INFLUENCE OF SOIL TYPES ON SEISMIC BEHAVIOUR OF RC FRAMED BUILDING WITH SHEAR WALL ON ROCKING FOUNDATION

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ABSTRACT

Growing demands of land and population-level lead to the construction of multi-storey RC frame buildings with shear walls even in high seismic regions though it is susceptible to severe damage due to increased seismic demand. Studies shown that presence of rocking foundation can reduce the seismic response of the shear wall, thereby minimizing associated damage by enhancing energy dissipation capacity through uplifting from the soil medium and re-centring ability at the level of rocking foundation due to the cyclic nature of the earthquake.

Present study is an attempt to investigate behaviour of RC building with shear wall on rocking foundation considering soil structure interaction. The study focuses on different foundation soil material to capture the beneficial response. For this study, a generic frame model has been selected with considerably different redundancy in longitudinal and transverse directions. Finite element analysis has been used to investigate the response of the soil and structure. The responses have been analysed for the roof displacement and settlement behaviour of the foundation. It has been observed that rocking base can be used as alternative foundation for medium dense and soft soil.

Keywords: *Rocking Foundation, Shear Wall, Finite Element Analysis, Soil Structure Interaction*

1. INTRODUCTION

Multi-storey RC frame building with Unreinforced Masonry infill or RC shear walls are commonly observed construction practice even in high seismic regions to meet the ever-increasing housing demand. Unfortunately, India has suffered many earthquakes in the last century and the devastating consequences of the poor performance of URM infilled and RC shear walled frame buildings, even in moderate earthquakes have highlighted the importance of understanding inelastic behaviour of these buildings in context of alternative design practices to account for their seismic safety [1-5]. Rocking behaviour of rigid block by Housner [6] brought new dimensions in earthquake resistant design where rocking mechanism can be used for the foundation to act as an isolation mechanism during seismic action. Earlier studies on the rocking rigid block shown that rocking mechanism may be beneficial for the structure [7-9]. Major conclusions drawn from the earlier studies shows that rocking behaviour is sensitive to minor changes in dimensions and also the ground motions. Later the studies carried out by Yim and Chopra [10]; and Psycharis [11] shows the behavior of SDOF (single degree of freedom) structures with soil structure interaction and gave various parametrical aspects of the system. Gazetas [12] proposed design chart for the stiffness values in six degrees of freedom along with the correction factor of foundation embedment depth.

Modern earthquake engineering researchers extended the concept to the behaviour of reinforced concrete structures. Gajan and Kutter [13] studied the behaviour of shear walls subjected to rocking and proposed contact element modelling based on the contact area ratio (A/A_c) where A is the footing area and A_c is the area required to transfer the axial load safely to ground without any permanent deformation. Gelagoti et.al. [14] considered a one bay two storey framed structure subjected to various ground motions and concluded rocking is advantageous for very strong seismic motions. Whereas Shear wall is one of the major structural components in modern seismic resistant design. However, failure of shear walls was noticed during seismic events were given by Fintel [15]. Rocking base isolation studies are limited for the complete structure. Hence an effort has been made on that.

The purpose of this study is to capture the seismic behaviour of a generic framed structure with shear wall components, where the shear wall foundation is allowed to uplift during earthquakes for various site conditions. In the above-mentioned studies soil structure interaction part were modelled by using continuum elements or Beam on Nonlinear Winkler Foundation (BNWF). Considering the computational effort BNWF model has been chosen for this study.

2. DESIGN PARAMETERS FOR STRUCTURE AND FOUNDATION

2.1 Design of Structure

A generic plan considered for the study has been shown in Fig.1. The height of each floor was chosen to be 3.3 m. The structure is assumed to be in seismic zone III, having zone factor value of 0.16g (peak ground acceleration). M20 concrete and Fe415 steel has been assigned for the design sections. The dead load and live load have been assigned as per IS 875 [16-17]. IS 1893 [18] has been used for the seismic design and the structure. The structure has been designed an SMRF with response reduction factor of 5. Planar shear wall has been considered for this study. Locations of the shear wall have been chosen in a way that centre of mass and rigidity of the structure remains same as per the guidelines given by the Indian standards. Table 1 provides the details of load combinations were used for designing the structure and foundation. The analysis and design were carried out in nonlinear software SAP 2000 [19].

