Seismic Response of RC Frame Buildings with Soft First Storeys

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ABSTRACT
Open first storey is a typical feature in the modern multistorey constructions in urban India. Such features are highly undesirable in buildings built in seismically active areas; this has been verified in numerous experiences of strong shaking during the past earthquakes. This paper highlights the importance of explicitly recognizing the presence of the open first storey in the analysis of the building. The error involved in modeling such buildings as complete bare frames, neglecting the presence of infills in the upper storeys, is brought out through the study of an example building with different analytical models. This paper argues for immediate measures to prevent the indiscriminate use of soft first storeys in buildings, which are designed without regard to the increased displacement, ductility and force demands in the first storey columns. Alternate measures, involving stiffness balance of the open first storey and the storey above, are proposed to reduce the irregularity introduced by the open first storey. The effect of soil flexibility on the above is also discussed in this paper.

INTRODUCTION
Many urban multistorey buildings in India today have open first storey as an unavoidable feature. This is primarily being adopted to accommodate parking or reception lobbies in the first storeys. The upper storeys have brick infilled wall panels. The draft Indian seismic code classifies a soft storey as one whose lateral stiffness is less than *50%* of the storey above or below [Draft IS:1893, 1997]. Interestingly, this classification renders most Indian buildings, with no masonry infill walls in the first storey, to be "buildings with soft first storey."

Whereas the total seismic base shear as experienced by a building during an earthquake is dependent on its natural period, the seismic force distribution is dependent on the distribution of stiffness and mass along the height. In buildings with soft first storey, the upper storeys being stiff, under go smaller inter-storey drifts. However, the inter-storey drift in the soft first storey is large. The strength demands on the columns in the first storey for third buildings is also large, as the shear in the first storey is maximum. For the upper storeys, however, the forces in the columns are effectively reduced due to the presence of the Buildings with abrupt changes in storey stiffnesses have uneven lateral force distribution along the height, which is likely to locally induce stress concentration. This has adverse effect on the performance of buildings during ground shaking. Such buildings are required to be analyzed by the dynamic analysis and designed carefully.

Many earthquakes in the past, *e.g.*, San Fernando 1971, Northridge 1994, Kobe 1995, have demonstrated the potential hazard associated with such buildings. Major damage to many reinforced concrete and steel buildings in the Hyogoken-Nanbu earthquake of January 17, 1995 [AIJ, 1995], and to critical hospital facilities in the San Fernando earthquake of 1971, were attributed to the soft first storey. Alarming amount of damage to the buildings with open basements for parking has been reported during the Northridge earthquake of January 17, 1994 [Hall, 1994; EQEI, 1994].

The recent Jabalpur earthquake of 22 May 1997 [Jain, *et al*, 1997] also illustrated the handicap of Indian buildings with soft first storey. This earthquake, the first one in an urban neighborhood in India, provided an opportunity to assess the performance of engineered buildings in the country during ground shaking. The damage incurred by Himgiri and Ajanta apartments in the city of Jabalpur are very good examples of the inherent risk involved in the construction of buildings with soft first storey. Himgiri apartments is a RC frame building with open first storey on one side for parking, and brick infill walls on the other side. The infill portion of the building in the first storey is meant for shops or apartments. All the storeys on top have brick infill walls. The first storey columns in the parking area were badly damaged including spalling of concrete cover, snapping of lateral ties, buckling of longitudinal reinforcement bars and crushing of core concrete (Fig. 1). The columns on the other side had much lesser level of damage in them. There was only nominal damage in the upper storeys consisting of cracks in the filler walls. This is a clear case of columns damaged as a result of the "soft first storey". The Ajanta apartments buildings are a set of almost identical four storey RC frame building located side-by-side. In each of these buildings, there are two apartments in each storey, excepting the first storey. One building has two apartments in the upper storeys, but only one apartment in the first storey. The open space on the other side is meant for parking, and hence has no infilled wall panels. Whereas, only nominal damages were reported in the building with two apartments the first storey, the first storey columns on the open side in the other building were very badly damaged. The damage consisted of buckling of longitudinal bars, snapping of ties, spalling of cover and crushing of core concrete.

