INDIAN JOURNAL OF SCIENCE AND TECHNOLOGY

RESEARCH ARTICLE

Check for updates

OPEN ACCESS

Received: 05.01.2022

Accepted: 28.01.2022

Published: 22.02.2022

Citation: Roopa M, Venugopal H, J, Nagaral M (2022) Soil Structure Interaction Analysis of a Single Layer Latticed Geodesic Dome . Indian Journal of Science and Technology 15(7): 292-299. https://doi.org/10.17485/IJST/v15i7.35

* **Corresponding author**.

roopam@ssit.edu.in

Funding: None

Competing Interests: None

Published By Indian Society for Education and Environment (iSee)

ISSN
Print: 0974-6846
Electronic: 0974-5645

Soil Structure Interaction Analysis of a Single Layer Latticed Geodesic Dome

M Roopa[1]*, H Venugopal[1], Jayachandra [2], Madeva Nagaral[3]

1 Civil Engineering Department, Sri Siddhartha Academy of Higher Education, Tumakuru, Karnataka, India
2 Assistant Professor, School of Civil Engineering, Reva university, Bangalore, India
3 Aircraft Research and Design Centre, HAL, Bangalore, 560037, India

Abstract

Objectives: To analyze the soil structure interaction (SSI) behaviour of a geodesic dome for in situ soil conditions by using the response spectrum method (RSM). **Methods**: An existing geodesic dome of diameter 31m and a total height of 23.6 m is modeled using SAP2000, and the model is evaluated for the soil structure interaction. The existing geodesic dome structure falls under seismic zone II according to IS: 1893-2016, so the in-situ soil properties of the structure are considered to design the soil springs. **Findings:** Base shear in SSI condition observed 3.72 % lesser compared to the nonSSI conditions and natural time period, has been increased to 60.8% compared to nonSSI as it affirms the flexibility of the geodesic dome. **Novelty:** The present study aims to evaluate the dynamic behavior of the geodesic dome, which is a nonconventional structure in design and shape. Few investigations were carried out to analyze the soil structure interaction behavior on such structures.

Keywords: Soil structure Interaction; geodesic dome; response spectrum method; SAP2000; dynamic behaviour

1 Introduction

Domes are one of the oldest types of architectural coverings. Attempts were made in ancient times to cover larger areas with dome constructions. They were full-walled, continuous domes, and it wasn't until the early 19th century that iron and steel technology allowed the creation of reticulated domes, such as strut domes [1]. Geodesic domes are advantageous space structures of a network of bar elements with connecting joints. The construction and assembly of individual elements of a geodesic dome are much easier compared to conventional structural works [2]. Structural analysis on an inverted monk bowled shape single layer geodesic steel dome performed by Naveed Anwar [3], it is modeled and analyzed for wind and seismic loads using the response spectrum method, the design forces are also determined with respect to the structural components and construction loads. A shake table test is performed on a single layer reticulated dome by Gui-boNie [4], to study the dynamic behavior of the proposed model under white noise excitation and fast size frequency to exhibit the natural frequency and damping factor. Nilson Barbieri[5] studied the dynamic behavior of an Aluminium alloy made geodesic dome with impulsive excitation and sweep frequency under laboratory conditions to describe the natural frequency of dome structures. Dominika Pilarska[6] performed a numerical analysis using time history on two geodesic domes as proposed by Fuli´nski. In addition, the axial force, displacements, velocity, and accelerations were also analyzed for designed domes. Hosseini, M[7] conducts a time history analysis on three types of single layer latticed domes such as Ribbed, Schwedler, and Diamatic Space type by varying height to span ratio keeping the span value constant under Gravity and earthquake loads. The different height to span ratios of single layer K8 pattern dome was studied by De-MinWeia[8] for vertical rare earthquakes using time history analysis and results were compared with that of pseudo static elastoplastic analysis. Zhiwei Yu[9] studied the failure mechanism of a single layer steel dome with different sizes of RC substructures under severe earthquakes. They found that the RC substructure significantly behaves under the seismic loads and which influences the failure characteristics of the reticulated dome. Zhang[10] showed that near and far field motions may affect differently on the dynamic response of Kiewitt single layer reticulated domes. Nonlinear dynamic analysis was performed to know the effect of seismic damage on the Keiwitt domes. Shehata E[11] studied the seismic behavior of a multi storey building with a raft foundation with different soil conditions using the response spectrum method. The numerical results for the SSI model are obtained and compared to fixed base conditions.

