International Journal of Soil Mechanics & Foundations – IJSMF
Volume 1 : Issue 1 [ISSN – 2475-272X]
Publication Date: 09 January 2014

Direct Approach to Numerical Simulation of Soil-Structure Interaction in Homogenous Building Clusters

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***Abstract*— The emerging concept of performance based design relies on a careful consideration of all aspects involved in structural analysis. One of these aspects of structural analysis involves soil-structure interaction (SSI). Current research has focussed on analysing the beneficial and sometimes detrimental effects of SSI to the performance of isolated structures. However, real structures are built in clusters (city blocks) and the seismic performance of one building influences the performance of surrounding buildings. To improve understanding of this effect, a number of building clusters with varying parameters are taken and their peak responses with varying frequencies have been studied in this paper. These results show that cluster effect is significant and the resulting response amplification in certain buildings of the cluster may justify structural retrofitting in existing buildings.**

Keywords— soil-structure interaction, seismic response, response amplification, site effect

I. Introduction

The emerging concept of performance based design relies on a careful consideration of all aspects involved in structural analysis. One of these aspects of structural analysis involves soil-structure interaction (SSI). Such interaction can completely change the dynamic characteristics of structures and may be detrimental or beneficial to the performance of the structure. (Gouasmia, Djeghaba 2007). Site conditions of the soil can be responsible for response amplification of structure (Semblat et. al. 2004). Ignoring these structural response amplifications may lead to under-designed structures. Again, research on SSI has focussed on single degree of freedom systems or on important structures such as nuclear power plants, bridges etc. Rarely has SSI study on regular buildings of short to medium heights in an urban environment been undertaken.

Yet SSI effects in building clusters is an important topic of study as topics such as cross-interaction effects, travelling wave effects, pounding between closely spaced structures have been established and studied as individual phenomena for decades but nowhere have they been studied comprehensively, taking care of all aspects of interaction that occurs between buildings. The SSI effects in building clusters is poorly understood and rarely implemented in actual design of structures.The complexity of interactions in a dynamic urban environment is such that the only approach to satisfactorily simulate it is by a direct approach. Yet the approach is too complicated for common engineering problems, especially for the low rise urban buildings, that are solved with an emphasis on ease and speed rather than on accuracy of calculation. Hence, there is a great need for research on this topic as more than 90% of all urban projects fall under this category.

The objective of this study as reported here is to numerically model cities represented by structural groups of reinforced concrete buildings of various storeys incorporating soft soil conditions. The parameters associated with structural groups including aspect ratio of buildings, group size, building position in the group etc is varied so that a clear picture of response variation with change in these parameters emerges.

II Problem Formulation

Conventional analysis applies the seismic excitation at the base of the structure. But current understanding suggests that this may not be accurate in cases where the structure rests on a compressible soil or where the properties of the foundation may alter the response of the structure. An accurate approach would be to analyze the entire SSI system as a whole, which includes modelling the structure, foundation, and the surrounding soil, and then calculating the response of the entire system (Kramer 1996). There are different approaches to model SSI systems, chiefly being of two types: direct method and substructure method. The city block considered is illustrated in Fig.1. The soil medium consists of four layers. The extent of the soil layer considered is 1250 m with the city block located at the centre. The buildings of the city block are modelled using plate elements (Fig.2).

Seismic wave induced vibrations are simulated in the soil by applying harmonic vibration at model boundary $\Gamma_{sa\sigma}$. These waves then travel from the far field of soil domain

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Ω_s^{ext} to impinge on the foundation of the structure Ω_b through the interface Γ_{SI}. This leads to a dynamic soil-structure interaction between the soil and the structure. It is accounted for by means of direct formulation (Burton, Miller 1971).

