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Soil-structure interaction effects on seismic response of open ground storey buildings

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Abstract. Bhuj earthquake in India, 2001 had witnessed spectacular failures of a class of reinforced concrete multi-storied buildings termed as Open Ground Storey (OGS) buildings, necessitated by a functional demand to provide a parking space within a building plan. Due to the absence of brick-infilled walls at the ground floor, a sudden reduction in the storey stiffness can cause enormous seismic displacement demand in the ground storey itself. Further, the column-side sway mechanism is developed due to the presence of soft storey between the stiff upper storey and rigid base by assuming the soil support is stiff enough. The present study focuses on the effect of soil flexibility on the seismic response of open ground storey buildings. Analytical studies on typical open ground storey building models considering the soil flexibility have been carried out in SAP2000 software and static nonlinear analysis (pushover analysis) has been used to study the lateral response. Variation in boundary conditions are incorporated by simulating three different soil conditions hard, medium and soft, classified as mentioned in IS 1893 (Part 1) 2016. It is observed from the present study that the soil flexibility increases the lateral displacement and secondary forces associated with the P-Delta effect. Further, a parametric study is carried out to study the influence of soil flexibility in OGS buildings of various slenderness ratios. The importance of considering the influence of soil-structure interaction has been highlighted for obtaining a realistic performance point of the building. In addition, for preliminary and quick seismic assessment of huge stock of existing OGS buildings in Indian urban regions, a simplified methodology for estimating the lateral behaviour of a flexible base open ground storey building has been developed. This methodology is useful to segregate the highly vulnerable OGS buildings that undergo a detailed assessment prior to retrofit. The developed methodology is validated with the detailed analytical studies made on open ground storey buildings.

Keywords. Soft storey; soil-structure interaction; soil flexibility; open ground storey; seismic performance.

1. Introduction

Due to the scarcity of land caused by rapid urbanization, the practice of constructing high-rise buildings with open ground stories to allow for parking facilities has emerged in few countries. India being a country with a huge population has many such Open Ground Storey (OGS) buildings that are highly vulnerable to earthquake. These open ground stories are forced to undergo excessive lateral displacement due to base shear and moment caused by lateral forces, as these stilt floors have very low stiffness compared to the stories above, due to the absence of infilled walls. This means that the ductility demand of the open ground storey is artificially hiked by a factor approximately equal to the number of stories [1]. The Indian seismic code IS: 1893 (Part 1): 2016 [2] classifies a soft storey as the one whose lateral stiffness is less than that in the storey above. Interestingly, this classification renders most of the buildings in India, with no masonry infill walls in the ground storey, to be 'buildings with soft storey'.

Quite a number of studies have been carried out globally on the performance and retrofit of open ground storey buildings but more number of OGS buildings is limited to few countries like India and Turkey. The significance of considering the open storey in the seismic analysis of building had been highlighted by Arlekar *et al* [3]. 2001 Bhuj earthquake had witnessed spectacular failures of OGS buildings [4]. Kaushik *et al* [5] using nonlinear analyses, deliberated the effectiveness in improving the performance of OGS buildings with various strengthening schemes. Varughese *et al* [6] suggested a modification to the existing displacement-based design procedure by proposing a new lateral load distribution for analysis of OGS buildings. Jothi Saravanan *et al* [1] quantified the vulnerability of OGS buildings using the displacement demand magnifier. Rama

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Rao *et al* [7] developed a simplified procedure for the assessment of OGS buildings.

Soil-Structure Interaction (SSI) discusses the influence of soil on the motion of the structure. The movement of soil under the foundation will interact with the response of the structure itself. The interaction phenomenon is generally affected by the mechanism of energy transfer between the soil and the structure, and primarily influences the natural period of vibration of the building. Toutanji [8] studied the interaction of shear walls and frames with fixed and flexible foundations using a simple method based on a continuum approach. Inertial SSI effects on seismic structural response are evaluated using the system identification techniques by Stewart *et al* [9]. The lateral natural periods of any building structure may significantly alter due to the effect of soil-structure interaction [10]. Han and Wang [11] revealed that the stiffness is overestimated and the damping is underestimated in case of ignoring the SSI and prediction made by assuming structure fixed on a rigid base. Kavitha *et al* [12] compared various soil models for the soil-structure interaction analysis. A plethora of studies are available on soil-structure interaction effect on a variety of structures with different methods and techniques, however, the soil-structure interaction studies focusing on open ground storey buildings are limited.

An analytical study is conducted to understand the effect of soil flexibility on the seismic response of OGS buildings. In the present work, the response of OGS buildings is examined with a focus towards (i) understanding the effect of soil flexibility on the global response of OGS building, (ii) assessing the influence of soil flexibility in OGS buildings of various slenderness ratios and (iii) developing a simplified methodology for approximately estimating the deformation capacity of a flexible base open ground storey building. Analytical studies on typical OGS building models have been carried out in SAP2000 software [13] and a static nonlinear analysis has been used to study the lateral response. As the deformations are expected to go beyond the elastic limits, a static nonlinear analysis also known as pushover analysis is used for the parametric study. Variation in boundary conditions are incorporated by simulating three different soil conditions hard or rock, medium and soft, classified as mentioned in IS 1893 (Part 1) 2016 [2]. The soil characteristics are modelled as translational and rotational springs. In addition, the study also includes two other cases of boundary conditions, i.e., fixed and hinged (or pinned) supports at the base for comparison purposes. The performance point obtained for various cases by verifying the seismic demand with the seismic capacity. Further, a parametric study is carried out to study the influence of soil flexibility in OGS buildings of various slenderness ratios. There is a huge stock of OGS buildings already in existence in the Indian urban regions and there is an urgent need to assess them for their structural seismic safety and carry out suitable retrofit measures. For assessing such a huge stock of OGS buildings, a simplified and quick method is very much required to segregate the highly vulnerable buildings, which then undergo a detailed assessment prior to retrofit. Also, correct representation of the seismic behaviour is evident only when SSI effects are also incorporated. A simplified methodology for estimating the lateral behaviour of a flexible base open ground storey building has been developed for preliminary and quick seismic assessment. The developed methodology is validated with the detailed analytical studies made on OGS buildings.

2. Open ground storey buildings

Open Ground Storey (OGS) buildings are Reinforced Concrete (RC) frames consisting of beams and columns with masonry infilled walls available only in the top stories. The ground storey left without infill. Residential and commercial multi-storey buildings with ground floor kept open for the purpose of parking vehicles are typical examples of open ground storey buildings. Sudden reduction of stiffness at the ground floor level of the building, causes discontinuity in force and displacement path, leading to excessive displacement demands in the ground floor during seismic actions. Upper floors have more stiffness due to infilled masonry; however, their stiffness and strength are uncertain and degrading. Past earthquakes in India has shown that the damage to such structures was concentrated in the ground floor and none of the other elements experienced any sign of damage. This is in sharp contrast to the capacity design concept of structures, wherein ductility and energy dissipation is primarily expected from pre-dominant flexural elements (like beams) and not from the structural actions of compression-dominated columns or other shear-dominated elements. The other common terminology for open ground storey buildings includes, ‘building-on-stilts’, ‘building on chop sticks’ or ‘building with tuck-in parking’.

Structural components of a building include foundation, columns, load-bearing walls, beams, floors and roof decks, staircases and other types of structural components that help to support the building. The load path is generally the reverse of the above hierarchy with loads (gravity or lateral) from slabs transferred to the beams, then to the columns and thereby to the foundation. The importance and factor of safety should decrease in the hierarchy of foundations, columns, beams and slabs. Any damage to the foundation or columns can lead to the progressive collapse of a major portion of the building and should be avoided. A normal framed structure (with uniform in-fill or uniform bare conditions along the height) is characterized approximately by a linear deformed shape or mode shape with a collapse state similar to the beam side-sway mechanism. Under the action of seismic forces, all the stories of these structures move uniformly and the normalized difference in the deformation between adjacent stories, termed as 'drift' is essentially the same in all stories throughout the height. However, an OGS building is characterized by a soft ground storey deformed shape or fundamental mode shape with a collapse state similar to the column side-sway mechanism. Under the action of seismic forces, all the deformation is concentrated in the ground storey columns and the drift in the ground storey is multi-folds the drift in the upper stories. Due to large drifts, the displacement demand is more in ground storey columns. Since, the ground storey columns are not designed to cater the additional or large drifts due to the soft storey effect, these OGS buildings are highly vulnerable. Following are few typical characteristics of open ground storey buildings:

- The total seismic displacement demand is expected only from the ground storey, whereas in a conventional structure, the seismic displacement demand is distributed over all stories.
- Axially loaded columns in the ground storey are incapable to meet the high ductility demand and large in-elastic rotations.
- The loss of stability in the open ground storey columns due to their large deformation are caused due to P-Delta effects or secondary moments.

Because of these reasons, the damage is sudden, unexpected and disastrous. OGS constructions in India are needed due to space constraints although they are potentially vulnerable to earthquake shaking because of stiffness irregularities. Special consideration has to be given for the structural action of infills in the OGS buildings, accounting for both the stiffness and strength in the design process. Soft storied buildings are characterized by column side sway mechanism and hence ground storey columns are to be appropriately designed to meet the increased displacement, ductility and force demands.