Foundation has been designed for the factor of safety of three with respect to bearing capacity for the conventional design and for the rocking design it has been reduced to two. To model the flexible foundation behaviour springs with varying have been attached to shear wall members. It has to be noted flexible foundation corresponds to behaviour of uplifting or foundation isolation not the internal deformations in the foundation. Similarly, rigid footing in the in the Fig 2. Mentions the foundation is rigid in terms of internal deformations. The interaction behaviour spring stiffness values, given in Fig.2 has been modelled using link elements considering FEMA 356 [20] guidelines. Considering orthogonality, the longitudinal direction of the plan has been considered for the analysis in this present study.

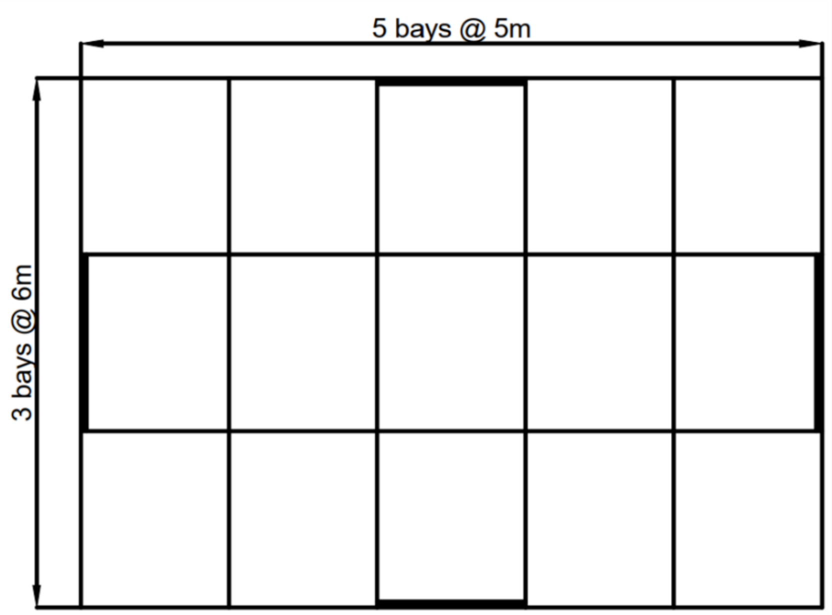
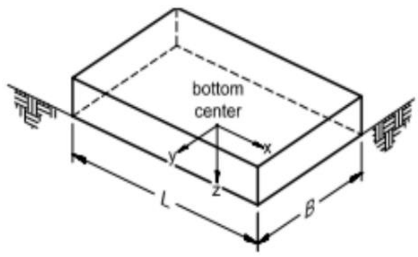


Fig. 1 - Plan of structure for the considered in the study

Table 1 – Load Combinations for Design

Load Combinations for Structural Elements as per IS 875 (Part 5)	1.5 (DL + IL)
	1.2 (DL + IL ± EL)
	1.5 (DL ± EL)
	0.9 DL ± 1.5EL
Load Combinations for Foundation as per IS 1904-1986	DL + IL
	DL + IL+ EL

* DL-Dead Load; IL- Imposed Load; EL- Seismic Load

Degree of Freedom	Stiffness of Foundation at Surface	Note
Translation along x-axis	$K_{x,\,sur} = \frac{GB}{2-\nu}\left[3.4\left(\frac{L}{B}\right)^{0.65}+1.2\right]$	
Translation along y-axis	$K_{y,\,sur} = \frac{GB}{2-\nu}\left[3.4\left(\frac{L}{B}\right)^{0.65}+0.4\frac{L}{B}+0.8\right]$	
Translation along z-axis	$K_{z,\,sur} = \frac{GB}{1-\nu}\left[1.55\left(\frac{L}{B}\right)^{0.75}+0.8\right]$	
Rocking about x-axis	$K_{xx,\,sur} = \frac{GB^3}{1-\nu}\left[0.4\left(\frac{L}{B}\right)+0.1\right]$	
Rocking about y-axis	$K_{yy,\,sur} = \frac{GB^3}{1-\nu}\left[0.47\left(\frac{L}{B}\right)^{2.4}+0.034\right]$	Orient axes such that $L \geq B$
Torsion about z-axis	$K_{zz,\,sur} = GB^3\left[0.53\left(\frac{L}{B}\right)^{2.45}+0.51\right]$	