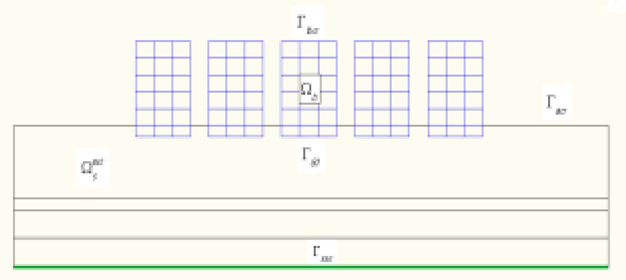


Figure 1: Geometry and notations of the sub-domains

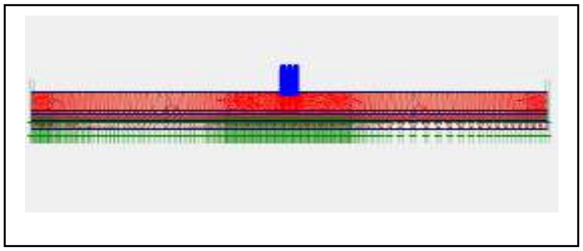


Figure 2: Computational model in Plaxis

Usual soil and concrete properties have been taken for analysis which are reported in table 1 and table 2 of appendix.

III Mathematical Formulation

The boundary of the structure Ω_b , denoted by $\Gamma_b = \Gamma_{b\sigma} \cup \Gamma_{SI}$, is composed of the boundary Γ_{SI} at soil structure interface and boundary $\Gamma_{b\sigma}$ for part of the structure free from soil contact. The traction $\bar{t}_b$ is applied at the soil-structure interface Γ_{SI}. Then, the following Navier equation and boundary conditions hold for the displacement vector u_b of the structure:

$$div\,\sigma_b(u_b) + \rho_b b = -\rho_b \omega^2 u_b \ in\ \Omega_b, \qquad (1)$$

$$t_b(u_b) = \bar{t}_b \ on\ \Gamma_{b\sigma}, \qquad (2)$$

$$u_b = u_s \ on\ \Gamma_{SI}, \qquad (3)$$

$$t_b(u_b) + t_s(u_s) = 0 \ on\ \Gamma_{SI}, \qquad (4)$$

Where $\rho_b b$ is the body force on the structure and $t(u)=\sigma(u).n$ is the traction vector on boundary with unit normal vector n. Similarly, the displacement vector u_s off the soil satisfies the following Navier equation and boundary conditions:

$$div\,\sigma_s(u_s) + \rho_s b = -\rho_s \omega^2 u_s \ in\ \Omega_s^{ext}, \qquad (5)$$

$$t_s(u_s) = 0 \ on\ \Gamma_{s\sigma}, \qquad (6)$$

$$u_s = u_b \ on\ \Gamma_{SI}, \qquad (7)$$

$$t_b(u_b) + t_s(u_s) = 0 \ on\ \Gamma_{SI}, \qquad (8)$$

The displacement vector used in the soil is generally decoupled using a Helmholtz decomposition, which results in a set of uncoupled partial differential equations representing the longitudinal and shear wave propagation.

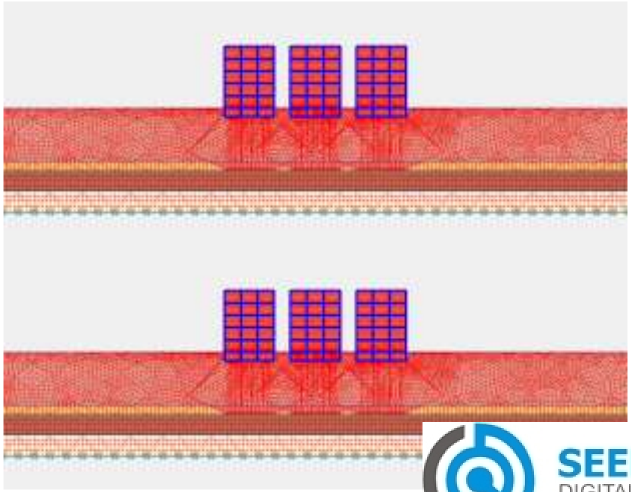
The basic equation for time-dependent movement of a volume under the influence of a dynamic load is:

$$M\ddot{u} + C\dot{u} + Ku = F \qquad (9)$$

Here, M is the mass matrix, u is the displacement vector, C is the damping matrix, K is the stiffness matrix and F is the load vector. The displacement, u, the velocity, $\dot{u}$, and the acceleration, $\ddot{u}$, can vary with time. The last two terms in equation (9) (Ku, F) correspond to static deformation.