3. Modelling of brick masonry infill walls

The space between the columns and beams in reinforced concreted framed buildings is commonly filled with brick masonry infill walls with required openings. At present, these infill walls are considered as non-structural elements in the design process. The infill walls' participation in structural action and their influence on the structural response is ignored. Therefore, neglecting masonry infill walls in the design procedure is not a realistic approach. By neglecting the masonry infill walls in the design process, the important phenomena of the soft storey effect during an earthquake could be left out, leading to unexpected changes in the dynamic behaviour of the building. Several methods have been proposed in the literature for modelling masonry infill walls, however, the equivalent diagonal strut method proposed by Smith and Carter [14] is more popular and most of the design codes also suggest using it with suitable modifications. The infill wall panel between the columns and beams can be replaced with an equivalent pin-jointed diagonal strut so that it can take only axial compression and not resist moments. The theoretical relation for the width of the diagonal strut was developed by Smith and Carter [14] based on the relative stiffness of infill and frame. The equivalent strut would have the same thickness as the infill wall panel it represented. This simplified macro-model approach of the equivalent strut for infill walls mainly exhibiting in-plane behaviour and the local effects related to cracking and crushing are considered. A certain extent contact interaction also will be represented. The out-of-plane behaviour is neglected.

In the present work, for modelling the Un-Reinforced Masonry (URM) infill walls, the procedure proposed in Clause 7.9 of IS 1893 (Part 1): 2016 [2] is followed. The brick masonry infill wall is modelled as an equivalent diagonal compression strut element. Both ends of the equivalent diagonal strut connect beam-to-column junctions with pin joint connection. Rigid joints connect the beams and columns. The effective width, strength and elastic modulus of the infill wall are calculated using the expression in Clause 7.9 of IS 1893 (Part 1): 2016 [2]. The length of the strut is given by the diagonal distance of the infill panel. The thickness of the equivalent diagonal strut is taken as same as the thickness of the infill wall. The mass of an infill wall should be incorporated separately as a uniform mass on the supporting beam. Modulus of the strut is taken as masonry Young's modulus, which is equivalent to $550f_m$, where f_m is the compressive strength of masonry prism in MPa.

$$f_m = 0.433 f_b^{0.64} f_{mo}^{0.36} \tag{1}$$

where f_{mo} is the compressive strength of mortar, in MPa and f_b is the compressive strength of brick, in MPa. For un-reinforced masonry infill walls without any opening, width (w_{ds}) of equivalent diagonal strut shall be taken as per IS 1893 (Part 1): 2016 [2].

$$w_{ds} = 0.175 \alpha_h^{-0.4} L_{ds} \tag{2}$$

$$\alpha_h = h\left(\sqrt[4]{\frac{E_m t \sin 2\theta}{4 E_f I_c h}}\right) \tag{3}$$

where E_f and E_m are the moduli of elasticity of the materials of the RC frame and URM infill wall, respectively; I_c is the moment of inertia of the adjoining column; t is the thickness of the infill wall; h is the clear height of URM infill wall between the top beam and bottom floor slab; θ is the angle of the diagonal strut with the horizontal and L_{ds} is the diagonal length of the strut. The direction of the infill strut in the model is decided in such a way that the diagonal strut should be in compression during earthquake loading applied in pushover case. 3D frame element in SAP2000 software [13] is used for the diagonal strut, but the density is not assigned. The mass of an infill wall should be incorporated separately as a uniform load/mass on the supporting beam. The percentage of wall openings is considered as 40% and to be used accordingly for infill mass calculation on supporting beams. The end moments are released so that they will act like a pin-jointed diagonal strut and will not offer any moment resistance. The differential elastic axial compression behaviour of masonry and equivalent diagonal strut is not significant; hence it is neglected in the present work.

4. Nonlinear modelling of open ground storey buildings

Pushover analysis is an effective tool for performance-based seismic design. Pushover analysis is a nonlinear static analysis that evaluates the lateral behaviour of the structure. The magnitudes of lateral loads or displacements are incrementally applied by maintaining a predefined load pattern along the height of the building. Local nonlinear effects are modelled in the form of hinges and the structure is pushed until a collapse mechanism is developed. The pushover curve is obtained by plotting the total lateral load applied (base shear) and the corresponding roof displacement at each load increment. Pushover curve gives an idea of ultimate capacity, maximum inelastic deflection and associated ductility (ATC-40 [15]). During the process of increasing the lateral loads, weak links and failure modes are exhibited. The nonlinear load-deformation behaviour of each element of the building is modelled separately and also separately for each failure mode in the form of plastic hinges. In the nonlinear analysis, the plastic hinge plays a vital role. It is assumed that all inelastic deformation takes place in the plastic hinge region, called as plastic hinge length. All the primary structural elements need to be modelled and define their nonlinear properties for identified failure mechanisms accordingly. Secondary elements need not be modelled; however, their mass should be included in the analysis. Pushover analysis using SAP2000 software [13] requires a predetermined lateral load pattern (e.g., code specified lateral load profile) that will be maintained throughout. However, it may be noted that the magnitude of the forces does not affect the pushover analysis results; it is only the shape of the profile that affects the analysis results. In a strict sense, this force profile needs to be modified in accordance with the progressive yielding of lateral stiffness contributing elements. For the OGS buildings the lateral load pattern should be in a rectangular pattern, and it will be more ideal than a parabolic load pattern. Moreover, a flexible soil base also influences the lateral load pattern. However, code specified lateral load profile i.e. parabolic load profile has been more preferred in general and the same is used in the present study. In the present study, the variation in response with different lateral load patterns is observed to be marginal. The lateral load profile is applied at the joints on the one side periphery of the respective floor. Finally, the P - Δ effect also needs to be considered in the analysis.

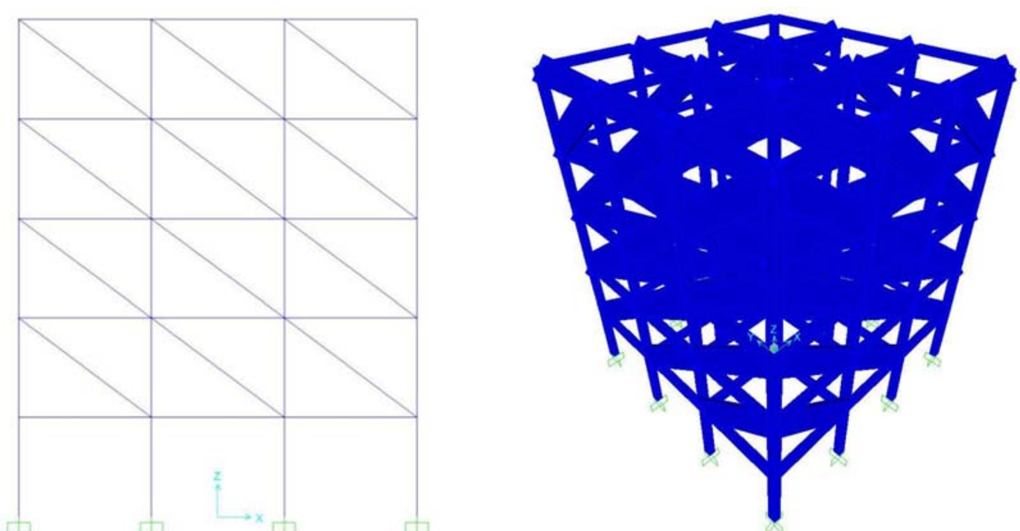
Firstly, the gravity loads are applied in a force-controlled manner till the design gravity load. Next, the lateral loads are applied in each direction separately in a displacement-controlled manner, until the control node displacement reaches the target value or the building has formed a collapse mechanism. In the present study, a five-storied building, square in plan with three bays in both directions are considered. SAP2000 software [13] is used for the present analysis. The typical structural models chosen for conducting analytical studies had been designed as per IS 456:2000 [16] and considering the load combinations from IS 1893 (Part 1): 2016 [2], earthquake load calculated for zone III. The bay width of 4 m is common for all the bays and storey height of 3 m is common for all the floors. 3D frame elements are used to model the beams and columns. Cross-sectional dimensions, reinforcement details and the type of materials used are assigned for beams and columns. The material properties of steel reinforcement and concrete including unit weight, modulus of elasticity, Poisson's ratio, shear modulus, characteristic compressive strength, yield stress and ultimate stress have been provided. The materials used are M25 grade concrete and Fe415 grade steel. Column of size 350 mm × 300 mm is used for all the models, with 300 mm depth oriented along X-direction. The reinforcement in the column is 8 no.'s of 16 mm diameter bars (1.53% reinforcement) and 6 mm diameter stirrups at 150 mm c/c. Beam of size 300 mm × 300 mm is used with 6 numbers of 16 mm diameter bars and 6 mm diameter stirrups at 150 mm c/c. Modification factor for moment of inertia of beam and column has been given as 0.5 and 0.7, respectively to account for the effect of cracking. The slab thickness of 120 mm is considered. The thickness of brick infill walls is taken as 230 mm. The floor finish on floors is taken as 1.0 kN/m^2 and the live load on floors is taken as 2.0 kN/m^2. The structural effect of slabs is taken by assigning diaphragm constraint action at each floor level. The self-weight and loads coming on the slab are applied separately on supporting beams. Beam-column joints have been modelled by giving end length offsets to the frame elements. Dead load and live loads are applied as gravity loading. Earthquake load has been calculated as per IS 1893 (Part 1): 2016 [2] and applied as a lateral load at the joints in the one side periphery.

