Published by :
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International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 12 Issue 08, August-2023

Comparitative Non-Linear Static Analysis of Buildings in Different Seismic Zones With Soil Structure Interaction

S. Bindu Poornima
Department of civil engineering
NRI Institute of Technology
Vijayawada, A.P, India.

M. Krishna Kumar
Department of civil engineering
NRI Institute of Technology
Vijayawada, A.P, India.

Abstract - High land prices and a lack of available open space, along with rapid urbanization and population mass migration, lead to the development of high-rise building clusters in major cities like Bangalore, Delhi, and Mumbai, where structures are frequently constructed next to one another without consideration for structural safety. Strong external forces, such as earthquakes, have a high likelihood of causing a dynamic interaction among closely built structures in these circumstances. For this reason, it is crucial to thoroughly study and comprehend the dynamic response of these structures by taking into account all potential contingencies that may negatively affect the response of the structure and giving safety and serviceability a higher priority. One of such theories is the interaction between soil and structure, which is a crucial consideration for designing earthquake-resistant constructions. The purpose of the study was to understand how soil structure interaction affected RC buildings. According to IS 1893:2016, multi-story structures with the same number of storeys (G+5) were studied. The models are considered to be located in all seismic zones and are meant to be supported on two primary soil types (Hard soil and soft soil). The effect of subterranean soil is simulated using Winkler's Soil Spring Model. ETABS v18 software is used to examine the models using both linear and non-linear methods. The models are analysed using both linear(Equivalent static analysis & Response spectrum analysis) and non-linear(Pushover analysis) techniques using ETABS v18 software. The non-linear static analysis is used to determine the structure's performance point, and the various performance levels for the various structural components are represented by different notations, such as Immediate occupancy (IO), Life safety (LS), and Collapse prevention (CP), which are all defined in FEMA 440 for zone IV & V cases.The outcomes of modelling the structures on a fixed base and on flexible base are studied. It is observed that the storey displacements increases with increase in the flexibility of the soil and base shear increases with the decrease in the hardness of the soil. When SSI effect is considered it is observed that the storey displacement increases and base shear decreases compared to the fixed base conditions for both hard and soft soils. It can be concluded that the effect of soil structure interaction increases with the increase in the flexibility of the soil, intensity of the seismic activity prevailing in that location, and increase in the height of the structure. However, the chances of failure of the structure are more in soft soil condition in zone V. Therefore, it is necessary to take into account the impact of SSI when building significant buildings in areas with high seismic activity and high soil flexibility.

Key Words: Linear Seismic Analysis, Non-Linear Static Analysis, Soil Structure Interaction, ETABS, Flexible base.

I. INTRODUCTION

A structure experiences vibrations as a result of the earthquake waves that have reached it. These motions rely on the architectural or structural plan as well as the vibrational properties of the structure. The interaction between the structure and the soil happens because the structure must overcome its own inertia in order to respond to the motion. The relative mass and stiffness characteristics of the soil and the structure determine how much the structural reaction may change the features of seismic movements seen at the foundation level. As a result, the physical characteristics of the foundation media have a significant role in how well-built structures based on it withstand earthquakes.

For the study of earthquake engineering, two aspects of the interaction between building foundations and earthquakes are crucial. First off, compared to a structure based on a hard foundation, a structure built on flexible soil may respond to seismic motion quite differently. Second, the motion captured at a structure's base or in its immediate surroundings may differ from the motion captured if there had been no building.

The process in which the response of the soil influences the motion of the structure and motion of the structure influences the response of the soil is termed as "**SOIL STRUCTURE INTERACTION"**. Most of the design codes use oversimplified design spectra, which attain constant acceleration up to a certain period, and thereafter decreases monotonically with period. Considering soil-structure interaction makes a structure more flexible and thus, increasing the natural period of the structure compared to the corresponding rigidly supported structure.

SSI can be broadly divided into 2 types:

1.Kinematic Interaction
2. Inertial Interaction

Many studies have been conducted in the past utilizing various techniques to ascertain the impact of soil-structure interaction. Winkler's idealization, which assumes that the foundation's

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 12 Issue 08, August-2023

deformation is limited to the area under the applied load, is one such approach. In plain English, the impact of soil flexibility is taken into account by thinking of a comparable soil spring system in place of the footings. Winkler's approach (Direct method), although having certain drawbacks in comparison to the finite element method, is nonetheless favorable due to its straightforward process. The entire set of algebraic formulae has been provided by Pais and Kausel (1988), and Gazetas and Mylonakis have further updated them.

1.1. *Objectives of study*

The primary goal of the study is the seismic behavior of buildings considering soil structure interaction. The presence of traditional constructions in seismically prone areas makes them exposed to greater shears and torsion as compared to conventional construction. In order to highlight the differences in behavior, which may further be influenced by the characteristics of the locally available foundation material, study has been conducted on six representative structures.

- To perform a detailed study on the previous available literature in the present area of study.
- Perform three dimensional space frame analysis for storey buildings under the action of seismic load with varying soil conditions.
- To investigate and compare the effect of soil structure interaction on different types of soil.
- To study the response of the structures i.e., Structure in zone IV & zone V with and without considering the soil structure interaction effect for two different types of soil conditions.
- To compare the response of the structure for two different seismic zones due to soil structure interaction effect.
- To determine the performance point of the structure in the zone IV & zone V for the cases considered.
- To define the performance levels and the hinge states of the structure.

