Dynamic Soil-Structure Interaction of Multi-Story Buildings using the Finite Element Method and Minimax Probability Machine Regression

Saurav Shekhar Kar
Department of Civil Engineering, Marathwada Mitramandal's Institute of Technology, India
kar.sauravshekhar2008@gmail.com (corresponding author)

Anupama Arunkumar Athawale
AISSMS Institute of Information Technology, Pune, India
athawale.anupama@gmail.com

Mani Bhushan
Department of Civil Engineering, Government Engineering College Khagaria, Bihar, India
mani.tuntun@gmail.com

Lal Bahadur Roy
Department of Civil Engineering, National Institute of Technology Patna, India
lbroy@nitp.ac.in

Received: 21 March 2023 | Revised: 5 April 2023 and 1 May 2023 | Accepted: 10 May 2023

 DOI: https://doi.org/10.48084/etasr.5870

ABSTRACT

Soil-Structure Interaction (SSI) issues are some of the most critical problems encountered in the design of structures prone to earthquake shaking. The damage caused by an earthquake mainly depends on the interaction between soil and structure. In this study, the effect of dynamic SSI on a multi-story building is examined using two methods, Finite Element Method (FEM) and Minimax Probability Machine Regression (MPMR). The MPMR was used to develop a model based on the input and output database generated from the FEM model. The performance comparison of these two models shows a good correlation. The MPMR model significantly reduced the computational time and can thus be utilized as a substitute for determining the response quantities.

Keywords-dynamic SSI; earthquake; FEM; MPMR

I. INTRODUCTION

Soil–Structure Interaction (SSI) becomes very crucial when massive and stiff structures are built on soft soil. Structures may be subjected to dynamic loads arising due to various natural or manmade sources (e.g. blasting, machine operations, quarrying, construction activities, action of water waves, earthquakes, etc.), out of which earthquake is the most important hazard to the structure and foundation. The damage caused by an earthquake mainly depends on the dynamic response of the soil layers [1]. In many cases, the damage caused is not due to the sole structural failure or sole soil failure, but it is due to the interaction between the soil and the structure. The properties of the soil vary from one place to another or along the direction (vertical or horizontal) [2-4]. Thus, in severe soil conditions, the interaction effects should be considered for the dynamic analysis of the structures built on the soil. The general structural dynamic system has mainly two characteristic differences from the SSI system which are the non-linear characteristics of the soil [5] and the unbounded nature of the soil medium [6]. The radiation damping, which is the radiation of energy towards infinity, is the most important characteristic in an unbounded soil medium and it is not experienced in a bounded soil medium.

Many studies have considered the effects of SSI on the dynamic behavior of the structures. Authors in [7] analyzed the effect of SSI on three-dimensional building distribution resting on a layered elastic-half-space. Authors in [8] proposed a simple relation to estimate the expected efficiency of the SSI effects for any city. Authors in [9, 10] studied the seismic response of an idealized 2D "city", constituted by 10 non equally-spaced and sized, homogenized buildings. Authors in [11] introduced two analytical methods that aim to investigate the effect of the urban environment on seismic motions. In [12], the nonlinear SSI behavior was modeled through a beam-on-nonlinear-Winkler-foundation approach. Authors in [13] studied the seismic behavior of braced and unbraced building structures affected by SSI. It was found that for the flexible buildings built on very stiff soil and rock the SSI effects may be ignored, but for structures built on comparatively soft soil, they should be necessarily considered [14–16]. During the past few decades, many analytical formulas have been developed to solve the difficult problems of SSI analysis. The effect of the non-linear nature of the soil on the dynamic response of the buildings has not been completely dealt with [17]. The use of analytical methods is very limited as the solutions are available only for systems with simple geometry. The ability of soft computing techniques like Minimax Probability Machine Regression (MPMR) has gained popularity in many research areas [18–24]. MPMR is basically a method used to arrive at a best solution for a given set of parameters. It provides an easy way to deal with a wide range of problems for which it is difficult to generate an analytical model. Soft computing techniques can be applied also when an exact analytical model cannot be defined. The MPMR technique has been applied to various engineering applications and appears to perform well.

In this study, the effect of dynamic SSI on a multi-story building resting on a raft foundation having different height to width (H/B) ratio, subjected to the seismic ground motion record of the EI-Centro and the Bhuj earthquakes, is examined. Different types of soils were used and the response of the framed structure was studied. The SSI problem has been analyzed using FEM and MPMR. The FEM model was developed and analyzed with SAP2000. Response quantities like Top Story Displacement (TSD), Displacement of Ground Level (DGL), and relative displacement between top story and ground level (RTSD) were found out. The training and testing data sets for the MPMR were obtained from the result of the FEM modeling. It is noticed that the computational time is considerably reduced for the MPMR model as compared to the FEM model.