User defined M3 and PMM hinge properties have been assigned for beams and columns respectively and defined at the two ends of the beam/column element. Shear hinge properties are also assigned for beams and columns. The hinge properties are calculated using section analysis, based on the concrete grade, cross-section dimensions and reinforcement detailing. Axial hinge is assigned to the infill diagonal strut in the middle and its properties are given based on the strength of the strut, which is the lowest of the sliding shear strength and crushing strength. The study is limited to analysis in X-direction only since it is a weak direction compared to the Y-direction. Figure 1 shows the elevation and 3D view of the model of the OGS building as developed in SAP2000 software [13]. The output from the pushover analysis contains the pushover curve, the demand and capacity spectra curves and their tabulated values are compared with corresponding results from fixed and flexible base models.

5. Soil-structure interaction of open ground storey buildings

Evaluation of structural response to the earthquake has been mostly based on the assumption of a fixed base structure since the soil-structure interaction effect is seldom incorporated in the seismic design. The natural frequency and the induced seismic loads on the structure are calculated based on this assumption. However, during actual seismic loading, the structural response is affected by interactions among the structure, footing and the soil surrounding and underlying the footing leading to simultaneous deformations in soil-foundation system. These changes contribute to the flexibility of the global structure thereby lengthening its natural time period. Based on the location of the elongated period in the response spectrum, the seismic loads acting on the structure are either increased or decreased [17]. The inherent complexity in soil behaviour has led to the development of analytical methods like direct or substructure approaches based on classical theories of elasticity and plasticity to evaluate the SSI effects. By representing the surrounding soil medium as a linear elastic continuum, the soil deformations can be assumed to be linear and reversible. Winkler's model and elastic half-space model fall under this category. Winkler's foundation model assumes that soil-foundation contact is discretized into number of points and each soil point response is independent of the neighbouring point and the surface development of the soil medium at every point is directly proportional to the stress applied to it at that point. This type of idealization uses a combination of mutually independent spring elements to represent the soil-foundation stiffness and these springs may be elastic or nonlinear. The elastic soil models do not consider any elastic-plastic or irreversible behaviour of the soil medium. The basic distinction between the purely elastic and elastic-plastic models is that, in the latter case, the stresses that can be induced in the soil medium are limited owing to the introduction of a yield or failure criterion.

To understand the effect of soil-structure interaction, OGS building models have been developed for five different boundary conditions which are (i) fixed base, (ii) hard or rock soil, (iii) medium soil, (iv) soft soil and (v) hinged base at the base of footings. The hinged condition is additionally considered in order to represent the current practice of modelling shallow isolated footings sometimes with a hinged base in the structural design offices. The soil classification has been done as per IS 1893 (Part 1): 2016 [2]. Nonlinear SSI phenomena have been considered with the source of nonlinearity being the yielding of superstructure elements and geometric nonlinearities in the superstructure. Due to structural yielding developing at lower drifts in the OGS buildings, elastic soil behaviour alone is assumed and the other soil nonlinear phenomena



(a) Elevation (b) 3D view

Figure 1. Elevation and 3D view of SAP2000 model of OGS building with fixed base.

such as soil yielding, gapping and base uplift have been ignored in the current study. The soil spring stiffness are calculated using the standard expressions from ASCE/SEI 41-17 [18], for rigid rectangular foundations resting on the surface. The stiffness formulations are function of footing size, shear modulus (G), shear wave velocity (V_s) and Poisson's ratio (ν). A reliable correlation in Eq. (4) between shear wave velocity (V_s) in m/sec and standard penetration test blow counts (N) established by Maheswari *et al* [19] has been used for obtaining shear wave velocity of soil. Standard Penetration Test (SPT) number has been chosen for hard, medium and soft soil such that it represents the lower range of SPT number (N) range suggested for hard, medium and soft soil in IS 1893 (Part 1): 2016 [2].

$$V_s = 95.64\,N^{\mathbf{0.301}} \tag{4}$$

A simplified form of frequency-independent shear modulus equation, Eq. (5) is used to calculate shear modulus (G). The initial shear modulus (G), is related to the shear wave velocity at low strains, V_s, and the mass density of soil, ρ, by the relationship

$$G = \rho V_s^2 \tag{5}$$

The value of mass density and Poisson's ratio for hard, medium and soft soil are appropriately assumed and are given in Table 1. Standard formulations for determining elastic spring stiffnesses for different degrees of freedom adopted from ASCE/SEI 41-17 [18] are Eqs. (6) to (11) as follows,

$$\text{Translation stiffness along B - direction} = \frac{GB}{2-\nu}\left[3.4\left(\frac{L}{B}\right)^{0.65} + 0.4\frac{L}{B} + 0.8\right] \tag{6}$$

$$\text{Translation stiffness along L - direction} = \frac{GB}{2-\nu}\left[3.4\left(\frac{L}{B}\right)^{0.65} + 1.2\right] \tag{7}$$

$$\text{Translation stiffness along vertical - axis} = \frac{GB}{1-\nu}\left[1.55\left(\frac{L}{B}\right)^{0.75} + 0.8\right] \tag{8}$$

$$\text{Rotational spring stiffness about B - axis} = \frac{GB^3}{1-\nu}\left[0.47\left(\frac{L}{B}\right)^{2.4} + 0.034\right] \tag{9}$$

$$\text{Rotational spring stiffness about L - axis} = \frac{GB^3}{1-\nu}\left[0.4\frac{L}{B} + 0.1\right] \tag{10}$$

$$\text{Rotational spring stiffness about vertical - axis} = GB^3\left[0.53\left(\frac{L}{B}\right)^{2.45} + 0.51\right] \tag{11}$$

where L and B = length and breadth of rectangular footing, the orientation of L such that it should be the longer dimension. In the case of square footing L-direction stiffness can be used for calculating the stiffness and the same can be used for other direction. The properties of soil used for calculating the geotechnical component parameters are tabulated in Table 1. The isolated footing is adopted with 2.0 m × 1.5 m size footing such that 1.5 m (B) is along X-direction (300 mm column direction) and 2.0 m (L) is along Y-direction (350 mm column direction). The value of angle of internal friction of soil (φ) and cohesion (c) for hard, medium and soft soil are appropriately assumed as per IS 6403:1981 [20] and given in Table 1. For foundation design, the required parameters are assumed appropriately and used the same. The translational and rotational stiffness value of springs representing various soil flexibilities are tabulated in Table 2. Figure 2 shows the elevation and 3D view of the SAP2000 model of OGS building incorporating soil flexibility.

6. Effect of soil flexibility on open ground storey building

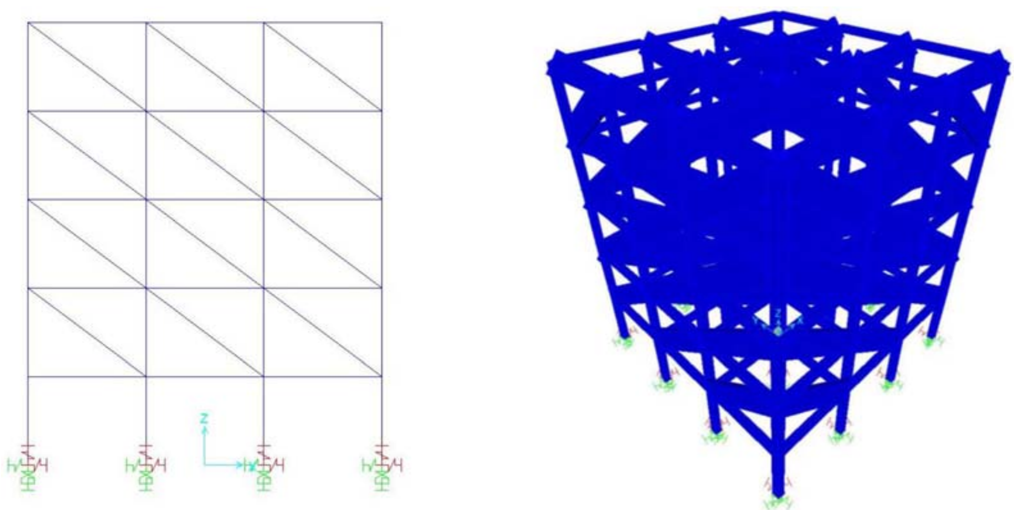
Pushover analysis has been performed on five similar dimensions building models with varying boundary conditions/connectivity with the ground, as mentioned previously. Variation in response parameters such as natural time period, base shear and deflection attained from the

Table 1. Details of soil parameters.