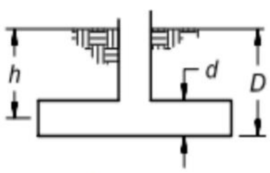
Degree of Freedom	Correction Factor for Embedment	Note
Translation along x-axis	$\beta_x = \left(1+0.21\sqrt{\frac{D}{B}}\right)\cdot\left[1+1.6\left(\frac{hd(B+L)}{BL^2}\right)^{0.4}\right]$	
Translation along y-axis	$\beta_y = \beta_x$	
Translation along z-axis	$\beta_z = \left[1+\frac{1}{21}\frac{D}{B}\left(2+2.6\frac{B}{L}\right)\right]\cdot\left[1+0.32\left(\frac{d(B+L)}{BL}\right)^{2/3}\right]$	d = height of effective sidewall contact (may be less than total foundation height)
Rocking about x-axis	$\beta_{xx} = 1+2.5\frac{d}{B}\left[1+\frac{2d}{B}\left(\frac{d}{D}\right)^{-0.2}\sqrt{\frac{B}{L}}\right]$	h = depth to centroid of effective sidewall contact
Rocking about y-axis	$\beta_{yy} = 1+1.4\left(\frac{d}{L}\right)^{0.6}\left[1.5+3.7\left(\frac{d}{L}\right)^{1.9}\left(\frac{d}{D}\right)^{-0.6}\right]$	For each degree of freedom, calculate $K_{emb} = \beta K_{sur}$
Torsion about z-axis	$\beta_{zz} = 1+2.6\left(1+\frac{B}{L}\right)\left(\frac{d}{B}\right)^{0.9}$	

Fig. 2 – Spring stiffness values for rigid footing (FEMA 356)

2.2 Site Classifications

According to NEHRP [21] site classifications based on the shear wave velocity of the foundation soil material three site conditions were selected for this study. The details of the site conditions selected for the study were given in Table 2.

Table 2 - Sites considered for the present study

Site Class	Shear Wave Velocity (m/s)	Description of site
C	360	Very Dense Soil and Soft rock
D	200	Stiff Soil
E	150	Soft Soil

2.3 Soil Properties

Anbazhagan et.al [22] provides the correlation in Eq. (1) to correlate the density of the soil with the shear wave velocity for the Indian environment. The correlations have been made by conducting field studies in Lucknow, India situated in seismic zone 3.

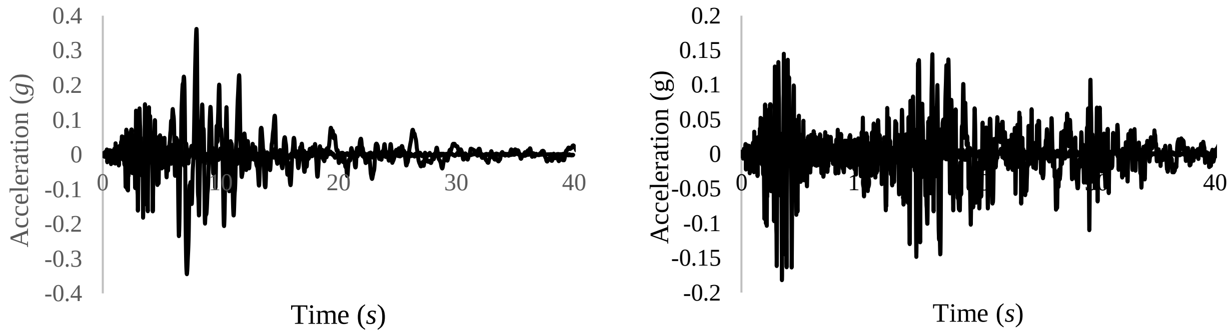
$$\rho_w = 0.412 V_s^{0.262} \quad (1)$$

