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# Along and Across Wind Responses of Tall Buildings Considering Soil Structure Interaction

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***Abstract*****:** ***Fora good wind resistant design, the exact behaviour of a building needs to be assessed. Thus it is important to consider the effect of the foundation and the underlying soil stratum flexibility along with the building during analysis which is investigated in this paper. A 180m high tall RCC building with piled raft foundation founded on different soil conditions is being considered here. The building is assumed to be located in terrain category IV and interference zone*** **IV*****as per theIS: 875 (Part 3): 2015 subjected to an average wind speed of 50 m/s. Linear analysis performed on the building with rigid base is compared with the integrated building-foundation-soil system considering material non-linearity of the soil. Drucker Prager model is used to represent the material non linearity of the soil stratum to consider soil structure interaction (SSI). Using numerical finite element analysis, the 3D structure is analysed for wind induced responses such as maximum lateral deflection and base moment with and without considering soil flexibility. On considering SSI, free vibration analysis, showed that the frequency decreases with increase in flexibility. It was also observed that, on considering SSI, displacement got increased by 18% and base moment got reduced by 85% of the structure without SSI effect for the building considered.***

***Index Terms: Acorss wind force, along wind force, finite element analysis, soil structure interaction***

## I. INTRODUCTION

To improve and optimise the designing of buildings, the responses and behaviour must be studied and analysed in detail. In tall buildings, wind is the critical load especially in cyclone prone areas. These structures are susceptible to vibration problems caused by wind due to their low damping characteristics. The wind is generated by the differential heating of the atmosphere by the sun. The two major driving factors of large-scale wind patterns are the differential heating between the equator and the poles due to difference in absorption of solar energy. The two types of effects exerted by wind on to a structure are static and dynamic effects. Static effect causes elastic bending and twisting of the structure while dynamic effect causes vibrations or oscillations. The dynamic character of wind is a constant mean wind velocity and a varying gust velocity. Thus, there is a mean and a fluctuating response to wind force. This is shown in Fig. 1.where '$\bar{v}$' is the mean velocity and '$\acute{v}$' is the fluctuating velocity.

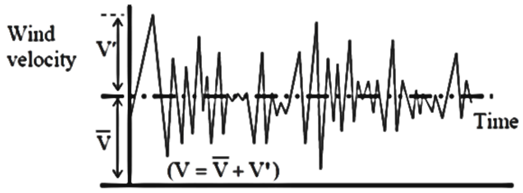

**Fig. 1.**Variation of wind velocity with time [1]

Flexible structures, such as tall buildings, subjected to dynamic wind loading experience fluctuating deflections in primarily three directions namely along-wind deflections in the direction of the wind, across-wind deflections in the direction normal to the wind and torsional deflections which are due to the non-uniform wind pressures over the surface of the building. This is illustrated in Fig. 2. One of the main tasks while designing tall buildings is its ability to absorb the horizontal forces and to transmit the resulting moment into the foundation. Any unexpected deflection can lead to additional lateral forces and must be considered. Hence, for a wind resistant design, there is an extreme need to assess the true behaviour of the building under wind.

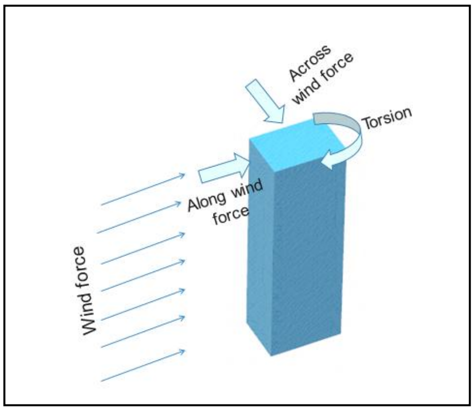

**Fig. 2.**Components of building response to wind excitation

In conventional engineering practice, structures are often designed considering the base of the structure fixed to the ground neglecting the flexibility of soil strata. Although this can be considered reasonable for low rise structures on relatively stiff soils, the effect of soil–foundation–structure interaction becomes prominent for heavy structures.

In this paper, effect of along and across wind responses of tall buildings considering soil structure interaction is studied using numerical finite element analysis.

