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Dynamic Soil-Structure Interaction Analysis of RC Framed Building with Various Positions of Shear Walls

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Abstract: In the present study, a three-dimensional dynamic soil–structure interaction analysis of symmetric buildings in time domain is performed using IS spectrum ground motion record corresponding to zone III to evaluate the dynamic response of structure-foundation-soil system. Three types of shear wall buildings of aspect ratio 1, 1.5, 2, 3 and 4 categorized based on the shear wall locations were considered in conjunction with four types of soil of shear wave velocities ranging from 150m/s to 1200 m/s, symbolizing soil classes B, C, D and E of FEMA-356:2000. Integrated structure-foundation-soil systems were analyzed using commercial finite element software LSDYNA, based on direct method of soil–structure interaction (SSI) assuming linear elastic behavior. The study shows considerable variation in dynamic characteristics and structural seismic response of the structure due to the incorporation of the effect of flexibility of soil and position of shear walls. Tall buildings with shear walls placed at the exterior corners experience the least base shear.

***Keywords:** Soil-structure interaction, Soil flexibility, Shear wall, Base shear, Time history*

1. Introduction

Post-earthquakes, it is observed that major destructions are usually caused by the collapse of multistoried buildings. The studies on seismic behavior of these buildings reveal that, dynamic responses are widely affected by the local site conditions. During earthquakes, there is a dynamic interaction between the structure and the soil on which it is constructed. This interaction between the structure and the soil is reflected by substantial modification of stress components and deflections in the structural system in comparison with behavior of the system on a rigid supporting foundation. The interaction of soil with the structure that it supports is generally termed as dynamic soil-structure interaction Wolf [1].

The structures supported on soil have different dynamic response as compared to identical structures supported on rigid ground since the flexible support structures have more degrees of freedom than the structures resting on rigid ground. Besides, a significant part of vibrational energy of the structure is dissipated by radiation of waves into the supporting medium.

An extensive literature review indicates that the seismic responses of buildings are generally altered by flexibility of soil. The flexibility of soil causes lengthening of lateral natural period due to overall decrease in lateral stiffness. The effects of lengthening of lateral natural period in buildings due to lessening of lateral stiffness were reported by [2-5]. Further studies on impact of dynamic soil-structure interaction on base shear, inter-storey shears, and moments of building were carried out by Saad et al.[6]. The role of dynamic soil-structure interaction in seismic behavior of mid-rise building frames in terms of increase in the lateral deflections, inter-storey drifts and changing performance level of structures from life, close to near collapse or total collapse was studied by Tabatabaiefar et al.[7]. The virtues of considering nonlinear soil–structure interaction analysis over conventional fixed-base and elastic-base models were addressed by Raychowdhury [8] to show the significant reduction in force and displacement demands. Shakib [9] evaluated the effects of base flexibility on response of torsionally coupled system using two simultaneous lateral components of El Centro 1940 earthquake records. A study on the transient response of elastic structure embedded in a homogeneous, isotropic and linearly elastic half space was presented by Yazdchi et al. [10] to determine the importance of including the foundation stiffness in the analysis. Azadi and Soltani [11] determined the influence of foundation-soil-structure interaction on non-linear dynamic behavior of a cement-storage silo structure using finite element program ANSYS. The study showed the significance of SSI on base-shear and overturning response of silo structure supported on soft soil. The influence of inelastic dynamic soil–structure interaction on seismic vulnerability assessment of buildings was studied by Sáez et al. [12]. The seismic vulnerability in study was evaluated in terms of analytical fragility curves constructed on the basis of non-linear dynamic finite element analysis.

The present study focuses on the three-dimensional SSI analysis of multi storied RC buildings with and without shear wall over raft foundation subjected to IS spectrum ground motion corresponding to zone III in time domain. Finite element method was utilized to evaluate the seismic responses in structure. Results of the analyses are expressed in terms of parameters such as aspect ratio (h/r) which is the height-to-base ratio of building, relative stiffness of superstructure (K_{sb}) and relative stiffness of raft (K_{rs}).

1.1 Soil-Structure Interaction

During ground motion, the response of structure is dependent on the motion of the supporting soil and response of the soil is influenced by the motion of structure. This interdependency of response between the structure and the soil is referred to as SSI. Present study adopts direct method of soil–structure interaction in which the entire soil-structure system is modelled in a single step. This method requires computer program to deal with the behavior of soil and structure simultaneously since solving the governing equations of motion for the structure incorporating soil interaction are relatively complex.

