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Progressive Collapse Assessment Of Reinforced Concrete Frame Structure With And Without Considering Actual Soil Condition

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Abstract

It has been found that the forces in the members of frame structures considering soil-structure interaction, differs than conventional method of analysis. Analysis considering soil-structure interaction is time-consuming process; hence, if the relation between two methods established, then by using conventional method, realistic results can be obtained. In the present work, effort has been made to study the impact of soil-structure interaction on the progressive collapse assessment of reinforced concrete frame structure (building). It is clear that the differential settlement of the foundation changes the load transfer system of the super structure. Differential settlement depends on the properties of the soil below foundation and the stiffness of the super structure. The objective of this study is to quantify the change in the reaction at the foundation level due to soil structure interaction. To achieve this target, the Winkler approach is used. In this model, soil below foundation is modelled as idealized springs. To study the effect of failure of load carrying elements i.e. columns on the entire structure; 15 storey moment resistant RC buildings is considered. The building is modelled and analyzed for progressive collapse using the structural analysis and design software SAP2000. Nonlinear static analysis is performed to understand the progressive collapse phenomena. The nonlinear static analysis is found to be the most efficient method for progressive collapse assessment of the reinforced concrete structure with consideration of soil effect. General Service Administration (GSA 2003) guideline is used for loading and procedure to assess the potential towards progressive collapse of structure.

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1 Introduction

It has been observed that the forces estimated in the members of the frame structure are different from the conventional method of analysis, if soil-structure interaction is considered. As soil interaction is a very complex issue, the present study is based on following considerations. 1) Three different soil data are taken based on the past worked projects and the average value of SBC is taken for iteration 2) The footing of the columns is considered as isolated spread footings. 3) The settlement occurs due to normal consolidation of clay layer. 4) The distribution of contact pressure is assumed to be uniform. 5) The depth of foundation is assumed to be same for all footing. 6) Overlapping of pressure bulb is not considered. All three soil data are taken from the existing projects in Ahmedabad. Data was selected in such a way that the whole range of the clay soil exist in the Ahmedabad region will be covered. Selected soil properties are as follows:

Table 1-Selected soil properties of Soil

Description	Symbol	Firm clay soil	Very stiff clay soil	Hard clay soil	Units
N-value	N	6	20	32	-
Field density	ϒ	0.00172	0.00184	0.00198	kg/cm^3
Natural water content	w	37.11	26.18	19.81	%
Cohesion	C	0.15	0.8	1.1	kg/cm^2
Unconfined compressive strength	Q	0.22	1.3	2	kg/cm^2
Specific gravity	G	2.67	2.69	2.7	-
Compression Index	Cc	0.44	0.19	0.15	-
Pre-consolidation pressure	Pc	1.5	2.05	2.2	kg/cm^2
Gravel		0	7	0	%
Sand		6	11	16	%
Silt/Clay		94	82	84	%
Liquid Limit	WL	75	59	64	%
Plastic limit	PL	30	22	21	%
Angle of shear resistance	φ	0	0	0	deg

About GSA guideline

The General Service Administration Guideline was developed to assess the Progressive Collapse Analysis and Design for federal buildings by U.S. The purpose of these Guidelines is to: 1) Assist in the reduction of the potential for progressive collapse in new Federal Office Buildings 2) Assist in the assessment of the potential for progressive collapse in existing Federal Office Buildings 3) Assist in the development of potential upgrades to facilities if required. The guidelines provide the independent methodology to minimizing the potential for progressive collapse in the design of building structure. The guideline not includes the explicit part of a blast design/analysis. These Guidelines address the need to protect human life and prevent injury as well as the protection of Federal buildings, functions and assets. The Guidelines take a flexible and realistic approach to the reliability and safety of Federal buildings.

2 Procedure To Find Out The Variation In Load Distribution And Simulate It For Progressive Collapse

The step wise procedure to be followed

1) Calculate safe bearing capacity for the given soil data.
2) Analyze structure with conventional method. (Fixed Support Condition)
3) Design footing size for all columns and Find out the total settlement of all columns.
4) Find out spring constants for all columns.
5) Analyze structure with springs as supports.
6) Adopt new reactions and find out new spring constants for next iteration
7) Repeat the iterations till the difference of reaction of two subsequent iterations are found within the specified accuracy.
8) Apply final corrected reactions to all the columns.
9) Perform the NLS analysis for all four column removal cases.
10) Compare the result based on plastic hinge formation and percentage of load attempt by structure.