Figure 1 :: Damage to columns in Himgiri apartment.

In a two-storey (plus stilt storey) C-shaped RC frame building (Youth hostel building) in Jabalpur, the damage to the columns in the stilt storey consisted of severe X-type cracking due to cyclic lateral shear (Fig. 2). Here also, the two storeys above the stilt storey have brick infilled wall panels. This makes the upper storeys very stiff as compared to the storey at the stilt level. There was no damage to the columns in the storeys above. The "soft first storey" at the stilt level is clearly the primary reason for such a severe damage.

In this paper, stiffness balancing is proposed between the first and second storey of a reinforced concrete moment-resisting frame building with open first storey and brick infills in the upper storeys. A simple example building is analyzed with different models. The stiffness effect on the first storey is demonstrated through the lateral displacement profile of the building, and through the bending moment and shear force in the columns in the first storey.

Figure 2 :: Damage to columns in the stilt storey of Youth Hostel building.

BUILDING STUDIED

The plan layout of the reinforced concrete moment resisting frame building with open first storey and Un-reinforced brick infill walls in the upper storeys, chosen for this study is shown in Fig. 3. The building is deliberately kept symmetric in both orthogonal directions in plan to avoid torsional response under pure lateral forces. Further, the columns are taken to be square to keep the discussion focused only on the soft first storey effect, without being distracted by the issues like orientation of columns. The building is considered to be located in seismic zone III and intended for residential use. The building is founded on medium strength soil through isolated footings (of size *2m×2m*) under the columns. When a central concrete service core is used, a *2m* wide footing is taken to go all around under the wall in the core. To show the effect of soil flexibility, the modulus of surged reaction of the soil is taken as *30,000* kN/m^3 [Prakash, 1981]. Elastic moduli of concrete and masonry are *28,500 MPa* and *3,500 MPa,* respectively, and their Poison's ratio is *0.2.* Performance factor (K) has been taken as *1.0* (assuming ductile detailing). The unit weights of concrete and masonry are taken as *25* kN/m^3 and *20* kN/m^3. The floor finish on the floors is *1* kN/m^2. The weathering course on roof is taken as *2.25* kN/m^2. The live load on floor is taken as *2* kN/m^2 and that on roof as *0.75* kN/m^2. In the seismic weight calculations, only *25%* of the floor live load is considered.

