Nonlinear Soil Structure Interaction Analysis of Rigid Tower Subjected to Earthquake Ground Motion

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ABSTRACT

Soil-structure interaction (SSI) analysis has gained importance over last few decades. However, during recent earthquakes, many structures performed poorly. Besides many contributing factors for damage, differential settlement has also been the cause for damages, especially in areas where weak soil is present. It is common practice in many earthquake prone areas around the world to analyse the structure using fixed base analysis. This is mainly due to lack of awareness regarding importance of SSI. In order to understand this phenomenon, a study has been performed to show the difference in response when the structure is on fixed base compared to flexible base.

Two case studies have been performed to understand the above phenomenon. First case study is on rigid tower on fixed base subjected to pushover loading and earthquake loading and second case same rigid tower but with flexible base with same loading condition. Both the case studies reveal that there is great difference in response due to SSI. In first case, it is observed that structure remain rigid whereas soil media has attained nonlinear state. In case two, soil as well as structure both reached nonlinear state.

***Keywords**: Differential settlement, Finite element method, modulus of subgrade reaction.*

1. INTRODUCTION

As past studies have shown earthquakes the structural collapse occurs due to the insufficient or incorrect analysis and design techniques, generally doing earthquake analysis for building we assumed foundation as fixed support. But recent studies have shown that soil-foundation interaction may also influence the analysis for structure. The analysis of the structure becomes more tedious if the interaction effect is included in the analysis. Foundation on soft clay has significant effect due to SSI.

Two case studies have been performed to show the effect due to soil structure interaction. First case studies a rigid transmission tower (steel, 70m) fixed base that means for that particular case there will be no effect of soil on structure is undergoing pushover and earthquake loading. Where as in second case the same tower but with flexible base that means foundation is on soft soil is undergoing same loading condition. It is observed that there is significant difference in response of structure in both cases.

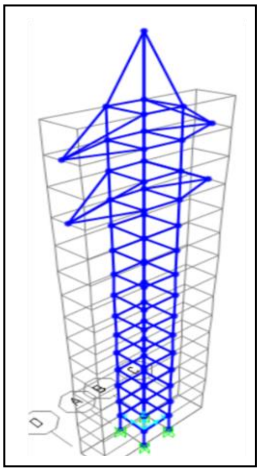
LITERATURE REVIEW

Many researchers (Iwan et al., 2000; Krawinkler et al., 2003; Galal and Naimi,2008; El Ganainy and El Naggar, 2009; Tabatabaiefar and Massumi, 2010; Tavakoliet al., 2011) have studied structural behavior structures subjected to earthquake under the influence of soil structure interaction. Various relations have been developed to solve complex practical problems assuming linear and elastic SSI (e.g. Stewart et al., 1999; Dutta et al., 2004; Khalil et al., 2007; Tabatabaiefar and Massumi, 2010; Maheshwari and Sarkar,2011).Although the effects of nonlinear behavior of the supporting soil and inelastic seismic response of structures have not been fully addressed in the literature. During the recent decades, the significance of dynamic soil-structure interaction for several structures founded on soft soils has been well conceded. Examples are given by Gazetas (1991) and Mylonakis et al. (2006) has given the elastic solution of rigid on footings on soft soils which are vulnerable to SSI.

2. SOIL-FOUNDATION SYSTEM

A rigid base Transmission tower of height 70m (see fig 2.1) its foundation is supported with infinite stiffness that means not deformable. Foundation on rock behaves like rigid base. But flexible base transmission tower of same height (see fig 2.2) refers to some finite stiffness value and there must be deformation in foundation as well as soil foundation in soft clay behaves like flexible.

Single degree of freedom structure with mass, m and stiffness, k with fixed base and other one with same mass and stiffness but flexible base with k_x(in x direction), k_z (in y direction) and k_{yy} (in x-z plane) as shown in fig-2.3. A static force F is acting on both system and causes deflection Δ, $\widetilde{\Delta}$ respectively.