II. METHOD OF ANALYSIS

The various methods used in the analysis of the SSI problem are discussed below.

A. Soil-Structure Interaction

SSI analysis takes into account of all the three linked systems, i.e. the building, the foundation, and the soil neighboring and underlying the foundation. It assesses the collective response of these systems to a specified ground motion. The interaction between the earth and structures is different in different situations. The type of foundations used in the structure and the type of structures used also influence the response of the soil-structure system [25]. Two types of interaction effects are observed in a SSI problem, the kinematic interaction and the inertial interaction [26].

1) Kinematic Interaction

The SSI effect which is related with the structural stiffness is termed as kinematic interaction. It arises due to the incapability of the foundation to conform to the dislocation of the free-field ground motion. By free-field motion we mean the motion of the soil layer which is not affected by structural vibration or by the scattering waves around the foundation. Due to the kinematic interaction, the motion at the foundation deviates from free-field motion. This interaction occurs due to the presence of stiff foundation elements. When the depth of the embedded foundation is equal to the wavelength of normally propagating shear waves, then the kinematic interaction generates torsion and rocking vibration in the structure, which never happens in the case of free field motion. By considering that the foundation and structure have stiffness but are massless, the deformation occurring due to the kinematic interaction can be evaluated. The equation of motion in this case is given as [15]:

$$[M_{soil}]\{\ddot{u}_{KI}\} + [K^*]\{u_{KI}\} = -[M_{soil}]\,\ddot{u}_b(t) \qquad (1)$$

where $[M_{soil}]$ is the mass matrix supposing that the structure and foundation has no mass, $\{u_{KI}\}$ is the foundation input motion, $[K^*]$ is the stiffness matrix, and $\ddot{u}_b$ is the acceleration at the boundary.

2) Inertial Interaction

The SSI effect which is related with the mass of the superstructure is known as the inertial interaction. It is caused due to the mass of the superstructure which develops additional movements at the base of the foundation. Due to the displacement of masses of the superstructure during a vibration, inertia forces are generated, which induce transverse shear and overturning moment to the structure. The deformation caused due to inertia interaction can be evaluated from [15]:

$$[M]\{\ddot{u}_{II}\} + [K^*]\{u_{II}\} = -[M_{structure}] \times\{\ddot{u}_{KI}(t) + \ddot{u}_b(t)\} \qquad (2)$$

where $[M_{structure}]$ is the mass matrix assuming that the soil has no mass.

III. MINIMAX PROBABILITY MACHINE REGRESSION (MPMR)

MPMR is based on the minimax probability machine classification by building a dichotomy classifier [23]. It maps the input vectors into a high-dimensional feature space. It reckons the mean and covariance matrix of the available data. In MPMR, the relation between input (x) and output (Y) is given by:

$$Y = \sum_{i=1}^{N} \beta_i K(x_i, x) + b \qquad (3)$$

where N is the datasets number, β_i and b are outputs of the MPMR, and $K(x_i, x)$ is the kernel function. One piece of data is obtained by shifting all of the training data + ∈ along the output variable axis. The other is obtained by shifting all of the regression data - ∈ along the axis. In MPMR, the training data set is classified into the following two classes:

$$u_i = (y_i + \in, x_{i1}, x_{i2}, \ldots, x_{in}) \qquad (4)$$

$$v_i = (y_i - \in, x_{i1}, x_{i2}, \dots, x_{in}) \quad (5)$$

The classification boundary between u_i and v_i represents the regression surface. Radial basis function has been used as a kernel function. MATLAB has been used to develop the MPMR model. For constructing the MPMR model, the design values of $\in$ and σ have been evaluated by the trial and error method. The coefficient of correlation (R) values come close to or equal to 1, so the developed MPMR is considered a very good model.

IV. METHODOLOGY

A. *Specification for the Soil Structure System*

The SSI problem has been analyzed using the specifications mentioned in IS 456:2000. The structural details and their speciation used in the analysis are given in Table I.

TABLE I. STRUCTURAL DETAILS USED IN THE SSI PROBLEM

Structural details	Specifications
Beam	0.35 m × 0.45 m
Column	0.35 m × 0.35 m
Storey height	3.0 m
Bay size	5.0 m
Grade of concrete	M40
Thickness of raft foundation	1.1 m

B. *Materials*

Seventy-five different types of soil were categorized based on Young's modulus (E), Poisson's ratio (μ), and unit weight (γ) in 5 groups, i.e. soft clay (saturated), stiff clay (saturated), sandy clay, loose sand, and dense sand. These different types of soil were used in the analysis of SSI problem having varying H/B ratio. The properties of the soils are shown in Table II.