III Numerical Application

The analysis model discussed before is applied to study the dynamic responses of RC building in cluster sizes of 1, 3, 5, 7 and 9 denoted as m1, m3, m5 and m9. Buildings with 3, 5, 7 and 9 storeys, denoted as s3, s5, s7 and s9 are taken into consideration. An additional case of buildings with rigid base (FF) is also studied for comparison. Harmonic vibrations of frequencies 0.2 to 2 Hz are applied at the base of the model to stimulate the dynamic conditions. The computational model employed is shown in Figure 6, and numerical results are obtained using Plaxis program. Peak displacement and acceleration response spectra are produced only for the highest points of the building.



The mesh is generated by a special version of triangle mesh generator (Ingenieurs et al.) which results in unstructured meshes. The numerical performance of such meshes is usually better than for structured regular meshes. Geometric nonlinearity is introduced by using an updated mesh analysis based on updated Lagrangian formulation (McMeeking, Rice, 1975). The buildings are considered to be 4.0 m × 3=12 m wide with height of each storey being 3 m. The depth of foundation is varied from 2 m for three and five storied buildings to 3 and 4 m for seven and nine storied buildings respectively. The total load acting on each floor is 15.12 kN/m. The Rayleigh coefficients of the buildings is calculated from their fundamental frequencies obtained by modal analysis in Staad-Pro 2004, using equation. The results are summarised in Table 1 and shown in graphs from fig. 4 to fig. 15.

Table 3: Fundamental frequency and Rayleigh co-efficient used in the model.

No: of storeys	**f_0**	**f_1**	**ω_0**	**ω_1**	**α_R**	**β_R**
3	11.497	11.809	72.23778	74.19814	3.660242	0.000683
5	7.942	8.377	49.90106	52.63424	2.561561	0.000975
7	6.14	6.66	38.57876	41.84601	2.007301	0.001243
9	5.049	5.621	31.7238	35.31778	1.671223	0.001492

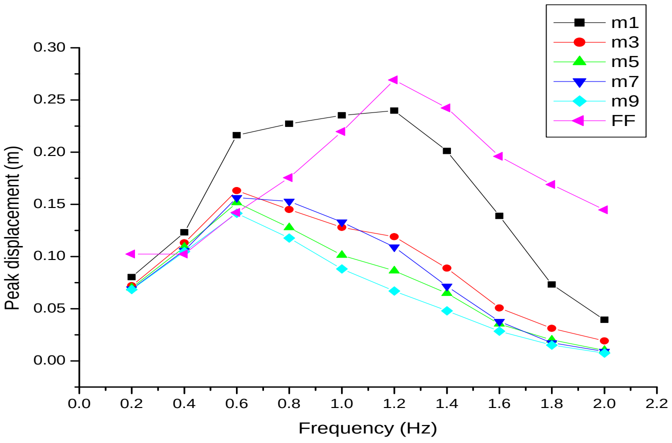


Figure 4: Variation of displacement response spectra with cluster size for three storied building group, at centre of cluster.