Dynamic analysis of geodesic domes is effectively analysed by many researchers through time history analysis using the ready ground motions, but the study on SSI behaviour of such nonconventional structure was critically found. This study aims to study the SSI analysis on an existing single layer latticed geodesic dome under raft foundation conditions. The load combination with respect to gravity and earthquake was considered according to IS:1893-2016 to facilitate the results like Base shear and the modal properties, and compared with non-SSI conditions.

2 Structural details of the Geodesic dome

The existing geodesic dome which is considered for the SSI analysis is located at SSIT, Tumakuru, Karnataka region. The geodesic dome is shown in Figure 1(a). The diameter and height of the dome are 31 m and 23.65 m respectively.

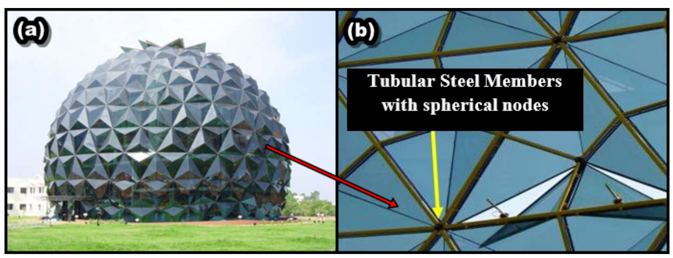

Fig 1. (a) The existing geodesic dome, (b) Tubular steel members with node connectors (source: SSIT, Library, Tumakuru)

The structure is made of tubular steel members with hollow spherical node connectors, which are shown in Figure 1(b). The glass panels of the dome are all right angled triangles, which has resulted in a minimum of wastage in a glass. The dome has no framing members visible outside giving a clean surface, enhancing the visual appeal and no glass panel touches any metal component. Glasses are being fixed to the dome using structural silicone sealants, which takes care of all differential thermal expansion in the glass.

3 Finite Element Modeling

3.1 Geodesic Dome modeling

In general, the octahedron or icosahedron is the most commonly utilized platonic polyhedron, with the tetrahedron and dodecahedron being less prevalent. The geodesic partition of a polyhedron faces into smaller triangles can be divided into three types as Class I, II, and III[11]. The geodesic dome under the present study is an icosahedron type of Class II with a 6V frequency which is represented in Figure 2. The modeling of the geodesic dome is performed using the SAP2000 V22, which is represented in Figure 3. The codebook IS 800:2007 code of practice for general construction in steel (clauses 3.5.1 and 5.3.3) is adopted for modeling the elements of the geodesic dome. The steel tubular pipes, spherical node connectors, and ring beam were modeled using frame elements and the glass (cladding) is modeled with shell elements.