TABLE II. SOIL PROPERTIES

Soil type	E (kPa)	μ	γ (kN/m³)	Soil type	E (kPa)	μ	γ (kN/m³)	Soil type	E (kPa)	μ	γ (kN/m³)
Soft clay (saturated)	2000	0.40	16.0	Hard clay (saturated)	7000	0.40	18.0	Dense sand	50000	0.30	19.0
	2200	0.40	16.2		7200	0.40	18.1		52000	0.31	19.0
	2400	0.40	16.4		7600	0.40	18.2		54000	0.32	19.0
	2600	0.41	16.6		8000	0.41	18.3		56000	0.33	19.2
	2800	0.41	16.8		8400	0.41	18.4		58000	0.34	19.2
	2900	0.42	17.0		8800	0.42	18.5		60000	0.35	19.2
	3000	0.42	17.2		9400	0.42	18.6		62000	0.36	19.4
	3200	0.42	17.4		10000	0.42	18.7		65000	0.37	19.4
	3300	0.43	17.6		10600	0.43	18.8		67000	0.38	19.4
	3500	0.43	17.8		11000	0.43	18.9		70000	0.39	19.6
	3600	0.44	18.0		12000	0.44	19.0		72000	0.40	19.6
	3700	0.44	18.2		13000	0.44	19.1		74000	0.41	19.7
	3800	0.45	18.4		13500	0.45	19.2		76000	0.42	19.7
	3900	0.45	18.6		14000	0.45	19.3		78000	0.43	19.8
	4000	0.45	18.8		15000	0.45	19.4		80000	0.45	20.0
Sandy clay	27000	0.20	16.0	Loose sand	10000	0.20	17.0				
	29000	0.20	16.3		11000	0.22	17.1				
	31000	0.21	16.6		12000	0.23	17.2				
	33000	0.21	16.9		13000	0.24	17.3				
	34000	0.22	17.2		14000	0.25	17.4				
	34500	0.22	17.5		15000	0.26	17.5				
	35000	0.23	17.8		16000	0.28	17.6				
	35500	0.23	18.0		17000	0.30	17.7				
	36000	0.24	18.2		18000	0.31	17.8				
	36500	0.24	18.3		19000	0.32	17.9				
	37000	0.25	18.5		20000	0.33	18.0				
	37500	0.26	18.7		21000	0.34	18.1				
	38000	0.27	19.0		22000	0.35	18.2				
	38500	0.28	19.2		23000	0.36	18.3				
	39000	0.29	19.4		24000	0.38	18.4				

C. *Implementation*

The implementation of analyzing the SSI problem is conducted using two different models, which are discussed below.

1) *FEM Model*

FEM modelling of the SSI problem was done using the software package SAP2000. The soil is considered to be a solitary stratum of 65 m depth and 270 m wide. The building members are modelled with framed elements. The interface between the soil and the structure foundation is modelled using nonlinear GAP connector elements. The GAP elements essentially consist of a spring combined with an opening such that no tensile force gets transmitted through the soil to the foundation. In this study, zero initial openings have been assumed for the GAP elements with spring stiffness value in order of 10^4 kN/m and were distributed at every one meter over the interface surface. Further, it is assumed that the sliding between the foundation and the soil is insignificant. This is demonstrated by imposing an equal horizontal displacement constraint for the interface nodes. The soil element sizes are increased as it moves away from the periphery of the soil layer. For appropriate modeling, the maximum size of the soil mesh is limited to $\lambda/10$ where λ is the wave length of the waves transmitted within the soil [25]. In terms of boundary conditions, a fixed boundary at the base and an absorbing boundary at the vertical edge of the soil were considered. These boundaries represent the missing soil beyond the periphery of the soil layer. Transmitting boundaries are implemented using viscous dampers having damping coefficient value related to the velocity of shear waves and pressure waves travelling in the soil media. The horizontal and the vertical coefficient for the dampers are found out using the following equations:

$$C_h = -\rho V_p \ , \ C_v = -\rho V_s A \quad (6)$$

$$V_p = \sqrt{(K/\rho)} \ , \ V_s = \sqrt{(G/\rho)} \quad (7)$$

$$G = \frac{E}{2(1+\mu)} \ , \quad K = \sqrt{\frac{E(1-\mu)}{\rho(1+\mu)(1-2\mu)}} \quad (8)$$

where C_h and C_v are the horizontal and vertical damping coefficients of the viscous dampers, V_p and V_s are the compressive and shear wave velocities in the soil media, respectively, A is the tributary area for the node attached to the damper, and ρ, K, G, and ν are mass density, bulk modulus, shear modulus, and Poison's ratio of the soil material.