Step 1: Calculate Safe Bearing Capacity for given soil data

In this section the calculation has been done to find the safe bearing capacity of very stiff clay as per specified in Table 1. These properties are based on experiments carried out in the laboratory. However, experimental tests are not included in the scope of work. Assumptions for calculating the SBC are 1) Depth of Foundation (Df) = 2m and 2) Width of Footing (B) = 2m. The value of SBC obtains using IS 6403:1981 and IS 8009:1976 is 250 kN/m^2

Step 2: Analyze structure with conventional method for gravity and Seismic loading

Considering fixed supports condition and load combinations as per IS:456, base shear and reations at supports are determined.

Step 3: Design footing size for all columns and Find out the total settlement of all columns.

The size of foundation and its settlement is determined using IS 6403 and IS 8009 respectively.

Step 4: Find out spring constants for all columns.
Sample calculation for the column shown as below.
$K_{1,1}$ = Ro1 / y
$K_{1,1}$ = 3520.36 / (5.84/100)
$K_{1,1}$ = 60280.14 kN/m
Where Ro = Unfactored load on column
y = Settlement of foundation
$K_{1,1}$ = Spring stiffness for 1st Iteration

Step 5: Analyze structure with springs as supports

After calculating "Equivalent Stiffness of Spring" for all columns these springs were attached to the column as a support. The snap shot (fig.1) shows the modelling scenario. After preparing new model with same configuration and spring supports, analysis was done. This analysis was considered as 1^{st} iteration. The table 2 shows support reaction after 1^{st} iteration for given structural system.

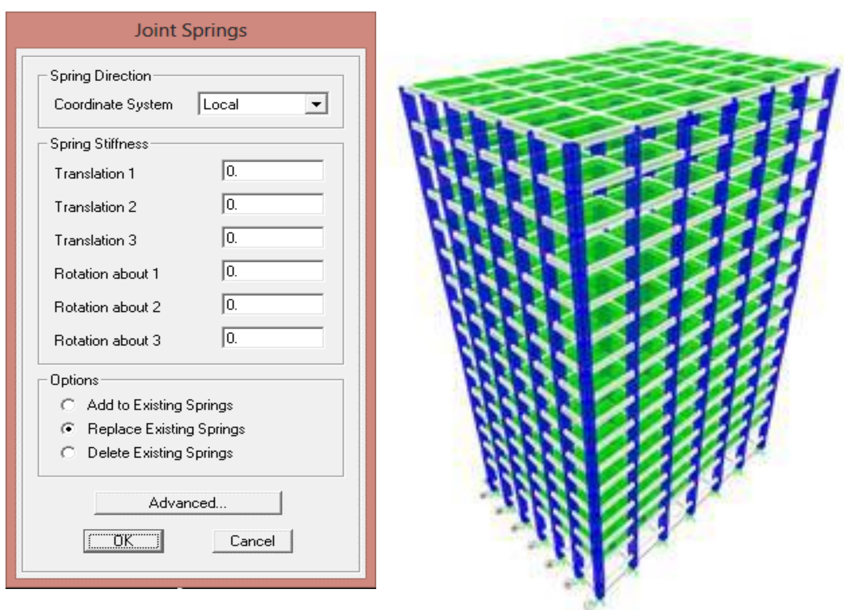


Figure 1 – Spring as Supports

Table 2 - Support Reaction after 1st Iteration

Column No.	Reactions kN	Column No.	Reactions kN	Column No.	Reactions kN
835	*4053.92*	852	*5985.29*	869	*4628.07*
836	*4952.59*	853	*5941.10*	870	*4498.58*
837	*5143.24*	854	*5722.27*	871	*5553.56*
838	*5182.79*	855	*4627.64*	872	*5762.63*
839	*5143.24*	856	*4658.58*	873	*5805.30*
840	*4952.59*	857	*5761.70*	874	*5762.63*
841	*4053.92*	858	*5983.24*	875	*5553.56*
842	*4497.60*	859	*6027.88*	876	*4498.58*
843	*5552.87*	860	*5983.24*	877	*4049.82*
844	*5762.12*	861	*5761.70*	878	*4953.62*
845	*5804.84*	862	*4658.58*	879	*5144.01*
846	*5762.12*	863	*4628.07*	880	*5183.50*
847	*5552.87*	864	*5722.60*	881	*5144.01*
848	*4497.60*	865	*5941.34*	882	*4953.62*
849	*4627.64*	866	*5985.50*	883	*4049.82*
850	*5722.27*	867	*5941.34*		
851	*5941.10*	868	*5722.60*		