Soil type	N value	V_s (m/s)	ρ (kg/m^3)	G (GPa)	ν	φ	c (kN/m^2)
Soft	1	95.64	1280	11.71	0.35	27	2
Medium	10	191.27	1760	64.39	0.3	30	0
Hard	30	265	2080	147.43	0.2	35	0

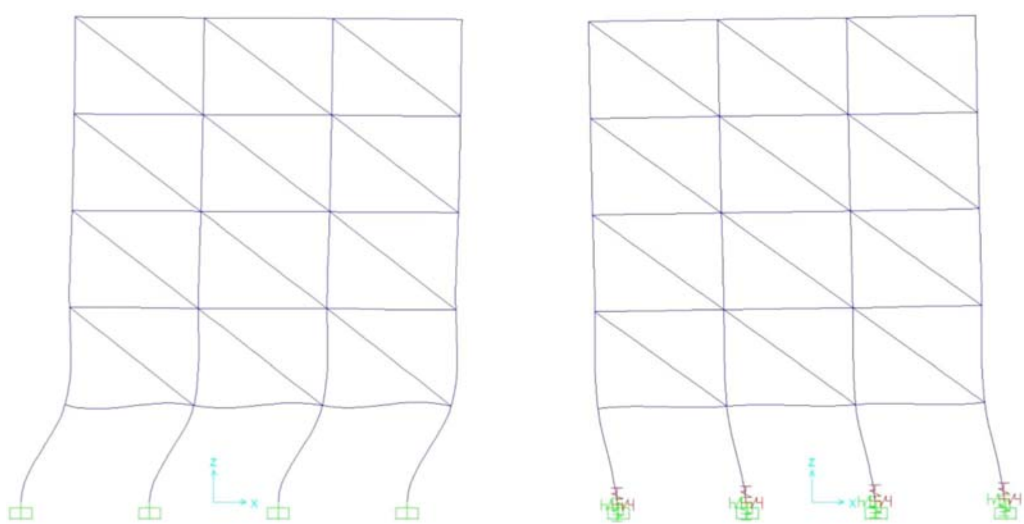
Table 2. Stiffness value of springs representing soil.

	Translational stiffness (N/mm)			Rotational stiffness (N-mm/rad)		
Soil type	K_x	K_y	K_z	K_{xx}	K_{yy}	K_{zz}
Soft	57050	55650	72597	5.83e10	3.80e10	6.17e10
Medium	304548	297074	370766	2.98e11	1.94e11	3.39e11
Hard	661254	645024	745836	5.99e11	3.90e11	7.80e11



(a) Elevation **(b) 3D view**

Figure 2. Elevation and 3D view of SAP2000 model of OGS building incorporating soil flexibility.



(a) Fixed base **(b) Flexible base (Soft soil)**

Figure 3. Deflected shape of OGS buildings with fixed base and flexible base.

analysis of SSI models are compared to corresponding results from the analysis of the model with a fixed base. Figure 3 shows the deflected shape of OGS buildings with fixed base and flexible base (soft soil) for fundamental translational mode in X-direction. Modal analysis is also performed to determine the time period of the models. Table 3 shows the time period of the various models. It can be seen that with an increase in soil flexibility, the time period has increased. Figure 4 shows the comparison of the lateral deflected profile along the storey level along with normalized values for OGS building models with varying the soil flexibility, obtained from the modal analysis and it represents the fundamental translational mode in X-direction. A slight reduction in the soft storey deflected profile is observed due to an increase in the soil flexibility.

Pushover curves for building models with varying soil flexibility are shown in figure 5. As soil flexibility increases, buildings show lateral flexible behaviour and there is not much lateral load capacity reduction. However, a significant reduction in the lateral load capacity by choosing a hinge base in the modelling has been observed. Lack of rotational rigidity due to hinge support and higher natural time period had caused significant differences in the case of the model with a hinged base. Soft storied buildings are characterized by column side sway mechanism due to the formation of hinges in the ground floor column; however, it is observed that, with soil becoming flexible, the initial hinge formation has moved from column to beam (figure 6). Nonetheless, the shift of hinge from column to beam is observed only at the initial yield hinge formation, later the collapse hinge (denoted as 'C') has formed in the columns only (figure 7). Although this leads to a reduction in soft storey deflected profile, it may not be treated as an improvement of behaviour due to exclusion of column side sway mechanism. As the soft storey mechanism requires a stiff medium above and below, the initial hinge formation shift from column to beam might probably be due to loss of stiff support below due to the presence of soft soil.

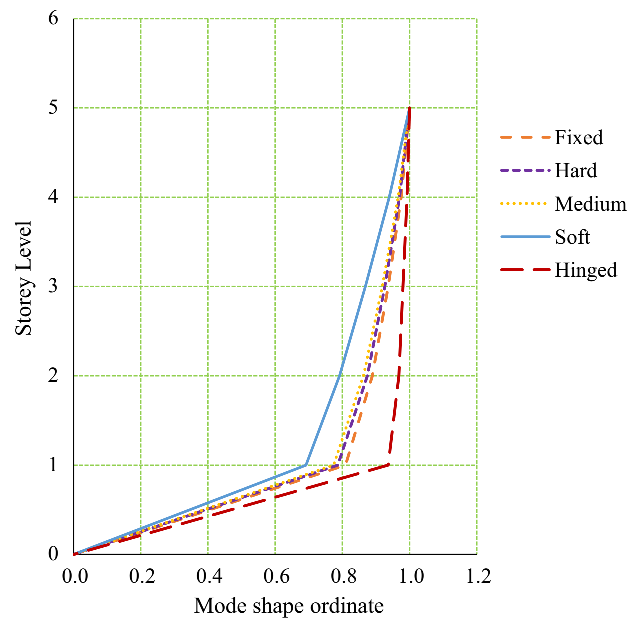


Figure 4. Comparison of lateral deflected profile.

7. Effect of slenderness ratio on open ground storey buildings

A parametric study is carried out to study the influence of soil flexibility in OGS buildings with varying slenderness. For the present study, OGS buildings with three different slenderness ratios 0.45 (3 storey, 5 × 5 bays), 1.25 (5 storey, 3 × 3 bays) and 2 (8 storey, 3 × 3 bays), resembling typical buildings in the Indian context, are studied. All the buildings are square in plan with a constant bay width of 4 m and storey height of 3 m is common for all the floors. The slenderness ratio 1.25 case is taken from the previous section. For 3 storey building (5 × 5 bays and slenderness ratio 0.45) same column design is followed, because 300 mm is the minimum column size specified by the IS 13920: 2016 [21]. Column of size 350 mm × 300 mm is used, 300 mm depth along X-direction. The longitudinal reinforcement in the column is 8 no.'s of 16 mm diameter bars (1.53% reinforcement) and the transverse reinforcement is 6 mm diameter stirrups at 150 mm c/c. The rectangular isolated footing of size 2.0 × 1.5 m is used. In case of 8 storey building the column of size 600 mm × 550 mm with longitudinal reinforcement of 12 no.'s of 25 mm diameter bars (2.0% reinforcement) and transverse reinforcement of 8 mm diameter stirrups at 150 mm c/c was used, 550 mm depth along X-direction. The rectangular isolated footing of size 3.0 × 2.5 m is used and the corresponding soil spring stiffness had been revised accordingly. All other dimensions and material properties remain the same for all cases. The materials used are M25 grade concrete and Fe415 grade steel for all the cases. Beams of size 300 mm × 300 mm is used with 6 no.'s of 16 mm diameter bars and 6 mm diameter stirrups at 150 mm c/c. The slab thickness of 120 mm is considered. Pushover analysis is carried out for the aforementioned OGS buildings for different soil conditions which are, soft, medium and hard, classified as per IS 1893 (Part 1): 2016 [2] and the results are analysed and compared with conventional fixed-base assumption. Figures 8 and 9

Table 3. Comparison of time period of SAP2000 models with fixed and flexible base.

