementation, notably simplified calculations for predicting maximum roof displacement, and the bending moment and shear forces that are developed within the rocking structure at the instance of building starts rocking compared with computer simulations. A comprehensive illustration of the simplified calculations and validation is elaborated in the subsequent sections.

2 Simplified Equations

Simplified mathematical equations for maximum roof displacement, base shear, bending moment of rocking structures are proposed here. The equations for maximum roof displacement are derived in four building categories, for stiff buildings and for flexible building with and without tendon restraints by taking moment about the pivot point as shown in Figure 1. In the derivation of equations for flexible buildings, the shifting of the centre of the mass of the floors up the height of the building is considered. Equations for base shear and bending moment are derived based on the known roof displacements. The proposed equations for the maximum roof displacement U_b for four building categories are shown in Table 1.

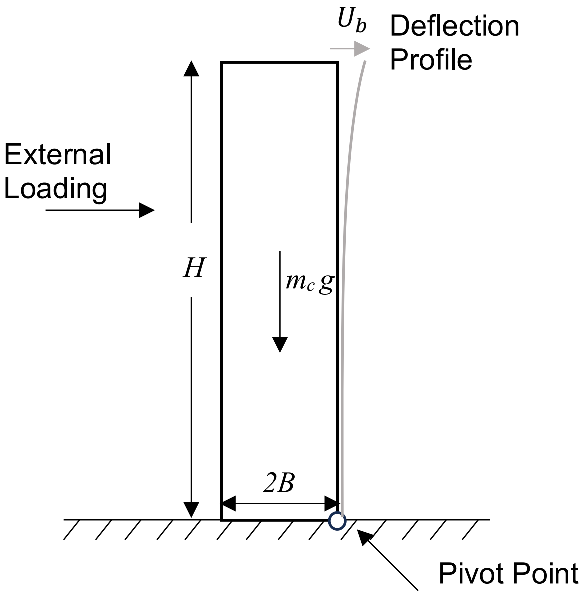


Figure 1. Rocking structure.

Table 1. Simplified equations for maximum roof displacements at the instance of building starts rocking

Building Configuration	Stiff Building	Flexible Building
Free Rocking	$U_b = \frac{40}{11}\frac{g}{\omega_1^2}\frac{B}{H}$	$U_b = \frac{gB}{\frac{11}{40}\omega_1^2 H + \frac{3}{8}g}$
Tendon Restrained Rocking	$U_b = \frac{m_c g\left(B - \frac{H}{2}sin(\theta_y)\right) + F_y B}{\frac{11}{40}\omega_1^2 m_c H}$	$U_b = \frac{m_c g\left(B - \frac{H}{2}sin(\theta_y)\right) + F_y B}{\frac{11}{40}m_c\omega_1^2 H + \frac{3}{8}m_c g}$

Where ω_1, H, B, m_c, F_y, g represents fundamental angular frequency, height, half width, and mass of the building, tendon force and gravitational acceleration respectively. The term θ_y represents the building rotation. Once the roof displacement is calculated, following Eqs (1) – (4) are proposed to calculate the base shear (V_b) and the bending moment (M_b) of buildings subjected to uniformly and triangularly distributed loads along the height of the building which represent the strong wind pressure.

For uniformly distributed loads,

$$V_b \approx 1.9\omega_1^2 m^* U_b \tag{1}$$

$$M_b \approx 1.27\omega_1^2 m^* U_b H \tag{2}$$

For triangularly distributed loads,

$$V_b \approx 2.7\omega_1^2 m^* U_b \tag{3}$$

$$M_b \approx 1.35\omega_1^2 m^* U_b H \tag{4}$$

Where, m^* is the seismic mass and $m^* = 0.235\, m_c$.

The proposed simplified equations are validated in section 3 by comparing with the results obtained from OpenSees commercial software.

3 Validation

Several studies have been conducted to obtain the response of rocking buildings by using OpenSees commercial software. In this study, several buildings which are having same base area (14m x 70m) with varying height of buildings have been analysed using OpenSees software to validate the implemented simplified calculations. The modelling of the building consists of two components for free rocking buildings and three components for tendon restrained rocking buildings. The building is modelled with beam-column elements which are having different young's modulus for the analysis of stiff (E= 30×10^9 kPa) and flexible (E= 1.7×10^9 kPa) structures. The rocking surface is modelled with zero-length fiber elements where there is no resistance in tension and elastic response in compression. Furthermore, to analyse the tendon restrained rocking buildings, the tendons are modelled with truss elements. The number of elements used to model these elements are based on a recent study by Vassiliou, M. F. et al. 2017. Therefore, the building has been modelled with 60 beam-column elements and the rocking surface with two zero-length fibre elements. The skeleton of the building model with different element types is shown in Figure 2. The beam-column elements are connected between node j and k, whereas zero length fiber elements are connected between node i and j. Furthermore, especially for tendon restrained rocking buildings, truss elements which represent the tendons are connected from node i to node k.