Step 6: Adopt new reactions and find out new spring constants for next iteration

Now onwards for all the iterations the value of “Equivalent Stiffness of the Spring” should be calculated from the Winkler’s formula given below.

$$K_{k,i} = \left[\frac{R_{k-1,i} - R_{k-2,i}}{2R_{0,i}} + 1\right] K_{k-1,i}$$

$K_{k,i}$ = Equivalent Spring attached to the ith support at k^{th} iteration
k = Number of iteration
$R_{k,i}$ = The reaction at support at the k^{th} iteration
$R_{0,i}$ = Reaction at the i^{th} support at Zero iteration

The value of “k” will increase with the increment of the number of iteration. For the third iteration the k equal to 3 and for forth iteration k equal to 4. Table 3 shows the equivalent stiffness of springs for second iteration.

Table 3 - Equivalent Stiffness of springs for 2^{nd} Iteration

Column No.	Spring For 2^{nd} iteration kN/m	Column No.	Spring For 2^{nd} iteration kN/m	Column No.	Spring For 2^{nd} iteration kN/m
835	*64848.28*	852	*78497.00*	869	*69034.10*
836	*71399.40*	853	*78210.41*	870	*68072.90*
837	*72764.29*	854	*76763.11*	871	*75614.34*
838	*73046.72*	855	*69030.86*	872	*77019.28*
839	*72764.29*	856	*69260.17*	873	*77301.06*
840	*71399.40*	857	*77027.68*	874	*77019.28*
841	*64749.53*	858	*78487.77*	875	*75614.34*
842	*68065.26*	859	*78776.22*	876	*68072.90*
843	*75609.78*	860	*78487.77*	877	*64714.45*
844	*77015.98*	861	*77027.68*	878	*71406.89*
845	*77298.07*	862	*69260.17*	879	*72769.81*
846	*77015.98*	863	*69034.10*	880	*73051.81*
847	*75609.78*	864	*76765.24*	881	*72769.81*
848	*68065.26*	865	*78211.96*	882	*71406.89*
849	*69030.86*	866	*78498.39*	883	*64714.45*
850	*76763.11*	867	*78211.96*		
851	*78210.41*	868	*76765.24*		

Step 7: Repeat the iterations till the difference of reaction of two subsequent iterations are found within the specified accuracy