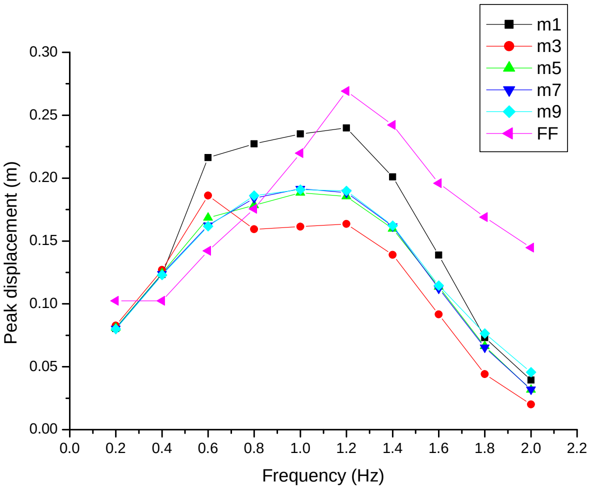


Figure 5: Variation of displacement response spectra with cluster size for three storied building group, at edge of cluster.

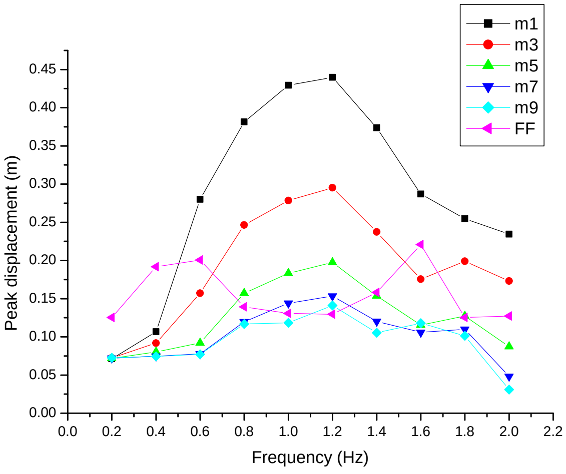


Figure 6: Variation of displacement response spectra with cluster size for nine storied building group, at centre of cluster.

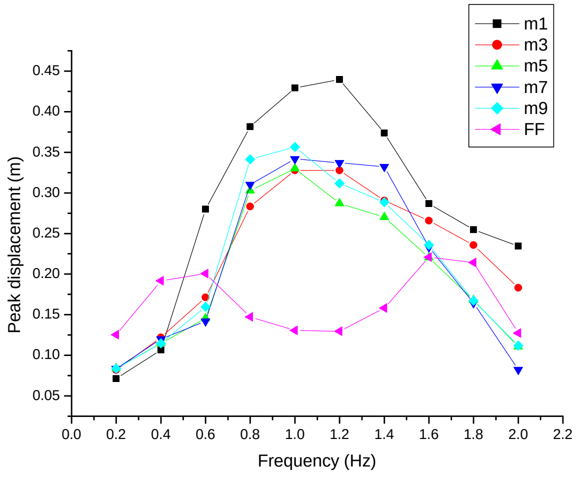


Figure 7: Variation of displacement response spectra with cluster size for nine storied building group, at edge of cluster.

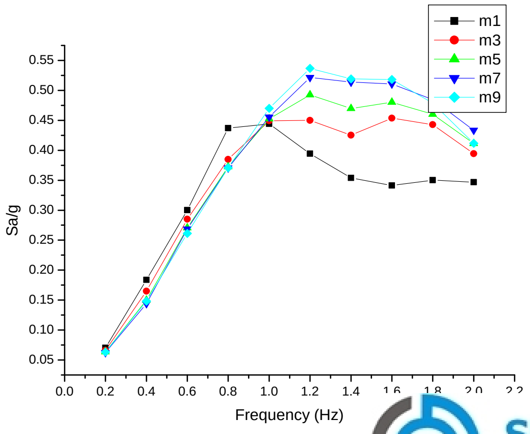


Figure 8: Variation of acceleration response spectra with cluster size for a three storied building group, at centre of cluster.

