

Effects of Subsoil Characteristics on the Earthquake Loading of Steel Lattice Telecommunication Towers in the South Asia

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ABSTRACT: self-supporting lattice towers, which are having quite a few unique structural features, play a vital role in communication networks. Ensuring structural stability of these giant structures under all possible natural and human threats are vital as failures of such structures may cause a catastrophic human & property damages. Further, possible communication outages caused by failure of tower/towers in disaster situation are a critical as it may hamper rescue and other emergency operations. This was experienced by South and South East Asian countries during 2004 Tsunami. Hence, need of mitigating these situations have been highlighted by various reports. Therefore, ensuring structural integrity of self-supporting lattice towers under seismic forces is an essential and timely need. This paper discusses a seismic performance of four leg and three leg lattice towers under Response Spectrum analysis under different sub soil conditions. Results of seismic analyses has also been compared with wind analyses results.

KEYWORD: subsoil condition, steel lattice telecommunication towers, seismic loading, Response Spectrum.

1 INTRODUCTION

With the availability of smart mobile devices at an affordable cost, an exponential growth in usage of mobile devices is observed in every part of the world especially in our region, South and South East Asia. As the last mile connectivity of mobile devices depend mostly on wireless technologies, telco operators are compelled to expand their tower networks to cater for this increasing demand. Other than few exceptions, steel is the material that has been used in almost all telecommunication towers in Sri Lanka and as well as in other countries because of its desirable characteristics such as light weightness, ease of fabrication, high strength etc, relevant to tower construction.

Quite a few different structural forms are available for steel towers. Three dimensional lattice type either three or four legs is the most popular structural form especially for taller towers (more than 30m). In the design of towers, owing to their tall and light weight nature, wind forces are often considered as the dominant forces. The subject of seismic effects on telecommunication towers has been rarely discussed in the South Asian Region even though the region has got several earthquake prone areas. Even in these few publications [1,2,3] covering the seismic effects on steel towers in the region, seismic force variations due to subsoil properties

have not been considered and a hard soil stratum had been assumed. However, it has been reported that weak soil strata are commonly present in the sub-continent. In Sri Lanka, soft soil deposits are common, especially in Colombo and its suburban areas in the Western Province[4]. In the meantime, most of telecommunication towers in the country located in these areas due to urbanization pattern. Thick soft sediments have been found in Kathmandu, the capital city of Nepal, and the amplification of seismic waves due to these sediments have been re-ported by Sharma et al.[5], during the catastrophic earthquake that struck the city in 2015. Similar situations can arise in other countries in the region as well because of the similarities in their geographical features.

The study of seismic performance of self-supporting towers built on different subsoil types, using regional seismic parameters has therefore become a timely need. Thus, the main objective of this study is to analyze the seismic behavior of self-supporting towers built on different sub soil conditions. A comparison of the seismic analysis results with the wind analysis results is also important as conventionally, wind loads are the dominant forcings considered in design of towers.

2 REGIONAL WIND AND SEISMIC DATA RESULTS

2.1 Seismic Characteristics Considered and the Development of Response Spectra

The code of practice that was used in the tower analysis and designs of this study is ANSI/TIA-222-G (2005) [6] which is highly recognized code. Seismic analysis of the towers was mainly done using response spectrum analysis which is described as model analysis in ANSI/TIA-222-G(2005)[6]. The basic site specific seismic spectral acceleration parameters required for the development of response spectra, according to this code, are the maximum considered earthquake spectral response accelerations, S_s , at short period and S_1 at 1.0s.

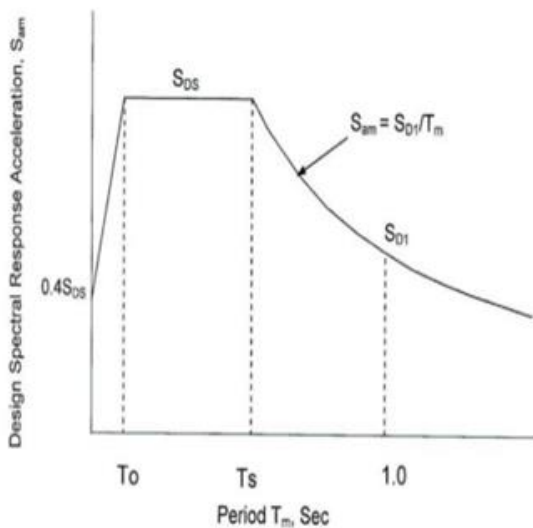


Figure 1 - Typical response spectrum curve given in ANSI/TIA-222-G(2005)

The above mentioned site specific seismic parameters, S_s and S_1 , have to be modified by two factors, namely F_a -acceleration based site coefficient adjusted for the site class and the spectral response acceleration at short period and F_v - velocity based site coefficient adjusted for the site class and spectral response acceleration at 1 second respectively, to obtain design spectral response accelerations, S_{DS} and S_{D1} , which give the coordinates for the response spectrum curve shown in Figure 1. In this study, three (03) soil conditions specified in ANSI/TIA-222-G(2005)[6] were considered to study the effects of sub soil properties. Details of the soil conditions considered are given in Table 1.