Table – 4 Support Reactions after Iterations

Column No.	5^{th} Iteration kN	6^{th} Iteration kN	7^{th} Iteration kN	8^{th} Iteration kN	9^{th} Iteration kN	10^{th} Iteration kN	11^{th} Iteration kN
835	4372.78	4376.75	4378.28	4378.88	4379.11	4379.21	4379.24
836	5030.12	5031.13	5031.55	5031.72	5031.80	5031.83	5031.84
837	5296.48	5299.29	5300.43	5300.89	5301.08	5301.16	5301.19
838	5362.88	5366.00	5367.23	5367.71	5367.90	5367.97	5368.00
839	5296.86	5299.68	5300.82	5301.28	5301.47	5301.55	5301.58
840	5031.35	5032.40	5032.83	5033.01	5033.08	5033.12	5033.13
841	4365.44	4369.28	4370.77	4371.34	4371.57	4371.66	4371.70
842	4587.34	4586.91	4586.59	4586.41	4586.32	4586.27	4586.25
843	5367.22	5363.84	5362.45	5361.87	5361.63	5361.53	5361.49
844	5649.81	5648.15	5647.44	5647.13	5647.00	5646.94	5646.92
845	5718.19	5716.78	5716.13	5715.83	5715.70	5715.64	5715.61
846	5650.10	5648.44	5647.73	5647.43	5647.29	5647.24	5647.21
847	5368.08	5364.72	5363.33	5362.76	5362.52	5362.42	5362.38
848	4589.38	4589.01	4588.73	4588.56	4588.48	4588.43	4588.41
849	4711.35	4711.79	4711.94	4712.00	4712.02	4712.03	4712.04
850	5531.32	5528.97	5528.11	5527.80	5527.69	5527.65	5527.64
851	5824.84	5824.24	5824.09	5824.06	5824.06	5824.06	5824.06
852	5895.05	5894.72	5894.63	5894.61	5894.60	5894.60	5894.60
853	5825.04	5824.45	5824.29	5824.26	5824.26	5824.26	5824.26
854	5531.88	5529.53	5528.68	5528.37	5528.26	5528.22	5528.21
855	4712.46	4712.92	4713.08	4713.14	4713.16	4713.17	4713.18
856	4749.52	4750.40	4750.76	4750.91	4750.98	4751.01	4751.02
857	5579.32	5577.45	5576.82	5576.61	5576.54	5576.52	5576.52
858	5876.29	5876.19	5876.26	5876.33	5876.37	5876.39	5876.40
859	5947.13	5947.29	5947.44	5947.52	5947.56	5947.57	5947.58
860	5876.42	5876.32	5876.39	5876.46	5876.50	5876.52	5876.53
861	5579.67	5577.80	5577.17	5576.96	5576.89	5576.87	5576.87
862	4750.20	4751.08	4751.45	4751.60	4751.67	4751.70	4751.71
863	4712.12	4712.57	4712.72	4712.78	4712.81	4712.82	4712.82
864	5531.75	5529.40	5528.55	5528.24	5528.13	5528.09	5528.08
865	5825.07	5824.47	5824.32	5824.28	5824.28	5824.28	5824.28
866	5895.19	5894.85	5894.76	5894.74	5894.74	5894.74	5894.74
867	5825.14	5824.54	5824.39	5824.36	5824.35	5824.36	5824.36
868	5531.96	5529.61	5528.76	5528.45	5528.34	5528.30	5528.28
869	4712.58	4713.03	4713.19	4713.25	4713.27	4713.28	4713.28
870	4589.36	4588.96	4588.66	4588.49	4588.40	4588.35	4588.33
871	5368.17	5364.80	5363.41	5362.84	5362.60	5362.50	5362.46
872	5650.30	5648.64	5647.93	5647.62	5647.49	5647.43	5647.41
873	5718.49	5717.08	5716.43	5716.14	5716.00	5715.94	5715.91
874	5650.32	5648.66	5647.95	5647.64	5647.51	5647.45	5647.43
875	5368.27	5364.90	5363.51	5362.93	5362.70	5362.60	5362.56
876	4589.68	4589.28	4588.98	4588.80	4588.71	4588.67	4588.65
877	4365.31	4369.22	4370.73	4371.32	4371.56	4371.65	4371.69
878	5031.74	5032.77	5033.19	5033.37	5033.44	5033.48	5033.49
879	5297.32	5300.14	5301.28	5301.74	5301.93	5302.00	5302.04
880	5363.45	5366.57	5367.79	5368.27	5368.46	5368.54	5368.57
881	5297.29	5300.10	5301.24	5301.70	5301.89	5301.97	5302.00
882	5031.73	5032.75	5033.17	5033.35	5033.42	5033.45	5033.47
883	4365.47	4369.39	4370.90	4371.49	4371.72	4371.81	4371.85

Step 8: Apply final corrected reactions to all columns and calculate the percentage of GSA loading taken by the structure after soil-structure interaction.

Step 9: Perform NLS analysis to specified column removal cases

As per the GSA guidelines, four cases of column removal as shown in fig.-2, shall be considered for the progressive collapse assessment of the framed structure. Nonlinear static analysis is carried out using SAP2000 software. Fig.-3 shows the local damage scenario by removing the external corner column C–1A and hinges developed during NLS analysis. GSA guideline prescribes loading as 2(DL+ 0.25LL) on the structure. Load is incremented till the chord rotation of beam members at column removal place reached within 0.015 radian as per the failure criteria prescribed in ASCE 41 and FEMA 356. Accordingly, for the given problem, when displacement at the place of column removal reaches to 100 mm is taken as the failure condition.

Fig. 4, 5, 6, & 7 shows the variation of % GSA load v/s displacement at the column removal place for four column removal cases respectively. Ultimate loads for NLS analysis considering fixed based and considering soil stiffness is also given below each figure.