2.0. MODELING

A G+5 storeyed reinforced concrete frame building situated (Table 1) in zone IV is taken for the purpose of the present study. The plan area of the building is 30m X 40m in Fig 1

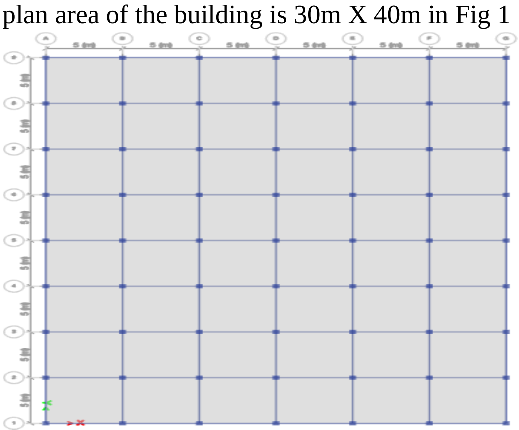

Fig. 1. Plan Of The Multi Storied Building

The models that have been considered:

- Regular building on plain ground in Zone IV for
- MODEL 1:Fixed base for both hard and soft soil conditions.
- MODEL 2:Soil Structure Interaction for both hard and soft soilconditions.
- Regular building on plain ground in Zone V for

MODEL 3: Fixed base for both hard and soft soil conditions.
MODEL 4:Soil Structure Interaction for both hard and soft soilconditions

The properties of the soil with the elastic constant for the type of the soil upon which structure is considered to be resting are considered as per Bowels in Table1.

Table 1. Soil Data

Soil type	Shear wave velocity (m/sec)	Mass density (KN/m^3)	Poisson ratio	Shear modulus KN/m^2 x 10^4	SBC KN/m^2
Hard rock	1250	2.10	0.30	328.13	570
Soft soil	150	1.85	0.4	4.16	120

2.1. Idealization by Winkler's method

Sub-structure approach (or) Winkler method where the effect of SSI is represented by using equivalent springs with 6 degrees of freedom shown in Fig 2 given by the researches such as Mylonakis and Gazetas as per Table2.

Degrees of freedom	**Stiffness of equivalent soil spring**
Vertical	$[{}^{2GL}/_{(1-\upsilon)}]$ $(0.73+1.54\chi^{0.75})$
Horizontal (lateral direction)	$[{}^{2GL}/_{(2-\upsilon)}]$ $(2+2.50\chi^{0.85})$
Horizontal (longitudinal direction)	$[{}^{2GL}/_{(2-\upsilon)}]$ $(2+2.50\chi^{0.85})$ – $[0.2/(0.75-\upsilon)]$ GL[1-(B/L)]
Rocking (about longitudinal)	$[G/(1-\upsilon)]I_{bx}^{0.75}(L/B)^{0.25}$ $[2.4+0.5(B/L)]$
Rocking (about lateral)	$[G/(1-\upsilon)]I_{by}^{0.75}(L/B)^{0.15}$
Torsion	$3.5GI_{bZ}^{0.75}(B/L)^{0.4}(I_{bz}/B)^{0.2}$

Where ,

$\chi = {}^{A_b}/_{4L^2}$

Ab = Area of the foundation considered; B and L = Half-width and half-length of a rectangular foundation respectively.

Ibx, Iby and Ibz = Moment of inertia of the foundation area with respect to longitudinal, lateral and vertical Axes, respectively.

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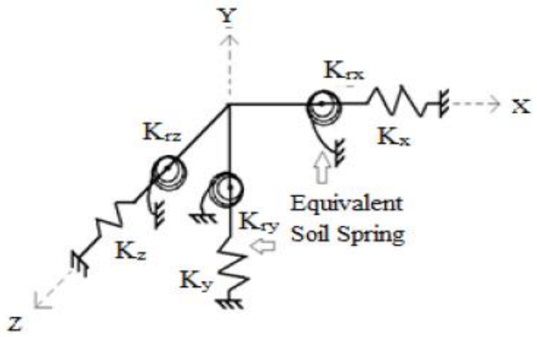

Fig.2. Equivalent Spring Stiffness

where in Fig 2, k_y, k_z = stiffness of equivalent soil springs along the translational degree of freedom along X, Y and Z axes. K_{rx}, k_{ry}, k_{rz} = stiffness of equivalent rotational soil springs along the rotational degree of freedom along X,Y and Z axes.

2.2. PUSHOVER ANALYSIS

Non-linear static analysis or pushover analysis has been most preferred method for the design and seismic performance evaluation purposes as it considers the post elastic behaviour.
In this method, a structure is subjected to gravity loading and a monotonic displacement-controlled lateral load pattern which continuously increases through elastic and inelastic behaviour until an ultimate condition is reached. Lateral load may represent the range of base shear induced by earthquake loading, and its configuration may be proportional to the distribution of mass along building height, mode shapes, or another practical means.
Presently, there are two non-linear static analysis procedures available, one termed as the Displacement Coefficient Method (DCM) included in the FEMA-356 document and the other termed as the Capacity Spectrum Method (CSM) included in the ATC- 40(5) document (ATC, 1996). Both of these methods depend on the lateral load- deformation variation obtained by using the non-linear static analysis under the gravity loading and idealized lateral loading due to the seismic action. This analysis is generally called as the pushover analysis.