$$\rho_d = 0.523 V_s^{0.193} \quad (2)$$

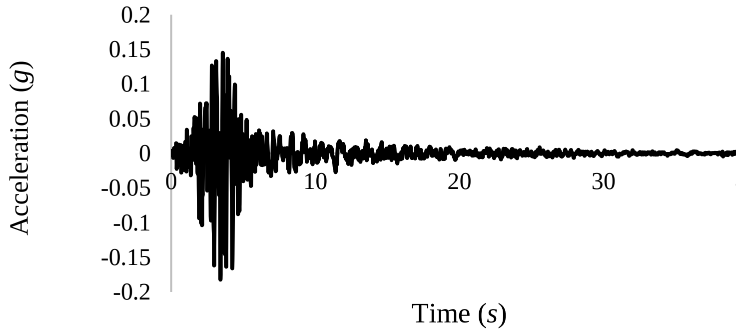
Where ρ_w and ρ_d are bulk and dry densities respectively, V_s corresponds to the shear wave velocity. Similarly, allowable bearing capacity of the soil and the shear modulus can be estimated using the correlations given by Tezcan [23] based on the shear wave velocity and density.

2.4 Dynamic Time History Data

The seismic behaviour of conventionally designed and rocking isolation design has been tested for various ground motions. Three ground motions have been selected in a way that it can cover various range of seismic motion based on PGA (peak ground acceleration) and acceleration response spectrum. Details of the ground motions has been shown in Fig. 3 and Fig.4.



(a) Hollister (b) Yermo



(c) Pomona

Fig. 3 – Acceleration time history plots for various selected ground motions

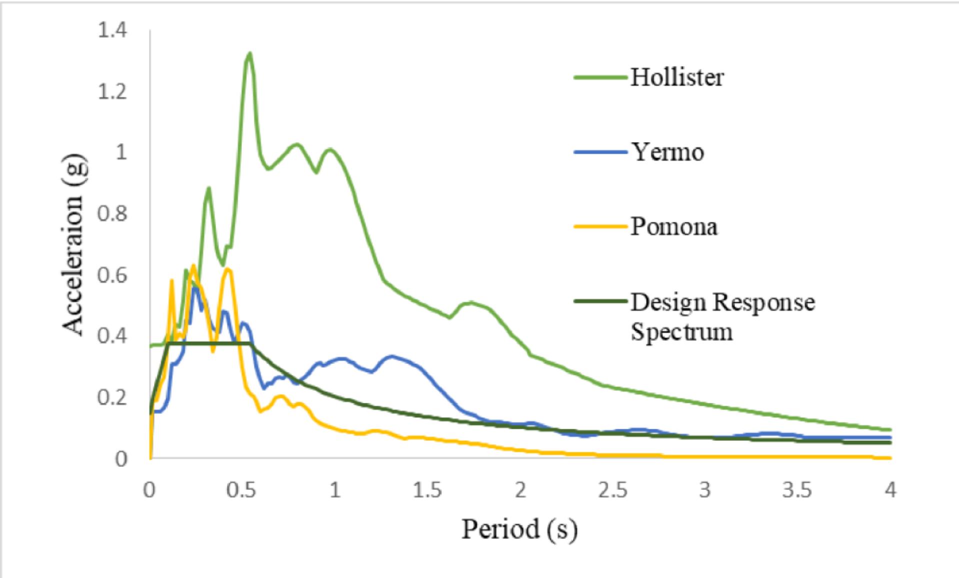
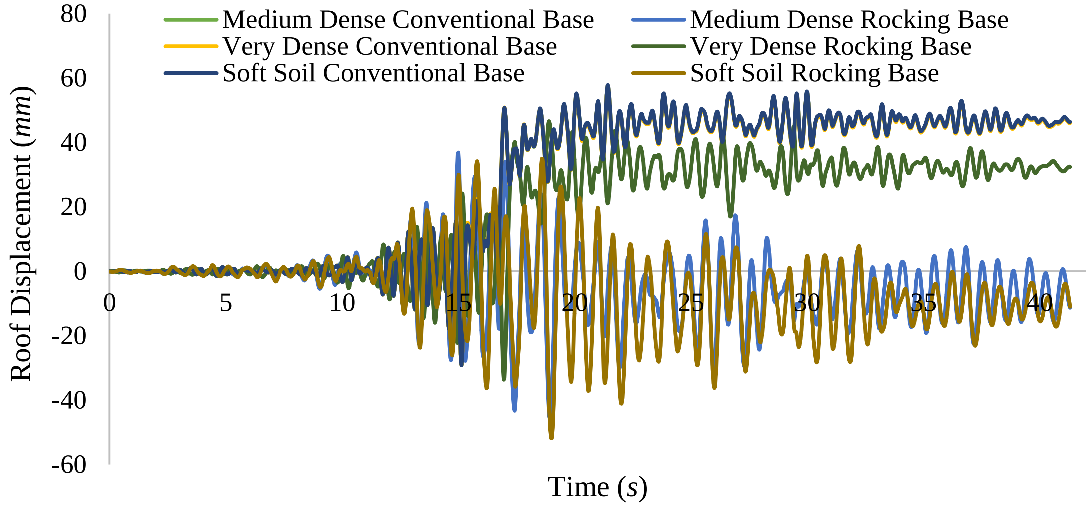