The dynamic equilibrium equation describing the motion of structure subjected to a transient external load can be written as.

$$\left[M^F\right]\left\{\ddot{u}^F\right\}+\left[C^F\right]\left\{\dot{u}^F\right\}+\left[K^F\right]\left\{u^F\right\}=\left\{F^F{}_{dyn}\right\}+\left\{F^F{}_{st}\right\}$$

Where,

$[M^F]$, $[C^F]$, $[K^F]$ are characteristic matrices for consistent mass, damping and stiffness of a system.

$\{F^F{}_{st}\}$ is the pre-dynamic load vector including self-weight of the structure and $\{F^F{}_{dyn}\}$ is the dynamic load vector.

$\{u^F\}$ is the vector of nodal displacements and a super imposed dot indicates the time derivative.

1.1.1 Structural idealization

Buildings considered in the study are multi-storey reinforced concrete framed buildings with and without shear wall on raft foundation of aspect ratio (h/r) 1, 1.5, 2, 3 and 4. Buildings are symmetric in plan with 3 bays along each direction having equal length. The effect of infill is being neglected in the study. RC framed building without shear wall and infill is designated as bare frame. Shear walls with same shearing area were placed symmetrically in either directions of the building in plan to study the effect of position of shear wall. In each building shear walls having the same mass and shearing area were placed at center bay of external frames, at the core and at all four corners of the building. These buildings are designated as SW1, SW2 and SW3. Storey height and length of all the bays of the building frames were chosen to be 3m and 4m respectively considering the buildings as domestic or small office building occupancy classification. Thickness of shear walls was varied from 150 to 250mm depending on the building height.

Based on respective Indian standard codes IS 456:2000 and IS13920:1993 the dimensions of building components were computed. Details of different geometric parameters of building components are as shown in Table 1.

1.1.2 Geotechnical idealization

Present study treats the soil as homogenous, isotropic and elastic half space medium in examining the soil-foundation and structure interaction. The inputs for linear elastic analysis were density, Young’s modulus (Es), and Poisson’s ratio (μ) of soil. Based on the shear wave velocity, four types of non-cohesive soils were considered in the analysis namely, S_b, S_c, S_d, and S_e symbolizing soil classes B, C, D and E of FEMA-356:2000. The details of soil parameters are as tabulated in Table 2. Boundaries of the soil are to be placed at a sufficient distance from structure such that static response in soil dies out at that distance Wolf [1]. In this study, perfectly matching layer (PML) concept was adopted for efficient approach toward the bounded-domain modelling of wave propagation on unbounded domains.

1.1.3 Finite Element Modeling

Finite element software LS DYNA was used in modeling and analyses of structure and soil in the study. The idealization of building frames were done using 3D space frames with Belytschko-Schwer resultant beam element having three translational and three rotational degrees of freedom per node. Slab components at various levels were modelled using Belytschko-Tsay shell element having four nodes with six degrees of freedom at each node. Belytschko-Tsay shell element possess both bending and membrane capabilities. The soil stratum is modelled using fully integrated S/R solid having three translational degrees of freedom at each node. At interface of structure and soil, to overcome the node incompatibility problem, a tied surface to surface contact between the soil surface and base of the raft is employed. Perfectly matching layer (PML) corresponding to infinite soil continuum and equivalent to an unbounded domain to absorb and attenuate all waves outgoing from it are placed adjacent to the truncated soil model.

Soil is an infinite elastic medium. PML model (Basu [13]) is one of the eminent approaches in bounded-domain modelling of wave propagation on unbounded domains. The model is accurate with small bounded domains at very low computational cost. The models are long-time stable, with time step sizes alike the matching fully elastic models. The idealized 3 bay x 3 bay frame with shear walls at various positions and idealized soil-foundation-structure model are as shown in Figure 1.

1.2 Methodology

Using finite element software LS DYNA the three-dimensional finite element model of the whole structure-foundation-soil system was generated. Time history analysis of this integrated system was carried out for zone III IS spectrum ground motion. The time histories of acceleration were applied in the global X direction for the integrated structure-foundation soil model. The damping ratio equivalent to 5% of critical damping was assumed for structures and soil. Lateral loads due to other causes were neglected.