2.3. PERFORMANCE POINT

The failure pattern of the structure is determined by non-linear static analysis or pushover analysis, where the structure is subjected to incremental horizontal loads until it reaches the ultimate state. Equivalent linearization method is adopted for the present work as per FEMA 440.

Fig 3: Typical Flexural Hinge Property Showing the Performance Level.

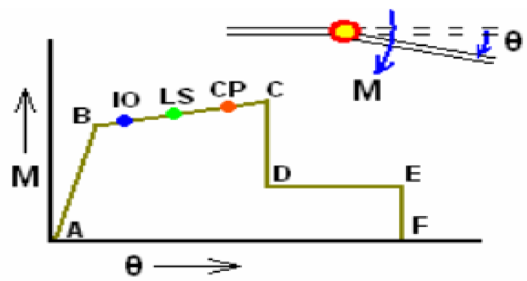

Table 3. Geometric and Material Properties of the Structure and Footing

Beam	230mm x 300mm
Column	450mm x 450mm
Slab	6" thick slab
Grade of concrete	M25 & M30
Live load	3 KN/m^2
Floor finish	1 KN/m^2
Footings	1.72 m x 1.72 m(Hard soil) 2.46 m x 2.46 m (Soft soil)

2.4. Load Combinations

Load combinations are used as per the regulations given in codes IS 456:2000 & IS 1893:2016.

- **1.5(DL+LL)**
- **1.2(DL+LL±EQX)**
- **1.2(DL+LL±EQY)**
- **1.5(DL±EQX)**
- **1.5(DL±EQY)**
- **0.9DL±1.5EQX**
- **0.9DL±1.5EQY**
- **DL+LL**
- **DL±EQX**
- **DL±EQY**
- **DL+0.8LL±0.8EQX**
- **DL+0.8LL±0.8EQY**

3.0 Analysis Results

3.1 Storey Displacements (mm)

TABLE 3.1.1. Storey displacements of structure in zone IV for Equivalent Static Analysis

STOREY DISPLACEMENTS IN ZONE IV FOR EQUIVALENT STATIC ANALYSIS								
STOREY NO	**X-DIRECTION**				**Y-DIRECTION**			
	WITHOUT SSI		**WITH SSI**		**WITHOUT SSI**		**WITH SSI**	
	HARD	SOFT	HARD	SOFT	HARD	SOFT	HARD	SOFT
1	2.903	4.848	3.468	5.792	2.728	4.556	3.26	5.445
2	7.715	12.884	10.408	17.382	7.221	12.058	9.755	16.291
3	12.596	21.035	18.084	30.201	11.766	19.649	16.919	28.254
4	16.901	28.225	25.088	41.897	15.771	26.337	23.441	39.147
5	20.148	33.648	30.551	51.02	18.788	31.375	28.514	47.619
6	22.023	36.778	34.189	57.095	20.518	34.264	31.869	53.221

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International Journal of Engineering Research & Technology (IJERT)
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TABLE 3.1.2. Storey displacements of structure in zone V for Equivalent Static Analysis

STOREY DISPLACEMENTS IN ZONE V FOR EQUIVALENT STATIC ANALYSIS								
STOREY NO	**X-DIRECTION**				**Y-DIRECTION**			
	WITHOUT SSI		**WITH SSI**		**WITHOUT SSI**		**WITH SSI**	
	HARD	SOFT	HARD	SOFT	HARD	SOFT	HARD	SOFT
1	4.355	7.272	5.203	8.688	4.093	6.835	4.891	8.167
2	11.573	19.326	15.612	26.073	10.831	18.088	14.633	24.437
3	18.894	31.553	27.127	45.301	17.649	29.474	25.378	42.382
4	25.352	42.337	37.632	62.846	23.656	39.506	35.162	58.721
5	30.222	50.471	45.827	76.53	28.181	47.063	42.772	71.428
6	33.034	55.167	51.283	85.642	30.776	51.396	47.803	79.831

TABLE 3.1.3. Storey displacements of structure in zone IV for Response Spectrum Analysis

STOREY DISPLACEMENTS IN ZONE IV FOR RESPONSE SPECTRUM ANALYSIS								
STOREY NO	**X-DIRECTION**				**Y-DIRECTION**			
	WITHOUT SSI		**WITH SSI**		**WITHOUT SSI**		**WITH SSI**	
	HARD	SOFT	HARD	SOFT	HARD	SOFT	HARD	SOFT
1	2.405	4.094	2.655	4.6	2.395	4.078	2.652	4.586
2	6.092	10.543	7.573	13.254	6.04	10.455	7.539	13.175
3	9.454	16.579	12.561	22.085	9.351	16.406	12.477	21.911
4	12.159	21.46	16.817	29.609	12.01	21.208	16.677	29.331
5	14.091	24.865	20.027	35.269	13.905	24.547	19.83	34.885
6	15.183	26.714	22.185	39.031	14.965	26.342	21.931	38.539

TABLE 3.1.4. Storey displacements of structure in zone V for Response Spectrum Analysis