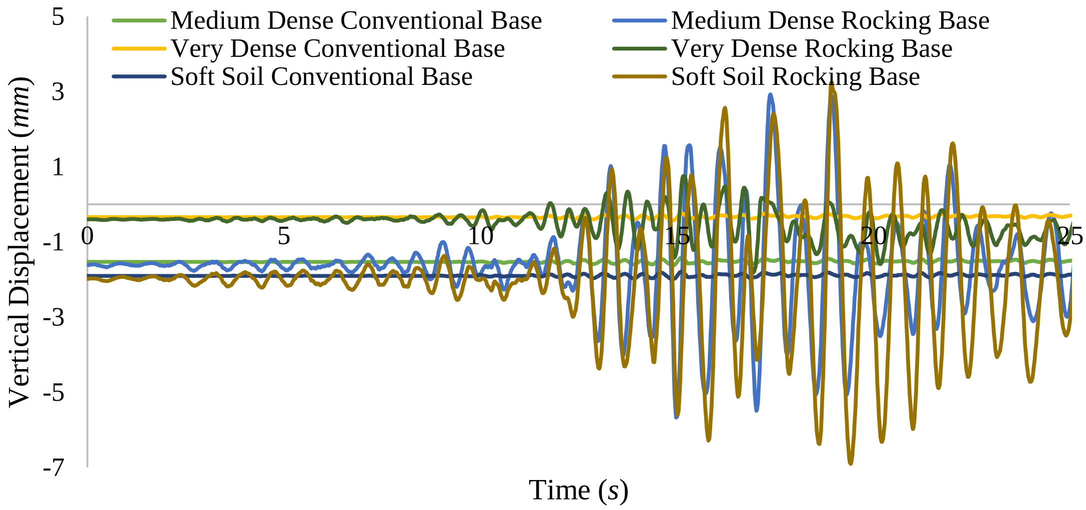
Fig. 4 – Acceleration spectrum of various selected earthquakes for the study

3. SEISMIC PERFORMANCE IN VARIOUS SEISMIC MOTION

The comparison of the conventional design and rocking base are shown in Fig.5 in terms of roof displacement and settlement for the structure subjected to Yermo ground motion. Fig.5a shows the roof displacement for the design alternatives for various site conditions. It has been seen clear that conventionally design foundation system leads excessive permanent roof displacement than the allowable roof displacement of 0.004H (where H is the height of the structure). Whereas rocking base system performs well without any permanent roof displacement. It has to be noted that in very dense soil both base leading to permanent roof displacement. But rocking base system shows roof displacement within allowable limits shows the possibility of rehabilitation and retrofitting for shear walls. From the vertical displacement plot shown in Fig.5b both of the design have lesser dynamic displacement for the very dense soil condition, it may be one of the reason for the permanent roof displacement where both design methods behaves in a similar manner.