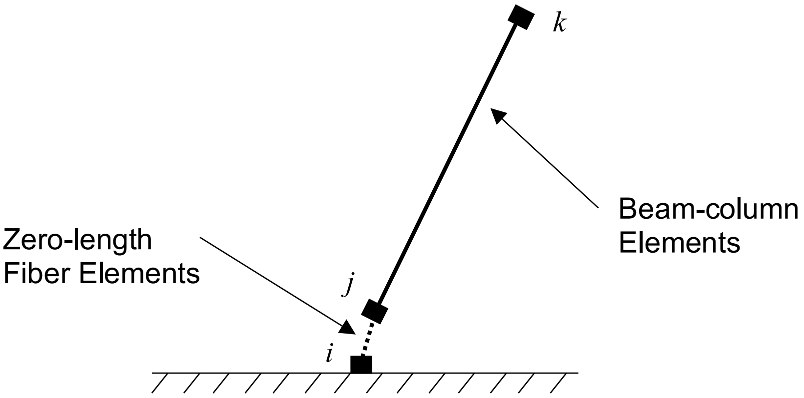


Figure 2. Skeleton of the OpenSees model.

The building models that are having varying heights have been analysed for uniformly distributed and triangularly distributed loads, and obtained the roof displacement at the instance of the building starts rocking. Figure 3 shows the comparison of roof displacements obtained from OpenSees software and the simplified calculations for free rocking stiff and flexible buildings with height of the building. The comparison of roof displacements for tendon restrained rocking buildings at the instance where the tendons start to elongate are shown in Figure 4.

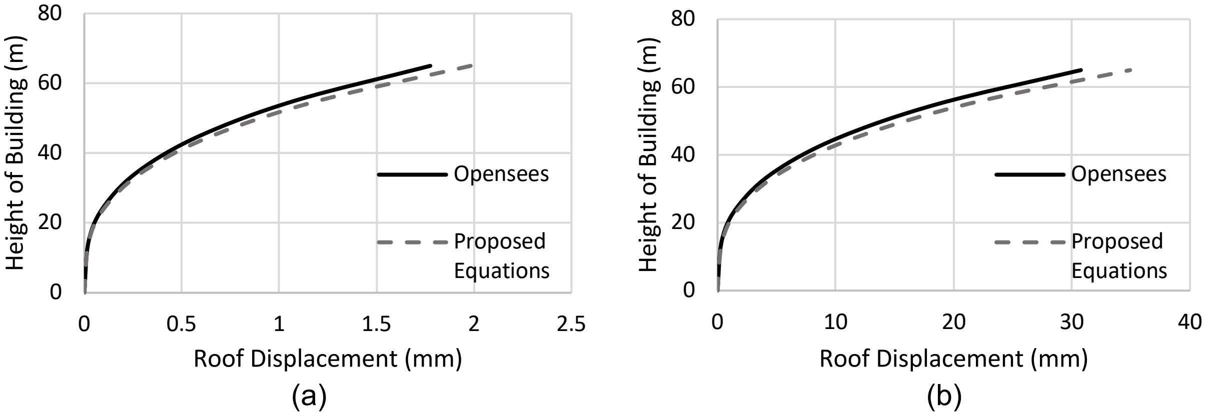
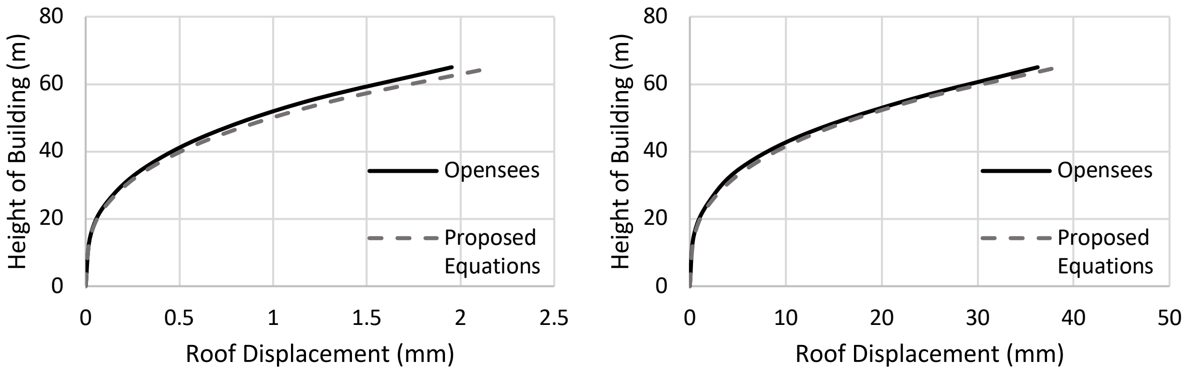