STOREY DISPLACEMENTS IN ZONE V FOR RESPONSE SPECTRUM ANALYSIS								
STOREY NO	**X-DIRECTION**				**Y-DIRECTION**			
	WITHOUT SSI		**WITH SSI**		**WITHOUT SSI**		**WITH SSI**	
	HARD	SOFT	HARD	SOFT	HARD	SOFT	HARD	SOFT
1	3.608	6.141	3.983	6.9	3.593	6.118	3.978	6.88
2	9.138	15.814	11.359	19.881	9.059	15.682	11.308	19.762
3	14.18	24.868	18.842	33.128	14.026	24.608	18.716	32.867
4	18.238	32.19	25.226	44.413	18.016	31.812	25.015	43.996
5	21.137	37.298	30.04	52.903	20.858	36.821	29.745	52.328
6	22.774	40.071	33.278	58.547	22.447	39.512	32.896	57.809

3.2. Storey shears (KN)

TABLE 3.2.1. Storey shears of structure in zone IV for Equivalent Static Analysis

STOREY SHEAR IN ZONE IV FOR EQUIVALENT STATIC ANALYSIS								
STOREY NO	**X-DIRECTION**				**Y-DIRECTION**			
	WITHOUT SSI		**WITH SSI**		**WITHOUT SSI**		**WITH SSI**	
	HARD	SOFT	HARD	SOFT	HARD	SOFT	HARD	SOFT
6	480.8788	803.067	276.285	461.39	487.6076	814.304	280.093	467.7558
5	971.2583	1622.00	611.905	1021.88	984.848	1644.69	620.339	1035.967
4	1285.101	2146.11	826.70	1380.5	1303.083	2176.1	838.096	1399.622
3	1461.638	2440.93	947.526	1582.36	1482.09	2475.09	960.585	1604.178
2	1540.098	2571.96	1001.22	1672.04	1561.649	2607.95	1015.02	1695.091
1	1559.714	2604.72	1014.65	1694.46	1581.538	2641.16	1028.63	1717.82

TABLE 3.2.2. Storey shears of structure in zone V for Equivalent Static Analysis

STOREY SHEAR IN ZONE V FOR EQUIVALENT STATIC ANALYSIS								
STOREY NO	X-DIRECTION				Y-DIRECTION			
	WITHOUT SSI		WITH SSI		WITHOUT SSI		WITH SSI	
	HARD	SOFT	HARD	SOFT	HARD	SOFT	HARD	SOFT
6	721.3181	1204.60	414.428	692.094	731.4114	1221.45	420.139	701.6336
5	1456.887	2433.00	917.858	1532.82	1477.273	2467.04	930.509	1553.95
4	1927.652	3219.17	1240.05	2070.89	1954.625	3264.22	1257.14	2099.433
3	2192.457	3661.40	1421.28	2373.55	2223.135	3712.63	1440.87	2406.267
2	2310.148	3857.94	1501.83	2508.06	2342.473	3911.93	1522.53	2542.637
1	2339.57	3907.08	1521.97	2541.69	2372.307	3961.75	1542.95	2576.73

TABLE 3.2.2. Storey shears of structure in zone V for Response Spectrum Analysis

STOREY SHEAR IN ZONE IV FOR RESPONSE SPECTRUM ANALYSIS								
STOREY NO	X-DIRECTION				Y-DIRECTION			
	WITHOUT SSI		WITH SSI		WITHOUT SSI		WITH SSI	
	HARD	SOFT	HARD	SOFT	HARD	SOFT	HARD	SOFT
6	482.4266	657.115	350.32	501.303	485.480	660.964	352.882	503.2589
5	846.8152	1299.30	544.08	910.696	857.233	1313.67	552.138	920.1724
4	1055.56	1761.40	668.07	1128.89	1070.40	1786.16	678.826	1145.879
3	1221.171	2126.12	771.35	1313.74	1238.91	2158.84	784.274	1335.591
2	1403.673	2425.15	879.61	1531.00	1424.15	2462.15	894.478	1554.381
1	1559.543	2604.42	1013.5	1694.44	1581.16	2642.84	1028.61	1717.802

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International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 12 Issue 08, August-2023

TABLE 3.2.4. Storey shears of structure in zone V for Response Spectrum Analysis

STOREY SHEAR IN ZONE V FOR RESPONSE SPECTRUM ANALYSIS								
STOREY NO	X-DIRECTION				Y-DIRECTION			
	WITHOUT SSI		WITH SSI		WITHOUT SSI		WITH SSI	
	HARD	SOFT	HARD	SOFT	HARD	SOFT	HARD	SOFT
6	723.64	985.673	525.491	751.955	728.2209	991.446	529.323	754.8884
5	1270.223	1948.95	816.123	1366.04	1285.85	1970.50	828.207	1380.259
4	1583.34	2642.11	1002.10	1693.34	1605.605	2679.25	1018.23	1718.819
3	1831.756	3189.19	1157.02	1970.61	1858.379	3238.26	1176.41	2003.387
2	2105.509	3637.68	1319.42	2296.51	2136.225	3693.22	1341.71	2331.571
1	2339.314	3906.63	152.276	2541.67	2371.754	3964.26	1542.92	2576.703

3.3. Lateral Forces (KN)

TABLE 3.3.1. Lateral forces of structure in zone IV for Equivalent Static Analysis