Table 1: *Dimensions of components of building*

h/r	Columns (m)		Shear wall thickness
	Up to 3 storey	Above 3 storey	(m)
1.0	0.32 x 0.32	0.32 x 0.32	0.15
1.5	0.35 x 0.35	0.35 x 0.35	0.15
2.0	0.40 x 0.40	0.35 x 0.35	0.20
3.0	0.50 x 0.50	0.40 x 0.40	0.20
4.0	0.60 x 0.60	0.50 x 0.50	0.25

Raft foundation slab: 0.3m
Roof and floor slab: 0.15m
Beams : 0.23X0.23m

Design of structural elements was carried out considering M20 grade concrete and Fe 415 grade steel.

Table 2: *Details of soil parameters considered [FEMA 356 (2000)]*

Soil profile type	Description	Shear wave velocity (V_s) (m/sec)	Poisson's ratio μ	Unit weight (ρ) (kN/m^3)	Young's modulus (E_s) (kN/m^2)
Sb	Rock	1200	0.3	22	8.40E+6
Sc	Dense soil	600	0.3	20	1.91E+6
Sd	Stiff soil	300	0.35	18	4.46E+5
Se	Soft soil	150	0.4	16	1.03E+5

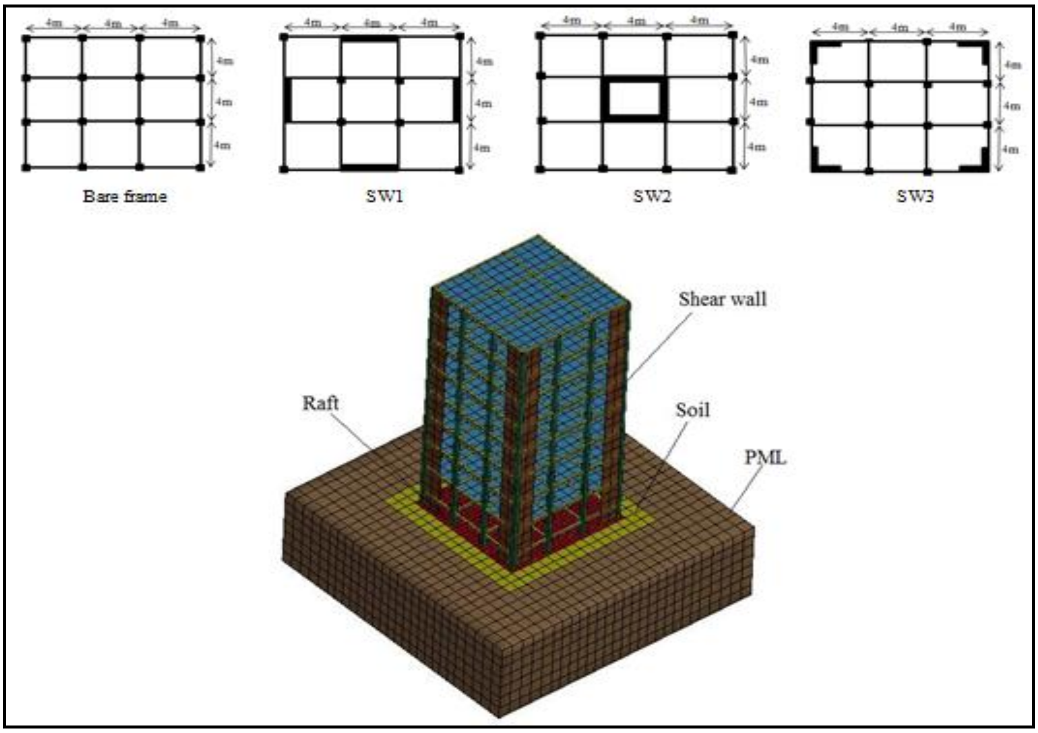


Figure 1: *Plan of bare frame and frame with various locations of shear wall and Idealized soil-foundation-structure model*

The variations in structural responses due to effect of soil flexibility and varying shear wall position were studied and responses in building founded on flexible base were further compared with conventional rigid base.