It was decided to select the seismic parameters of Sri Lanka, Pakistan and Nepal where seismicity conditions vary from mild to severe, to represent the different seismicity conditions found in the South

Asian Subcontinent. Sri Lanka and Maldives have the lowest seismic vulnerability in the region while Nepal has the highest seismic vulnerability in the region. In Pakistan, the seismicity conditions vary from moderate to high.

Table 1 - Details of soil conditions

Site Class	Description of upper 30.5 m of soil at the site location
C	Very dense soil, soft rock or highly fractured and weathered rock (SPT N >50)
D	Stiff soil (15 < SPT N < 50)
E	Weak soil -soil profiles over 3 m thick PI >= 30, moisture content >= 40%, $S_u < 25$ kpa

S_1 and S_s values for Nepal and Pakistan were obtained from the US Geological Survey (USGS) website (www.usgs.gov) [8] which match well with the values recommended in the local literature [8,9,10]. The values identified for Nepal were $S_s = 2.14$ and $S_1 = 0.86$ and the values identified for Pakistan were $S_s = 1.22$ and $S_1 = 0.49$. However, the values recommended for Sri Lanka by the USGS were found to be too low ($S_s = 0.03$ and $S_1 = 0.01$) when compared to the values provided by local researchers in their recent findings. In a recent research carried out by Uduweriya et al. [11], the value recommended for PGA in Sri Lanka for a 10% probability of exceedance in 50 years is 0.10 g. Therefore, it was decided to use this value to calculate S_s and S_1 for Sri Lanka. Values obtained for S_s and S_1 using above PGA value for Sri Lanka using the approximate method developed by Global Seismic Hazard Assessment Programme (GSHAP) published in USGS website[8] were 0.5 and 0.2 respectively. This method requires the PGA values to be multiplied by 5 and 2 to obtain S_s and S_1 respectively. The equivalent PGA values calculated for Nepal and Pakistan for a 10% probability of exceedance in 50 years using same method were 0.43 and 0.25 respectively.

Accordingly, response spectrum curves were developed for PGA values of 0.1, 0.25 and 0.43. Response spectrum curves developed for analysis are given in Figure 2.

For the comparison of results, a static equivalent analyses were also carried out as per the guideline of ANSI/TIA-222-G(2005)[6]. Two static equivalent analysis procedures describe in this code namely Equivalent Lateral Force procedure (Method 1) and

Equivalent Model Analysis procedure(Method 2). The code has restricted the usage of Method 1 only for towers having heights less than 30m in case of self-supporting tower case and for Method 2 no height restriction is defined.

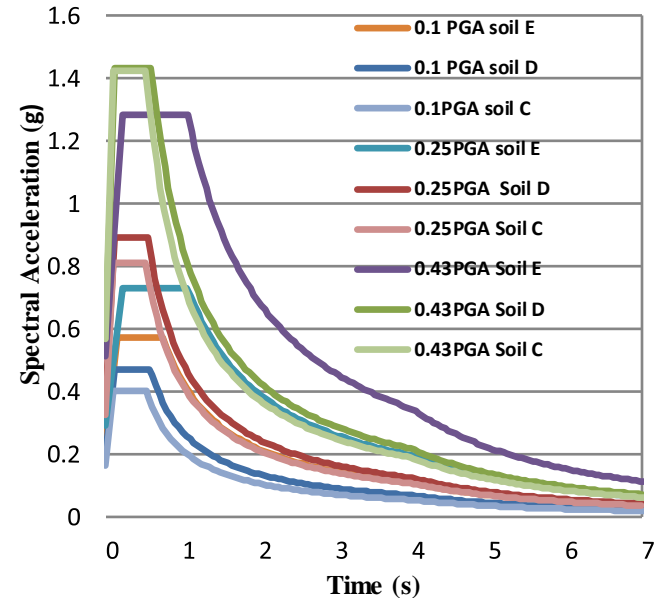


Figure 2- Response Spectrum curves

Further, from the initial trails done using Method 1 for 30m towers, it was observed that results of Method 1 are highly over conservative compared to Response spectrum analysis. Therefore, Method 2 was selected for all towers to carry out Static Equivalent analysis for the comparison.

2.2 Tropical Wind Data

Wind forces are the main forces considered in the design of steel lattice telecommunication towers. The two wind speeds selected to compare the seismic analysis results with wind analysis results are as follows:

1. 3s Gust wind speed of 50 m/s (180 km/h), design wind speed recommended for normal structures in Zone 1 of Sri Lanka.
2. 3s Gust wind speed of 33.5 m/s (120 km/h), design wind speed recommended for normal structures in Zone 3 of Sri Lanka

Above figures are based on recommendations of Design of buildings for high winds-Sri Lanka, Ministry of Local Government, Housing and Construction, Sri Lanka[12]. When these wind speeds are compared with the design wind speeds recommended for other countries in the South Asian Region in their respective wind codes [13,14,15], 50 m/s can be considered as a good up-

per bound wind speed for the subcontinent except for a few areas in Eastern India, Nepal and Bangladesh. Similarly, it was observed that 33.5m/s as a good lower bound wind speed. Wind analyses were carried out for all selected towers based on the above two wind speeds as per criteria defined in ANSI/TIA-222-G(2005)[6].