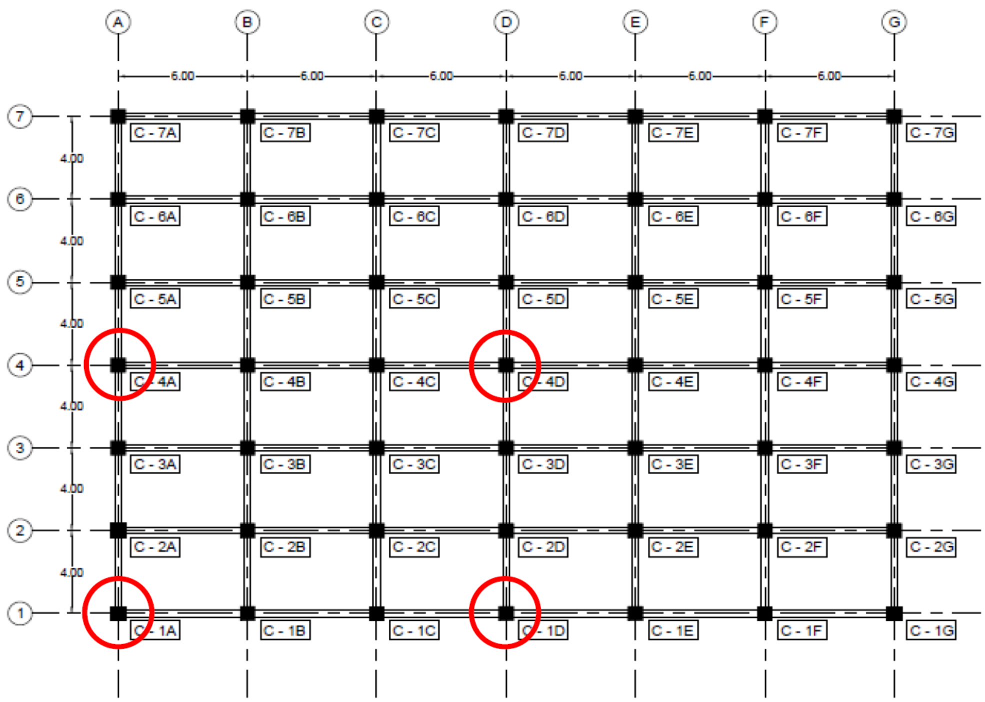


Figure 2 – Column removal location

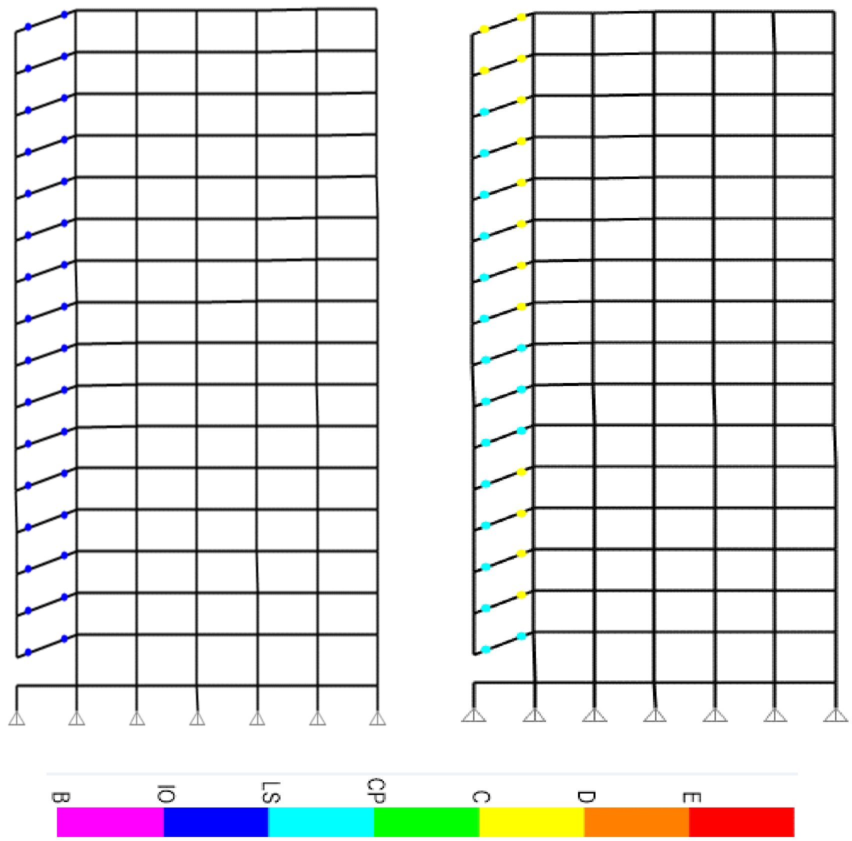
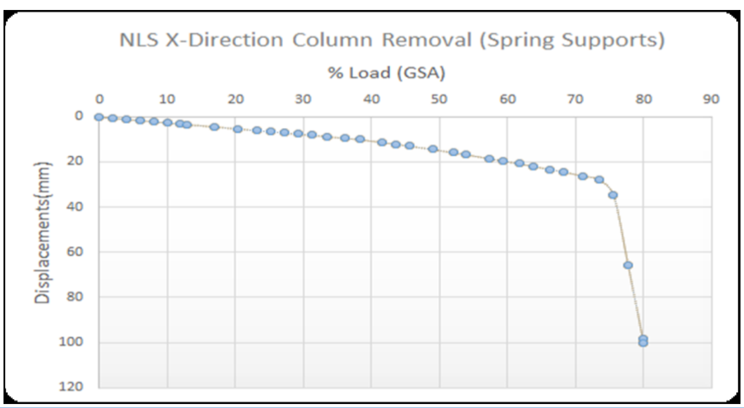
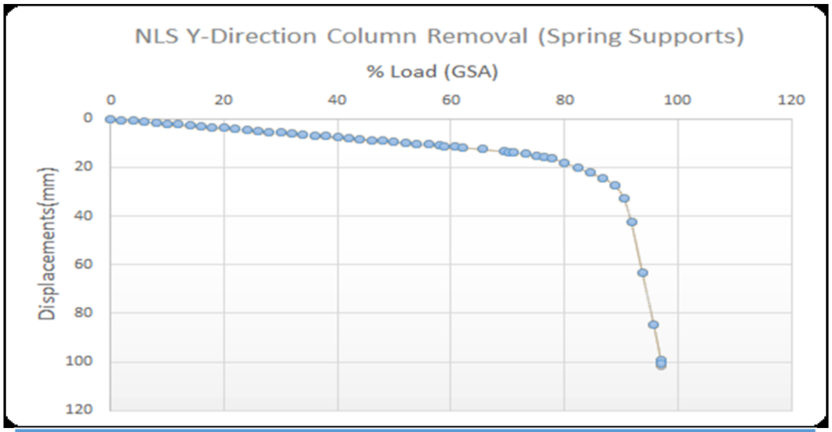


Figure 3 – Building frames with hinge formation along major and minor direction of building respectively at corner column removal