In the present study, interaction amid the super structure, raft and soil are expressed in terms of relative stiffness of raft and soil (k_{rs}) and relative stiffness of soil and structure (k_{sb}), which are the ratios of absolute stiffness of super structure (k_b), raft

(k_r), and soil (k_s). The relative stiffness k_{rs} and k_{sb} in the study are expressed as per Hemsely[14] and Wu[15] recommendations which are as follows.

$$K_{rs} = \frac{E_r(1-\upsilon_s^2)}{E_s(1-\upsilon_r^2)}\left(\frac{t_r}{B}\right)^3$$

$$K_{sb} = \frac{V_s}{h\omega_u}$$

Where,

E_s = Elastic modulus of soil; E_r = Elastic modulus of raft; υ_s = Poisson's ratio of soil; t_r = thickness of raft; B= width of the raft; υ_r = Poisson's ratio of foundation material; V_s= shear wave velocity; h= Height of the building; ω_u= cyclic frequency of the structure.

Analyses were performed for K_{sb} values ranging from 1 to 17 and K_{rs} values ranging from 0.00001 to 0.001. Lower limit of K_{sb} values corresponds to building of high aspect ratio over soft soil and higher limit corresponds to building of lower aspect ratio over hard soil. Similarly lower limit of K_{rs} corresponds to foundation over hard soil and higher limit corresponds to foundation over soft soil.

1.3 Results & Discussions

Three-dimensional SSI analyses were carried out on finite element models of integrated soil- foundation-structure system. The effects of SSI were studied regarding four different soil types and three shear wall positions. Responses were evaluated in terms of variation in base shear and inter-storey drift due to the effect of soil flexibility and varying shear wall positions. The absolute maximum base shear was determined from the response time history. Further, the seismic responses determined from SSI analysis were compared with conventional rigid base condition to determine the effect of soil flexibility.

1.3.1 Lateral Natural Period

The values of natural period found from the free vibration analysis of integrated SSI system are plotted in Figure 2. From Figure 2 it is observed that natural period values of buildings with consideration of soil flexibility are higher than the conventional fixed based condition. The value of natural period increases with increase in value of K_{rs} and aspect ratio. The value of natural period in buildings with shear wall are very much lower than bare frame building due to increased building stiffness with the addition of shear wall. Among shear wall buildings, the higher values of natural period are observed in SW3 buildings and lower in SW2 buildings.

1.3.2 Base shear

Representative time history plot of base shear in SW3 type shear wall building with an aspect ratio of 1 is as shown in Figure 3. The absolute maximum base shear of SW3 shear wall building with raft foundation is obtained at different times when the structure-foundation- soil system interacts with different types of soil. The absolute maximum base shear occurred at 15.5 sec, 15.9 sec, 15.7 sec, and 15.1 sec for Krs values of 0.00001, 0.00008, 0.001 and 0.001 respectively. However with conventional fixed based condition absolute maximum base shear occurred at 10.5 sec.

As depicted in Figure 4 it is observed that, base shear values obtained by the conventional fixed base condition were observed to be very much higher than the values obtained by considering the effect of soil. In general, base shear values decrease with increase in value of K_{rs} and increase with increase in h/r ratio. In shear wall buildings maximum base shear values are observed in SW1 for all values of K_{rs} except for K_{rs}=0.001 wherein SW3 configuration shows the highest value. However, the minimum value of base shear is observed in SW3 shear wall configuration for K_{rs} value ranging from 0.00001-0.0001 for very tall buildings having aspect ratio 3 and 4. For buildings with aspect ratio ranging from 1 to 2 and K_{rs} value 0.0001-0.001, SW2 shows the least base shear value.

1.3.3 Inter-storey drift

Inter-storey drift is the significant index in determining the structural performance of buildings. It is defined as the relative translational displacement between two consecutive floors. The expression for inter-storey drift between two consecutive floors is as follows

$$drift = \frac{(d_{i+1} - d_i)}{h}$$

Where,

d_{i+1} and d_i are the deflections at (i+1) and i^{th} floor level respectively.

h is the storey height.

The representative figure of inter-storey drift of building with aspect ratio of 4 is as shown in Figure 5.

From Figure 5, it is observed that the inter-storey drift of buildings for the applied ground motion are within the drift limit of 0.004 times the storey height for all the values of K_{rs} as per Indian seismic code IS 1893:2002. It is also evident that the storey drift reduces with the provision of shear wall in the structure. For all the values of K_{rs}, least value of inter-storey drift is observed in SW2 type shear wall building with aspect ratio above 2. The storey drift variation due to the modification in storey stiffness corresponding to changes in column dimension and shear wall thickness are also evident in this figure.