The resulting finite element model created in SAP2000, showing the transmitting boundaries is shown in Figure 1. The soil medium is assumed to be isotropic and homogeneous and the damping of the structure and the soil is taken as 5% and 8%, respectively.

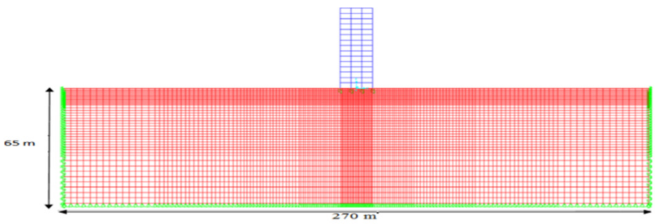

Fig. 1. The FEM model in SAP 2000.

The FEM model is subjected to time history analysis using the ground motion records of the El-Centro and Bhuj earthquakes. The ground motion is applied at the fixed base of the soil layer for five different types of soil and for different H/B ratios of the symmetric multi-story building. The soil-structure system used in the study has a soil layer of fixed depth and width with a concrete structure placed on the top. The foundation used is a reinforced concrete raft foundation that supports all the columns of the structure. The loads of the columns in the raft foundation are shown in Table III.

TABLE III. DESIGN LOADS

Load type	Load case	Load value
Slab own weight	Dead	5 kN/m^2
Services	Dead	2.5 kN/m^2
Live load	Live	2 kN/m^2
Flooring	Dead	1 kN/m^2

2) *MPMR Model*

The output results, such as TSD, DGL and RTSD, from the finite element analysis with SAP2000 are used as the input data to the minimax probability machine regression model. Along with the above obtained data, the soil properties and different height to width ratios were also used as input in the MPMR model. A total of 75 responses were obtained from SAP2000 and were further divided into training and testing data sets for the MPMR model, in a 70-30 ratio. Pre-processing of the response data set from finite element analysis was conducted before using it as input in MPMR. Normalization was carried out to pre-process the data using the following equation:

$$y_i = \frac{x_i - x_{min}}{x_{max} - x_{min}} \quad (9)$$

where x_i is any response quantity, x_{min} and x_{max} represent the minimum and maximum values, respectively, of the response quantities, and y_i is the corresponding normalized value. The MPMR model of the problem as stated above is shown in Figure 2.

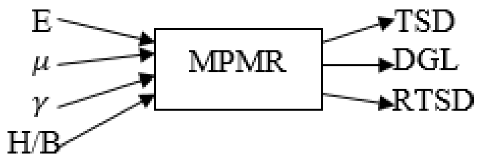

Fig. 2. Representation of the MPMR model.

V. RESULTS AND DISCUSSION

A. *FEM*

The results of the FEM analysis in SAP2000 were obtained for different types of soil and for different height to width (H/B) ratios (i.e. H/B = 6, 5, 4, 3, 2). The response quantities TSD, DGL, and RTSD were obtained for the data of the El-Centro and the Bhuj earthquakes and the obtained results are shown in Tables IV-VIII. The obtained results of the average value of TSD, DGL, and RTSD for different soil types are presented in Tables IX and X.

TABLE IV. RESULTS OF THE FEM MODEL FOR H/B = 6

Soil type	OUTPUT					
	El-Centro earthquake			Bhuj earthquake		
	TSD (cm)	DGL (cm)	RTSD (cm)	TSD (cm)	DGL (cm)	RTSD (cm)
Soft clay (saturated)	16.71	15.88	0.83	17.87	15.32	2.55
	16.75	15.94	0.81	17.72	15.36	2.36
	16.83	16.01	0.82	17.63	15.42	2.21
	16.64	15.81	0.83	17.30	15.20	2.10
	16.73	15.90	0.83	17.27	15.27	2.00
	16.53	15.68	0.85	17.02	15.03	1.99
	16.63	15.78	0.85	17.06	15.12	1.94
	16.73	15.88	0.85	17.06	15.20	1.86
	16.49	15.63	0.86	16.77	14.92	1.85
	16.59	15.72	0.87	16.79	14.99	1.80
	16.31	15.43	0.88	16.46	14.66	1.80
	16.40	15.52	0.88	16.52	14.74	1.78
	16.07	15.17	0.90	16.15	14.37	1.78
	16.16	15.26	0.90	16.20	14.44	1.76
	16.25	15.34	0.91	16.25	14.52	1.73