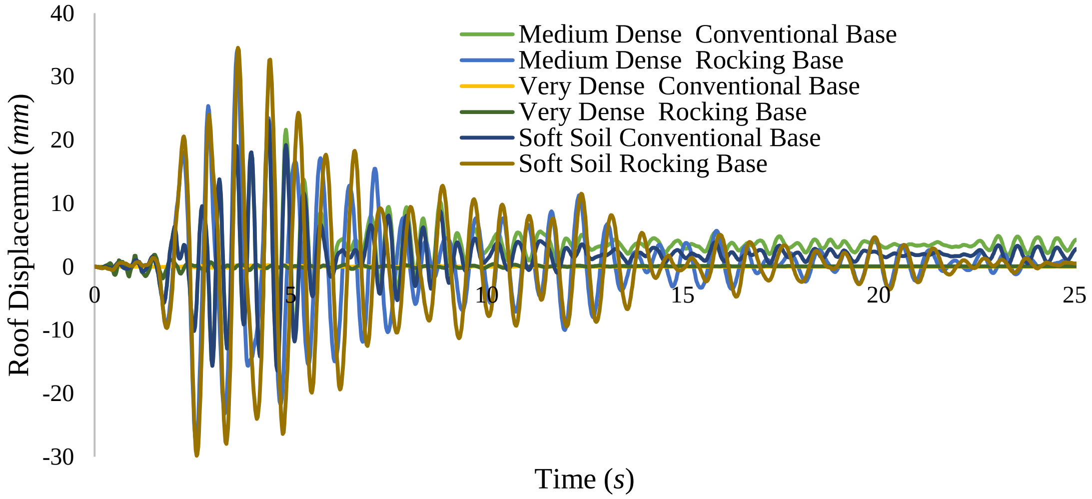
(a)



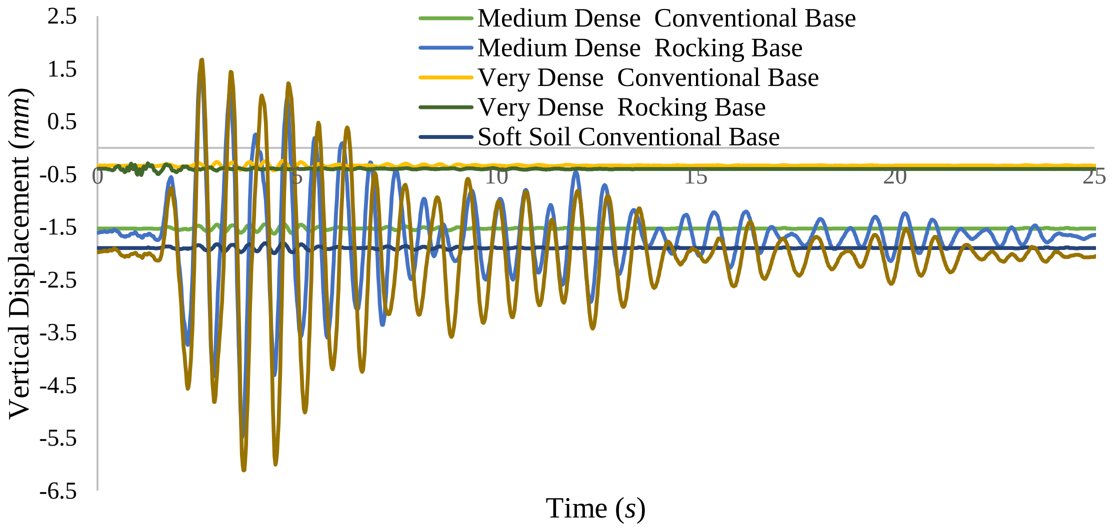
(b)

Fig. 5- Typical comparison of time-displacement plot for various site conditions for Yermo seismic motion (a) Roof displacement plot; (b) Vertical displacement plot

The comparison of the conventional design and rocking base are shown in Fig.6 in terms of roof displacement and settlement for the structure subjected to Pomona ground motion. Fig.6a shows the roof displacement for the design alternatives for various site conditions. It has been seen clear that both of the foundation system behaves similarly without any excessive roof displacement. Whereas rocking base system experienced higher roof displacement because of uplifting nature but the roof displacement are within allowable limits. Similar behaviour can be noted from the vertical displacement plot shown in Fig.6b.