LATEAL STOREY FORCES IN ZONE IV FOR EQUIVALENT STATIC ANALYSIS								
STOREY NO	X-DIRECTION				Y-DIRECTION			
	WITHOUT SSI		WITH SSI		WITHOUT SSI		WITH SSI	
	HARD	SOFT	HARD	SOFT	HARD	SOFT	HARD	SOFT
6	480.88	803.07	276.29	461.40	487.61	814.30	280.09	467.76
5	490.38	818.93	335.62	560.49	497.24	830.39	340.25	568.21
4	313.84	524.12	214.80	358.71	318.23	531.45	217.76	363.66
3	176.54	294.82	120.82	201.78	179.01	298.94	122.49	204.56
2	78.46	131.03	53.70	89.68	79.56	132.86	54.44	90.91
1	19.62	32.76	13.42	22.42	19.89	33.22	13.61	22.73

TABLE 3.3.2. Lateral forces of structure in zone V for Equivalent Static Analysis

LATEAL STOREY FORCES IN ZONE V FOR EQUIVALENT STATIC ANALYSIS								
STOREY NO	X-DIRECTION				Y-DIRECTION			
	WITHOUT SSI		WITH SSI		WITHOUT SSI		WITH SSI	
	HARD	SOFT	HARD	SOFT	HARD	SOFT	HARD	SOFT
6	721.32	1204.60	414.43	692.10	731.41	1221.46	420.14	701.63
5	735.57	1228.40	503.43	840.73	745.86	1245.59	510.37	852.32
4	470.76	786.18	322.20	538.07	477.35	797.18	326.64	545.48
3	264.81	442.22	181.24	302.66	268.51	448.41	183.73	306.83
2	117.69	196.54	80.55	134.52	119.34	199.29	81.66	136.37
1	29.42	49.14	20.14	33.63	29.83	49.82	20.41	34.09

3.4. Pushover Results:

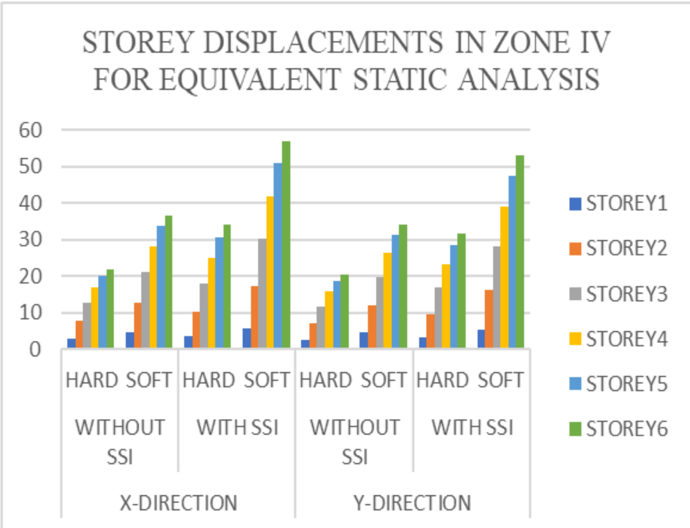
Table 3.4.1. Performance of the structure for PUSHX

Model	Performance Point		Hinge States									
	Base Shear (KN)	Displacement (mm)	A-B	B-C	C-D	D-E	>E	A-IO	IO-LS	LS-CP	>CP	Total
Hard	7258.2	162.96	1473	603	0	0	0	1689	366	19	2	2076
Soft	8180.3	413.82	1527	547	2	0	0	1813	261	0	2	2076

Table 3.4.2. Performance of the structure for PUSHY

Model	Performance Point		Hinge States									
	Base Shear (KN)	Displacement (mm)	A-B	B-C	C-D	D-E	>E	A-IO	IO-LS	LS-CP	>CP	Total
Hard	7660.54	160.87	1509	567	0	0	0	1885	191	0	0	2076
Soft	8953.74	409.45	1448	610	11	7	0	1619	394	40	23	2076

Fig 3.1. Graphical representation of storey displacements in zone IV for Equivalent Static Method



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International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 12 Issue 08, August-2023

Fig 3.2. Graphical representation of storey displacements in zone V for Equivalent Static Method

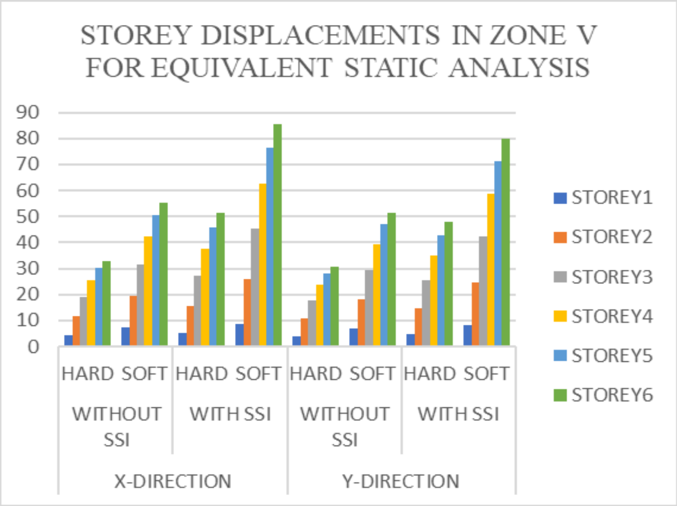


Fig 3.3. Graphical representation of storey displacements in zone IV for Response Spectrum Method