Figure 3. Variation of roof displacement with height of buildings at the instance of starts rocking for free rocking (a) stiff buildings (b) flexible buildings.



(a) (b)

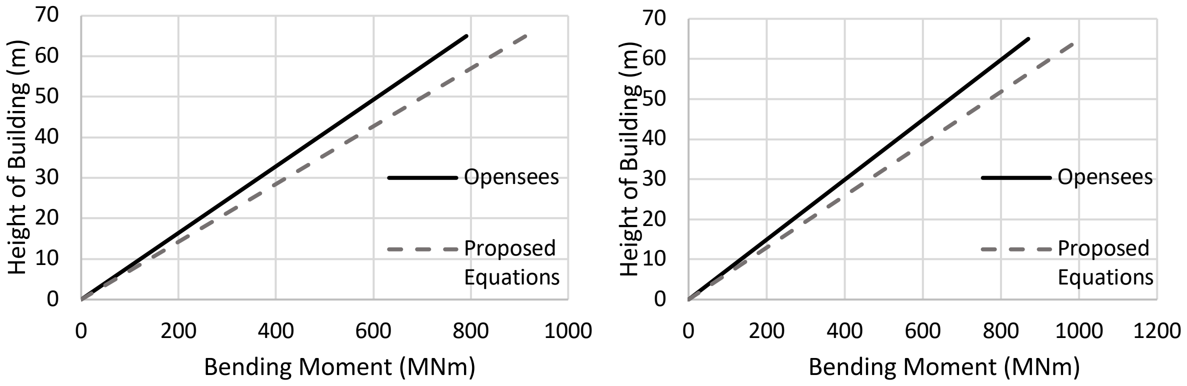
Figure 4. Variation of roof displacement with height of buildings at the instance of tendons starts elongating for tendon restrained rocking (a) stiff buildings (b) flexible buildings.

Moreover, using the calculated roof displacement, base shear and bending moment have been calculated from the simplified equations for uniformly and triangularly distributed loads, and compared with results obtained from OpenSees software. The base shear is a constant value with varying building heights for free rocking buildings (at the instance of starts rocking) and for tendon restrained rocking buildings (at the instance of tendons start to elongate) under both loading conditions. The base shear of tendon restrained rocking buildings shows higher values compared to the free rocking buildings as the tendons affect the rocking response and resistance against external forces. The results are shown in Table 2.

Table 2. Base shear values for free rocking buildings and tendon restrained rocking buildings for uniform and triangular loads.

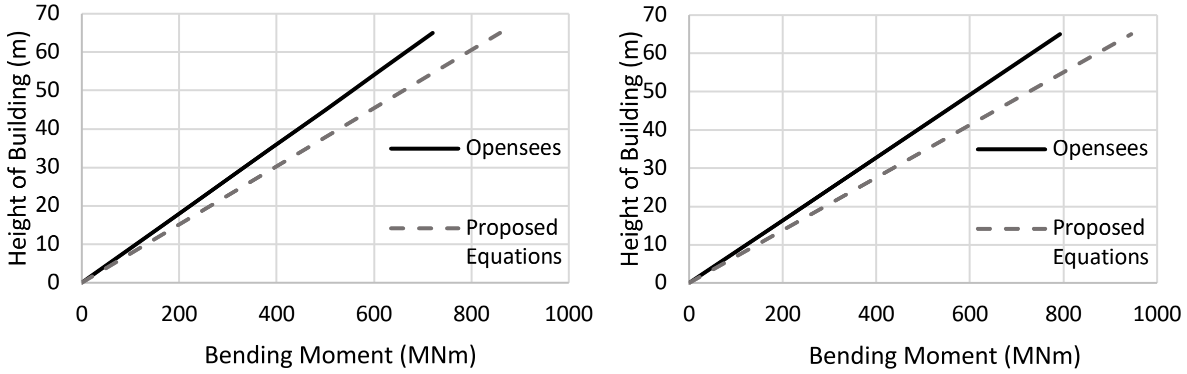
Building Configuration	Base Shear (MN)			
	Uniformly Distributed Loads		Triangularly Distributed Loads	
	OpenSees	Simplified Calculations	OpenSees	Simplified Calculations
Free Rocking	24.3	28.1	16.7	19.8
Tendon Restrained Rocking	26.8	30.9	18.4	21.7