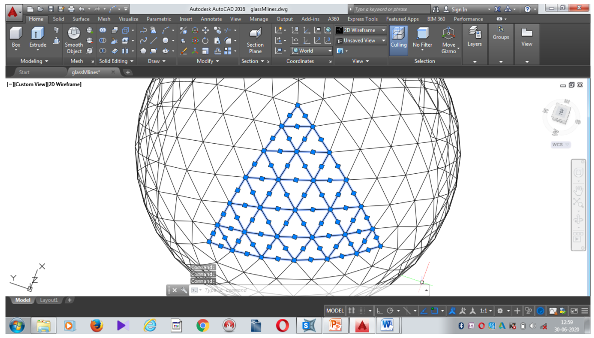

Fig 2. Frequency identification of the geodesic dome

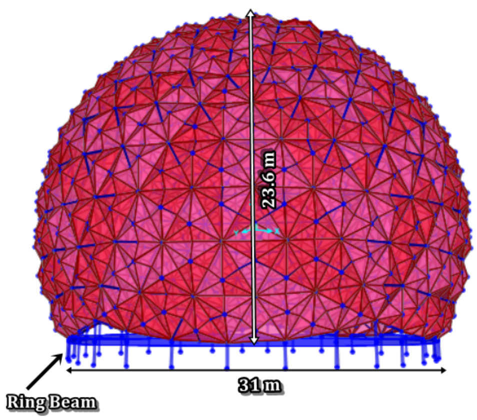

Fig 3. A 3D extruded view of the Geodesic dome in SAP2000

3.2 Soil modeling

When the interaction between the structure and soil medium is considered critical, the geometrical shape and the rigidity would become more important for both the superstructure and foundation. The foundation type is chosen based on the soil properties and the seismic excitation [12,13]. Soil conditions at the site location of the geodesic dome are studied by conducting the soil test. The depth extent of the in-situ soil is shown in Figure 4, and the properties of soil considered for SSI are presented in Table 1.

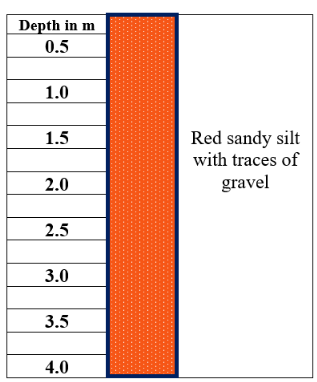

Fig 4. Depth extent of Red sandy silt soil

Table 1. ***In situ*** **Soil Properties**

Red sandy soil parameters			Calculated values
SPT No.	N	50	50
Shear wave Velocity	Vs	$80xN^{1/3}$	294.722 m/s
Mass density	ρ	ρ	1834.86 kg/m^3
Shear modulus	G	ρV_s^2	159.3 MPa
Poisson's Ratio	⊠	0.25-0.3	0.3

The soil spring values based on soil properties are calculated according to Richart and Lysmer (1966)[14]. The soil spring values obtained are represented in Table 2. The schematic of soil spring with six degrees of freedom (DOF) is shown in Figure 5.

Table 2. Soil Spring values according to Richart and Lysmer [1966]

Direction	Notation	Spring Values (N/m)
Vertical	K_z	15418652710
Horizontal	K_x= K_y	13139373613
Rocking	K∅x=K∅y	3048767623689.71
Twisting	K∅z	4268274673165.59

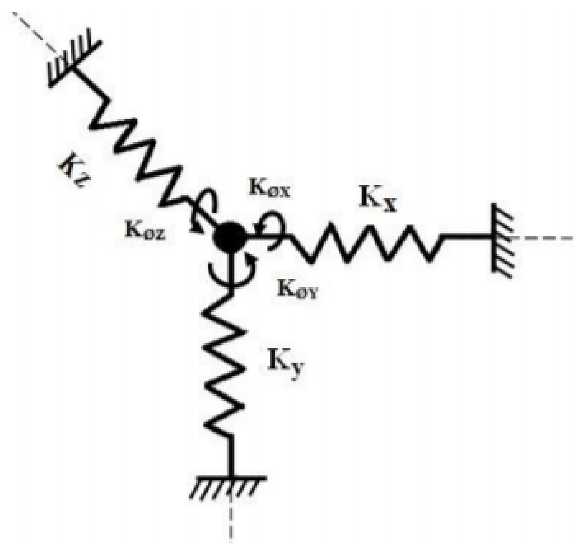

Fig 5. Schematic of soil spring stiffness with six DOF

3.3 Raft foundation modeling

Buildings with moderate height are generally supported with a raft or mat foundation. The soil stiffness is one of the important factors to be considered in designing raft to analyze the moments and shears in the foundation[15]. In this study, a raft foundation with 31.78 m x31.78 m x 0.3 m dimension is modeled as per the design calculation of the weight of the superstructure and it is modeled as four noded shell elements with each node having six degrees of freedom. The Soil Springs (three translational and three rotational) behave independently with each other according to the Winkler spring method. The Winkler method predicts that the Raft foundation defines vertical soil springs represents the linear elastic soil.[16] JayalekshmiB.R.[17] also reported that the Winkler spring method assumes the soil medium as a closely spaced series of springs on which the foundation slab rests. The 3D view of the raft and geodesic dome resting on the raft foundation with assigned spring values is shown in Figure 6.