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## II. SOIL STRUCTURE INTERACTION

It is the process in which response of the soil influences the motion of the structure and the motion of the structure influences the response of the soil [2]. SSI effects can amplify the lateral deflections and corresponding inter-storey drifts of unbraced building structures founded on soft grounds, forcing the structure to behave in the inelastic range, resulting in severe damage of the building structures.

Methods that can be used to evaluate the SSI effects can be categorized as direct and substructure approaches [2]. In a direct analysis, the entire structure foundation- soil system is modelled and analysed in a single step as a complete system using a finite element platform. The soil is often represented as a continuum along with foundation and structural elements, transmitting boundaries at the limits of the soil mesh, and interface elements at the edges of the foundation as depicted in Fig. 3. In a substructure approach, the SSI problem is partitioned into distinct parts that are combined to formulate the complete solution using principle of superposition.

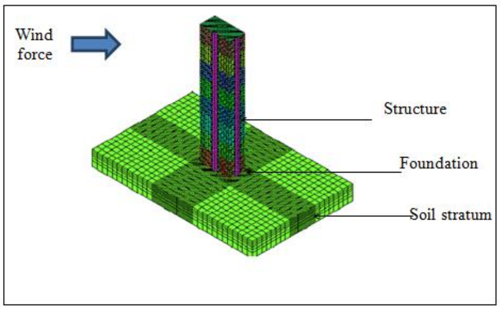


**Fig. 3.Direct approach of SSI**

There are various types of soil models used in SSI such as Winkler model, FilanenkoBorodich model, Hetenyi's model, Pasternak model, Kerr model, elasto-plastic model, elastic continuum models, Mohr-Coulomb model, Drucker-Prager (DP) model etc. The DP yield criterion is a pressure-dependent model for determining whether a material has failed or undergone plastic yielding. The criterion was introduced to deal with the plastic deformation of soils and have been applied to rock, concrete, polymers, foams, and other pressure-dependent materials. In DP, parameters related to friction angle and cohesion govern the yielding and hardening criteria, while the parameter related to plastic dilation determines the flow rule.

Extensive studies have been conducted on the role of SSI in seismic response of structures considering 3D structural system [3-6] and it was deduced that SSI affects the responses of structures such as increased the displacements, reduced base shear and base moments etc. It was also observed that failure sequences are influenced by SSI [4]. Effect of SSI on wind responses were also investigated [7-12] by idealising the structure to equivalent lumped mass system. It was deduced that SSI effect on wind responses are detrimental. Based on literature studies it was observed that very few researches have been undergone on the wind responses of an integrated structure-foundation-soil system. In this study, direct approach of SSI is used to determine the along and across wind responses by considering the material non-linearity of the soil stratum using DP model.

## III. IDEALISATION OF THE STRUCTURE

A tall 180m high RCC building with core having a base dimension of 30 m x 60 m was analysed for along and across wind loads. The storey height was taken as 3m. For a high rise structure, incorporation of shear wall system is necessary to resist the lateral forces and hence, shear walls were placed on the periphery and at the center to act as the lateral load resisting system. Piled raft foundation with piles located at a minimum spacing of 3 times the pile diameter [13] was chosen for the building. The plan view of building showing shear walls and the piled raft foundation are illustrated in Fig. 4 and Fig. 5 respectively. The parameters of the building and foundation are listed in Table 1. The sizes of RCC columns considered are enlisted in Table 2.

TABLE 1. STRUCTURAL PARAMETERS OF BUILDING

| | | |
|---|---|---|
| Building | - | RC building with core and shear walls |
| Foundation type | - | Piled raft foundation |
| Plan dimension | - | 30m x 60m |
| Plan area | - | 1800 m$^2$ |
| Storey height | - | 3m |
| Number of storeys | - | 60 |
| Grid size | - | 5m x 5m |
| Beam size | - | 0.3m x 0.5m |
| Slab thickness | - | 0.125m |
| Shear wall thickness | - | 0.25m |
| Pile diameter | - | 1.2m |
| Raft dimension | - | 45 x 75 x 2.5 m |
| No. of piles | - | 247 |