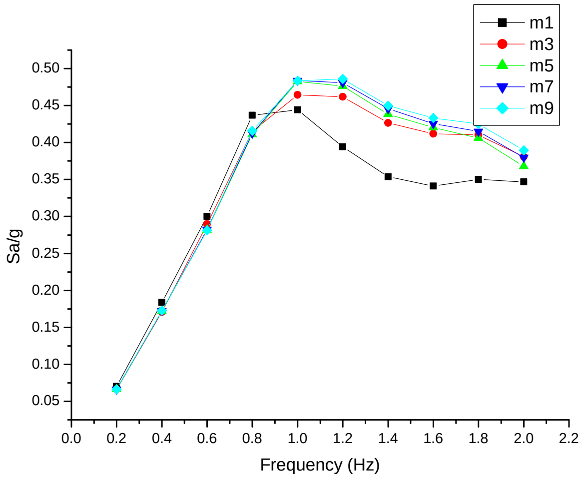


Figure 9: Variation of acceleration response spectra with cluster size for a three storied building group, at edge of cluster.

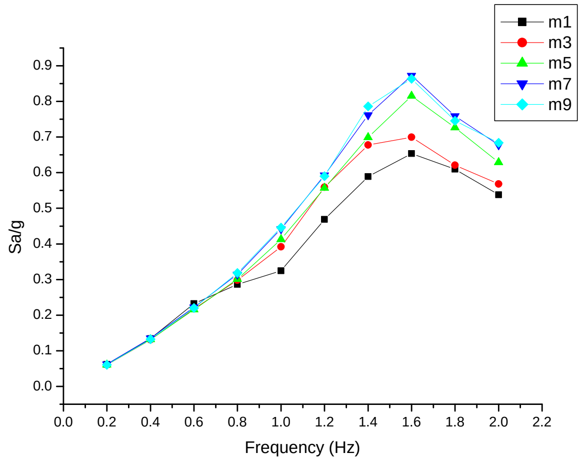


Figure 10: Variation of acceleration response spectra with cluster size for a nine storied building group, at centre edge of cluster.

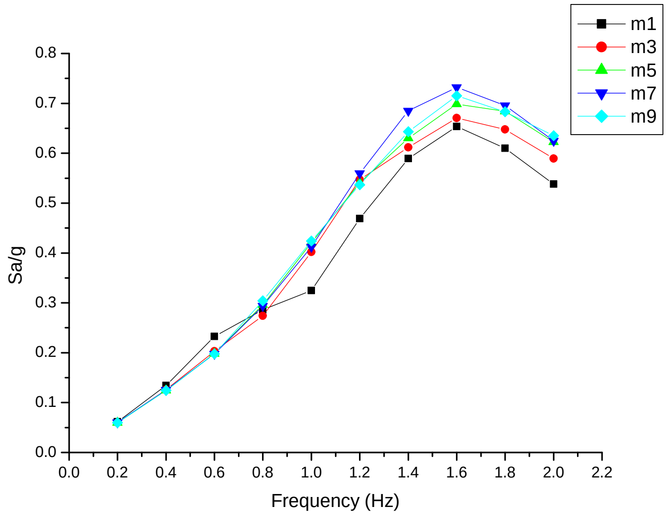


Figure 11: Variation of acceleration response spectra with cluster size for a nine storied building group, at edge of cluster.

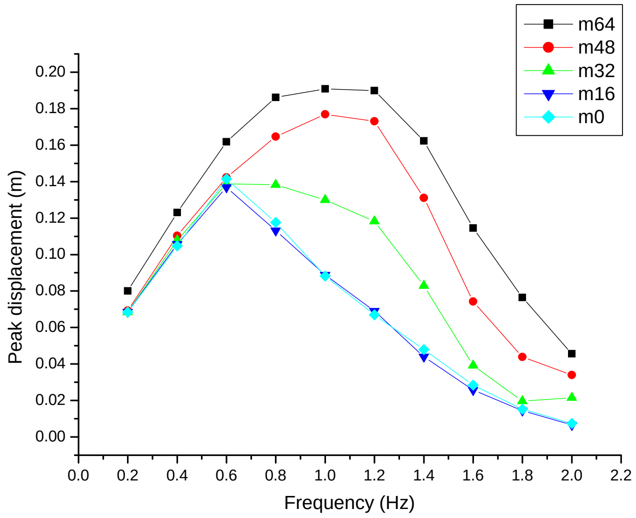


Figure 12: Variation of displacement response spectra with position in cluster for a three storied building group.