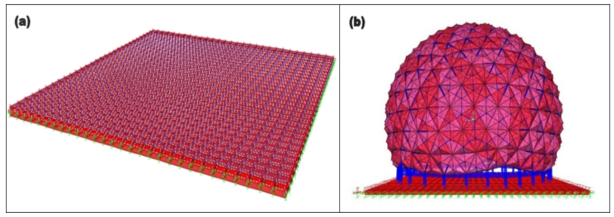

Fig 6. (a) 3D view of the raft (b) Geodesic dome with raftfoundation

4 Soil Structure Interaction analysis

The SSI mainly occurs as two interactions, namely Kinematic and Inertial. Wave motions transfer cyclically between the structure and soil, where the structure reacts to the response from soil and soil reacts to the response from the structure[18]. The dynamic analysis was conducted using the response spectrum method. The spectrum curve determined to damping ratio of 5% for soil type I (Hard Soil) according to IS 1893:2016, which is represented in Figure 7.

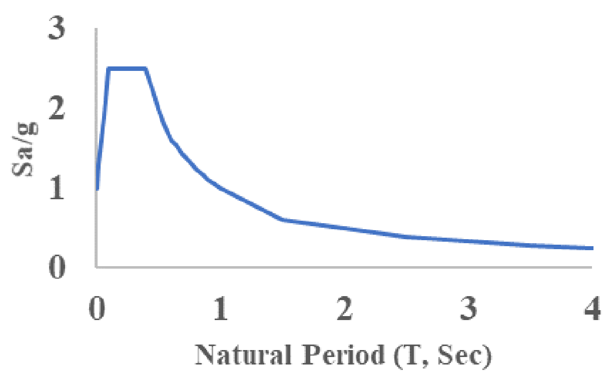

Fig 7. Response Spectrum curve for hard soil as per IS -1893

5 Results and Discussion

The seismic response of the geodesic dome with in situ soil conditions is analyzed using the response spectrum method. A parametric study was made to compare the base shear, modal time period, and joint displacements of the SSI model to that of non-SSI model.

5.1 Base shear

The total horizontal force is referred to as base shear, which is mainly based on structural mass, natural time period, and modal shape. The variation in base shear for geodesic dome with SSI is obtained for all zone types and is compared with that of non-SSI is shown in Figure 8.

A 3.72% reduction is observed in the base shear for SSI compared to the non-SSI condition (Fixed base) and the V zone shows maximum base shear value compared to the other Zones. The variation in base shear is mainly due to the structural characteristics and Soil conditions[19].

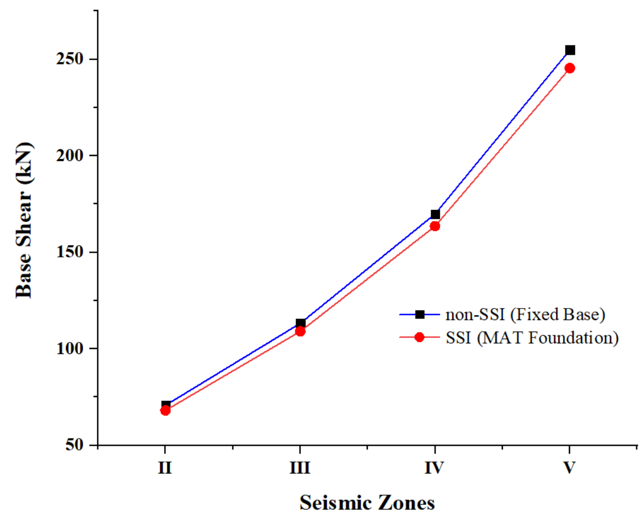

Fig 8. Variation in base shear for Fixed base and RAT foundation

5.2 Modal Characteristics

The seismic design of any high rise building includes the fundamental period as the most essential dynamic property which closely relates to the mass distribution and stiffnes [20] of the superstructure $. The modal mass participation of the sum of all the modal masses in defined directions would be at least 90% of the total seismic mass according to clause [21].7.5.2 of IS 1893:2016 $. The comparison of natural time periods for nonSSI and SSI models is shown in Figure 9.