TABLE 2. DIMENSION OF COLUMN

| Storey | | Size of column (m) |
|---|---|---|
| 0-10 | - | 1.20 x 1.20 |
| 10-20 | - | 0.85 x 0.85 |
| 20-30 | - | 0.75 x 0.75 |
| 30-40 | - | 0.60 x 0.60 |
| 40-50 | - | 0.50 x 0.50 |
| 50-60 | - | 0.40 x 0.40 |

The grade of concrete was chosen as M40 for the building and M25 for the piled raft foundation whose modulus of elasticity [14] are 3.16 x 10$^4$ N/mm$^2$ and 2.50 x 10$^4$ N/mm$^2$ respectively and the grade of steel was chosen as Fe 415. The Poisson's ratio of concrete and steel were taken as 0.15 and 0.3 respectively. The density of concrete and steel was taken as 2500kg/m$^3$ and 7850kg/m$^3$ respectively.

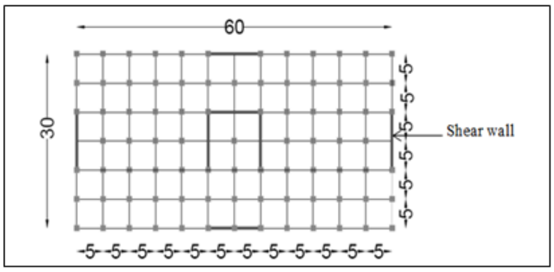


**Fig 4. Plan view of the building**

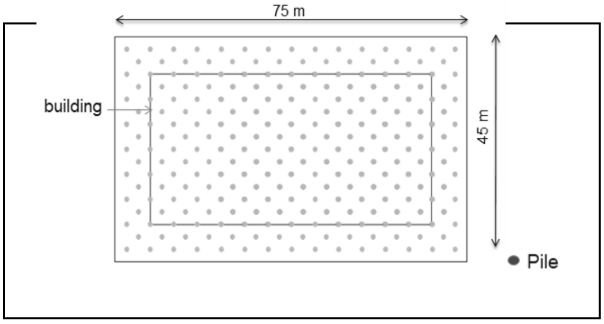


**Fig 5. Plan view of piled raft foundation**

## IV. CALCULATION OF WIND LOADS

Gravity load of the structure [15], an imposed load of 2kN/m$^2$ [16] and wind load [17] were calculated and applied to the building. As per IS 875 (Part 3):2015, there are two methods for determining wind loads acting on a structure namely force coefficient method and dynamic analysis method. For structures with aspect ratio of more than five or natural frequency less than 1Hz, dynamic method of load determination is recommended as per the above IS specification. Both along and across wind loads were calculated considering wind direction at 0$^0$ and 90$^0$. The wind action at 0$^0$ shall be designated as long body orientation and that at 90$^0$ shall be designated as short body orientation. This is shown in Fig. 6. The structure is assumed to be located in wind terrain category IV and interference zone IV as per IS 875 Part 3: 2015 subjected to a basic wind speed of 50 m/s. Modal analysis was performed to obtain the modal frequencies for the building with lateral load resisting system. The wind loads were computed based on this without considering soil stratum flexibility. The procedure for wind load estimation is outlined in the following subsections.

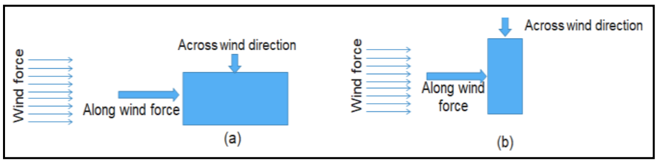


**Fig 6. Different plan orientations of the building subjected to wind force (a) Long body, (b) Short body**

### *A. Along wind Load*

The along wind load on a structure on a strip area at any height *z* is [17]

$$F_z = C_{f,z}.\ A_z.\overline{p_d}.G \tag{1}$$

where$C_{f,z}$ is the drag force coefficient for the building corresponding to $A_z$;$A_z$is the effective frontal area considered for the structure at height *z* in m$^2$;$\overline{p_d}$ is the design hourly mean wind pressure at height *z* due to hourly mean wind and *G* is the gust factor.

