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Seismic response of elevated rectangular water tanks considering soil structure interaction

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Abstract. The overhead staged water tanks are susceptible for high lateral forces during earthquakes. Due to which, the failure of beam-columns joints, framing elements and toppling of tanks arise. To avoid such failures, they are analyzed and designed for lateral forced induced by devastating earthquakes assuming the base of the structures are fixed and considering functional needs, response reduction, soil types and severity of ground shaking. In this paper, the flexible base was provided as spring stiffness in order to consider the effect of soil properties on the seismic behaviour of water tanks. A linear time history earthquake analysis was performed using SAP2000. Parametric studies have been carried out based on various types of soils such as soft, medium and hard. The soil stiffness values highly influence the time period and base shear of the structure. The ratios of time period of flexible to fixed base and base shear of flexible to fixed base were observed against capacities of water tank and the overall height of the system. The both responses are found to be increased as the flexibility of soil medium decreases

1. Introduction

Generally, liquid storage tanks are used to store water, oil, petrol, diesel, etc. Elevated water tanks are also a type of tank that provide to supply water in many cities. It also plays a major role in the municipality as well as for extinguishing fires. This kind of structure is very essential so that to remain operational after a destructive seismic event. While investigating the damage survey conducted following few severe Indian earthquakes such as Jabalpur earthquake 1997, Bhuj earthquake 2001, etc., the various failures of which are shown in Figure.1 [1]. The performance of the elevated tanks during California earthquake was also studied well by Knoy [2]. To control the major devastating effects of elevated staged water tanks, many researchers carried out their study. It was seen by Sudhir and Sameer [3] that due to absence of suitable performance factor for tanks, the code provides low design seismic forces for these structures. Chen and Kianoush [4] proposed a procedure for computing hydrodynamic pressures considering the effect of flexibility of tank walls. Kianoush and Ghemmaghami [5], Soroushnia et al. [6], Moslemi et al. [7], Chaduvula et al. [8], Livaoglu Dogangun [9] and Dogangun et al. [10] studied the seismic performance of liquid storage elevated tanks while the dynamic performance was studied by Kianoush et al. [11]. The behaviour of rectangular tank was studied by various researchers considering vertical [12, 13] and horizontal vibration [15], Lagrangian fluid finite method [10], wall flexibility [13] and frequency content [14]. For analysis and design of the water tank, they are considered to be fixed ignoring soil medium beneath it. In some places, structures found to be failed due to absence of soil interaction properties. In the beginning, Veletsos and Tank [16] considered soil structure interaction (SSI) effects on circular cylindrical liquid storage

tanks which are excited laterally by horizontal component of ground shaking. The seismic performance of x-braced elevated water tanks supported on isolated footings was analyzed to investigate the dynamic interaction between the tower and the supporting soil medium that the effects reduces member end actions except near base of the tower [17]. A similar study was carried out by researchers such as using wavelet based random vibration theory [18], alternate frame staging configurations [19], fluid structure interaction (FSI) [8, 20], frequency domain [21], torsional vulnerability [22] and earthquake frequency [23]. The fluid structure interaction in addition to SSI was exclusively studied by Livaoglu [24,25,26] and Chaduvula et al. [8]. The torsional response of elevated water tanks subjected to lateral forces was studied by Dutta et al. [27, 28]. Thus to overcome these problems in the tanks and also to prevent structural failure from earthquakes, it is essential to perform dynamic analysis. Hence, the acceleration time history values are collected and scaled down to match the design spectrum given in IS1893:2002 [29] in order to find out the behaviour of liquid storage structures during earthquake. The effect of SSI considering all types of soil medium on seismic performance of rectangular staged water tank is limited. Despite various frame configurations are considered by authors [19, 22], simple beam column frame resting on various soil mediums are presented.

(a) Collapsed circular shaft   (b) Collapsed weak frame staging
Figure 1. Failures of staged water tanks during Bhuj earthquake. (Rai [1])

In this present study, three various capacities of RC framed staging rectangular over-head water tanks supported on three different soil conditions such as soft, medium and hard are studied by linear time history analysis using SAP2000 [30].

2. Analysis and design of fixed base water tank

To study the seismic behaviour of over-head water tanks, three types of tanks with various capacities are considered. The depth of water tank in all the models is assumed as 3 m. The length and breadth of the tanks are arrived from capacity and the details of which are given in Table 1. The water load is assumed as hydrostatic pressure acting on side walls and base slab. The sloshing effect of water and lumped mass approach such as impulsive and convective mass are ignored in the analysis. The walls of water tanks in all the models are assumed to be fixed in sides and bottom, and free at top. The thickness of wall, vertical and horizontal reinforcements were calculated as per IS: 3370-2009 [31,32,33,34]. The elevated staged tanks with fixed base are modelled using SAP2000 [30], which are shown in Figure 2. Dutta et al. [22] studied the performance of elevated circular water tanks considering shaft and framed staging. In this study, framed staging is provided to support the water tanks. The ratio of height (H) of the system to length of water tank (L) is kept constant as 3 for all the models. The grade of concrete and steel are assumed as M25 and Fe415 respectively. The frames are designed according to IS: 456-2000 [35].