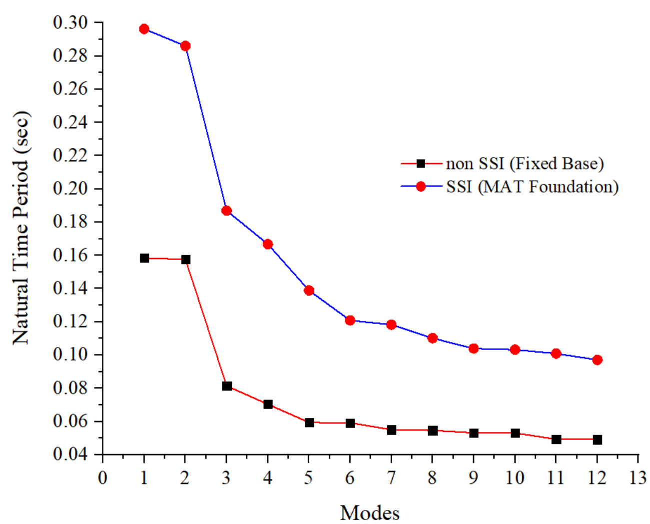

Fig 9. Natural time periods ofnonSSI and SSI models

In design consideration of any building, defining centers of gravity located on a vertical axis and the elastic centers on another vertical axis is common. This condition provides the eccentricity which includes torsional motion [22]. It is observed that the modal mass participation is maximum in the Torsional direction compared to the lateral directions as the structural characteristics of the geodesic dome are different from any regular structures. The modal properties of both non-SSI and SSI models are presented in Table 3.

The first three modes are responsible for the largest mass participation of the geodesic dome with respect to x (translational), y (translational), and z (rotational). Here more than 65% total mass participation is achieved with the first 3 modes according to

Table 3. Modal properties of geodesic dome of non-SSI and SSI models

Mode	NonSSI model (Fixed Base)				SSI model (Raft Foundation)			
	Period (Sec)	Modal Mass Participating Ratio (%)			Period (sec)	Modal Mass Participating Ratio (%)		
		X	Y	Rz		X	Y	Rz
1	0.1584	0.4636	0.24461	0.0000905	0.296	0.43968	0.33086	0.00079
2	0.1576	0.2428	0.46017	1.134E-12	0.286	0.35166	0.46279	0.0159
3	0.0814	0.000002693	0.00000142	0.94542	0.187	0.00138	0.02118	0.76309
4	0.0704	0.000001118	0.000002115	3.583E-14	0.167	0.0053	0.01486	0.15489
5	0.0594	0.00038	0.0002	0.00039	0.139	0.00931	0.00063	0.0306
6	0.0592	0.00002772	0.00005261	2.92E-12	0.121	0.00921	0.00528	0.00089
7	0.0551	0.00502	0.00265	0.00036	0.118	0.0115	0.0004	0.00122
8	0.0546	0.00016	0.00031	2.151E-13	0.110	0.04368	0.01987	0.00019
9	0.0532	0.13951	0.07355	0.00007411	0.104	0.00219	0.00067	0.00011
10	0.0531	0.07357	0.13954	1.743E-12	0.103	0.03535	0.0857	0.00199
11	0.0493	0.00596	0.00315	0.00005283	0.101	0.04895	0.02417	0.00004629
12	0.0492	0.00519	0.00983	1.518E-12	0.097	0.01383	0.00018	0.0000869

IS 1893: 2016. Approximately 10 modes were participated to reach 90% mass participation in each direction. The modal shapes of the first 10 modes for both non-SSI and SSI models are represented in Figure 10.