TABLE V. RESULTS OF THE FEM MODEL FOR H/B = 5

Soil type	OUTPUT			OUTPUT		
	El-Centro earthquake			El-Centro earthquake		
	TSD (cm)	DGL (cm)	RTSD (cm)	TSD (cm)	DGL (cm)	RTSD (cm)
Hard clay (saturated)	15.95	14.98	0.97	16.00	14.77	1.23
	16.02	15.00	1.02	16.04	14.81	1.23
	16.12	14.98	1.14	16.07	14.83	1.24
	15.92	14.66	1.26	15.79	14.51	1.28
	16.03	14.65	1.38	15.81	14.53	1.28
	15.80	14.29	1.51	15.49	14.18	1.31
	15.96	14.26	1.70	15.51	14.18	1.33
	16.12	14.23	1.89	15.52	14.18	1.34
	15.90	13.84	2.06	15.16	13.78	1.38
	16.00	13.84	2.16	15.18	13.79	1.39
	15.80	13.38	2.42	14.76	13.33	1.43
	15.98	13.33	2.65	14.73	13.30	1.43
	15.64	12.88	2.76	14.30	12.84	1.46
	15.72	12.87	2.85	14.29	12.85	1.44
	15.85	12.83	3.02	14.26	12.81	1.45

TABLE VI. RESULTS OF THE FEM MODEL FOR H/B = 4

Soil type	OUTPUT			OUTPUT		
	El-Centro earthquake			El-Centro earthquake		
	TSD (cm)	DGL (cm)	RTSD (cm)	TSD (cm)	DGL (cm)	RTSD (cm)
Sandy clay	17.25	14.41	2.84	15.17	14.86	0.31
	17.15	14.54	2.61	15.25	14.94	0.31
	16.99	14.56	2.43	15.22	14.96	0.26
	16.87	14.69	2.18	15.29	15.04	0.25
	16.86	14.73	2.13	15.32	15.10	0.22
	16.99	14.91	2.08	15.48	15.26	0.22
	17.05	14.95	2.10	15.53	15.33	0.20
	17.10	15.05	2.05	15.62	15.43	0.19
	17.09	15.02	2.07	15.60	15.43	0.17
	17.07	15.07	2.00	15.63	15.46	0.17
	17.05	15.03	2.02	15.59	15.45	0.14
	17.02	14.98	2.04	15.54	15.43	0.11
	17.05	14.98	2.07	15.55	15.46	0.09
	16.99	14.91	2.08	15.48	15.42	0.06
	16.93	14.83	2.10	15.39	15.36	0.03

TABLE VII. RESULTS OF THE FEM MODEL FOR H/B = 3

Soil type	OUTPUT			OUTPUT		
	El-Centro earthquake			El-Centro earthquake		
	TSD (cm)	DGL (cm)	RTSD (cm)	TSD (cm)	DGL (cm)	RTSD (cm)
Loose sand	17.15	14.52	2.63	15.66	15.16	0.50
	16.95	14.35	2.60	15.42	15.00	0.42
	16.79	14.28	2.51	15.31	14.90	0.41
	16.62	14.20	2.42	15.18	14.80	0.38
	16.43	14.11	2.32	15.05	14.68	0.37
	16.24	14.02	2.22	14.91	14.59	0.32
	15.94	13.76	2.18	14.59	14.35	0.24
	15.62	13.47	2.15	14.23	14.07	0.16
	15.38	13.33	2.05	14.05	13.91	0.14
	15.14	13.17	1.97	13.85	13.74	0.11
	14.88	13.00	1.88	13.64	13.56	0.08
	14.62	12.81	1.81	13.41	13.37	0.04
	14.33	12.61	1.72	13.18	13.15	0.03
	14.04	12.39	1.65	12.94	12.92	0.02
	13.50	11.87	1.63	12.42	12.36	0.06

TABLE VIII. RESULTS OF THE FEM MODEL FOR H/B = 2

Soil type	OUTPUT			OUTPUT		
	El-Centro earthquake			El-Centro earthquake		
	TSD (cm)	DGL (cm)	RTSD (cm)	TSD (cm)	DGL (cm)	RTSD (cm)
Dense sand	13.02	12.33	0.69	12.42	12.19	0.23
	12.76	12.10	0.66	12.15	11.96	0.19
	12.48	11.87	0.61	11.87	11.72	0.15
	12.30	11.72	0.58	11.69	11.56	0.13
	12.00	11.47	0.53	11.40	11.30	0.10
	11.70	11.20	0.50	11.09	11.02	0.07
	11.48	11.01	0.47	10.88	10.82	0.06
	11.12	10.68	0.44	10.52	10.48	0.04
	10.78	10.37	0.41	10.18	10.16	0.02
	10.48	10.09	0.39	9.89	9.87	0.02
	10.11	9.75	0.36	9.52	9.51	0.01
	9.77	9.43	0.34	9.19	9.17	0.02
	9.38	9.05	0.33	8.79	8.76	0.03
	8.99	8.68	0.31	8.42	8.38	0.04
	8.23	7.92	0.31	7.63	7.59	0.04