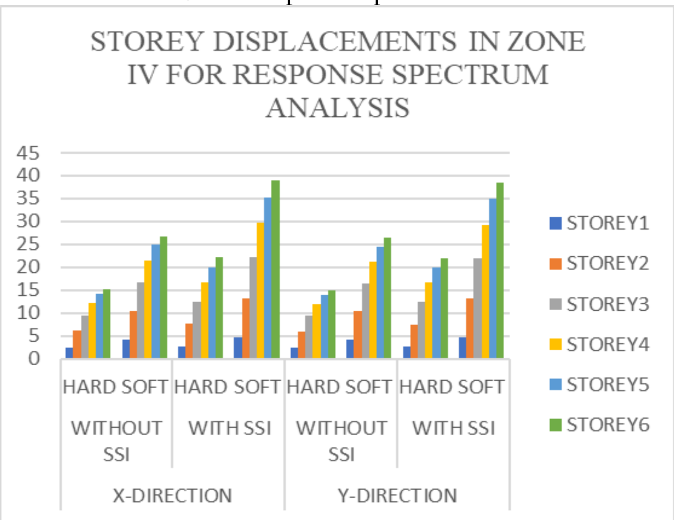


Fig 3.4. Graphical representation of storey displacements in zone V for Response Spectrum Method

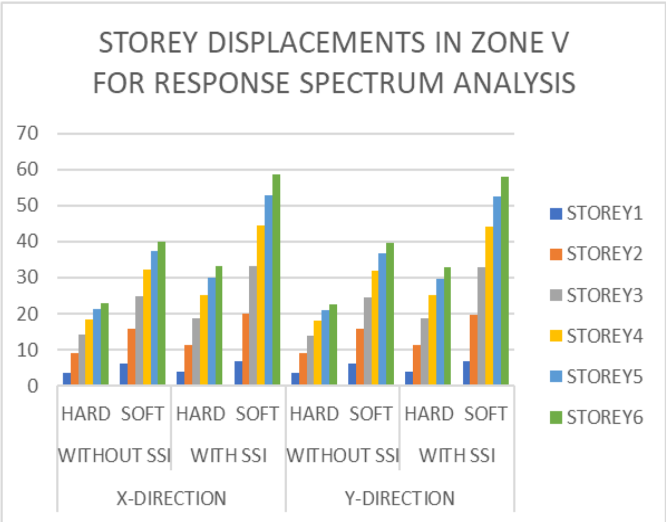


Fig 3.5. Graphical representation of storey shears in zone IV for Equivalent Static Method

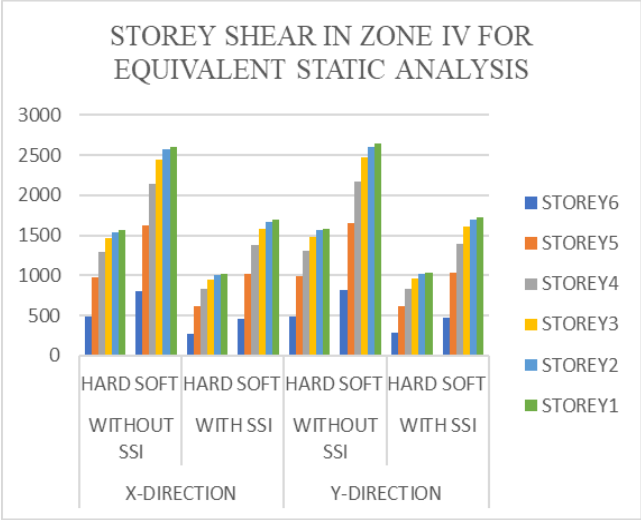


Fig 3.6. Graphical representation of storey shears in zone V for Equivalent Static Method

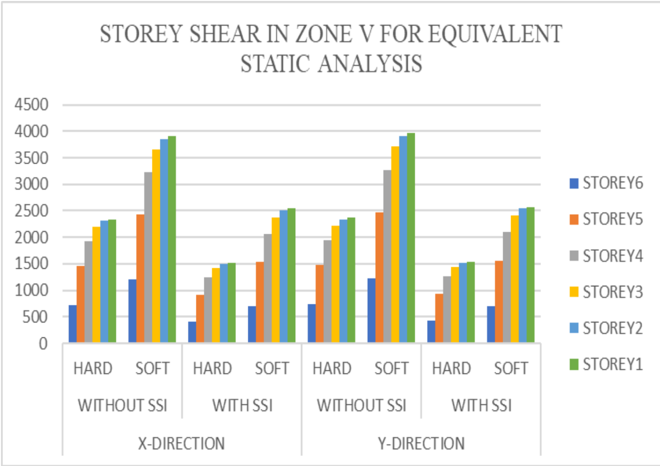
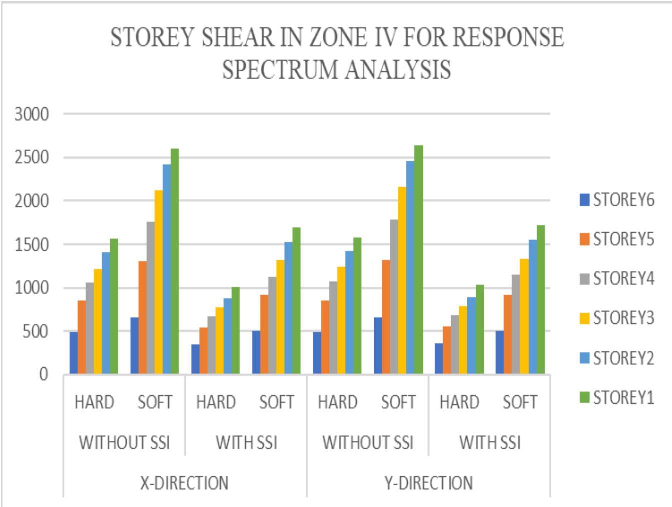