3 TOWER ANALYSIS

Four leg lattice self-supporting towers having heights of 30 m, 50 m, 80 m and three leg towers having heights of 30m, 45m and 60m were considered in this analysis. Usually height of four leg towers varies from 30m to 120m (other than few exceptional cases) and towers taller than 80m are rare. In cases of three leg towers, towers taller than 60m are extremely rare as achieving required structural capacity for taller towers with three leg geometry may be a concern. Modeling of towers was carried out by preparing 3D computer models using SAP2000 structural analysis software. Firstly, the tower models were analyzed using the design wind speeds as 50 m/s and 33.5 m/s. Thereafter, each tower was analyzed using the nine (09) response spectrum curves presented in Figure 2. During the analysis, a sufficient number of mode shapes were considered for each case in order to satisfy the code's requirement of achieving at least 85% of combined modal mass participation. Accordingly, in the case of four leg towers of 30 m and 50 m, first 12 modes were considered while for the 80 m tower first 30 modes had to be considered. For all three leg towers (30m, 45m and 60m) consideration of first 12 modes was sufficient to achieve the above criteria. Damping ratio was selected as 5% as per specifications given in ANSI/TIA-222-G(2005)[6]. Since all nonstructural elements such as antenna ladders, feeder cables, platforms etc., make a significant contribution to the total mass of a steel lattice tower, the weight of all ancillary items were considered in addition to the self-weight of the structural members when modeling.

4 RESULTS AND DISCUSSION

4.1 Effects of tower type, height and Soil Properties on the Seismic Forces on the Towers

Natural period of vibration of a tower is an important parameter that affecting to Response spectrum analysis results. Natural periods of 1st mode obtained from SAP 2000 models of considered towers are given in Table 2.

Table 2 - Natural periods of 1st mode

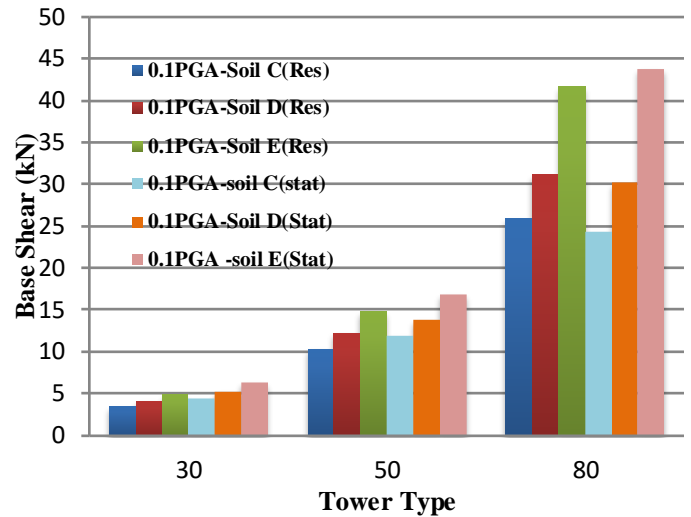
Tower height	Tower type	Natural period vibration of 1 st mode (s)
30m	4 Leg	0.39
50m	4 Leg	0.43
80m	4 Leg	0.83
30m	3 Leg	0.40
45m	3 Leg	0.39
60m	3 Leg	0.51

It can observe that generally it increases with the increase of height of the tower. But in case of three leg tower case Natural period vibration of 1st mode has slightly dropped from when it goes from 30m tower to 45m tower. Probable reasons may be the geometrical differences, members sizes, etc of towers.

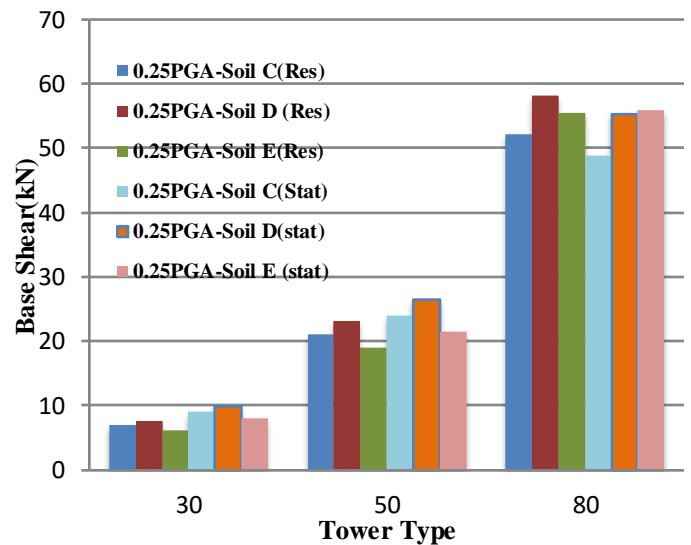
Base Shear and Base moments of the towers are most important parameters to assess structural performance of a tower under seismic loading. Figures 3 and 4 illustrate the variation of base shear and base moment of four leg towers with different seismicity levels and subsoil conditions. Base shear and moment obtained from Static Equivalent analysis and Response Spectrum analysis were plotted in same diagrams to compare the results.