TABLE IX. AVERAGE TSD, DGL, AND RTSD VALUES FOR THE EL-CENTRO EARTHQUAKE

Displacement values	Soil type				
	Soft clay	Hard clay	Sandy clay	Loose sand	Dense sand
TSD (cm)	16.52	15.92	17.03	15.58	10.97
DGL (cm)	15.66	14.00	14.84	13.46	10.51
RTSD (cm)	0.86	1.92	2.19	2.12	0.46

TABLE X. AVERAGE TSD, DGL, AND RTSD VALUES FOR THE BHUJ EARTHQUAKE

Displacement values	Soil type				
	Soft clay	Hard clay	Soft clay	Loose sand	Soft clay
TSD (cm)	16.94	15.26	15.44	14.26	10.38
DGL (cm)	14.97	13.91	15.26	14.04	10.30
RTSD (cm)	1.97	1.35	0.18	0.22	0.08

B. MPMR Result

The results obtained from the finite element analysis were used as the input data set to the MPMR model. The obtained data were normalized before being utilized. The dataset was divided into 70 % training and 30 % testing sets. The program of MPMR was executed in MATLAB. The obtained results for the EI-Centro earthquake are shown in Figures 3-5. The obtained results from the MPMR for Bhuj earthquake are shown in Figures 6-8.

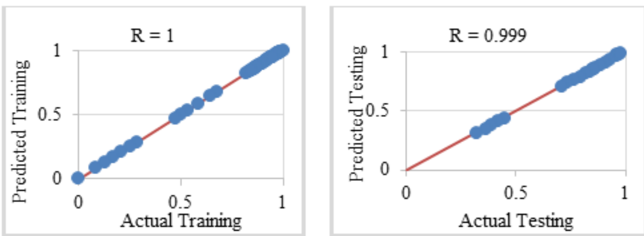

Fig. 3. TSD ρesults for EI-Centro earthquake (training and testing).

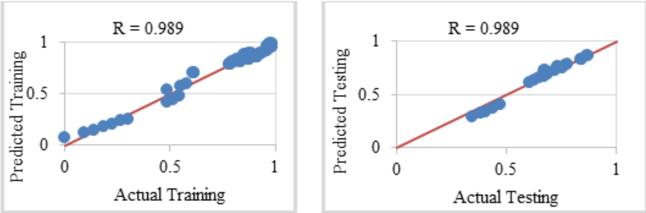

Fig. 4. DGL ρesults for EI-Centro earthquake (training and testing).

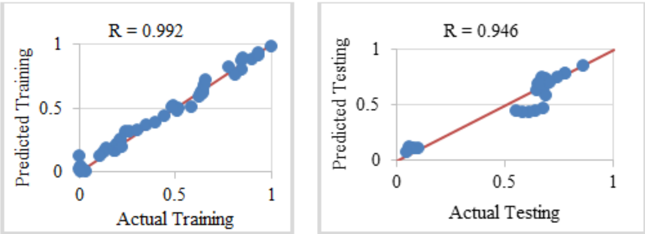

Fig. 5. RTSD ρesults for EI-Centro earthquake (training and testing).

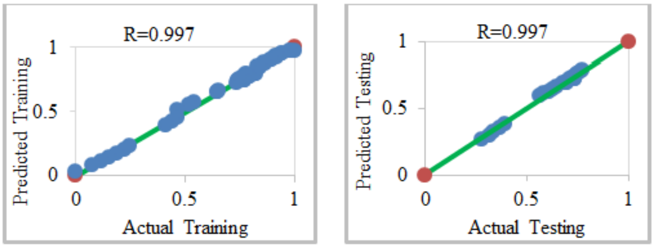

Fig. 6. TSD ρesults for Bhuj earthquake (training and testing).

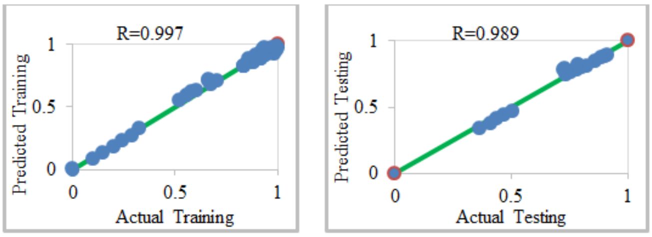

Fig. 7. DGL ρesults for Bhuj earthquake (training and testing).