Fig 3.7. Graphical representation of storey shears in zone IV for Response Spectrum Method



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International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 12 Issue 08, August-2023

Fig 3.8. Graphical representation of storey shears in zone V for Response Spectrum Method

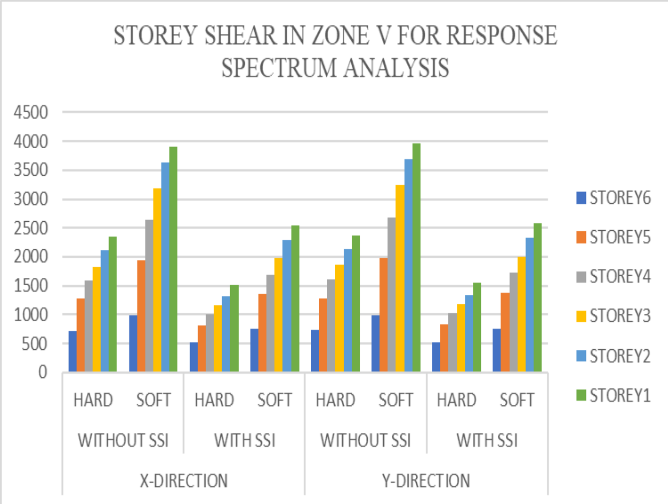


Fig 3.9. Graphical representation of Lateral Forces in zone IV for Equivalent Static Method

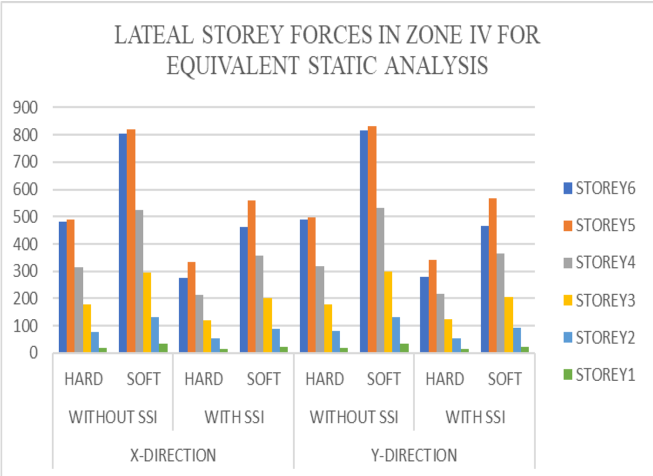


Fig 3.10. Graphical representation of Lateral Forces in zone V for Equivalent Static Method