Base condition	Time period (s)
Fixed	0.568
Hard soil	0.579
Medium soil	0.591
Soft soil	0.687
Hinged	1.081

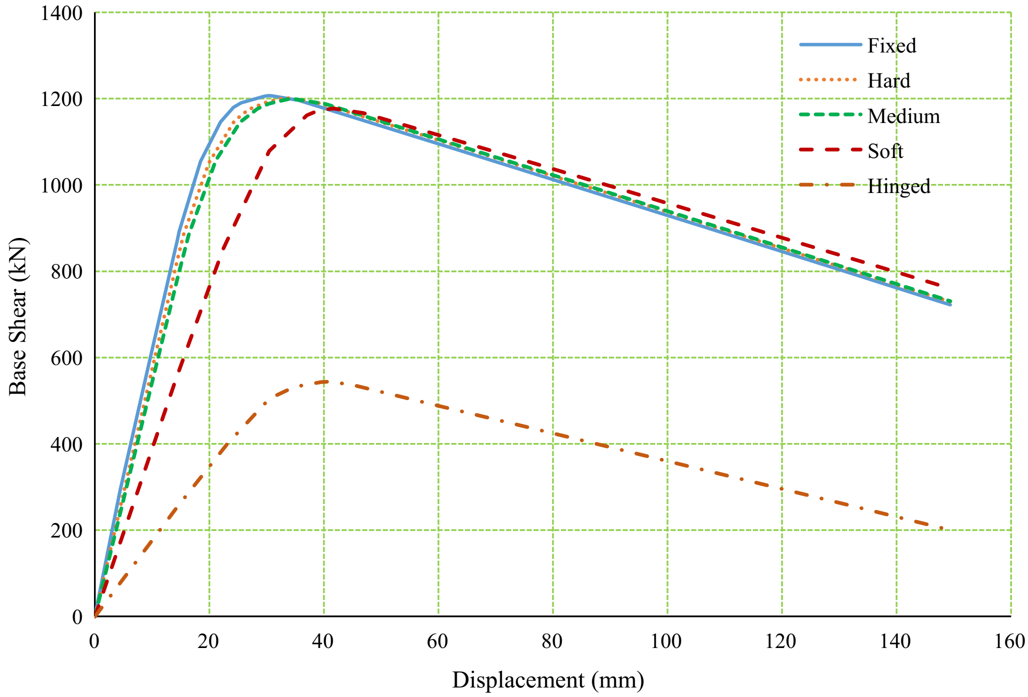


Figure 5. Pushover curve for open ground storey buildings with different base conditions.

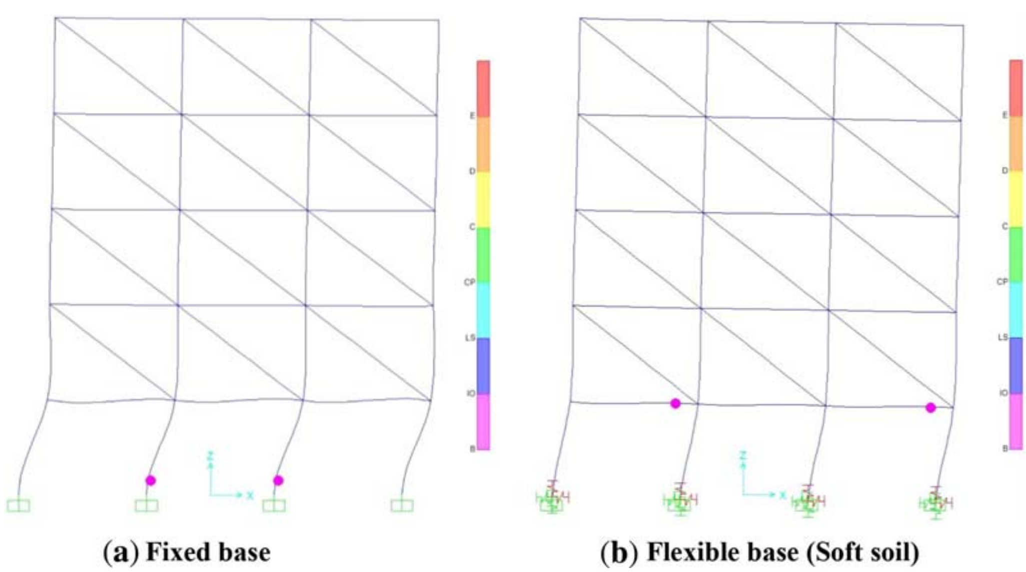


Figure 6. Initial hinge formation in OGS buildings with fixed base and flexible base.

show typical OGS buildings with fixed and flexible base of slenderness ratios 0.45 and 2.0 respectively. Figures 10 and 11 show pushover curves for buildings with fixed and flexible base of slenderness ratios 0.45 and 2.0, respectively. Table 4 shows the time period of the various models. It can be seen that with an increase in soil flexibility, the time period has increased. The percentage increase of natural time period from fixed support condition to hard, medium and soft soil support conditions has increased as the slenderness ratio increases. But in cases of the hinged condition, a decreasing trend is observed. It is clear that the influence of soil-structure interaction is more significant for higher slenderness ratio structures due to additional P - Δ effects and foundation rotation. However, caution is required while interpreting this result for taller buildings since other parameters such as soil-structure stiffness ratio can become more important controlling factors for SSI influence [17]. Lower estimation of the natural time period

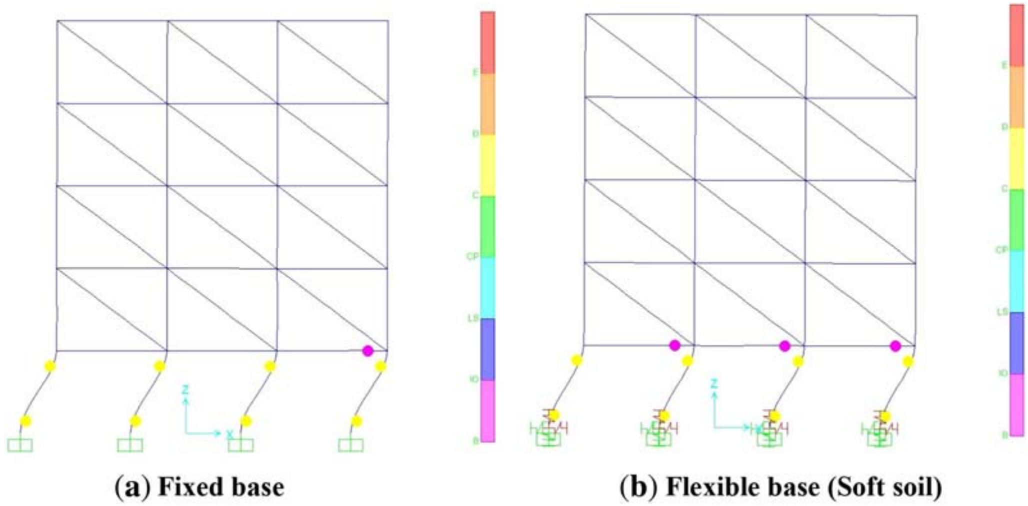


Figure 7. Final collapse hinge formation in OGS buildings with fixed base and flexible base.

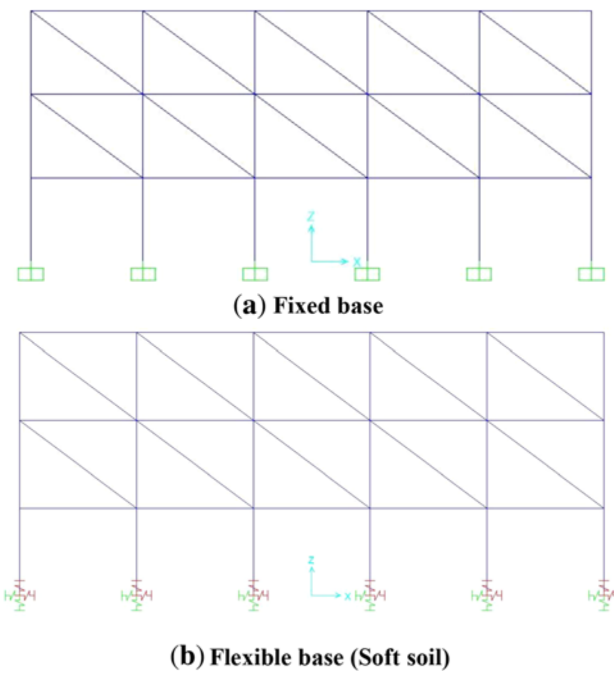


Figure 8. OGS buildings of slenderness ratio 0.45 with fixed base and flexible base.

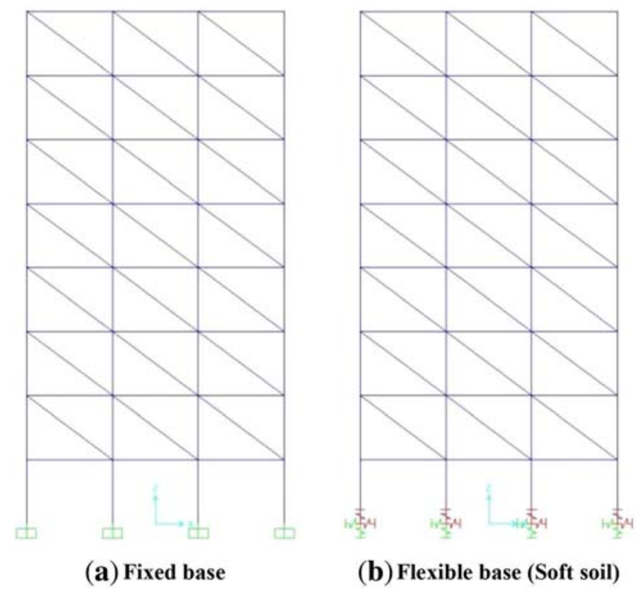


Figure 9. OGS buildings of slenderness ratio 2 with fixed base and flexible base.

by assuming fixed support condition might alter the lateral seismic load on the structure.