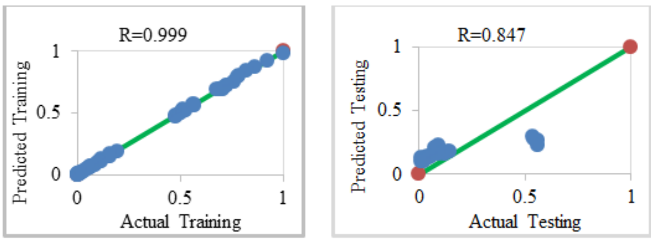

Fig. 8. RTSD ρesults for Bhuj earthquake (training and testing).

VI. SUMMARY AND CONCLUSION

In this study, the effects of the SSI on the dynamic response of a multi-story building having different H/B ratios were investigated. Five different kinds of soil were modelled with the structure and the structure response for each soil type was obtained. The ground motions of the El-Centro and the Bhuj earthquakes were applied to study the time history analysis of the structure. FEM and MPMR analysis methods were performed to study the SSI problem. A comparison of the performance of the above two model was conducted which shows a good correlation between the trained models and the of FEM model. The developed model based on the MPMR technique is very fast and performed well. It was noticed that the computational time for FEM analysis is enormous whereas the solution time is quite fast in the performance of the MPMR model. Thus, the MPMR model can be used as an alternative efficient tool for the SSI problems.

REFERENCES

[1] D. Lombardi, S. Bhattacharya, F. Scarpa, and M. Bianchi, "Dynamic response of a geotechnical rigid model container with absorbing boundaries," *Soil Dynamics and Earthquake Engineering*, vol. 69, pp. 46–56, Feb. 2015, https://doi.org/10.1016/j.soildyn.2014.09.008.

[2] S. S. Kar and L. B. Roy, "Probabilistic Based Reliability Slope Stability Analysis Using FOSM, FORM, and MCS," *Engineering, Technology & Applied Science Research*, vol. 12, no. 2, pp. 8236–8240, Apr. 2022, https://doi.org/10.48084/etasr.4689.

[3] S. Kumar and L. B. Roy, "Investigating the Slope Stability and Factor of Safety Properties of Soil Reinforced with Natural Jute Fibers under Different Rainfall Conditions," *Engineering, Technology & Applied Science Research*, vol. 13, no. 1, pp. 9919–9925, Feb. 2023, https://doi.org/10.48084/etasr.5481.

[4] I. C. Thakur and L. B. Roy, "Soil Liquefaction Potential in Different Seismic Zones of Bihar, India," *Engineering, Technology & Applied Science Research*, vol. 12, no. 6, pp. 9471–9476, Dec. 2022, https://doi.org/10.48084/etasr.5292.

[5] A. M. Halabian and M. H. EI Naggar, "Effect of non-linear soil–structure interaction on seismic response of tall slender structures," *Soil Dyanamics and Earthquake Engineering*, vol. 22, no. 8, pp. 639-658, Sep. 2002, https://doi.org/10.1016/S0267-7261(02)00061-1.

[6] D.-K. Kim and C.-B. Yun, "Time-domain soil–structure interaction analysis in two-dimensional medium based on analytical frequency-dependent infinite elements," *International Journal for Numerical Methods in Engineering*, vol. 47, no. 7, pp. 1241–1261, 2000, https://doi.org/10.1002/(SICI)1097-0207(20000310)47:7<1241::AID-NME807>3.0.CO;2-9.

[7] D. Clouteau and D. Aubry, "Modifications of the ground motion in dense urban areas," *Journal of Computational Acoustics*, vol. 9, no. 4, pp. 1659-1675, 2001, https://doi.org/10.1142/S0218396X01001509.

[8] P. Gueguen, P. Y. Bard, and F. J. Chavez-García, "Site city seismic interaction in mexico city–like environments: an analytical study," *Bulletin of the Seismological Society of America*, vol. 92, no. 2, pp. 794-811, Mar. 2002, https://doi.org/10.1785/0120000306.

[9] C. Tsogka and A. Wirgin, "Simulation of seismic response in an idealized city," *Soil Dyanamics and Earthquake Engineering*, vol. 23, no. 5, pp. 391-402, Jul. 2003, https://doi.org/10.1016/S0267-7261 (03)00017-4.