According to results, base shear values of Response spectrum analysis and Static Equivalent analysis of respective cases are very close to each other in all three towers under all PGA values and soil conditions (see Figure 3). But, base moment results of Static Equivalent analysis considerably deviate from the results of Response Spectrum analysis (see Figure 4). This is quite understandable as higher vibration modes would also contribute for seismic response of these type of tall light weight structures under response spectrum analysis. But, capturing all such higher modes effects through a simple static equation may not be quite practical.

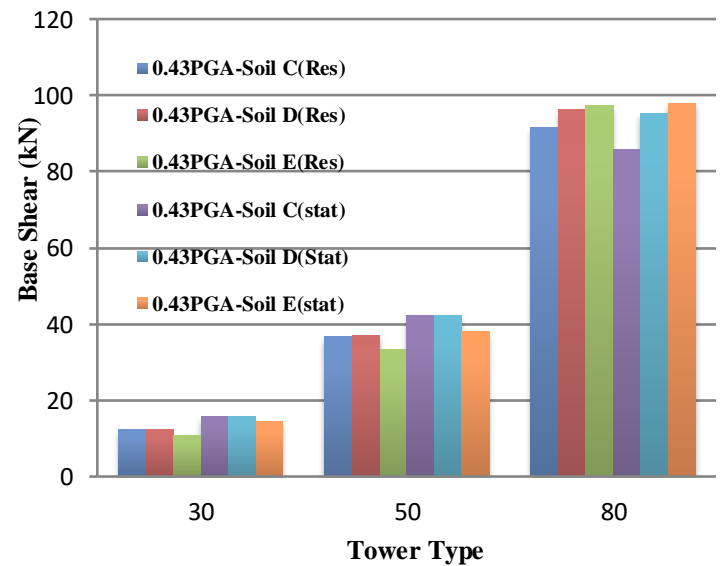
However, as this static equivalent equation given in ANSI/TIA-222-G (2005)[6], which seems to be mainly depend on First Mode of vibration have proven it's conservativeness.