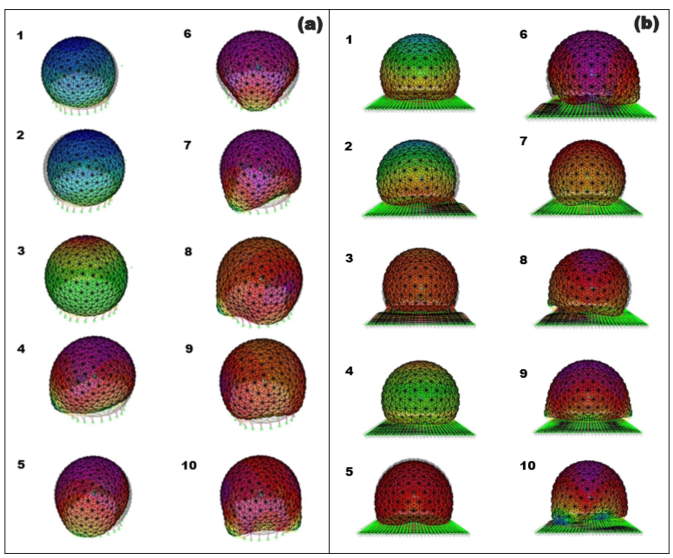

Fig 10. Modal Shapes of the first 10 modes of nonSSI (a) and SSI model (b)

6 Conclusion

This study conducts a dynamic analysis of an existing geodesic dome through soil structure interaction. The variation in base shear and modal characteristics are compared with non-SSI model. The main conclusions are drawn from the results are as follows,

(1) Analyzing the structural safety of modern structures like geodesic domes would be insufficient without the consideration of SSI, where the Soil structure interaction plays a major role in the seismic response of the geodesic structures in translational and rotational deflections.

(2) The base shear reduced approximately to 3.72% with flexible base (SSI) condition in comparison with fixed base (non-SSI) condition.

(3) The modal characteristics of both SSI and non-SSI models were studied. In both the models first three modes achieved 65% mass participation in translational and rotational directions.

(4) The first 10 modes are involved in achieving 90% mass participation of geodesic dome structure in each direction.

(5) RSM was found as the most effective method of seismic analysis for geodesic dome structures, where the response spectrum curve can be adopted to achieve the most accurate results.

Acknowledgment

The authors greatly acknowledge with gratitude to SSAHE University, Tumakuru for providing the required inputs to accomplish this work. We also thank the anonymous resource persons for their useful suggestions and comments on this study.