[10] J. P. Groby, C. Tsogka, and A. Wirgin, "Simulation of seismic response in a city-like environment," *Soil Dyanamics and Earthquake Engineering*, vol. 25, no. 7-10, pp. 487-504, Oct. 2005, https://doi.org/10.1016/j.soildyn.2004.11.007.

[11] C. Boutin and P. Roussillon, "Assessment of the urbanization effect on seismic response," *Bulletin of the Seismological Society of America*, vol. 94, no. 1, pp. 251-268, Feb. 2004, https://doi.org/10.1785/0120030050.

[12] P. Raychowdhury, "Seismic response of low-rise steel moment-resisting frame (SMRF) buildings incorporating nonlinear soil–structure interaction (SSI)," *Engineering Structures*, vol. 33, no. 3, pp. 958-967, Mar. 2011, https://doi.org/10.1016/j.engstruct.2010.12.017.

[13] H. R. Tabatabaiefar and T. Clifton, "Significance of considering soil-structure interaction effects on seismic design of unbraced building frames resting on soft soils," *Australian Geomechanics Journal*, vol. 51, no. 1, pp. 55–64, Jan. 2016.

[14] Y. Lu, I. Hajirasouliha, and A. M. Marshall, "Performance-based seismic design of flexible-base multi-storey buildings considering soil–structure interaction," *Engineering Structures*, vol. 108, pp. 90–103, Feb. 2016, https://doi.org/10.1016/j.engstruct.2015.11.031.

[15] S. L. Kramer, *Geotechnical Earthquake Engineering*, 1st ed. Upper Saddle River, N.J, USA: Pearson, 1996.

[16] H. R. Tabatabaiefar and A. Massumi, "A simplified method to determine seismic responses of reinforced concrete moment resisting building frames under influence of soil–structure interaction," *Soil Dyanamics and Earthquake Engineering*, vol. 30, no. 11, pp. 1259-1267, Nov. 2010, https://doi.org/10.1016/j.soildyn.2010.05.008.

[17] S. C. Dutta and A. Roy, "A critical review on idealization and modeling for interaction among soil–foundation–structure system," *Computers and Structures*, vol. 80, no. 20-21, pp. 1579-1594, Aug. 2002, https://doi.org/10.1016/s0045-7949(02)00115-3.

[18] M. Kumar, M. Mittal, and P. Samui, "Performance assessment of genetic programming (GP) and minimax probability machine regression (MPMR) for prediction of seismic ultrasonic attenuation," *Earthquake Science*, vol. 26, no. 2, pp. 147–150, Apr. 2013, https://doi.org/10.1007/s11589-013-0018-z.

[19] T. Strohmann and G. Z. Grudic, "A Formulation for Minimax Probability Machine Regression," *Advances in Neural Information Processing Systems*, vol. 15, pp. 769-776, 2002.

[20] H. Mori and S. Urano, "Short-term load forecasting with chaos time series analysis," in *Proceedings of International Conference on Inteligent System Application to Power System*, Orlando, FL, USA, 1996, pp. 133–137, https://doi.org/10.1109/ISAP.1996.501057.

[21] Y. Kong, X. W. Liu, and S. Zhang, "Minimax probability machine regression for wireless traffic short term forecasting," in *2009 First UK-India International worshop on cognitive wireless Systems*, New Delhi, India, 2009, pp. 1–5, https://doi.org/10.1109/ukiwcws.2009.5749407.

[22] X. Mu, N. Tang, W. Gao, L. Li, and Y. Zhou, "A one-step network traffic prediction," in *4th International Conference on Intelligent Computing*, Shanghai, China, 2008, pp. 616–621, https://doi.org/10.1007/978-3-540-85984-0_74.

[23] J. Sun, "Modelling of chaotic time series using minimax probability machine regression," in *2009 WRI International Conference on Communications and Mobile Computing*, Kunming, China, 2009, pp. 321–324, https://doi.org/10.1109/cmc.2009.35.

[24] G. H. Cheng and Z. X. Liu, "Chaotic load series forecasting based on MPMR," in *2006 International Conference on Machine Learning and Cybernetics*, Dalian, China, 2006, pp. 2868–2871, https://doi.org/10.1109/icmlc.2006.259071.

[25] I. Chowdhury and S. P. Dasgupta, *Dynamics of Structure and Foundation - A Unified Approach: 1. Fundamentals*. Upper Saddle River, NJ, USA: Routledge, 2009.

[26] E. Kausel, "Early history of soil–structure interaction," *Soil Dynamics and Earthquake Engineering*, vol. 30, no. 9, pp. 822–832, Sep. 2010, https://doi.org/10.1016/j.soildyn.2009.11.001.