a) under 0.1 PGA

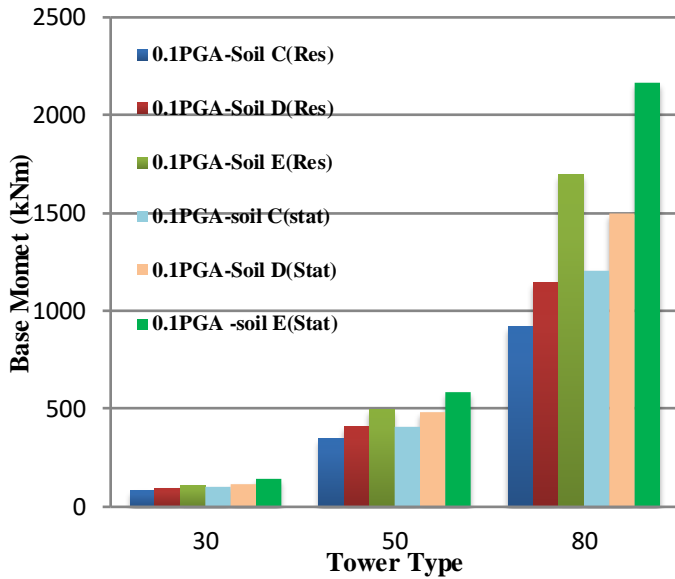


b) under 0.25 PGA

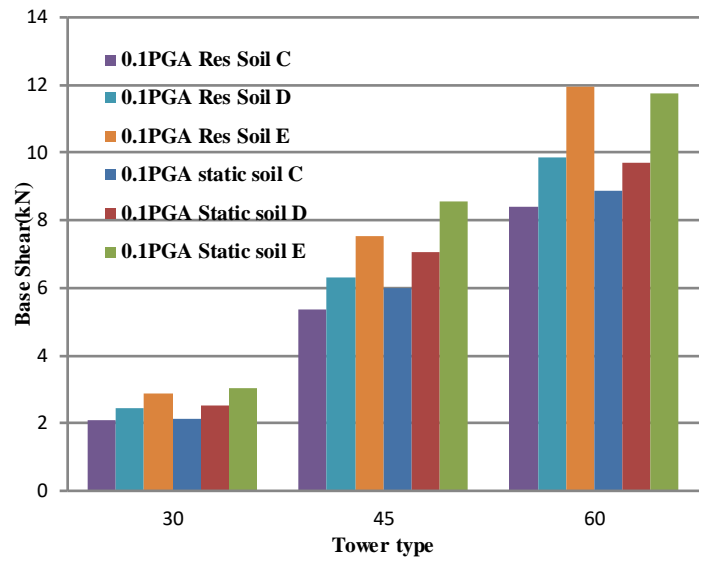


c) under 0.43 PGA

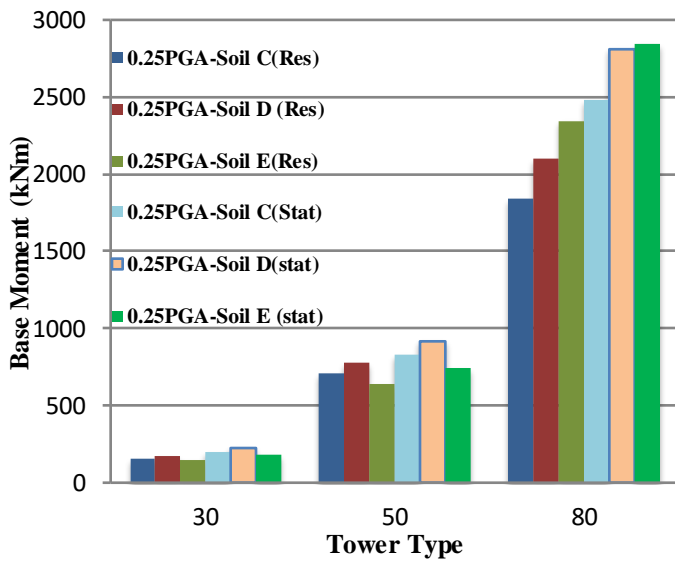
Figure 3 - Variation of base shear in Four leg towers