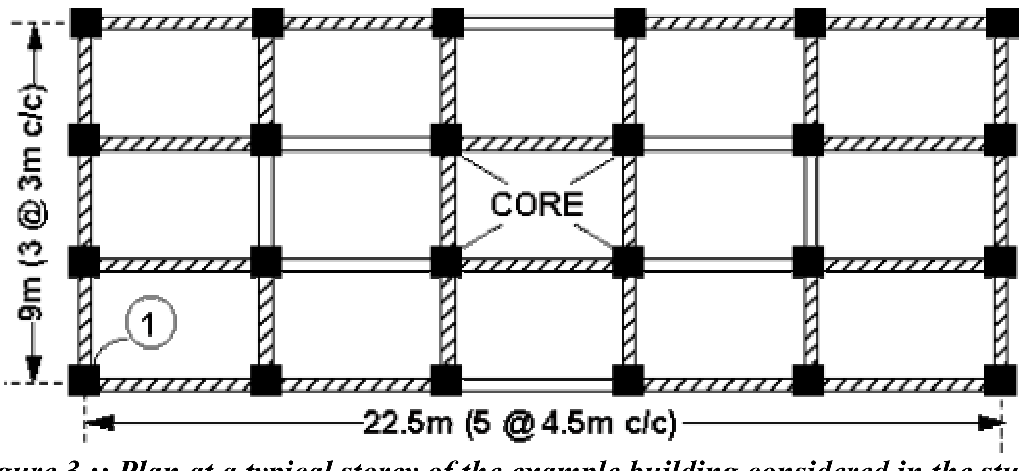
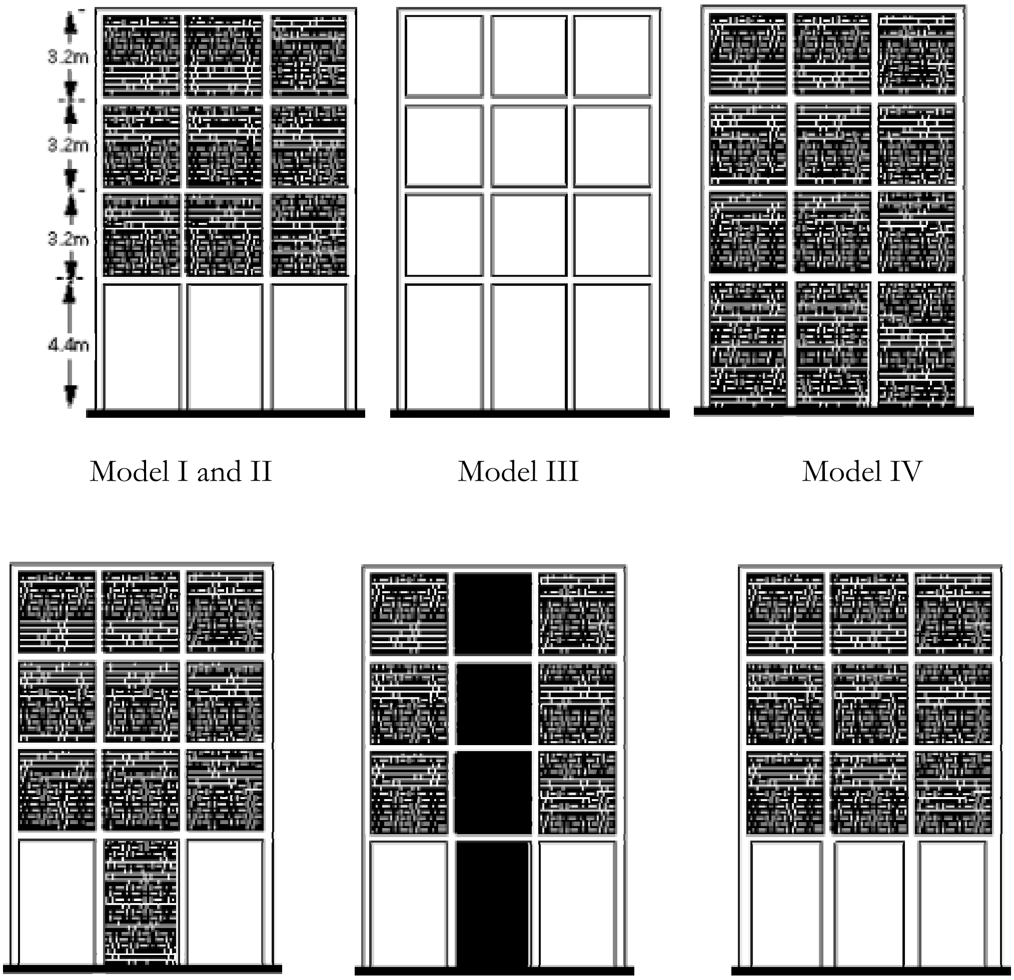


Figure 3 :: Plan at a typical storey of the example building considered in the study.



Model I and II　　Model III　　Model IV

Model V　　Model VI, VIII and IX　　Model VII

Figure 4 :: Elevation of different building models considered in this study.

Nine different models of the building are studied (Fig. 4). These are :

Model I :: Building has no walls in the first storey and one full brick infill masonry walls (*220 mm* thick) in the upper storeys.

Model II :: Building has no walls in the first storey and half brick infill masonry walls (*110 mm* thick) in the upper storeys.

Model III :: Building modeled bare frame. However, masses of the walls as in *model I* are included in the model.

Model IV :: Building has one full infill masonry wall (*220 mm* thick) in all storeys, including the first storey.