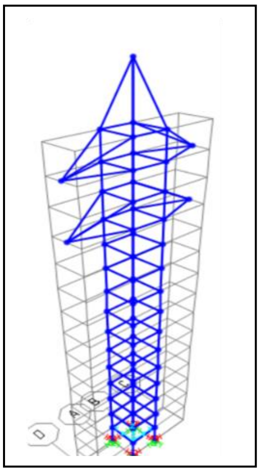


Fig 2.1: Tower with Fixed base(T=5.3sec)   Fig2.2: Tower with Flexible base(T=5.8sec)

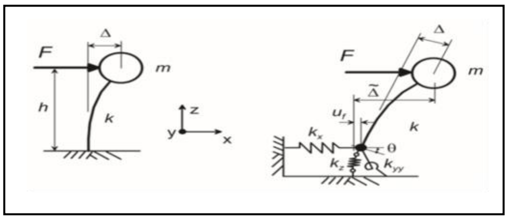


Figure 2.3 single degree of system with fixed and flexible base

Ratio of time period of fixed based system (T) and flexible base system ($\tilde{T}$)

$$\frac{\tilde{T}}{T} = \sqrt{1 + \frac{K}{K_x} + \left(\frac{K.h^2}{k_{yy}}\right)} \qquad (2.1)$$

This equation (2.1) is called period lengthening which will be always greater than 1 i.e time period of fixed base is always is less than flexible base, and vary with shear wave velocity.

2.1 Soil properties and foundation dimension

In order to calculate stiffness value flexible base (see fig 2.2), soil properties and foundation dimension must be known values. Soft clay has been taken for the analysis because soft clay plays more significant role in SSI and its properties are as follows:
Density (ρ) = 1575kn/m
Porosity (e) = 1.23
Water content (w) = 45%
Shear wave velocity V_s is varies with depth of soil(clay) so up to 20m depth $V_s = 55m/s$
foundation dimension 2B(breadth)= 0.8m, 2L(length)=0.8m i.e square footing(see fig 2.2.1).

2.2 Equation for shallow foundation stiffness

Stiffness value k_j is function of shear modulus (G), dimension of foundation, Poisson's ratio (v), dynamic stiffness modifiers(α_j) and embedment modifiers(η_j) .

$$k_j = K_j \times \alpha_j \times \eta_j \qquad (2.2.1)$$
$$K_j = GB^m f(B/L, v) \qquad (2.2.2)$$

α_j and η_j are function of footing dimension ,depth of footing and frequency of earthquake. But while calculating these values for the soft soil and square footing which is height less than 1.5m values of α_j and η_j are approximately 1. Gazetas (1991) and Mylonakis et al. (2006) has been given the formula for K_j shown in table-3.

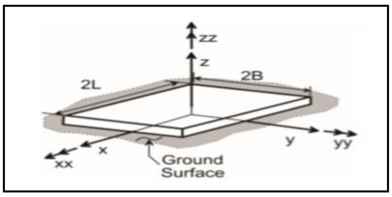


Figure 2.2.1: Foundation of tower

Where I_i = area moment of inertia of soil foundation contact, i denotes which axis to take the surface around. $J_t = I_x + I_y$ polar moment of inertia of soil-foundation contact surface and G is shear modulus which has relation with shear wave velocity.

$$V_s = \sqrt{G/\rho_s} \qquad (2.2.3)$$

Table-3 Stiffness values for given soil and foundation dimension

Stiffness formula	**Calculated values of stiffness for given soil and foundation**
$K_z = \frac{2GL}{1-v}\left[0.73 + 1.54\left(\frac{B}{L}\right)^{0.75}\right]$	10669 Kn/m
$K_y = \frac{2GL}{2-v}\left[2 + 2.5\left(\frac{B}{L}\right)^{0.85}\right]$	9520 Kn/m
$K_x = K_y - \frac{0.2GL}{0.75-v}\left(1 - \frac{B}{L}\right)$	9520Kn/m
$K_{zz} = G\left({J_t}^{0.75}\right)\left[4 + 11\left(1 - \frac{B}{L}\right)^{10}\right]$	2503 Kn-m/rad
$K_{yy} = \frac{G}{1-v}\left({I_y}^{0.75}\right)\left[3\left(\frac{B}{L}\right)^{0.15}\right]$	1413 Kn-m/rad
$K_{xx} = \frac{G}{1-v}\left({I_x}^{0.75}\right)\left(\frac{L}{B}\right)^{0.25}\left[2. + 0.5\left(\frac{B}{L}\right)\right]$	1177 Kn-m/rad

3. Nonlinear pushover static analysis

Pushover nonlinear static analysis is simple technique to estimate permanent deformation or plastic behavior in any structure using plastic hinges which define in structure. This analysis involves a horizontal load pattern which is in incremental manner and gives the result between applied force or base shear and displacement. Transmission tower (see figure-2.1 and figure-2.2) fixed base and flexible base respectively are undergoing nonlinear pushover static analysis with monitored displacement of111 top most point (joint-16) for both of the tower. As load in lateral direction is increases in every step of pushover, nonlinear behavior in structure can be seen (hinges will form).