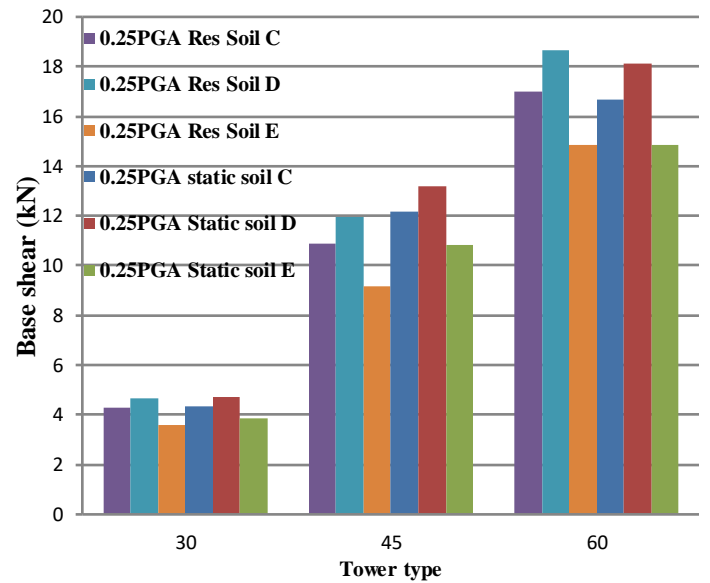
a) under 0.1 PGA



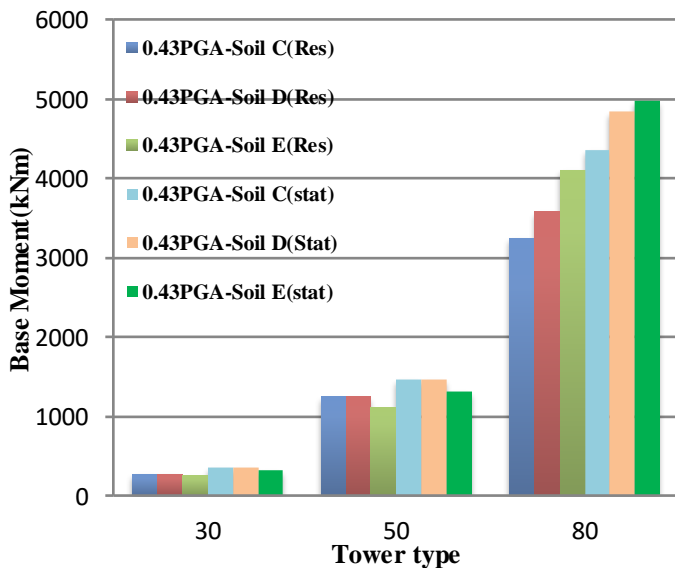
a) under 0.1 PGA



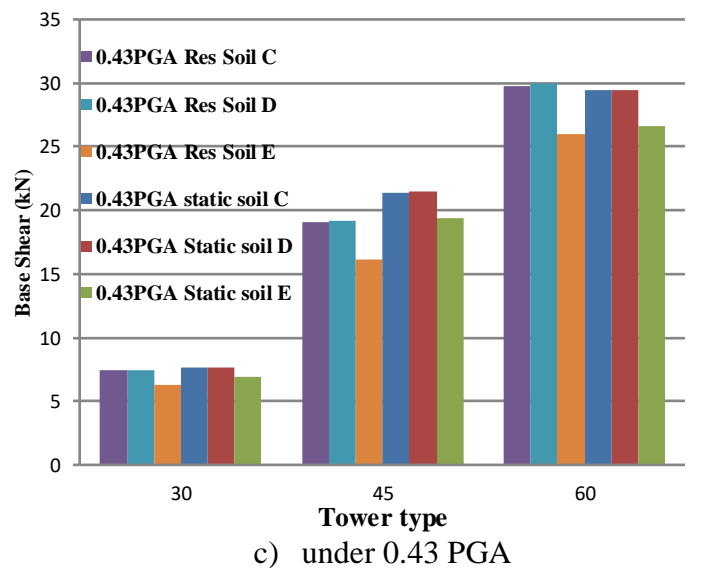
b) under 0.25 PGA



b) under 0.25 PGA



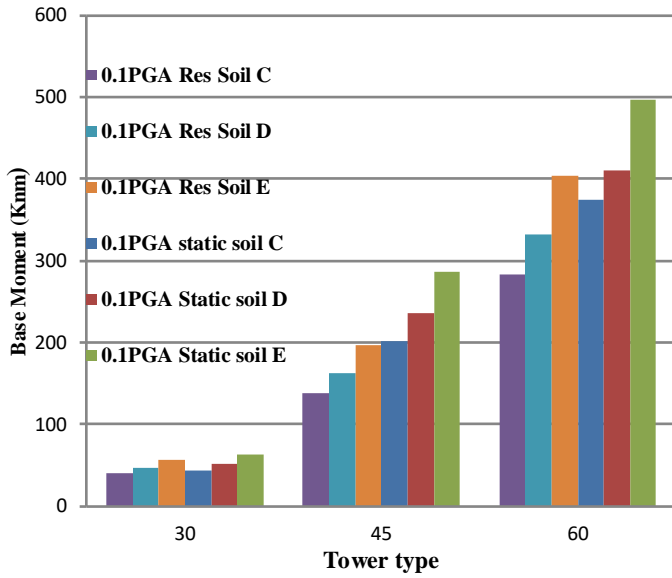
c) under 0.43 PGA



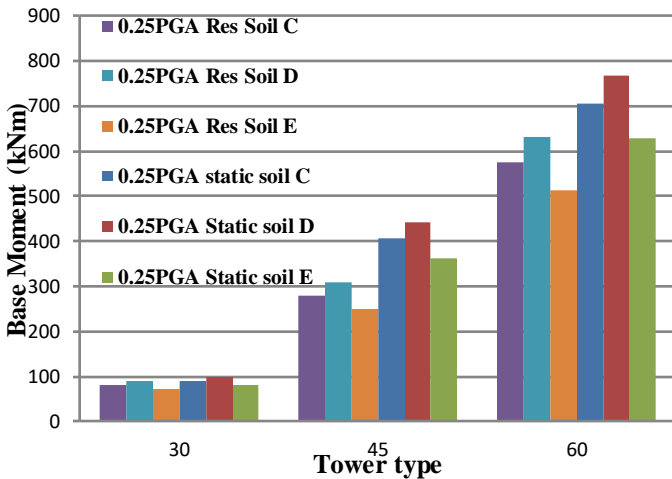
c) under 0.43 PGA

Figure 4 - Variation of base moments in Four leg towers

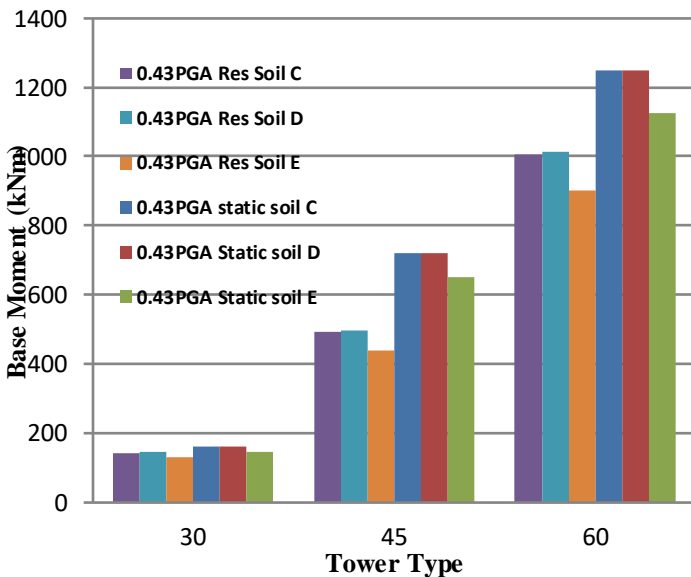
Figure 5 - Variation of base shear in three leg towers



a) under 0.1 PGA



b) under 0.25 PGA



c) under 0.43 PGA

Variation of seismic forces, based on sub soil characteristics can also be clearly identified from Figure 3,4,5 and 6. According to above graphs, seismic actions (especially Base moment) on tower do not always increase with the weakness of sub soil properties. As an example if it considers results of four leg towers, changing patterns of Base shear and moment of three towers (30m, 50m and 80m) are quite different to each other under different soils classes and PGA values. In case of 80m tower, base shear and moment have increased when sub soil classes change as C, D and E (when soil properties weaken) under all seismic conditions (see Figure 3 & 4). But, as per results of 30m and 50m towers, same pattern was not observed. In those towers, Base shear and moment values have increased when soil classes change as C, D and E only under 0.1 PGA value (see Figure 3(a) & 4(a)). In contrast, under higher PGA values (0.25 & 0.43), Base shear and Moment increase when sub soil changes from C to D and values have decreased when sub soil class changes from D to E (see Figure 3(b), 3(c), 4(b) and 4(c)). Therefore, it can clearly observe that amplification of seismic forces on towers do not entirely depend changes of sub soil classes. According to results, spectral acceleration values of respective response spectrum curves at time value equal to Natural period of vibration of 1st mode of respective towers influence to the Base moment variations. As an example Natural period of vibration of 1st mode of 80m four leg tower is 0.83s. Spectral accelerations under 0.25PGA of soil C, Soil D and Soil E at 0.83s are 0.50g, 0.58g and 0.73g respectively (see Figure 7). Base moments calculated using Response Spectrum analysis of 80m tower under 0.25PGA reduces following same pattern when changing soil types (see Figure 4(b)). But Static Equivalent analysis have not perfectly captured this variation may be due to inherent deficiencies of the method. If it considers 60m Three leg tower under 0.43 PGA, Spectral accelerations of soil C, Soil D and Soil E at 0.51s are 1.42g, 1.43g and 1.28g respectively (see Figure 7). When it compares Base moments under above cases, soil C and D have almost equal Base moments while soil E shows relatively less value (see Figure 6(c)) and is fully compatible with variation of spectral acceleration values. Same observation can be made regarding other cases too.