8. Verification of seismic demand to seismic capacity

In addition to modal analysis and pushover analysis results, the performance point of various cases had been determined for verifying the seismic demand with the seismic capacity. For this purpose, the pushover curve is converted into a capacity spectrum and plotted in Acceleration Displacement Response Spectrum (ADRS) format. The elastic demand is plotted in ADRS format by converting IS 1893 (Part 1): 2016 [2] spectrum, corresponding to the seismic zone-III and for varying soil type hard, medium and soft. The spectral displacement has been derived from spectral acceleration and time period. The inelastic demand spectrum is obtained using SAP2000 software [13] and following the ATC-40 [15] capacity spectrum method. The seismic capacity, elastic and inelastic demand spectrum of hard, medium and soft soil support conditions of 5 storey

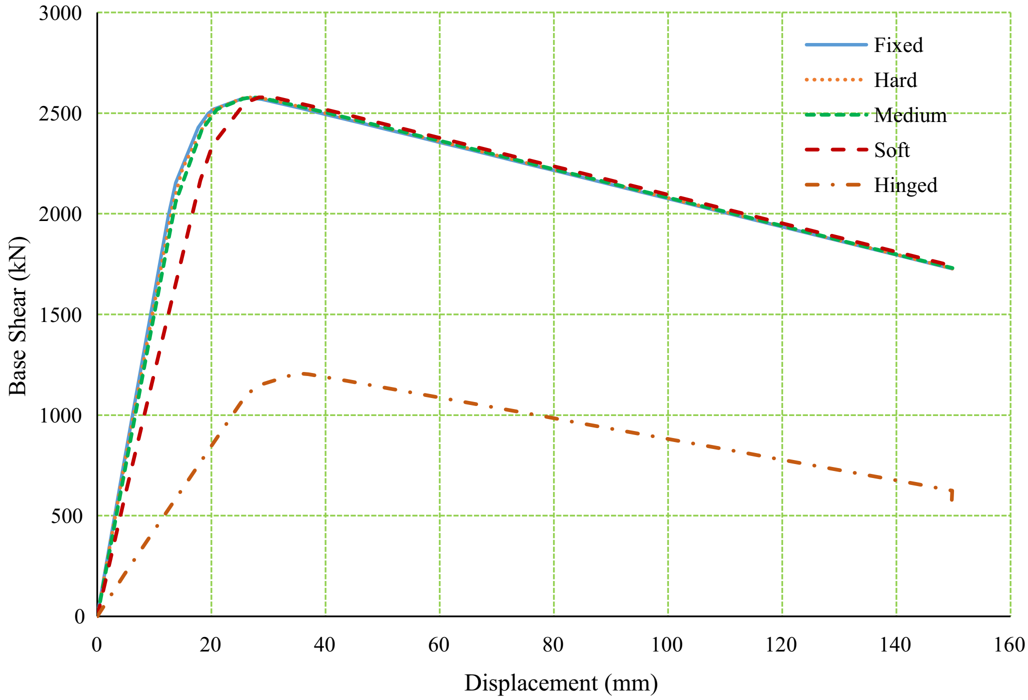


Figure 10. Pushover curve for open ground storey buildings with slenderness ratio 0.45.

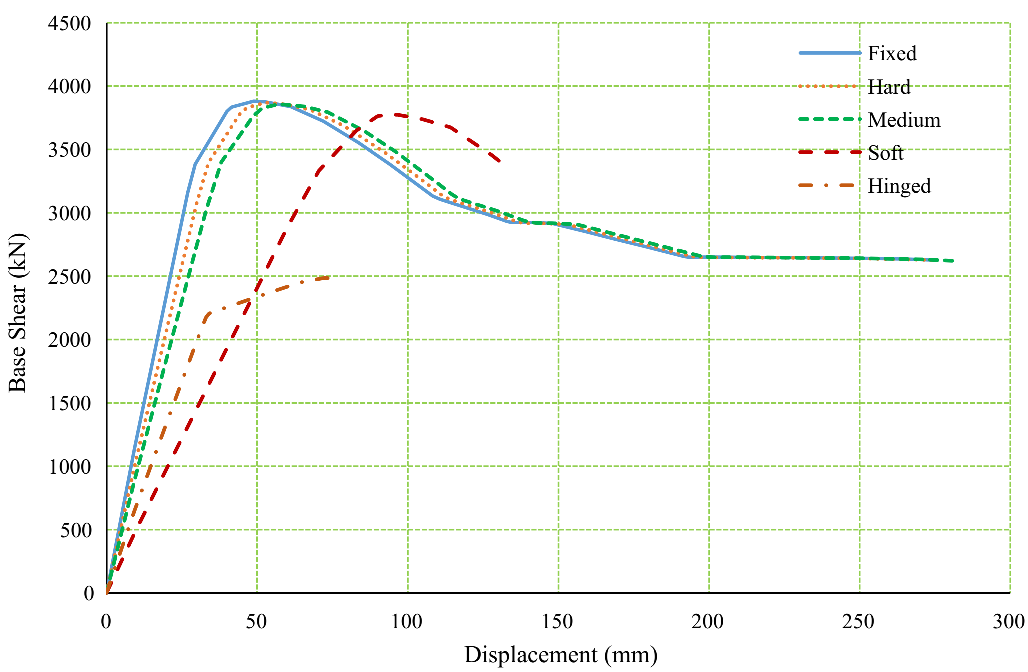


Figure 11. Pushover curve for open ground storey buildings with slenderness ratio 2.

OGS building case is presented in figure 12. The performance point is taken as the intersection of seismic capacity and inelastic demand of corresponding soil support condition. Tables 5, 6 and 7 present the information of base shear (V_b), roof displacement (Δ_{roof}), spectral acceleration (S_a) and spectral displacement (S_d) at performance point for the OGS buildings considered in the present study (3, 5 and 8 storey OGS buildings respectively). Additionally, for the

Table 4. Comparison of time period of all models with fixed and flexible base.

Base Condition	Slenderness ratio- 0.45 T (s)	Slenderness ratio- 0.45 % increase	Slenderness ratio-1.25 T (s)	Slenderness ratio-1.25 % increase	Slenderness ratio- 2.0 T (s)	Slenderness ratio- 2.0 % increase
Fixed	0.439	–	0.568	–	0.513	–
Hard soil	0.445	1.4	0.579	1.9	0.543	5.8
Medium soil	0.452	3.0	0.591	4.0	0.572	11.5
Soft soil	0.503	14.6	0.687	21.0	0.772	50.5
Hinged	0.858	95.4	1.081	90.3	0.756	47.4

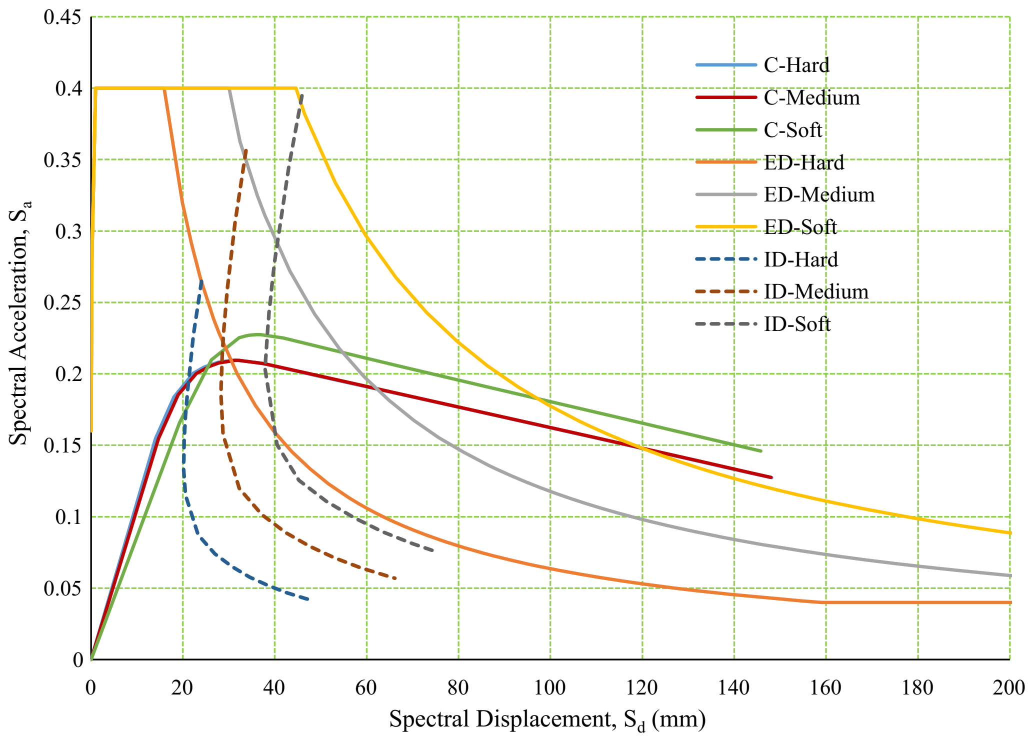


Figure 12. Seismic demand and capacity comparison for varying soil support conditions of 5 storey OGS buildings (C - Capacity, ED - Elastic Demand and ID - Inelastic Demand).

fixed and hinged support models, soil type influence is considered only in the seismic demand which is the usual practice by designers.