Model V :: Building has one full brick infill masonry walls (*220* mm thick) in the upper storeys. Further, a central service core is introduced in the building, by providing *220 mm* thick brick masonry walls within the frame panels formed by the columns and beams in the central bay in the first storey.

Model VI :: Building has one full brick infill masonry walls (*220* mm thick) in the upper storeys. Again, a central service core is introduced in the building, by providing reinforced concrete walls (*220 mm* thick in the first storey and *100* mm in the upper storeys) within the frame panels formed by the columns and beams in the central service core in all storeys.

Model VII :: Building has no walls in the first storey and one full brick infill masonry walls (*220 mm* thick) in the upper storeys. However, the columns in the first storey are much stiffer (*850mm×850mm*) than those in the upper storeys *(400mm×400mm)* to reduce the stiffness irregularity between the open first storey and the storey above.

Model VIII :: Building as in Model VI with soil flexibility introduced only under the concrete walls in the central core area; the columns are assumed to be fixed at their base.

Model IX :: Building as in Model VI with soil flexibility introduced under the concrete walls in the central core area as well as all the columns.

ANALYSIS OF THE BUILDING

Linear elastic analysis is performed for the nine models of the building using *ETABS* analysis package [Habibullah, 1995]. The frame members are modeled with rigid end zones, the walls are modeled as panel elements, and the floors are modeled as diaphragms rigid in-plane. The soil flexibility is introduced as linear Winkler springs under the footing. When the central service core is used in models VIII and IX, the walls in the core are discretised finely into *250 mm* wide vertical strips to enable the modeling of a continuous soil support through linear Wrinkler springs. Two different analysis are performed on the models of the building considered in this study, namely the equivalent static analysis and the multi-modal dynamic analysis. These are briefly described below.

Equivalent Static Analysis

The natural period of the building is calculated by the expression, $T = 0.09H/\sqrt{D}$ given in IS:1893-1984, wherein H is the height and D is the base dimension of the building in the considered direction of vibration. Thus, the natural periods for all the models in this method, is the same. The lateral load calculation and its distribution along the height is done as per IS:1893-1984. The seismic weight is calculated using full dead load plus *25%* of live load.

Multi-Modal Dynamic Analysis

Dynamic analysis of the building models is performed on *ETABS*. The lateral loads generated by *ETABS* correspond to the seismic zone III and the *5%* damped response spectrum given in IS:1893-1984. The natural period values are calculated by *ETABS*, by solving the eigen value problem of the model. Thus, the total earthquake load generated and its distribution along the height correspond to the mass and stiffness distribution as modeled by *ETABS*. Here, as in the equivalent static analysis, the seismic mass is calculated using full dead load plus *25%* of live load.

RESULTS AND DISCUSSIONS

The displacements and forces from the equivalent static method are consistently larger by about *20%* than those from the multi-modal dynamic analysis method.

Storey Stiffness

For the building models at hand, the storey stiffness of the first and second storeys are shown in Table 1. The storey stiffness is defined as the magnitude of the force couple required at the floor levels adjoining the storey to produce a unit lateral translation within the storey, letting all the other floors to move freely.

Table 1 :: Storey stiffness of first and second storeys for different building models.

Building Model	***Storey Stiffness (kN/mm)***			
	Transverse		***Longitudinal***	
	First	***Second***	***First***	***Second***
Open First Storey:: 220mm thick walls in upper storeys	230	3448	227	5263
Open First Storey:: 110mm thick walls in upper storeys	225	2083	220	3030
Bare Frame	185	365	166	291
Brick Infilled Completely	2273	3571	3571	5263
Open First Storey + Brick Service Core	474	3333	694	5000
Open First Storey + Concrete Service Core	2346	4349	4167	7143
Open First Storey with Stiffer Columns	2941	3846	2778	5556
Open First Storey + Concrete Service Core + Flexible Soil under Core only	300	3125	308	4546
Open First Storey + Concrete Service Core + Flexible Soil	205	1613	220	2857