Figure 6 - Variation of base moment in three leg towers

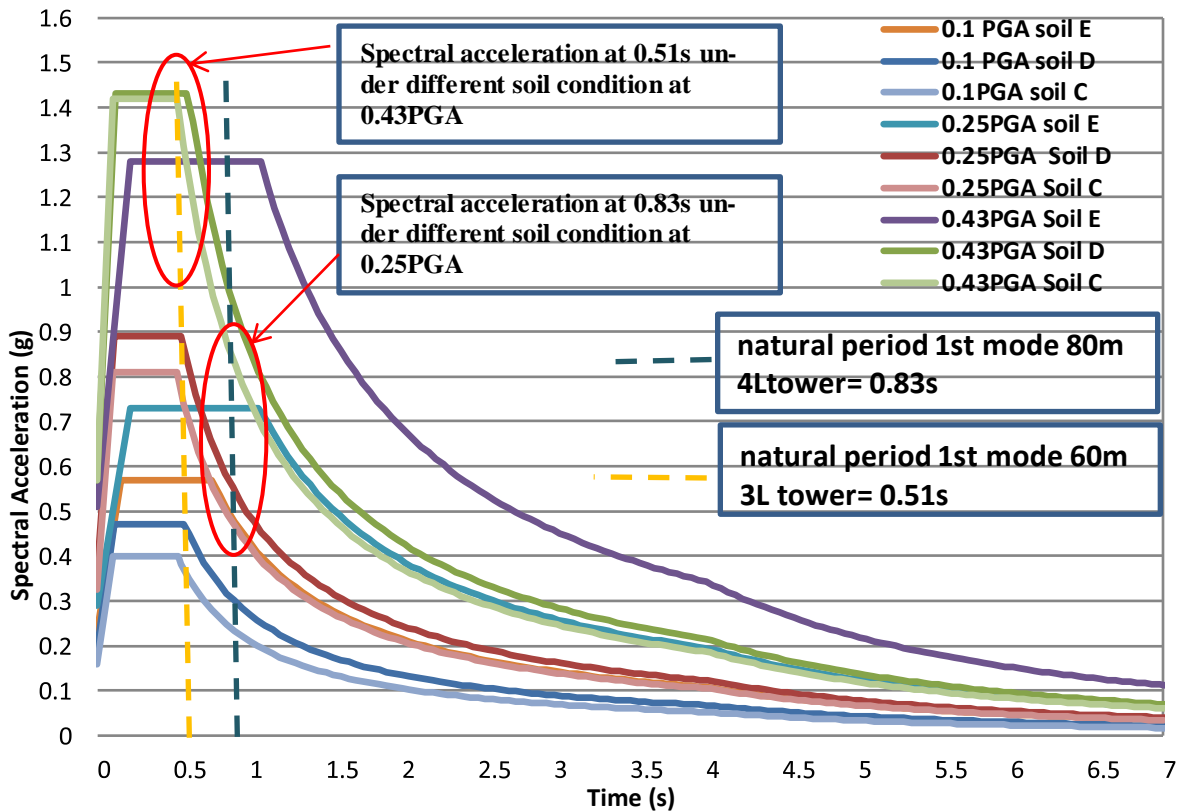


Figure 7 – Response Spectrum curves with natural period of vibration of first mode of selected cases

Therefore, it can clearly understand a strong correlation between Base moment and spectral acceleration value relevant to natural Period of vibrations of first mode of respective tower as per relevant response spectrum curves. Hence, amplification or reduction of seismic forces on steel telecommunication lattice towers would not entirely depends on the changes of response spectrum curves under different sub soil properties and free vibration characteristics of the respective tower is also a critical factor in this regard.

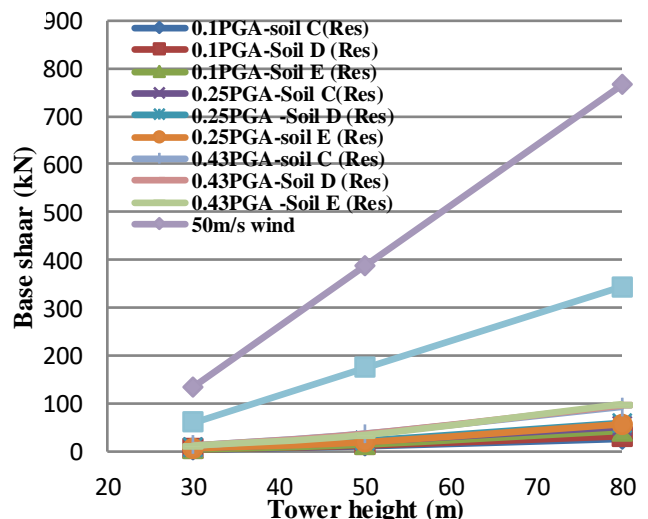
4.2 Comparison of Seismic Forces with Wind Forces

The results obtained from the seismic analysis were compared with the results obtained from the wind analysis.