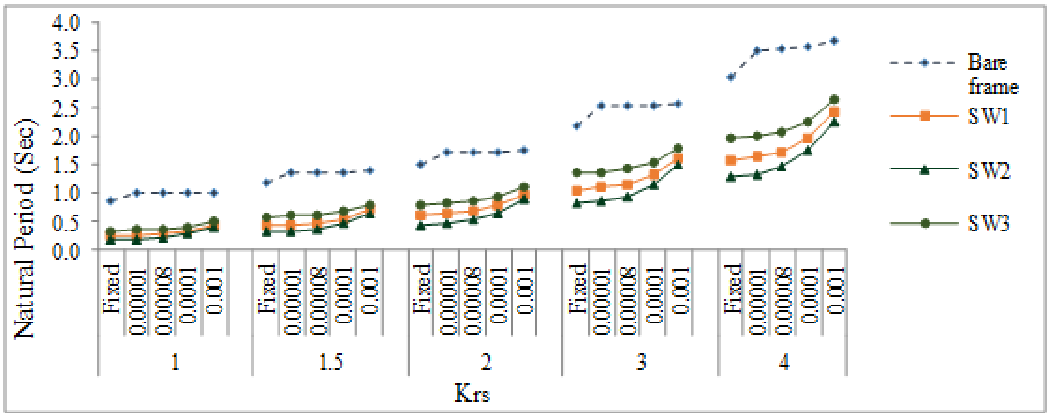


Figure 2: *Natural period values of building for varying K_{rs} values*

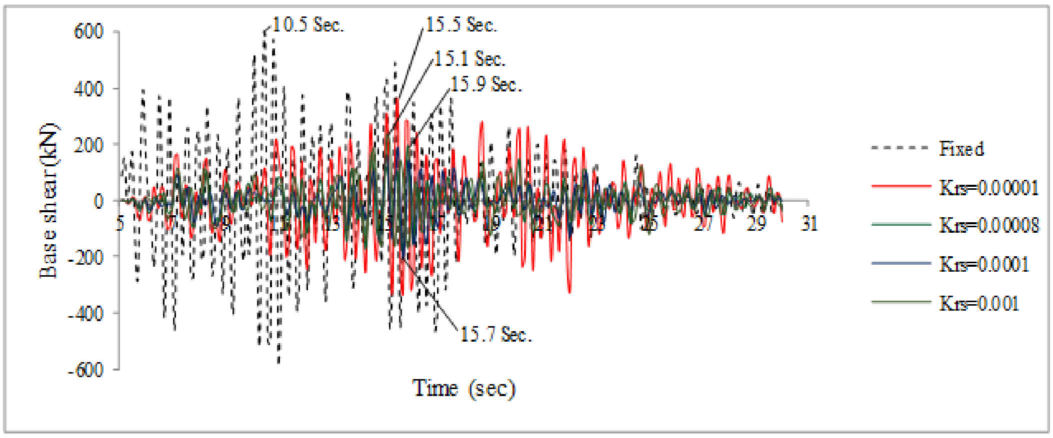


Figure 3: *Time history of base shear of SW3 type shear wall building with aspect ratio 1*