Then the design peak along wind base bending moment can be obtained by summing the moments resulting from design peak along wind loads acting at different heights along the height of the building as

$$M_a = \sum F_z Z \tag{2}$$

### *B. Across wind Load*

The across wind design peak base bending moment $M_c$ for enclosed buildings is given by the following formula [17]

$$M_c = 0.5 g_h \bar{p}_h b h^2 (1.06 - 0.06k)\sqrt{\frac{\pi C_{fs}}{\beta}} \tag{3}$$

where $g_h$is a peak factor in cross wind direction for resonant response;$\bar{p}_h$ is hourly mean wind pressure at height *h* (Pa);*k* is a mode shape power exponent for representation of the fundamental mode shape and $C_{fs}$ is across wind force spectrum coefficient generalized for a linear mode.

Then, the across wind load distribution on the building obtained from $M_c$ using linear distribution of loads as:

$$F_{z,c} = \left(\frac{3M_c}{h^2}\right)\frac{z}{h} \tag{4}$$

## V.SOIL STRATUM IDEALISATION

Three types of clayey sand c-ϕ soil were considered for the analyses and these include soft, medium and hard clayey sand which shall be designated as S, M and H respectively. The compressibility of underlying soil stratum was idealizedusing Drucker Prager model. The bedrock was assumed to be at a depth of 30m below the soil stratum.The lateral boundaries of the supporting soil medium are taken as four times the respective lateral dimensions of the raft for which the response as static load is expected to be died out [18]. This leads to a finite domain for the soil which was modelled similar to the structure. The structural system was analysed based on direct method of SSI. The properties of the soil stratum chosen are listed in Table 3. The analysis in which soil structure effect is ignored will be designated as fixed base.

## VI. FINITE ELEMENT ANALYSIS (FEA)

The integrated building-foundation-soil system was analysed using FE method. The types of elements used are shown in Fig. 7.

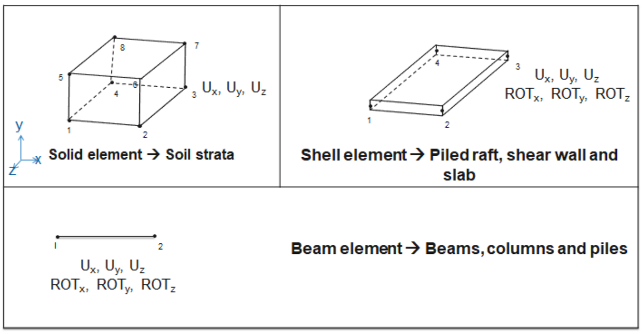


**Fig 7. Elements used for FEM**

Using FEM, modal analysis was performed to find the frequency of the building for calculating the wind forces. The columns were meshed to an element aspect ratio of three while beams, raft and slabs were meshed to an element aspect ratio of 2.5. The piles and the soil stratum were meshed to an element aspect ratio of ten. The FEM model of the building and the integrated building-foundation-soil structure system is shown in Fig. 8 and Fig. 9 respectively. Isometric view of the piled raft foundation and the enlarged view of pile are shown in Fig. 10. The base and lateral boundaries of the soil stratum were constrained in all degrees of freedom.Free vibration analysis was performed to obtain the fundamental frequencies of the building for wind load computation. Then, the wind forces computed as per IS 875 (Part 3):2015 were applied as point loads at every floor level. The responses in terms of maximum deflection and base moment of the non-linear structure considering SSI were compared with that of the linear structure with fixed base in order to assess the effect of SSI.

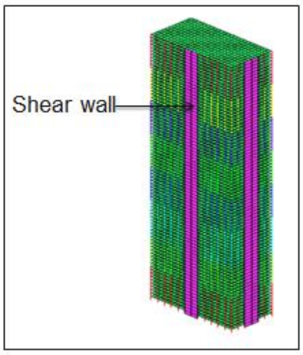


**Fig. 8. Isometric view the building**

TABLE 3. PROPERTIES OF SOIL STRATUM [2, 19]

| Designation of soil | Cohesion, C (kN/m$^2$) | Elastic modulus, $E_s$ (kN/m$^2$) | Poisson's ratio, μ | Unit weight, $\gamma$ (kN/m$^3$) | Angle of friction, $\phi$ ($^o$) |
|---|---|---|---|---|---|
| S | 50 | 50 x 10$^3$ | 0.3 | 1.6 | 32 |
| M | 100 | 100 x 10$^3$ | 0.25 | 1.8 | 34 |
| H | 200 | 150 x 10$^3$ | 0.2 | 2 | 48 |