3.1 Plastic hinge formation

Plastic hinges has to be define for every element of transmission tower. Mainly two types of plastic hinges can be define in steel structure first one is steel beam flexure (M3) and second is steel column flexure (M3) define at just near the joints. These hinges will show nonlinear behavior as they move from B to E (see fig 3.2.1) by changing its color. The structural performance levels based on the roof drifts are as follows:

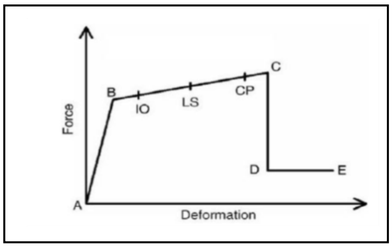


Figure 3.2.1 force vs displacement curve

A to B - Elastic state.
Point A corresponds to Zero loading condition(unloaded condition).
Point B corresponds to the onset of yielding.
B to IO - Below immediate occupancy.
IO to LS - Between immediate occupancy and life safety.
LS to CP – Between life safety to collapse prevention.
CP to C – Between collapse prevention and ultimate capacity,
Point 'C' corresponds to the ultimate strength.
C to D - Between C and residual strength.
Point 'D' corresponds to the residual strength.
D to E - Between D and collapse.
Point 'E' Corresponds to Collapse.

3.2 Results of nonlinear pushover static analysis

After completing nonlinear pushover static analysis (displacement control) in software. The results obtained (see fig 3.3.2(a) and fig 3.3.2(b)) hinges is formed in flexible as well as fixed base after final step of pushover analysis respectively.

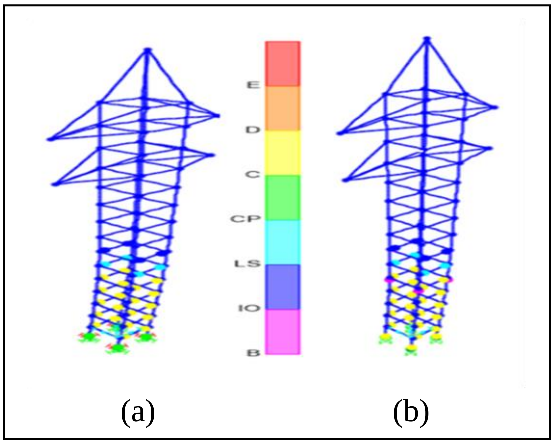


Figure 3.3.2: Hinge formation after final step of pushover analysis

Pushover Table-1 and Table-2 it can be easily notice that the flexible base transmission tower is showing nonlinear behavior (first hinge formation) when base shear exceeds 68kn, where as in fixed base that base shear value is approximately 81Kn at the time of first hinge formation. Also that in nonlinear pushover curve (see figure 3.3.1) describe that after yielding point, Slop is reduce to some extent but the curve is still bilinear. But in case of flexible base after yielding point slop is continuously changing and curve is like parabola (see figure3.3.1).

Table 1: Nonlinear pushover table for flexible base

Step	**Displace-ment(m)**	**Base force (Kn)**	**A to B**	**B to IO**	**IO to LS**	**LS to CP**	**CP to C**	**C to D**	**D To E**	**Beyond E**	**Total hinges**
0	0	0	280	0	0	0	0	0	0	0	280
1	0.6	20.975	280	0	0	0	0	0	0	0	280
2	1.2	41.951	280	0	0	0	0	0	0	0	280
3	1.8	62.926	280	0	0	0	0	0	0	0	280
4	1.972	68.962	276	4	0	0	0	0	0	0	280
5	2.359	78.965	268	4	8	0	0	0	0	0	280
6	2.961	87.629	260	4	8	8	0	0	0	0	280
7	3.814	95.650	256	0	8	4	8	4	0	0	280
8	4.678	99.760	248	4	8	4	0	16	0	0	280
9	5.278	100.234	248	0	12	0	4	16	0	0	280
10	5.752	100.609	248	0	4	8	0	20	0	0	280
11	6	100.659	248	0	4	4	4	20	0	0	280