The performance point is checked with various performance criteria suggested by the ATC-40 [15]. In all the present cases the performance point lies within the immediate occupancy criteria. Similar to the pushover analysis case, the variation is observed to be marginal and the performance point lies within the same performance criteria irrespective of the type of flexible base. From the additional study made on fixed support condition and soil type influence considered only in seismic demand, it is observed that the displacement at performance point is underestimated when soil becomes flexible. For the hinged support condition and soil type influence considered only in seismic demand, the displacement at the performance point is observed to be overestimated and the lateral load at the performance point is underestimated when soil becomes flexible. These situations can lead to erroneous performance-based seismic designs. This highlights the importance of considering the SSI effect in OGS buildings. From the verification of seismic demand to seismic capacity studies (Tables 5, 6 and 7), it is observed that when soil becomes flexible, in addition to considering soil type in demand alone, the capacity also should be obtained from the analysis considering the flexible support condition to achieve the realistic performance point. In the present case study OGS building models, the performance points are existing because seismic demand is related to lower seismic zone III, however, in the case of higher seismic zones (Zone-V), the performance point may not exist for the OGS buildings with deficient columns.

Table 5. Comparison of performance point for 3 storey OGS buildings.

5 × 5 bays 3 storey (Zone – III)		Performance point on pushover curve		Performance point on capacity curve	
SAP2000 model support condition	Seismic demand - soil type considered	V_b (kN)	Δ_{roof} (mm)	S_a	S_d (mm)
Fixed	Hard soil	2375.402	16.9	0.281	16.1
	Medium soil	2467.775	18.6	0.292	17.8
	Soft soil	2467.775	18.6	0.292	17.8
Hard soil	Hard soil	2366.008	17.4	0.279	16.5
Medium soil	Medium soil	2482.933	20.0	0.293	19.0
Soft soil	Soft soil	2511.058	24.8	0.296	23.4
Hinged	Hard soil	1181.083	32.0	0.14	31.7
	Medium soil	1185.841	40.6	0.14	40.2
	Soft soil	1139.718	49.7	0.135	49.4

Table 6. Comparison of performance point for 5 storey OGS buildings.

3 × 3 bays 5 storey (Zone – III)		Performance point on pushover curve		Performance point on capacity curve	
SAP2000 model support condition	Seismic demand - soil type considered	V_b (kN)	Δ_{roof} (mm)	S_a	S_d (mm)
Fixed	Hard soil	1153.844	22.5	0.201	20.8
	Medium soil	1203.149	29.0	0.209	27.1
	Soft soil	1199.552	33.9	0.209	32.1
Hard soil	Hard soil	1126.427	23.4	0.197	21.3
Medium soil	Medium soil	1190.429	31.1	0.208	28.5
Soft soil	Soft soil	1193.518	46.1	0.203	40.5
Hinged	Hard soil	543.325	39.7	0.095	39.7
	Medium soil	510.246	53.1	0.089	52.7
	Soft soil	443.758	73.9	0.077	73.6

Table 7. Comparison of performance point for 8 storey OGS buildings.

3 × 3 bays 8 storey (Zone – III)		Performance point on pushover curve		Performance point on capacity curve	
SAP2000 model support condition	Seismic demand - soil type considered	V_b (kN)	Δ_{roof} (mm)	S_a	S_d (mm)
Fixed	Hard soil	3221.254	27.6	0.288	21.4
	Medium soil	3568.107	34.1	0.315	27.0
	Soft soil	3575.139	34.3	0.315	27.1
Hard soil	Hard soil	3078.03	29.9	0.277	22.9
Medium soil	Medium soil	3483.491	40.5	0.311	31.1
Soft soil	Soft soil	3371.42	72.0	0.307	52.8
Hinged	Hard soil	2213.115	34.9	0.18	30.0
	Medium soil	2276.197	42.6	0.185	37.2
	Soft soil	2340.103	50.5	0.19	44.5

9. Simplified method for soil-structure interaction of open ground storey buildings

A simplified method for obtaining lateral nonlinear behaviour of open ground storey building considering the soil-structure interaction has been developed using the plastic hinge concept. The whole building has been idealized as a Single Degree Of Freedom (SDOF) system i.e. a stick model with a heavy mass concentrated at the top such that the entire nonlinear deformation of the building is experienced by the OGS columns alone. Assuming that, predominantly same column size is followed in the ground floor and a representative sub-portion is idealized as SDOF system (figure 13). The assumption of slab in-plane rigidity leads to uniform lateral deformation in all OGS columns. Open ground storey lateral deformation is the same as lateral deformation of representative sub-portion of idealized SDOF system.

Further, the columns in the OGS are rotationally restrained at top of the stilt floor and are free to only translate at top of the stilt floor. At the foundation level, translational and rotational soil springs are added to simulate the soil flexibility. The lateral displacement capacities are calculated using yield and ultimate curvature of the representative column section in the open ground storey. Assuming that, predominantly same column size is followed in the ground floor and a representative sub-portion is idealized as SDOF system with same lateral deformation, the total building force capacity can now be taken as the total number of columns times the force capacity of the representative column. The lateral displacement capacities obtained from the proposed simplified procedure are validated with the pushover analysis results obtained from the SAP2000 model of 5 storey OGS buildings.

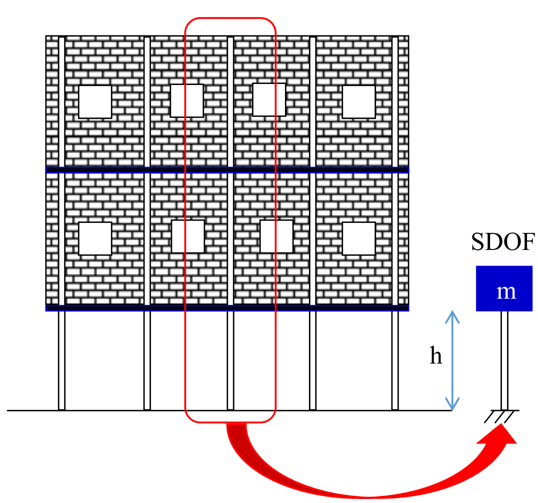


Figure 13. SDOF idealization of open ground storey building.

The cross-section analysis of the representative column is carried out to calculate the moment and curvature at the yield and ultimate using the 'Section Designer' tool, which is an integrated utility, available in SAP2000 software [13]. Mander's model [22] for confined concrete and default steel stress-strain behaviour available in SAP2000 software [13] has been adopted for the section analysis. The yield force will be equal to yield moment divided by half of the height of the representative column as given in Eq. (14), since the OGS columns bend in double curvature, assuming fixed base condition. Further, to avoid premature shear failure in the plastic hinge region, it should be ensured that the yield (or ultimate) force is lower than the shear strength of the column. As the translation alone is allowed at top of the stilt floor for the representative column, the corresponding yield displacement (Δ_y) can then be accordingly calculated using the yield curvature (ϕ_y) as per Eq. (12). The displacement capacity (Δ_u) of the representative column is the sum of yield and plastic displacement due to post-yield plastic rotation of the open ground storey columns and it can be worked out as the function of the ultimate curvature (ϕ_u), yield curvature (ϕ_y), plastic hinge length and height of the open ground storey by the following Eq. (13) as suggested by Jothi Saravanan *et al* [1].

$$\Delta_y = \frac{\phi_y h^2}{6} \tag{12}$$

$$\Delta_u = (\phi_u - \phi_y) l_p (h - l_p) + \frac{\phi_y h^2}{6} \tag{13}$$

where h is the height of the representative column; l_p is the plastic hinge length which is estimated either using standard expressions given in the literature or assuming as half the depth of the column section. The flexural stiffness of the representative column (K) can be calculated as per Eq. (15) using yield force and yield displacement estimated previously. Further, the natural time period of the representative column is a function of the stiffness and mass on the representative column in the open ground storey, as given in Eq. (16), which may be considered as approximately equal to the natural time period (T) of the building.

$$F_y = \frac{M_y}{h/2} \tag{14}$$

$$K = \frac{F_y}{\Delta_y} \tag{15}$$

$$T = 2\pi\sqrt{\frac{m}{K}} \tag{16}$$

In the present work, on the conservative side, yield force capacity is assumed to be the same as ultimate force capacity. The total yield force capacity of the OGS building is calculated from the yield force capacity of the