In Figure 8 and 9, base shear and moments of the towers when subjected to seismic and wind forces are presented. It can be clearly observed that the wind forces on all towers dominate over seismic forces. Even under the lower wind speed of 33.5 m/s, the design wind forces have a fair margin above seismic forces calculated for the most severe seismicity and worst soil conditions.

One main reason for this dominance could be the fairly high wind speeds specified in the design codes of the countries in South Asia owing to the tropical climatic conditions that exist in the region.

Hence, even a significant increase in the seismic forces that occur with a change in the subsoil class in certain cases, would not be a serious concern from a structural design perspective as the wind forces appear to dominate over seismic forces when calculations are done based on regional wind design data.



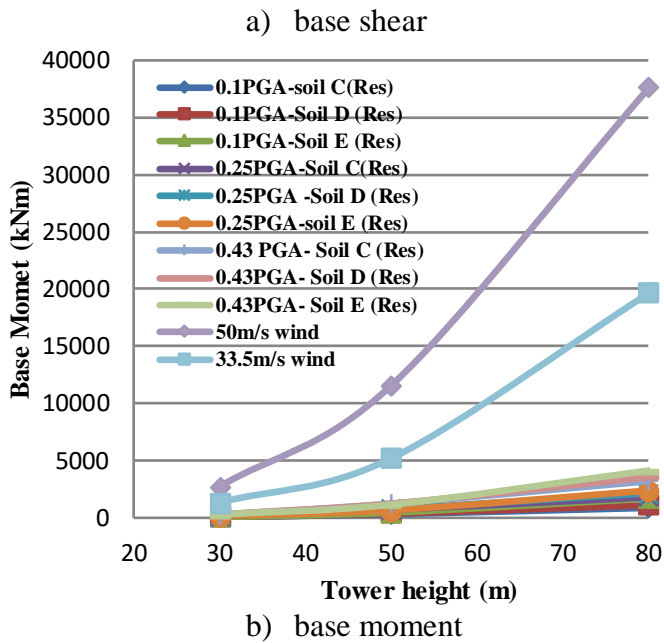


Figure 8 – Base shear and Base moments under wind and seismic loading of four leg towers

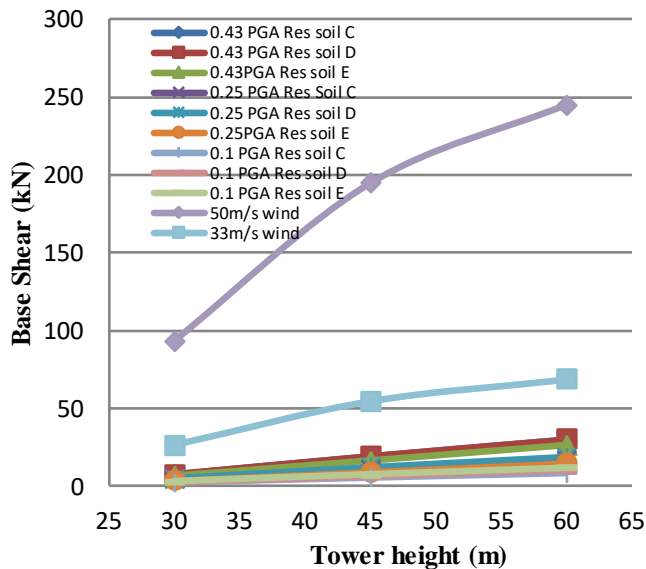


Figure 9 – Base shear & Base moments under wind and seismic loading of three leg towers

5 CONCLUSION

There can be considerable changes in the seismic forces on the towers due to subsoil characteristics. These mainly depend on changes of response spectrum curves due to soil properties and vibration characteristics, i.e., natural period of vibration of the tower. Spectral acceleration of the relevant response spectrum at the natural period of vibration of the tower is found to be the governing factor in this regard.

However according to the results, structural adequacy of the selected towers when subjected to seismic loading is quite satisfactory even under very severe seismic conditions, i.e., at a PGA of 0.43 provided the towers have been adequately designed at least for the lowest observed wind speed of 33.5 m/s in the South Asian Region, irrespective of subsoil properties. Therefore in general, the structural performance of steel lattice telecommunication towers in the region would not get affected when an earthquake occurs if such towers have been properly designed taking into consideration the local wind speeds recommended.

Although this study has provided highly satisfactory results about the structural performance of steel lattice telecommunication towers when under seismic loading, the stability of towers, however, can get affected due to indirect effects such as liquefaction, slope failures etc., the study of which falls outside the scope of this study.

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