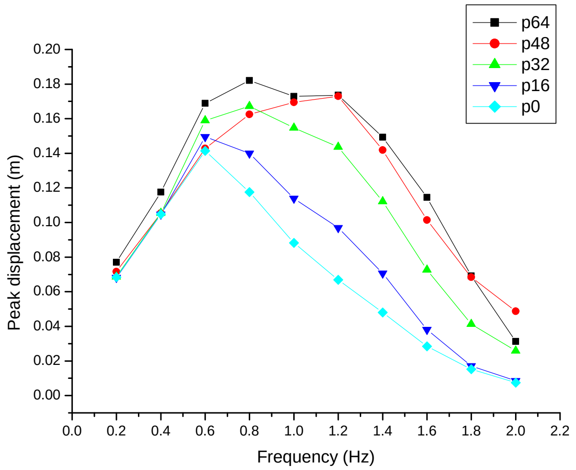


Figure 13: Variation of displacement response spectra with position in cluster for a three storied building group.

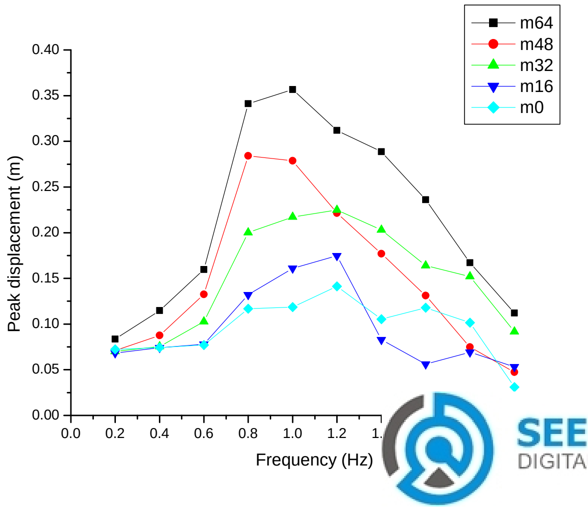


Figure 14: Variation of displacement response spectra with position in cluster for a nine storied building group.

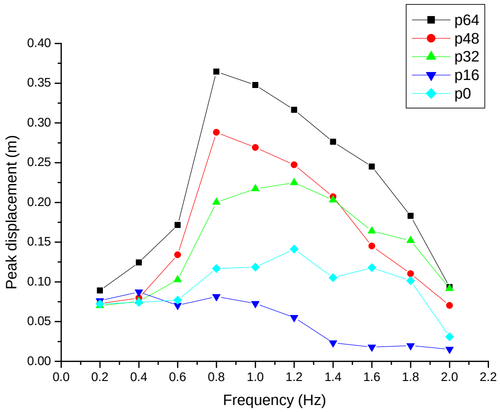


Figure 15: Variation of displacement response spectra with position in cluster for a nine storied building group.

IV Result and discussion

A. Variation of response spectra with cluster size of different building groups

The response spectra of building groups of different storey heights varies with cluster size and is depicted in fig. 4 to fig. 11. From the displacement and acceleration based response spectra it can be concluded that:

1. Displacement response of structures decline with cluster size. The highest response is always observed in single building case which then declines for higher cluster sizes.
2. The effect of cluster sizes on displacement response is more pronounced at the centre of the cluster than the edge of the cluster. In other words, building clusters show higher displacement response at edge than at centre. However, this effect ceases for buildings of height more than 24 m (eight storeys).
3. The displacement response of building clusters is found to often exceed that of buildings with fixed foundations. This is because of the compliance of soil with the structure.
4. In contrast, acceleration response of building clusters has been found to increase with cluster size.
5. The effect of cluster size on acceleration response of buildings is negligible for low frequency vibrations i.e. vibrations of frequency less than 0.6-0.8 Hz. However, at higher frequencies, effect of cluster size on acceleration response increases.
6. The acceleration response at higher frequencies is effected by cluster size more at centre of the cluster than at the edge of the cluster. The edge of the building clusters are negligibly effected by cluster size throughout. However, this effect ceases for buildings of height more than 24 m (eight storeys).