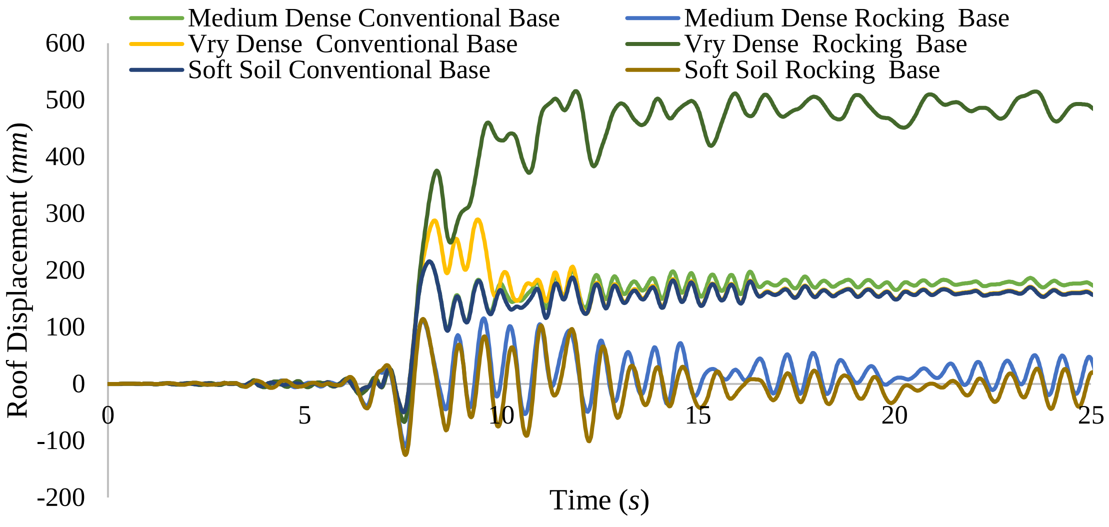
(a)



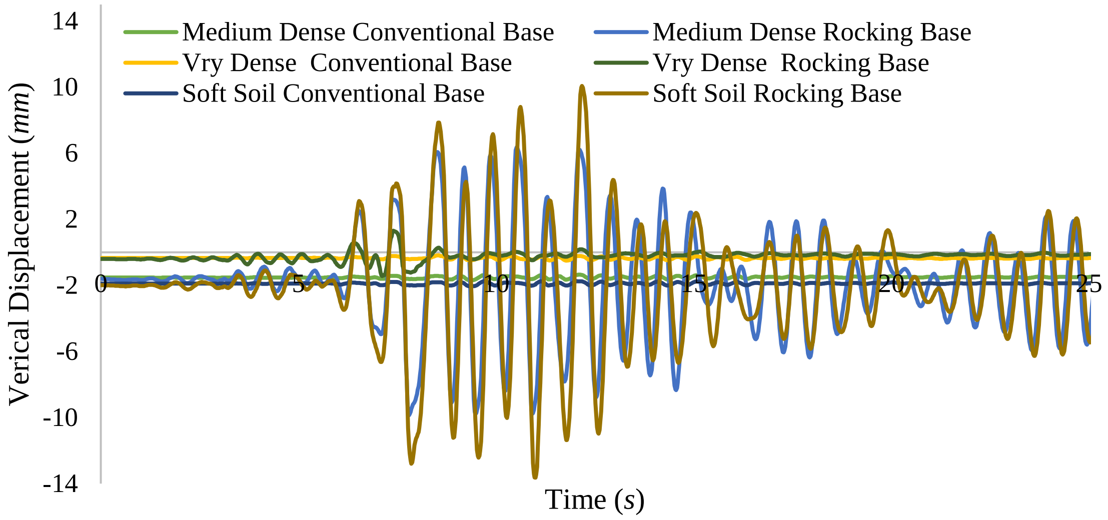
(b)