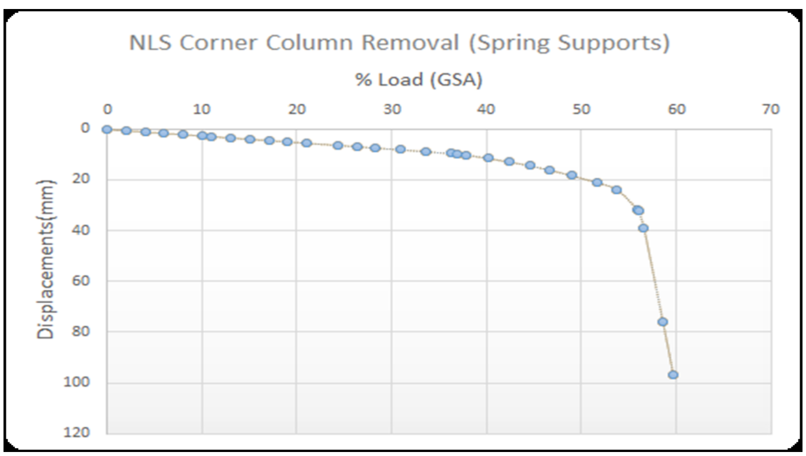
CASES	GSA LOADING	% GSA Load Attempt
Non-Linear Static	**2(DL+0.25LL)**	**87.92**
Non-Linear Static - Soil	**2(DL+0.25LL)**	**79.94**

Figure 4 - % load attempt for Case 1 Non-Linear Static Analysis (Soil)