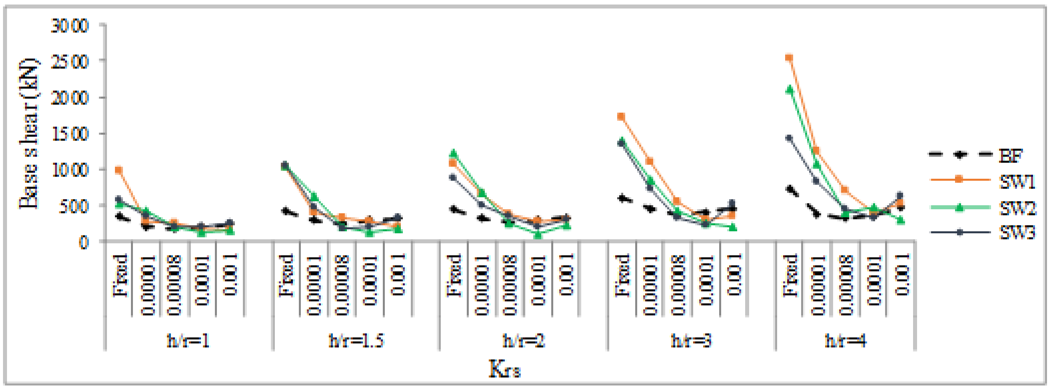
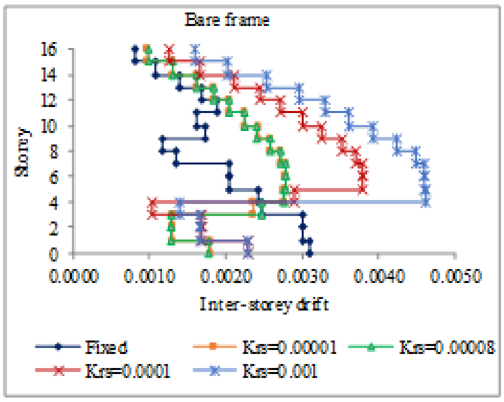
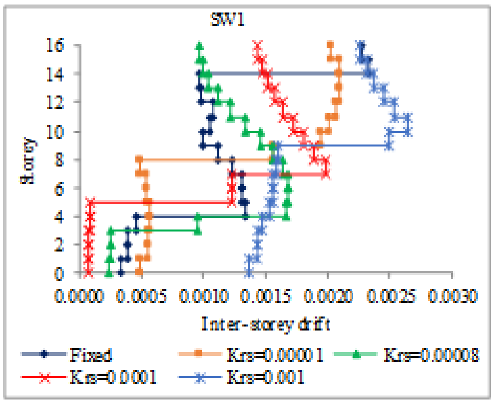


Figure 4: *Base shear values of building for varying K_{rs} values*





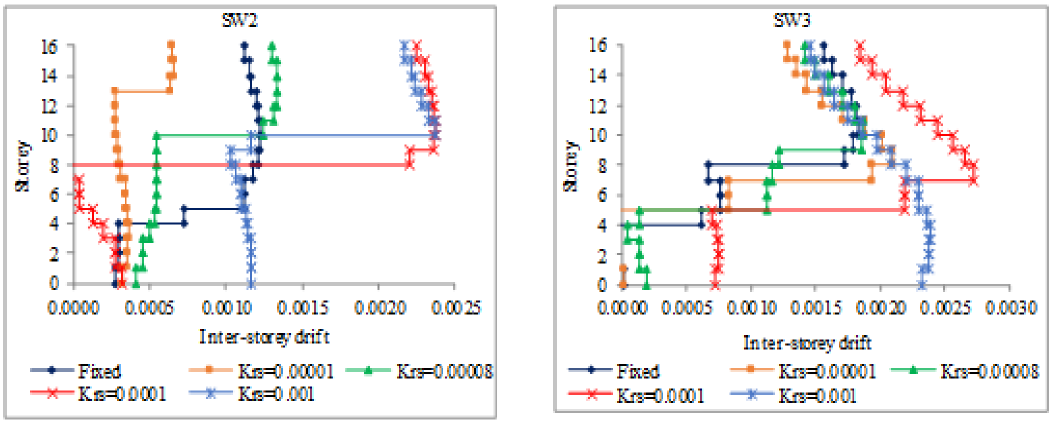


***Figure 5**: Inter-storey drift values of building of aspect ratio 4 for varying values of K_{rs}*

1.4 Conclusion

Effects of SSI were studied on multi storied RC frame buildings with shear walls at various locations subjected to IS spectrum ground motion record corresponding to zone III. To understand the significance of SSI, material properties of soil and geometric properties of buildings were varied. Seismic responses such as lateral natural period, base shear and inter storey drift were considered for the study. The absolute maximum base shear from SSI analysis was compared with conventional analysis.

The following conclusions are drawn from the present study.

- Natural period values of buildings with consideration of soil flexibility are higher than the conventional fixed based condition. Variation increases with increase in value of K_{rs} and height of building. Highest and lowest values of natural period are observed in SW3 and SW2 type shear wall buildings.
- Base shear values obtained by the conventional fixed base condition are very much higher than the values obtained by considering the effect of soil. Base shear values decrease with increase in value of K_{rs} and increase with increase in h/r ratio.
- In general, SW3 shear wall buildings, with shear walls places at exterior corners in either direction of building has the least base shear.
- Least value of inter-storey drift is observed in shear wall buildings with SW2 type shear wall configuration for buildings with aspect ratio above 2.

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