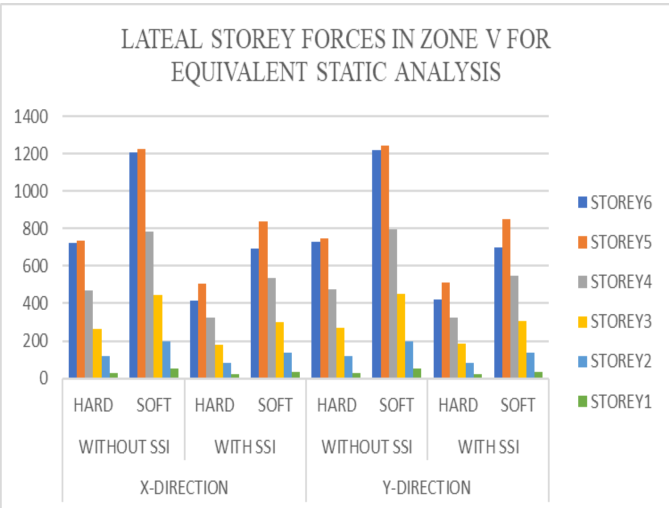


Fig 3.11. Capacity Spectrum Curve For PUSH X Hard Soil

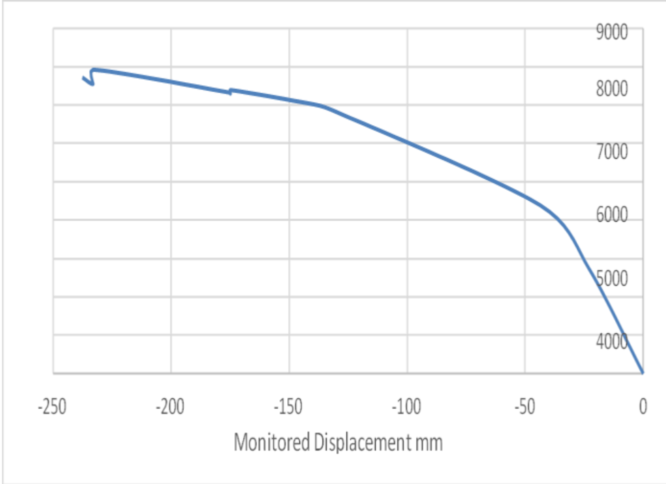


Fig3.12. Capacity Spectrum Curve For PUSH X Soft Soil

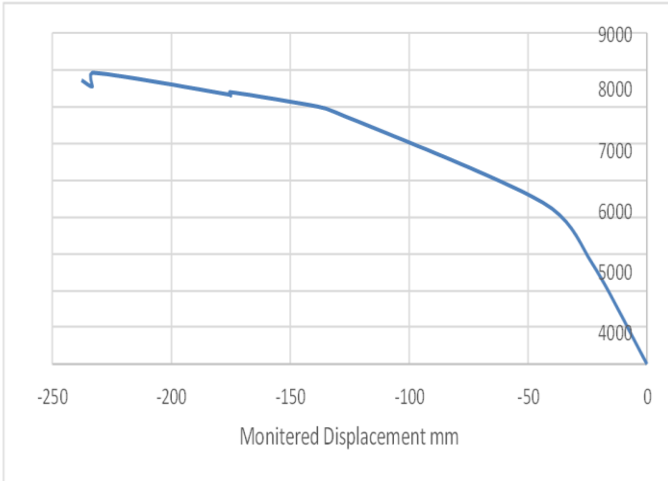


Fig 3.13. Capacity Spectrum Curve For Hard Soil PUSH Y

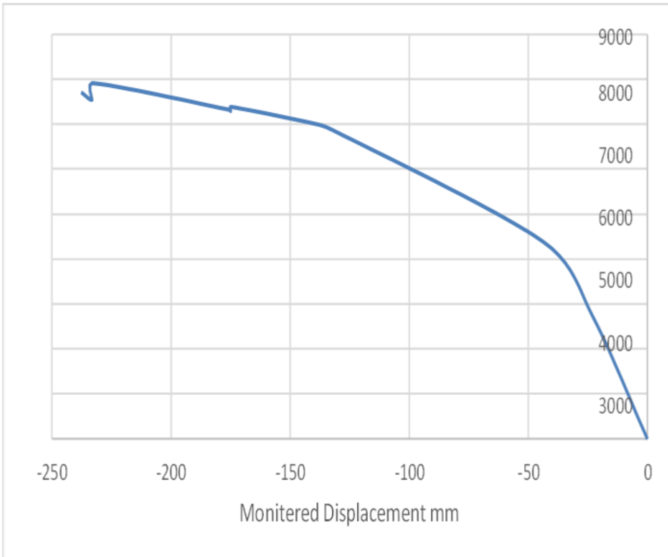
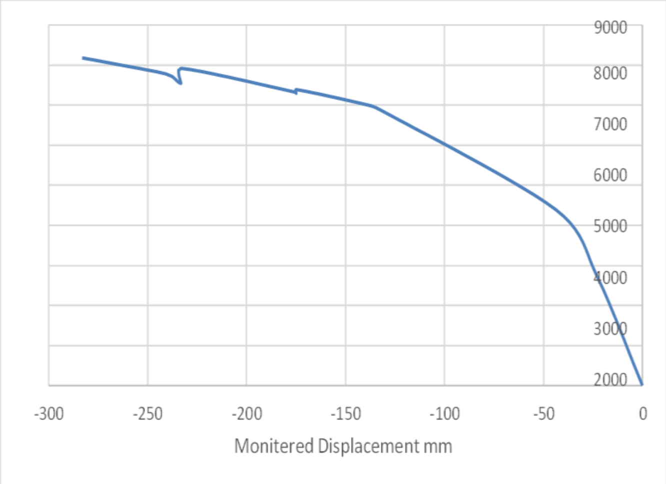


Fig 3.14. Capacity Spectrum Curve For Soft Soil PUSH Y



4.0.CONCLUSIONS

- In zone IV & V the storey displacements increases gradually with the increase in the flexibility of the soil. It is observed that the storey displacement is increased by 67% in case of building resting on the soft soil when compared to the resting on hard soil for the fixed base condition.
- When compared to their respective fixed base models, all flexible base building models with soil structural interaction exhibit an increase in top story displacement.
- In zone IV & V the base shears increases gradually with the decrease in the hardness of the soil. The storey shear is increased by 67% in case of building resting on the soft soil when compared to the fixed base condition.
- The SSI impact will be greater for structures built on Soft soil than Hard soil since the stiffness of the subsoil rises from Soft soil to Hard soil.
- The storey displacements and base shears of the structure in zone V is increased by 150% compared to structure in the zone IV.
- The earthquake generated forces in a building increase as the Seismic zone type increases, hence the SSI impact will be greater for a structure placed in a higher seismic zone.
- The results of non-linear static analysis are represented in tables 3.4.1&3.4.2. The values performance point for the structure for the considered models are recorded along with their respective performance levels i.e. IO,LS, CP.
- It can be said that the structure is not safe against failure since few hinges lies beyond the CP level for hard soil and Soft soil conditions.
- However, the chances of failure of the structure is more in soft soil condition in zone V compared to others since there are 23 hinges formed beyond CP.

It can be concluded that the effect of soil structure interaction increases with the increase in the flexibility of the soil, intensity of the seismic activity prevailing in that location and increase in the height of the structure .Hence, it is required to consider the effect of SSI in the construction of important structures in the region of high seismic intensity and high soil flexibility.

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