The stiffness irregularity in building models with soft first storey is evident from the fact that the stiffness of the first storey for model *I, II,* and *V* is about *5%,10%* and *15%* respectively. Of the second storey stiffness. Models *I* and *II* represent the actual buildings. It is seen that the reduction of the wall thickness in the upper storeys and addition of the brick service core reduces only marginally the stiffness irregularity. The stiffness of the first storey in model *III* (bare frame) is about *55%* of that of the second storey. However, this does not imply that the building does not have stiffness irregularity. In fact, the bare frame idealization of the building, considering only the mass of the infill brick walls, is a grossly incorrect model for the building considered in this study. The use of RC service core (model *VI*) or stiffer columns (model *VII*) in the first storey reduces the stiffness irregularity. The first storey stiffness in these models are more than *50%* of the second storey stiffness. For model *VII*, this value is larger (*77%*) in the transverse direction than in the longitudinal direction (*50%*). This effect is also observed in other models having fully open first storey. It is interesting to note that the percentage stiffness values for model *IV* (brick infilled completely) and model *VI* are very close. The introduction of foundation flexibility under the concrete service core (model *VIII*) drastically increases the stiffness irregularity; first storey stiffness is only *10%* of the second storey.

Natural Periods

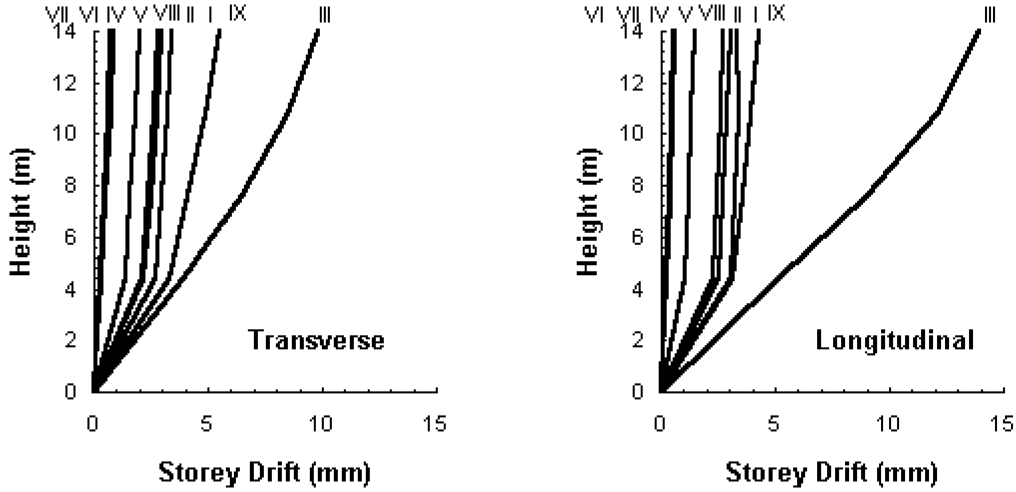
The codal (IS:1893-1984) and analytical (*ETABS*) natural periods of the building models are shown in Table 2. It is seen that the analytical natural periods do not tally with the natural periods obtained from the empirical expression of the code. The bare frame idealization in *model III* leads to a severe overestimation of the natural period compared to the (actual) open first storey building in *model I*. This leads to an underestimation of the design lateral force in model *III*.

Table 2 :: Codal and analytical fundamental natural periods of different building models.