References

1) Pilarska D. Two subdivision methods based on the regular octahedron for single- and double-layer spherical geodesic domes. *International Journal of Space Structures*. 2020;35(4):160–173. Available from: https://dx.doi.org/10.1177/0956059920956944.
2) Ramaswamy GS, Eekhout M, Suresh GR. Analysis, Design and Construction of Steel Space Frames;vol. 350. and others, editor;Thomas Telford Publishing. 2002.
3) Anwar N, Praminnorachan T, Aung. Case Study: Challenges of a Single-layer Reticulated Dome. In: IABSE Conference - Structural Engineering: Providing Solutions to Global Challenges. 2015.
4) bo Nie G, long Zhu X, dong Zhi X, Wang F, Dai J. Study on Dynamic Behavior of Single-Layer Reticulated Dome by Shaking Table Test. *International Journal of Steel Structures*. 2018;18(2):635–649. Available from: https://dx.doi.org/10.1007/s13296-018-0021-2.
5) Barbieri N, Machado RD, Barbieri L. Dynamic Analysis of a Geodesic Dome. In: Procceedings of the 24th ABCM International Congress of Mechanicl Engineering. ABCM. 2017;p. 24–28.
6) Pilarska D, Maleska T. Numerical Analysis of Steel Geodesic Dome under Seismic Excitations. *Materials*. 2021;14(16):4493–4493. Available from: https://dx.doi.org/10.3390/ma14164493.
7) Hosseini M, Hajnasrollah S, Herischian M. A Comparative Study on the Seismic Behavior of Ribbed, Schwedler, and Diamatic Space Domes by Using Dynamic Analyses. *Proceedings of the 15WCEE*. 2012;p. 24–28.
8) De-Minweia. Seismic response analysis of K8 pattern single-layer reticulated domes under vertical rare earthquakes. Procedia Engineering. *Sheng-FuGaob*. 2017;210:417–424. doi:10.1016/j.proeng.2017.11.096.
9) Yu Z, Li S, Lu D, Lu C, Liu J. Failure mechanism of single-layer steel reticular domes with reinforced concrete substructure subjected to severe earthquakes. *International Journal of Steel Structures*. 2016;16(4):1083–1094. Available from: https://dx.doi.org/10.1007/s13296-016-0025-8.
10) Chang M, Zhang M. Architecture Design of Datacenter for Cloud English Education Platform. *International Journal of Emerging Technologies in Learning (iJET)*. 2019;14:24–24. Available from: https://dx.doi.org/10.3991/ijet.v14i01.9464.
11) Raheem SEA, Ahmed MM, Alazrak TMA. Evaluation of soil–foundation–structure interaction effects on seismic response demands of multi-story MRF buildings on raft foundations. *International Journal of Advanced Structural Engineering*. 2015;7(1):11–30. Available from: https://dx.doi.org/10.1007/s40091-014-0078-x.
12) Wong H, Leung. Dynamic soil-structure interaction. Pasadena, California. 1975.
13) Hokmabadi AS, Fatahi B. Influence of Foundation Type on Seismic Performance of Buildings Considering Soil–Structure Interaction. *International Journal of Structural Stability and Dynamics*. 2016;16(08):1550043–1550043. Available from: https://dx.doi.org/10.1142/s0219455415500431. doi:10.1142/s0219455415500431.
14) Lysmer J, Richart FE. Dynamic Response of Footings to Vertical Loading. *Journal of the Soil Mechanics and Foundations Division*. 1966;92:65–91. Available from: https://dx.doi.org/10.1061/jsfeaq.0000846.
15) Poulos HG. Tall building foundations: design methods and applications. *Innovative Infrastructure Solutions*. 2016;1(1). doi:10.1061/JSFEAQ.0000846.
16) Loukidis D, Tamiolakis GP. Spatial distribution of Winkler spring stiffness for rectangular mat foundation analysis. *Engineering Structures*. 2017;153:443–459. Available from: https://dx.doi.org/10.1016/j.engstruct.2017.10.001.
17) Jayalekshmi BR, Chinmayi HK. Soil–Structure Interaction Effect on Seismic Force Evaluation of RC Framed Buildings with Various Shapes of Shear Wall: As Per IS 1893 and IBC. *Indian Geotechnical Journal*. 2015;45(3):254–266. Available from: https://dx.doi.org/10.1007/s40098-014-0134-2.
18) Badry P, Satyam N. Seismic soil structure interaction analysis for asymmetrical buildings supported on piled raft for the 2015 Nepal earthquake. *Journal of Asian Earth Sciences*. 2017;133:102–113. Available from: https://dx.doi.org/10.1016/j.jseaes.2016.03.014.
19) Tahghighi H, Mohammadi A. Numerical Evaluation of Soil–Structure Interaction Effects on the Seismic Performance and Vulnerability of Reinforced Concrete Buildings. *International Journal of Geomechanics*. 2020;20(6):04020072–04020072. Available from: https://dx.doi.org/10.1061/(asce)gm.1943-5622.0001651.
20) Zhou Y, Zhou Y, Yi W, Chen T, Tan D, Mi S. Operational Modal Analysis and Rational Finite-Element Model Selection for Ten High-Rise Buildings based on On-Site Ambient Vibration Measurements. *Journal of Performance of Constructed Facilities*. 2017;31(5):04017043–04017043. Available from: https://dx.doi.org/10.1061/(asce)cf.1943-5509.0001019.
21) 2016-Indian standard criteria for earthquake resistant design of structures, part 1: general provisions and buildings (Sixth Revision). In: Bureau of Indian Standards. 2016.
22) Penzien J. Earthquake response of irregularly shaped buildings. In: Proc. 4th World Conf. Earthquake Engineering;vol. 2. 1969;p. 75–89.