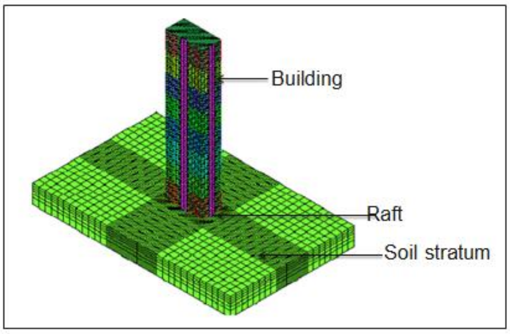
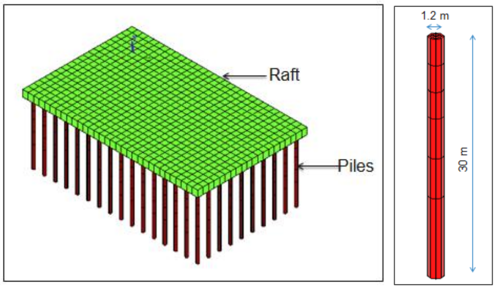


**Fig. 9. Isometric view the integrated building-foundation-soil structure**



(a) (b)

**Fig 10. Isometric view of foundation (a) Piled raft, (b) Enlarged view of one pile**

## VII. RESULTS AND DISCUSSIONS

In order to investigate the effect of SSI on wind responses of a tall building, FEA was conducted on the 180m high building-foundation-soil system. The along and across wind loads acting on the building for long body and short body orientation was computed asper IS 875 (Part 3): 2015. The base moment obtained are shown in Table 4. It was observed thatthe along and across wind forces acting on short body orientation were greater than that for short body orientation and hence response to wind in short body orientation was considered for analysis.

Table 4. Base moment as per IS 875 (Part 3): 2015

| Base moment (kNm) | Long body orientation | Short body orientation |
|---|---|---|
| Along wind induced | 3.10 x 10$^6$ | 6.42 x 10$^6$ |
| Across wind induced | 6.84 x 10$^5$ | 7.92 x 10$^5$ |

Across wind induced base moment were found to be lesser than the along wind induced base moment for both long and short body orientation respectively. Hence along wind loads corresponding to the short body orientation (at a wind angle of 90$^0$) shall be considered as the governing wind load for the building considered.

The along and across wind loads were applied as point loads to the integrated building-foundation-soil system for FEM analysis. Free vibration analysis was conducted to assess the effect of SSI on modal frequencies. The responses in terms of maximum lateral deflection and base moment variations were assessed and compared with respect to the conventional analysis in which SSI effect is ignored. Normalised responses which is the ratio of response by the structure considering SSI to that of the structure without SSI is being used to express the effect of SSI.

### *A. Variation of Frequency*

Free vibration analysis was conducted to analyse the effect of SSI on modal frequency of the building. The modal frequencies corresponding to first three modes under varying conditions of flexibility are tabulated in Table 5. The natural frequency corresponding to the first mode is found to be reduced more compared to the other two modes on considering SSI. For all the type of soil strata considered, natural frequency becomes 0.94 times that of the fixed system. It is observed that frequency decreases with increase in flexibility of the structural system. The maximum variation of frequency from that of the fixed base was seen when founded on soft soil strata 'S'.

This might be because as the flexibility of the system increases, number of vibrations increases thereby increasing its time period and hence frequency of vibration decreases.

Dynamic behaviour of a building is dependent on its frequency. Overestimations of frequencies without considering SSI while designing for lateral loads may affect the structural stability and serviceability especially when dampers which require tuning are used. Hence, the effect of SSI should be considered in free vibration analysis.