Table 2: Nonlinear pushover table for fixed base

Step	**Displace-ment(m)**	**Base force(Kn)**	**A to B**	**B to IO**	**IO to LS**	**LS to CP**	**CP to C**	**C to D**	**D To E**	**Beyond E**	**Total hinges**
0	0	0	280	0	0	0	0	0	0	0	280
1	0.6	30.739	280	0	0	0	0	0	0	0	280
2	1.2	61.479	280	0	0	0	0	0	0	0	280
3	1.575	80.741	276	4	0	0	0	0	0	0	280
4	1.716	85.806	264	12	4	0	0	0	0	0	280
5	2.152	92.614	256	4	20	0	0	0	0	0	280
6	2.918	98.315	252	0	8	12	8	0	0	0	280
7	3.328	100.832	248	4	4	4	12	8	0	0	280
8	3.580	101.706	248	0	8	4	8	12	0	0	280
9	3.669	101.880	248	0	8	4	4	16	0	0	280
10	3.760	101.789	248	0	8	4	0	20	0	0	280
11	4.360	100.842	248	0	8	0	4	20	0	0	280
12	4.960	99.984	248	0	4	4	4	20	0	0	280
13	5.722	98.527	248	0	4	4	0	24	0	0	280
14	6	97.976	244	4	4	4	0	24	0	0	280

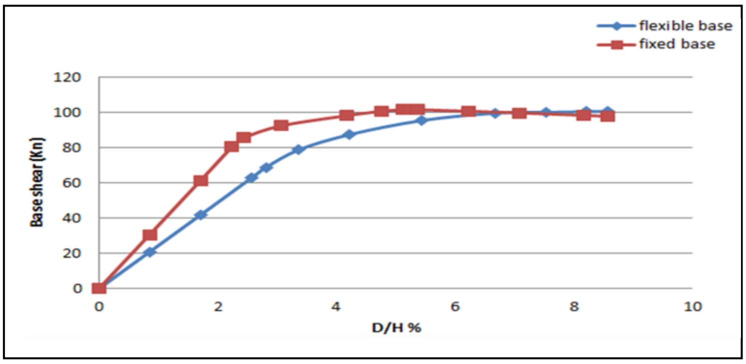


Figure 3.3.1:- Pushover curve for both fixed and flexible base where D is displacement of top joint and H is total height of building.

4. Nonlinear Time history analysis

Time history analysis is technique for structural seismic analysis especially when the evaluated structural response is nonlinear. To perform such an analysis, a representative earthquake time history is required for a structure being evaluated. Time history analysis is a step-by-step analysis of the dynamic response of a structure to a specified loading that may vary with time. Time history analysis is used to determine the seismic response of a structure under dynamic loading for given earthquake.

Earthquake ground motion Chamoli has given as input in both cases fixed base transmission tower and flexible base transmission tower. It is easily observable (see fig 4.1) that in flexible case frequency is less but amplitude is higher as compare to fixed base. Although there is variation of base shear with time (see fig 4.2) in both cases but important aspect is that maximum base shear in both cases is nearly same so this implies in dynamic force also flexible base structure will go in to nonlinearity before fixed base structure.

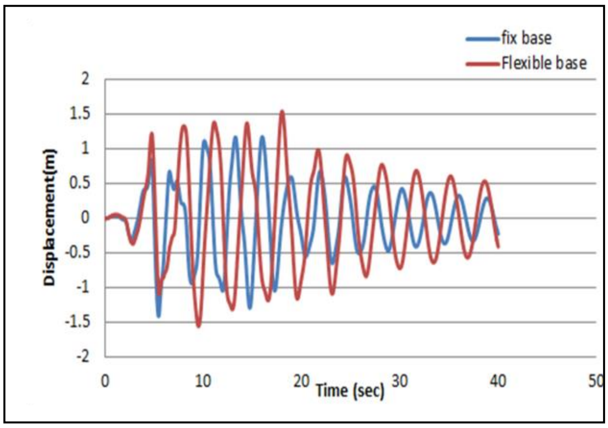


Figure 4.1: Response history of Top joint when When subjected to Chamoli earthquake.