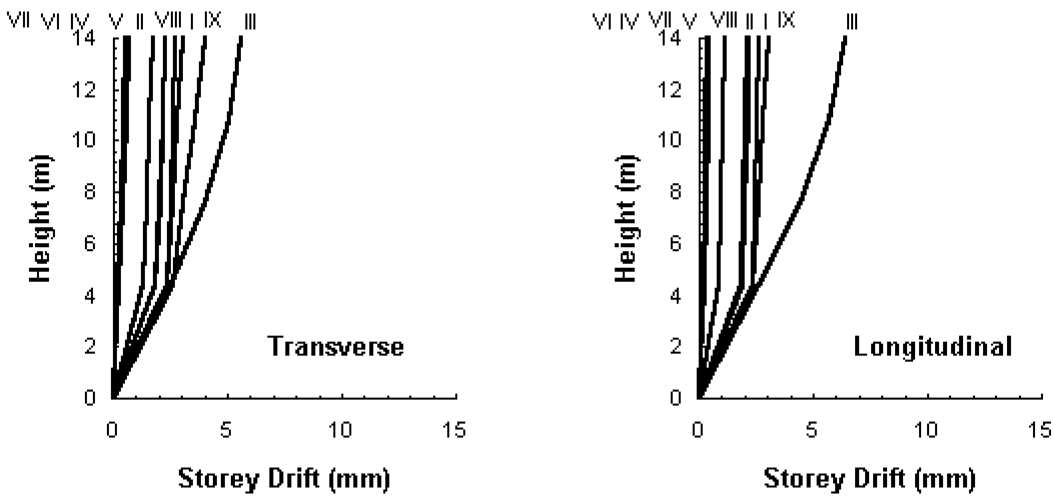
Model	***Fundamental Natural Period (sec)***			
	Transverse		***Longitudinal***	
	Code	***Analysis***	***Code***	***Analysis***
	0.42	0.43	0.27	0.42
	0.42	0.38	0.27	0.38
	0.42	0.64	0.27	0.71
	0.42	0.18	0.27	0.15
	0.42	0.31	0.27	0.26
	0.42	0.18	0.27	0.13
	0.42	0.16	0.27	0.15
	0.42	0.38	0.27	0.37
	0.42	0.5	0.27	0.44

Lateral Deformation

The lateral displacement profiles of the various models for the two different analysis performed in this study are shown in Fig. 5. In these figures, the abrupt changes in the slope of the profile indicate the stiffness irregularity. All displacement profiles corresponding to models having stiffness irregularity (*I, II, V, VIII* and *IX*) have a sudden change of slope at first floor level. However, the other models *i.e.*, *III, IV, VI* and *VII*, show smooth displacement profiles. The displacements at first floor level are shown in Table 3. The inter-storey drift demand is largest in the first storey for all the models with soft ground storey. This implies that the ductility demand on the columns in the first storey, for these models, is the largest. For the models which do not have stiffness irregularity the first floor displacement is small, approximately *10%* of the corresponding values in model *I*. Thus, the drift ductility demand in the first storey can be greatly reduced by ensuring that the storey stiffness at least equal to *50%* of the second storey.



(a)



(b)

Figure 5: Lateral Displacement Profile by (a) Equivalent Static Analysis and (b) Multi-Modal Dynamic Analysis.

Bending Moment and Shear Force in Columns

The maximum bending and maximum shear forces in the columns in the first and the upper storeys are shown in Table 3; the bending moment and shear force (strength) demands are severely higher for first storey columns, in case of the soft first storey buildings. The introduction of walls in the first storey (model *IV*) reduces the force in the first storey columns. As the force is distributed in proportion to the stiffness of the members, the force in the columns of the upper storeys, for all the models (except model *III*), are significantly reduced due to the presence of brick walls. These forces (bending moment and shear force) are about *10-20%* of the corresponding values in the first storey columns. The use of brick service core is not very effective in reducing the strength demand on the first storey columns. However, the force values are around *50%* of the values in case of model *I*. When concrete service core is used, the demand on the columns is significantly reduced (by a factor of about *10.0*). Interestingly, the drift demands on the first storey columns in case of model *IV* (completely infilled) and model *VI* (stiffer columns in first storey) are very close. This is true for strength demands also. Thus, it is possible to replace all the brick infills in the first storey with a single concrete core as far as the drift and strength demands on the first storey columns are concerned. Model *VII* (stiffer columns in first storey) results in first storey drift demands similar to that of model *IV* (completely infilled), but the strength demand on the first storey columns is very large; the strength demands in model *VII* are around *10%* of those in model *IV*.

Table 3 :: Displacement at first floor, maximum forces in first storey columns and average of the maximum forces in the columns of the storeys above for different models.