**Table 5. Frequency**

| Structure-soil system | Mode 1 | Mode 2 | Mode 3 |
|---|---|---|---|
| S | 0.248 | 0.272 | 0.312 |
| M | 0.249 | 0.274 | 0.313 |
| H | 0.250 | 0.275 | 0.314 |
| Fixed | 0.265 | 0.287 | 0.325 |

### *B. Variation of Maximum Lateral Deflection*

The maximum deflection for along wind and across wind loads were obtained from FEM analysis. These deflections were found to be increased with increase in flexibility. The variation of deflection with varying conditions of soil flexibility is shown in Table 6. The along wind induced deflection is found to be greater by 74% compared to the across wind induced response for all the structure-soil system. This may be because the across wind forces acting on the building is much less than the along wind forces. Hence responses corresponding to along wind loads shall be assessed to investigate the effect of SSI.Upon considering SSI effect, the maximum variation in deflection compared to the fixed base system was found to be for the soft soil strata. The deflection got increased by 17, 15 and 14% of that of the fixed base system for the soil strata types S, M and H respectively. The variation of normalised along wind induced maximum deflection is shown in Fig. 10. It can be observed from the figure that on considering SSI effect, the wind induced deflection becomes almost 1.2 times that of the building system without SSI for all the types of soil strata considered. This increase in deflection owes to the flexibility incorporated on considering the SSI effect.

**Table 6. Maximum lateral deflection**

| Structure-soil system | Maximum lateral deflection (m) | |
|---|---|---|
| | Along wind induced | Across wind induced |
| S | 0.251 | 0.066 |
| M | 0.246 | 0.065 |
| H | 0.244 | 0.064 |
| Fixed | 0.214 | 0.056 |

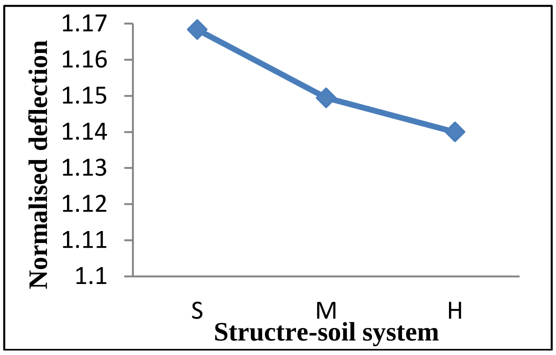


**Fig.10. Normalised maximum deflection**

### *C. Variation of Base Moment*

The base moment induced by along wind force was considered for assessing the effect of SSI. The base moment was found to be decreased with increase in flexibility. On considering SSI, base moment got reduced by 86, 85 and 78% of that of the system without SSI effectfor the soil strata types S, M and H respectively. The variation of the normalised base moment is shown in Fig. 11. On considering SSI, base moment was found to be 0.14 times that of the fixed base system when founded on lower strength soil strata types and 0.22 times ofthe fixed base system when founded on hard strata. Thus SSI effect was found to be conservative in case of base moment. It may be due to the stiffness offered by the piled raft foundation.

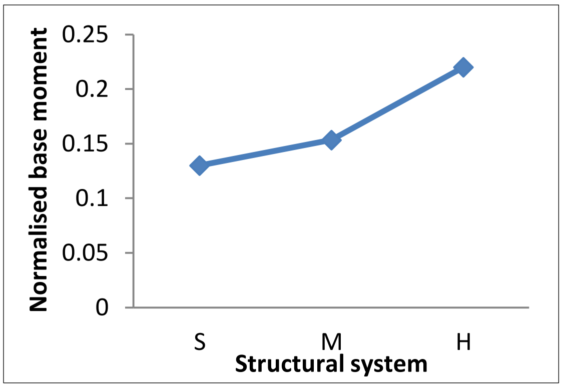


**Fig. 11.Normalised base moment**

## VIII. CONCLUSION

To assess the effect of SSI on wind responses of tall buildings, FEM analysis was conducted on 180m high building with piled raft foundation founded on three types of soil conditions. The wind loads calculated as per IS 875 (Part 3):2015 were applied as point loads at every floor level to compare the responses with and without considering SSI. On comparing the variation of various responses of integrated structure-soil system with respect to the structure system without SSI, the following conclusions can be made.

(i) Modal frequency decreases with increase in flexibility of the soil strata.
(ii) The maximum lateral deflection was found to be 1.2 times that of the building without effect. Hence SSI effect is significant in the case of deflection response.
(iii) On considering the SSI effect, the base moment of the building got reduced by 86-78% of that of building which ignores SSI effect.

Hence for the better optimizedperformance of the structure, effect of SSI should be considered in the design phase.

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