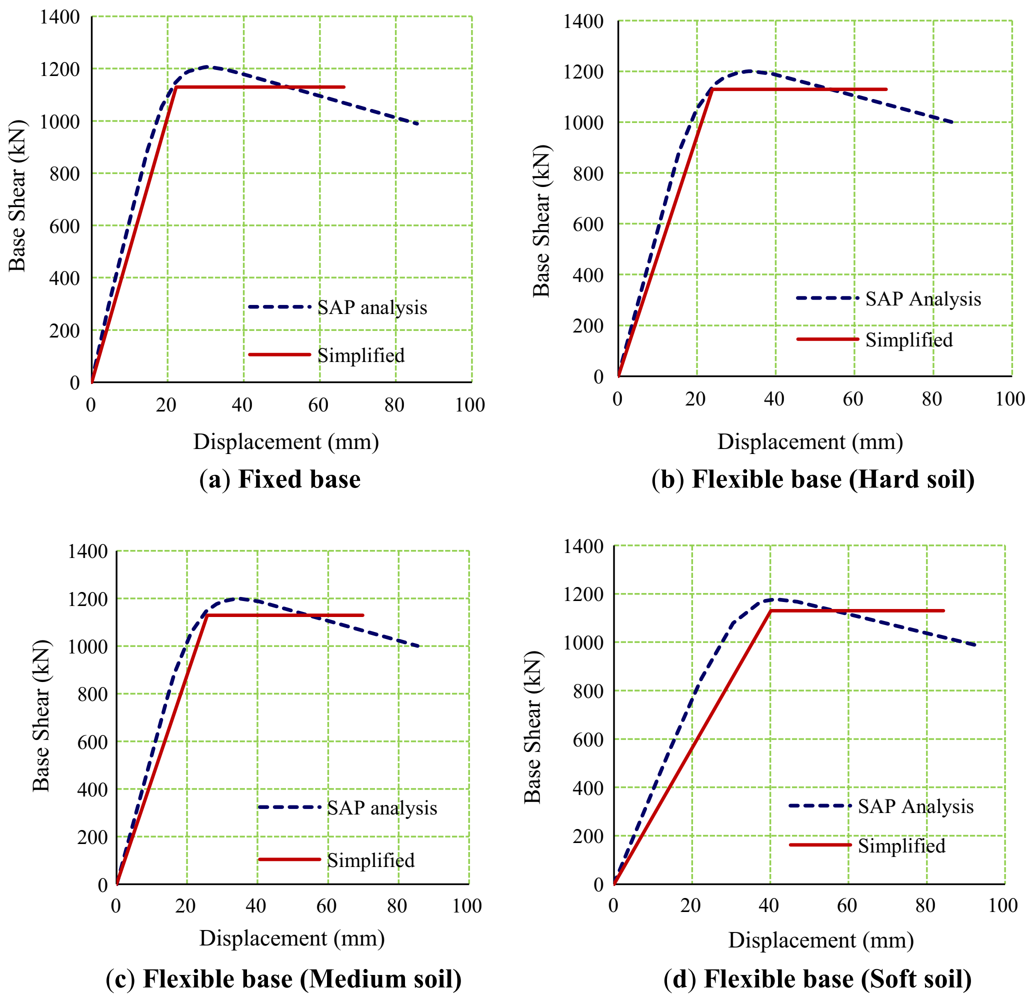


Figure 14. Comparison of pushover curves for SAP2000 analysis and simplified method.

representative column multiplied by the number of columns.

The overall displacement capacity considering the soil-structure interaction can be estimated based on the simplified replacement oscillator approach developed by Avilés and Pérez-Rocha [23, 24]. The replacement oscillator is essentially a SDOF system fixed at the base and defined by an effective time period that incorporates the foundation flexibility effect. This concept assumes equal yield strengths and maximum plastic deformations developed in fixed and flexible systems under monotonic loading. In addition, it is inherently assumed that the translational and rotational responses of the foundation are the same for yielding and ultimate conditions, meaning elastic soil behaviour and elastoplastic structural behaviour. Using this approach for studying the SSI effects on the representative column, the expressions for effective time period $\left(\tilde{T}\right)$, effective yield $\left(\tilde{\Delta}_y\right)$ and effective ultimate deformation $\left(\tilde{\Delta}_u\right)$ of the replacement oscillator are given by Eqs. (17), (18) and (19).

$$\tilde{T} = T \cdot \left(\sqrt{1 + \frac{K}{K_x} + \frac{K \cdot h^2}{K_{yy}}} \right) \tag{17}$$

$$\tilde{\Delta}_y = \left(\frac{\tilde{T}}{T} \right)^2 \cdot \Delta_y \tag{18}$$

$$\tilde{\Delta}_u = \tilde{\Delta}_y + \Delta_u - \Delta_y \tag{19}$$

The effective period is a function of the representative column stiffness (K), soil translational stiffness (K_x) and rotational stiffness (K_{yy}). The yield displacement is obtained by equating the yield strengths of the original and replacement oscillator and the ultimate displacement is obtained from the equal plastic deformations assumption. The lateral load deformation behaviour capacities obtained from SDOF methodology is compared with the SAP2000 analysis results for the 5 storey OGS buildings with fixed base, hard, medium and soft soil flexible base (figure 14). For comparison, the total building force capacity could be taken as the total number of columns times the yield force capacity of the representative column. In SAP2000 analysis results, the displacement on the pushover curve at 20% reduction in yield force, has been considered as ultimate displacement capacity. The proposed simplified procedure has shown a reasonable comparison with the SAP2000 analysis results and it can be used for quick or preliminary seismic assessment. In the case of 8 storey building, idealizing it as a SDOF system may not be valid, so the proposed method is limited up to 5 storey buildings, which are very common in Indian urban areas.

10. Conclusions

Open ground storied building frames with fixed and flexible base have been analysed for different boundary conditions using pushover analysis. Variation in boundary conditions are incorporated by simulating three different soil conditions hard or rock, medium and soft, classified as mentioned in IS 1893 (Part 1) 2016 [2]. The soil characteristics are modelled as translational and rotational springs. In addition, the study also includes two other cases of boundary conditions, i.e., fixed and hinged supports at the base for comparison purposes. The seismic response of the building frames such as lateral deflection and time period are compared. Further, a parametric study is carried out to study the influence of soil flexibility in OGS buildings of various slenderness ratios. The performance point obtained for various cases by verifying the seismic demand with the seismic capacity. From the SSI of open ground storey building study and parametric study the following observations are made:

- The natural period of the OGS building appreciably alter by considering the soil-structure interaction. The flexible base increases the time period, thus a slight change in the seismic force.
- Neglecting the soil flexibility in the modeling of OGS buildings, the drift in the ground storey columns can be underestimated.
- Variation in the base shear of the building models with boundary conditions as hard, medium and soft soil is observed to be marginal.
- A slight reduction in the soft storey deflected profile is observed due to an increase in the soil flexibility, however, it is observed only at the initial yield hinge formation stage.
- The percentage increase of natural time period from fixed support condition to hard, medium and soft soil support conditions has increased as the slenderness ratio increases. But in cases of the hinged condition, a decreasing trend is observed. Therefore, neglecting soil-structure interaction in higher slenderness ratio cases can lead to erroneous results.
- The influence of soil-structure interaction on lateral behavior is more significant in frames with a higher slenderness ratio.
- Seismic demand to capacity studies highlighted the importance of considering the influence of soil flexibility in seismic capacity evaluation to obtain a realistic performance point, apart from the usual practice of considering soil type in seismic demand alone.

A simplified methodology for estimating the lateral behaviour of a flexible base open ground storey building has been developed for preliminary and quick seismic assessment. The developed methodology is validated with the detailed analytical studies made on open ground storey buildings. This methodology can be used for seismic safety evaluation of huge stock of OGS buildings already in existence in the Indian urban regions. Further, highly vulnerable OGS buildings can then be segregated and detailed evaluation procedures can be conducted for them prior to undertaking retrofit decisions.

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List of symbols

f_m	Compressive strength of masonry prism (MPa)
f_{mo}	Compressive strength of mortar (MPa)
f_b	Compressive strength of brick (MPa)
w_{ds}	Width of equivalent diagonal strut
L_{ds}	Diagonal length of the strut
E_f	Modulus of elasticity of the RC frame material
E_m	Modulus of elasticity of the URM infill wall material
I_c	Moment of inertia of the adjoining column
θ	Angle of the diagonal strut with the horizontal
G	Shear modulus of soil
V_s	Shear wave velocity of soil
ν	Poisson's ratio of soil
N	Standard penetration test blow counts
ρ	Mass density of soil
φ	Angle of internal friction of soil
c	Cohesive strength of soil
K_i	Translational spring stiffness in i^{th} degree of freedom
K_{ii}	Rotational spring stiffness in ii^{th} degree of freedom
Δ_y	Yield displacement of the representative column
ϕ_y	Yield curvature of the representative column cross-section
Δ_u	Ultimate displacement capacity of the representative column
ϕ_u	Ultimate curvature of the representative column cross-section

l_p	Plastic hinge length of column
T	Natural time period
K	Initial stiffness of the representative column
F_y	Yield force capacity of the representative column
M_y	Yield moment of the representative column
$\tilde{T}$	Effective time period of the replacement oscillator
$\tilde{\Delta}_y$	Effective yield displacement of the replacement oscillator
$\tilde{\Delta}_u$	Effective ultimate displacement of the replacement oscillator
Δ_{roof}	Roof displacement
V_b	Base shear
S_a	Spectral acceleration
S_d	Spectral displacement

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