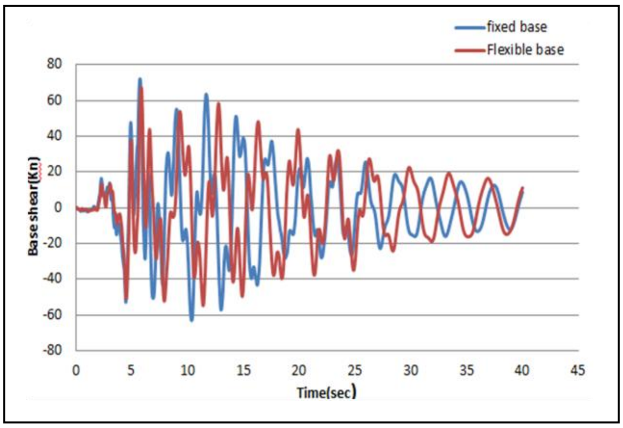


Figure 4.2: Response history of base shear When subjected to Chamoli earthquake.

As natural time period is more if structure has flexible so clearly frequency will be lesser in flexible base, So that's why maximum amplitude(2m) occur at lesser frequency compare to fixed base tower which has maximum amplitude(1.4m)(see figure 4.3).

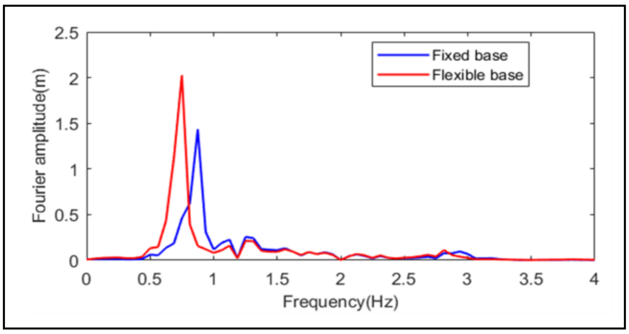


Figure 4.3: Frequency domain of top joint when subjected to Chamoli earthquake.

5. CONCLUSION

Nonlinear pushover static analysis and nonlinear time history analysis leads to conclude that flexible base reached in to nonlinearity before the fixed base structure. Also drift value is more in flexible base as compare to the fixed base. SSI leads to increase in natural time period of structure. When fixed base structure subjected to an earthquake lower part of structure will move with ground there is no relative motion between ground and foundation so that means lower part of structure will not participate in any of mode in modal analysis i.e lower part will have less stress compare to flexible base. But while in case of flexible base there is relative motion between ground and foundation so lower part will also participate in modal analysis and hinges will form in bottom part as well.

REFERENCES

P. Colajanni and B. Potenzone (2008) ON THE DISTRIBUTION OF LATERAL LOADS FOR PUSHOVER ANALYSIS. *World Conference on Earthquake Engineering October 12-17, 2008, Beijing, China.*

NEHRP Consultants Joint Venture A partnership of the Applied Technology Council and the Consortium of Universities for Research in Earthquake Engineering. Soil-Structure Interaction for Building Structures. *National Institute of standards and technology (NIST GCR 12-917-21).*

G.H.Mahmoud, B.S.Tork, S.A.EL-Beshlawy (Sep.-Oct. 2016) Structural Capacity and Failure Mechanisms of Transmission Towers under High Intensity Wind Loading *IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)*

M. H. T. Rayhani and M. H. El Naggar Dynamic properties of soft Clay and Loose sand from Seismic Centrifuge Tests *Geotech Geol Eng DOI 10.1007/s10706-008-9192-5 springer Science+Business Media B.V. 2008*

Gaurav D. Dhadse Response of Flexible base with Different Shapes of Raft Footings:A soil structure interaction Analysis (2017)*International Journal of Innovative Research in Science,Engineering and Technology (20-21 January 2017)ISSN (Online): 2319 - 8753*

Nicholas W.Trombetta, S.M.ASCE; H. Benjamin Mason, M.ASCE; Tara C. Hutchinson, M.ASCE; Joshua D.Zupan, S.M.ASCE; Jonathan D.Bray, F.ASCE; and Bruce L._Kutter, M.ASCE Nonlinear Soil–Foundation–Structure and Structure–Soil–Structure Interaction: Centrifuge Test Observations *Journal of Geotechnical and Geoenvironmental Engineering/ / Volume 140 Issue 5 - May 2014.*