Furthermore, the calculated bending moment values from the simplified calculations and results from OpenSees software for free rocking buildings (at the instance of building starts rocking) and for tendon restrained buildings (at the instance of tendons start to elongate) subjected to uniformly distributed load are shown in Figure 5 and, Figure 6 represents the buildings subjected to triangularly distributed loads.



(a) (b)

Figure 5. Bending moments of buildings subjected to uniformly distributed loads for (a) free rocking buildings (b) tendon retrained buildings.



(a) (b)

Figure 6. Bending moments of buildings subjected to triangularly distributed loads for (a) free rocking buildings (b) tendon retrained buildings.

Based on the results from both simplified calculations and OpenSees commercial software, the simplified calculations provide estimates that are slightly higher but reasonably close to the results obtained from OpenSees models. The roof displacements, bending moments and shear forces at the instance of building start rocking values calculated from simplified equations are consistently higher by approximately 5 – 15% which can be attributed to the conservative nature that can be advantageous to ensure safety by providing upper-bound estimates. The developed simplified equations provide a satisfactory level of accuracy for practicing engineers particularly in preliminary design stage where computational efficiency and rapid assessments are prioritized.

4 Conclusion

In this study, simplified equations were developed to estimate the roof displacements for rocking buildings at the instance of buildings start rocking. Once the displacements are calculated, outcomes can be used to estimate the base shear forces and bending moments at the base of the structure under uniform and triangular pressure along the height of the building. The developed equations were validated with detailed numerical models developed in OpenSees commercial software. The simplified calculations yield slightly conservative results, with a deviation ranging from 5 – 15%. In the context of engineering design, where conservative estimations are often preferred to accommodate for uncertainties, these differences are acceptable. According to the findings from this study, the developed simplified equations offer a practical and efficient alternative to follow in the preliminary design and assessment of rocking structures by ensuring the safety and resilience of structures.

6 References

Aghagholizadeh, M. (2020). A finite element model for seismic response analysis of vertically-damped rocking-columns. Engineering Structures, 219. https://doi.org/10.1016/j.engstruct.2020.110894

Geoffrey R. Martin (2000). Earthquake resistance design of foundations-retrofit of existing foundations.

Ghobarah, A. (2001). Performance-based design in earthquake engineering: state of development. In *Engineering Structures* (Vol. 23). www.elsevier.com/locate/engstruct

Li, S., Tsang, H. H., & Lam, N. (2022). Seismic protection by rocking with superelastic tendon restraint. Earthquake Engineering and Structural Dynamics, 51(7), 1718–1737. https://doi.org/10.1002/eqe.3635.

Li, S., Tsang, H. H., & Lam, N. (2023). Seismic internal force in rocking shear frame with superelastic tendon restraint. Earthquake Engineering and Structural Dynamics, 52(7), 2272–2293. https://doi.org/10.1002/eqe.3882.

McKenna F, Fenves GL, Scott MH. Open system for earthquake engineering simulation. University of California: Berkeley, CA, 2000.

Nitti, G., Lacidogna, G., & Carpinteri, A. (2021). An analytical formulation to evaluate natural frequencies and mode shapes of high-rise buildings. Curved and Layered Structures, 8(1), 307–318. https://doi.org/10.1515/cls-2021-0025.

Vassiliou, M. F., Mackie, K. R., & Stojadinović, B. (2017). A finite element model for seismic response analysis of deformable rocking frames. *Earthquake Engineering and Structural Dynamics*, *46*(3), 447–466. https://doi.org/10.1002/eqe.2799.