B. Variation of response spectra with position of building in the group

The response spectra of building groups of different storey heights depends on the position of the building in the cluster. It is depicted in fig. 12 to fig. 15 for a cluster size of nine buildings. From the displacement and acceleration based response spectra it can be concluded that:

1. Peak response is always recorded at the edge of the building cluster than at the centre of the building.
2. Position of building is less a factor in affecting the peak acceleration response of the buildings.
3. Position of building is less a factor in affecting its peak displacement response at low frequencies of vibration (lower than 0.4 Hz) up to 15 m height.

V. Conclusion

After extensive computational study on building clusters of various types and sizes, there are a few general conclusions that can be applied to all the models. First and foremost, it must be understood that building deflection is higher in building clusters than buildings with fixed base though buildings with fixed base tend to have higher acceleration response. So, vigorous analysis of SSI effects is necessary for important structures, especially in soft soils. Also, buildings with high deflection may suffer from the problem of pounding in dense urban clusters and hence, care must be taken.

Another observation is that generally large cluster sizes are beneficial for overall seismic performance of the area, especially those with mixed buildings. Buildings at the edge of the cluster are particularly vulnerable to earthquakes in terms of displacement and acceleration response. They must be carefully studied for structural retrofitting needs.

Acceleration response of building clusters is dependent on cluster size only at high frequency vibrations. It is unaffected by building position in the cluster.

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APPENDIX

Table 1: Soil properties implemented in soil sub-domains

Mohr-Coulomb Layer name		**1 Clay**	**2 Sand**	**3 Deep Sand**	**4 Deep Clay**
Type		Drained	Drained	Drained	Drained
Depth	[m]	13	2	5	5
$\boldsymbol{\gamma}_{sat}$	[kN/m³]	18.00	20.00	21.00	18.50
k_x	[m/s]	0.000	1.000	0.500	0.010
k_y	[m/s]	0.000	1.000	0.500	0.010
e_{init}	[-]	0.500	0.500	0.500	0.500
E_{ref}	[kN/m²]	10000.000	80000.000	120000.000	20000.000
ν	[-]	0.330	0.300	0.300	0.330
G_{ref}	[kN/m²]	3759.398	30769.231	46153.846	7518.797
E_{oed}	[kN/m²]	14816.453	107692.308	161538.462	29632.906
c_{ref}	[kN/m²]	5.50	1.00	1.00	4.00
φ	[°]	24.00	31.00	33.00	25.00
ψ	[°]	0.00	1.00	3.00	0.00
Rayleigh **α** Rayleigh **β**		0.425 0.040	23.890 0.001	11.53 0.002	3.390 0.005
$R_{inter.}$		0.70	1.00	1.00	1.00
Interface		Neutral	Neutral	Neutral	Neutral

Note: $\boldsymbol{\gamma}_{sat}$- Saturated unit weight of soil , k_x, k_y-Permeability of soil in x and y directions , e_{init}-initial void ratio of soil, E_{ref} – Young's modulus, ν- Poisson's ratio, G_{ref} – Shear modulus , E_{oed}- Oedometer modulus, c_{ref} - cohesion, **φ**- Friction angle, **ψ**- Dilatancy angle

Table 2: Plate properties implemented in structure sub-domain.

No.	**Identification**	**EA**	**EI**	**w**	**v**
		[kN/m]	[kNm²/m]	[kN/m/m]	[-]
1	Concrete Beam	2.25E6	16875.00	15.12	0.17
2	Concrete Column	2.25E6	16875.00	2.16	0.17