Model	Displacement (mm) at First Floor		Maximum Moment (kNm)				Maximum Shear (kN)			
			Transverse		Longitudinal		Transverse		Longitudinal	
	Trans.	Long.	First	Rest	First	Rest	First	Rest	First	Rest
Equivalent Static Analysis										
	2.7	3.1	56.4	6.2	62.7	4.8	27.2	4.5	30.1	3.6
	2.2	2.5	45.0	8.2	50.4	7.2	21.6	6.0	24.1	5.8
	3.9	5.2	70.4	43.9	85.3	49.9	31.7	32.3	36.5	37.5
	0.3	0.2	6.6	6.2	4.5	6.4	3.1	4.4	2.1	3.5
	1.4	1.0	27.5	5.4	20.8	4.7	13.1	3.7	10.0	3.3
	0.3	0.2	6.7	8.2	3.9	6.3	3.4	5.8	1.9	4.3
	0.2	0.3	76.2	5.3	84.1	3.8	32.9	3.9	34.9	2.9
	2.1	2.3	46.8	15.6	45.8	6.8	23.3	10.7	22.0	4.8
	3.3	3.2	70.6	31.1	71.1	34.6	34.5	21.8	35.4	24.7
Multi-Modal Dynamic Analysis										
	2.3	2.4	48.1	4.5	48.7	4.7	23.2	3.4	23.5	3.2
	1.9	1.9	38.0	6.0	44.0	7.1	18.3	4.5	18.8	4.8
	2.5	2.6	45.2	23.4	39.1	22.4	20.4	17.5	19.0	17.6
	0.3	0.2	5.8	4.7	3.6	3.9	2.8	3.4	1.8	2.9
	1.3	0.9	25.9	4.0	17.7	3.3	12.4	2.8	8.4	2.3
	0.3	0.1	6.1	7.1	3.1	5.1	3.1	5.0	1.6	3.5
	0.2	0.2	65.5	4.0	67.8	2.9	28.4	2.9	28.2	2.3
	1.8	1.8	41.9	14.1	37.2	5.1	21.1	9.7	17.9	3.6
	2.6	2.4	57.5	28.6	55.2	30.0	28.5	20.0	27.8	21.4

Foundation Flexibility

From the above discussion, it is seen that the concrete service core is as effective as providing infilled panels in the first storey of the building. However, the foundation flexibility, if present, can substantially impair its effectiveness. In models *VIII* and *IX*, where the flexibility of the soil is also modeled, both first storey drift and the forces in the columns increase. For model *IX*, these are about *25%* higher than those in model *I*. Thus, it is important to incorporate the soil flexibility, if present, in the modeling of the buildings, failing which the drift and strength demands in the first storey columns can be under-estimated, resulting in an incorrect design of the building.

CONCLUSIONS

RC frame buildings with open first storeys are known to perform poorly during in strong earthquake shaking. In this paper, the seismic vulnerability of buildings with soft first storey is shown through an example building. The drift and the strength demands in the first storey columns are very large for buildings with soft ground storeys. It is not very easy to provide such capacities in the columns of the first storey. Thus, it is clear that such buildings will exhibit poor performance during a strong shaking. This hazardous feature of Indian RC frame buildings needs to be recognized immediately, and necessary measures taken to improve the performance of the buildings.

The open first storey is an important functional requirement of almost all the urban multi-storey buildings, and hence, cannot be eliminated. Alternative measures need to be adopted for this specific situation. The under-lying principle of any solution to this problem is in (a) increasing the stiffnesses of the first storey such that the first storey is at least *50%* as stiff as the second storey, *i.e.*, soft first storeys are to be avoided, and (b) providing adequate lateral strength in the first storey. The possible schemes to achieve the above are (i) provision of stiffer columns in the first storey, and (ii) provision of a concrete service core in the building. The former is effective only in reducing the lateral drift demand on the first storey columns. However the latter is effective in reducing the drift as well as the strength demands on the first storey columns.

The soil flexibility needs to be examined carefully before finalizing the analytical model of a building. Flexible soil conditions may require alternate solutions than those described in this paper, to reduce seismic drift and strength demands on the columns in the first storey.

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