Fig. 6 - Typical comparison of time-displacement plot for various site conditions for Pomona seismic motion (a) Roof displacement plot; (b) Vertical displacement plot

Fig.7a shows the roof displacement for the two design alternatives for various site conditions. It has been seen clear that conventionally design foundation system leads excessive permanent roof displacement than the allowable roof displacement of 0.004H (where H is the height of the structure). Whereas rocking base system performs well without any permanent roof displacement. It has to be noted that in very dense soil both base leading to permanent roof displacement. From the vertical displacement plot shown in Fig.7b both of the design has lesser dynamic displacement for the very dense soil condition, it may be one of the reasons for the permanent roof displacement where both design methods behave in a similar manner. In soft soil the vertical displacement is more for rocking base but within the allowable limits of 25mm.



(a)



(b)

Fig. 7 - Typical comparison of time-displacement plot for various site conditions for Hollister seismic motion (a) Roof displacement plot; (a) Vertical displacement plot

4. PERFORMANCE OF COLUMN NEAR ROCKING FOUNDATION

When the Shear wall foundation is allowed to rock then there will be additional forces and transmitted to the nearby columns. Those additional forces should not cause the column to fail during the seismic motions to ensure the safety of structure. The comparison of Moment for Hollister earthquake which is quite strong relative to other two earthquakes has been shown in Fig.8 for medium dense soil and soft soil. However, for the conventional design and rocking design there induced a permanent moment because of the failure of structural members. For the soft soil response is nonlinear because of the settlement associated with it whereas in medium dense soil response is linear.

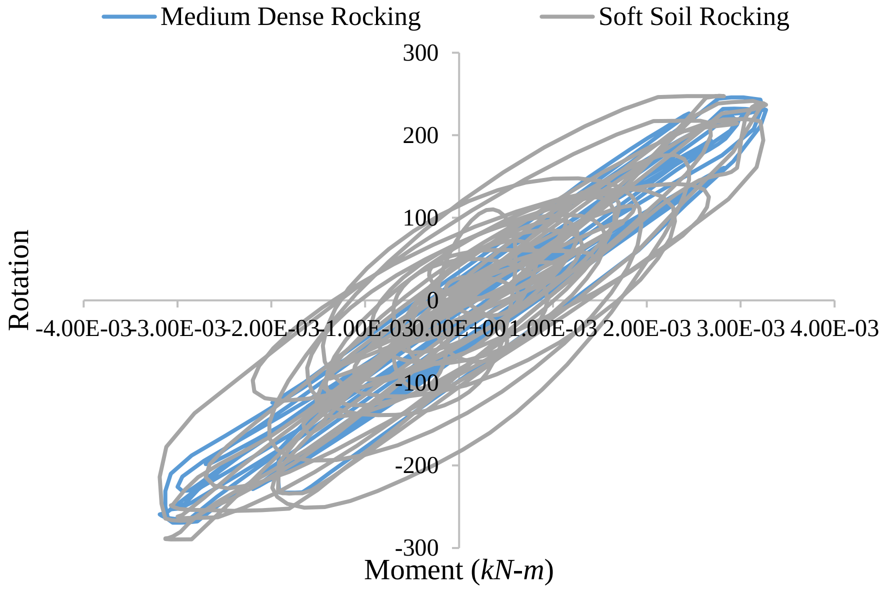


Fig. 8- Comparison of moment rotation curve for different site conditions subjected to Hollister seismic motion

5. CONCLUSIONS

The seismic performance of the conventional foundation design and the rocking base design has been evaluated to capture the benefits of the rocking base over the conventional foundation system of the buildings. It has been found that the rocking base can be used as an alternative design practice to account for seismic safety of the RC frame buildings with shear walls as the rocking mechanism helps in dissipation of the energy faster without collapse. Further, it has been observed that under moderate to strong ground excitation, rocking base performs satisfactorily in medium and soft soil compared to very dense soil for the building with regular plan dimensions and with regular placement of RC shear walls. In very dense soil, rocking base experiences the smaller roof displacement which are within allowable roof drift limits prescribed in seismic design standard.

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