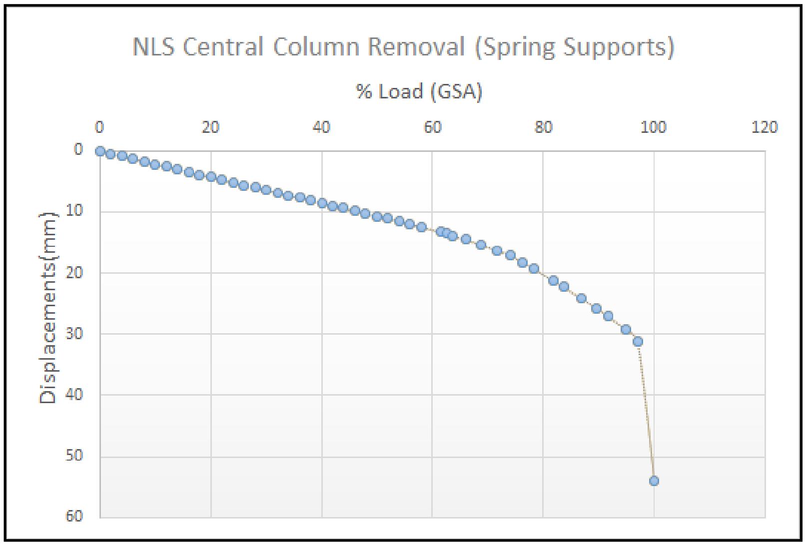
CASES	GSA LOADING	% GSA Load Attempt
Non-Linear Static	2(DL+0.25LL)	99.97
Non-Linear Static - Soil	2(DL+0.25LL)	97.09

Figure 5 - % load attempt for Case 2 Non-Linear Static Analysis (Soil)



CASES	GSA LOADING	% GSA Load Attempt
Non-Linear Static	2(DL+0.25LL)	78.26
Non-Linear Static - Soil	2(DL+0.25LL)	59.63

Figure 6 - % load attempt for Case 3 Non-Linear Static Analysis (Soil)



CASES	GSA LOADING	% GSA Load Attempt
Non-Linear Static	2(DL+0.25LL)	98.21
Non-Linear Static - Soil	2(DL+0.25LL)	99.97

Figure 7 - % load attempt for Case 4 Non-Linear Static Analysis (Soil)

3 Results and Discussion

In the present study, G+15 storied RC framed structures is analyzed for progressive collapse assessment using GSA guideline. The effect of soil stiffness in the progressive collapse assessment is also shown in this paper. From the result, it can be seen that,

1. The ultimate load considering soil stiffness found lesser value than without soil stiffness in all four column removal cases except in central column removal case, there is marginally increase.
2. In the corner column removal case (Fig. 6), the ultimate load varies significantly with and without considering soil stiffness. i.e. 59.63% of GSA load with soil stiffness and 78.26% of GSA load without soil stiffness.
3. In the exterior bay column removal case (fig. 4&5), the ultimate load does not much vary. In the exterior bay column removal, the variation is little more in long exterior bay (fig. 4) than short exterior bay (fig. 5) column removal case.
4. The interior column removal case (fig. 7), the variation in the ultimate load with & without soil stiffness is almost negligible.

In the progressive collapse analysis, considering soil stiffness may vary the results due to change in the soil stiffness after removal of column condition. The soil stiffness determined by achieving equilibrium of forces at foundation gets disturbed once column is removed from the structure at foundation level. But in the present study, this part is ignored and the same soil stiffness are taken before and after column removal condition.

4 Conclusion

Following conclusions can be drawn from the study of progressive collapse assessment of G+15-storied RC framed structure with & without effect of soil stiffness.

- The support reactions of the footing changes considerably considering fixed based support condition and soil structure interaction.

- The structure was checked for potential of progressive collapse using GSA guideline with & without consideration of actual soil condition. The NLS analysis for all four cases of column removal prescribed in the GSA guideline shown that the ultimate load is lesser with consideration of soil stiffness than without soil stiffness case. That means that progressive collapse assessment of RC frames structure considering soil stiffness is more vulnerable than without soil stiffness case.

- For evaluating progressive collapse assessment, again corner column removal case gives worst effect. i.e. about 20% lesser value of ultimate load in the case of consideration of soil stiffness than not considering it.

In summary, the process of analysis using actual soil condition is time consuming and tedious, but the role of soil affects a lot in the behavior of progressive collapse of structure, so it is recommended that the role of soil should be considered in progressive collapse assessment of structure.

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