Table 1. Model description

Model ID	Length (m)	Breadth (m)	Depth (m)	Quantity (m^3)
M1	3.0	3.0	3.0	27.0

M2	6.0	6.0	3.0	108.0
M3	9.0	9.0	3.0	243.0

(a) Model 1	(b) Model 2	(c) Model 3
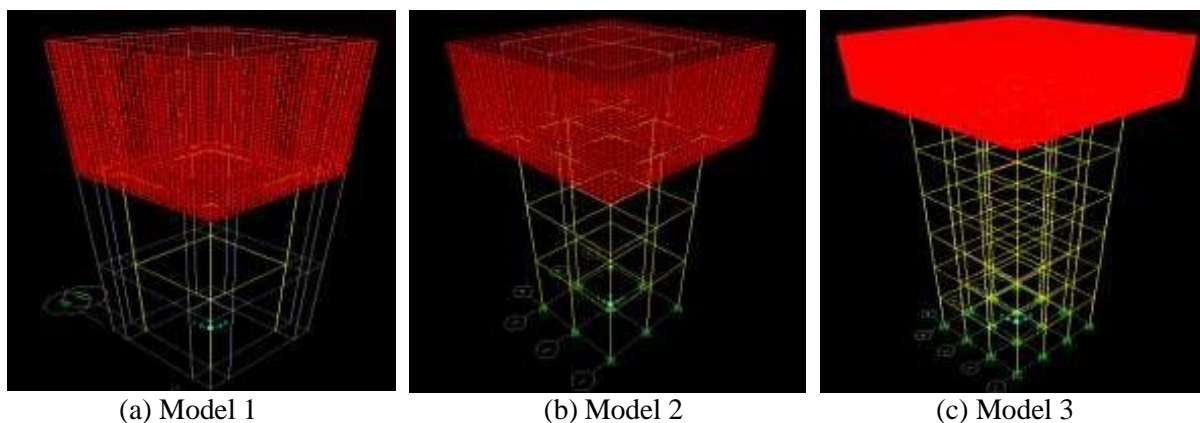
Figure 2. Fixed base overhead water tanks with framed staging

The axial forces of ground storey columns of all models were observed and the footings were designed according to Indian Standards. The safe bearing capacity of soft, medium and hard clay soils are assumed as 100 kN/m^2, 250 kN/m^2 and 450 kN/m^2 respectively. The dimensions of footings for *M1*, *M2* and *M3* for all types of soil conditions are given in Table 2.

Table 2. Dimensional Properties of Footings

| Soil Type	Model ID	Elastic Modulus (kN/m^2)	Poisson's Ratio	Safe Bearing Capacity (kN/m^2)	Length (m)	Breadth (m)
Soft	M1	15000	0.45	100	1.0	1.0
	M2				1.2	1.2
	M3				1.4	1.4
Medium	M1	35000	0.45	250	0.6	0.6
	M2				0.8	0.8
	M3				0.9	0.9
Hard	M1	75000	0.45	450	0.5	0.5
	M2				0.6	0.6
	M3				0.7	0.7

3. Seismic analysis of water tanks

The current designs of supporting structures of elevated water tanks are tremendously vulnerable under lateral forces due to an earthquake and the Bhuj (India) earthquake provided another illustration when a great number of water tanks with frame staging suffered damage and a few collapsed [6]. In this chapter the procedures to select and scale the ground motion, analysis of fixed and flexible base water tanks are carried out.

3.1. Selection and scaling of ground motion

For linear dynamic analysis of staged water tanks, real ground motions are used. The real accelerograms are to be scaled in order to match the crustal properties of location at which the buildings are to be built and analyzed. An application, SEISMOMATCH [36], which is capable of adjusting real earthquake ground motions to match a specific target response spectrum, is used for scaling the ground motions in this study. The four earthquake record such as Northridge, Chi Chi,

Imperial Valley and Loma Prieta are chosen from the library of SEISMOMATCH for the analysis. The Indian standard [29] design spectrum is used as a target spectrum for which the selected ground motions are matched. The scaled response spectrum and time history records of selected ground motions are shown in Figures 3 and 4.

(a) Northridge

(b) Chi Chi

(c) Imperial Valley

(d) Loma Prieta
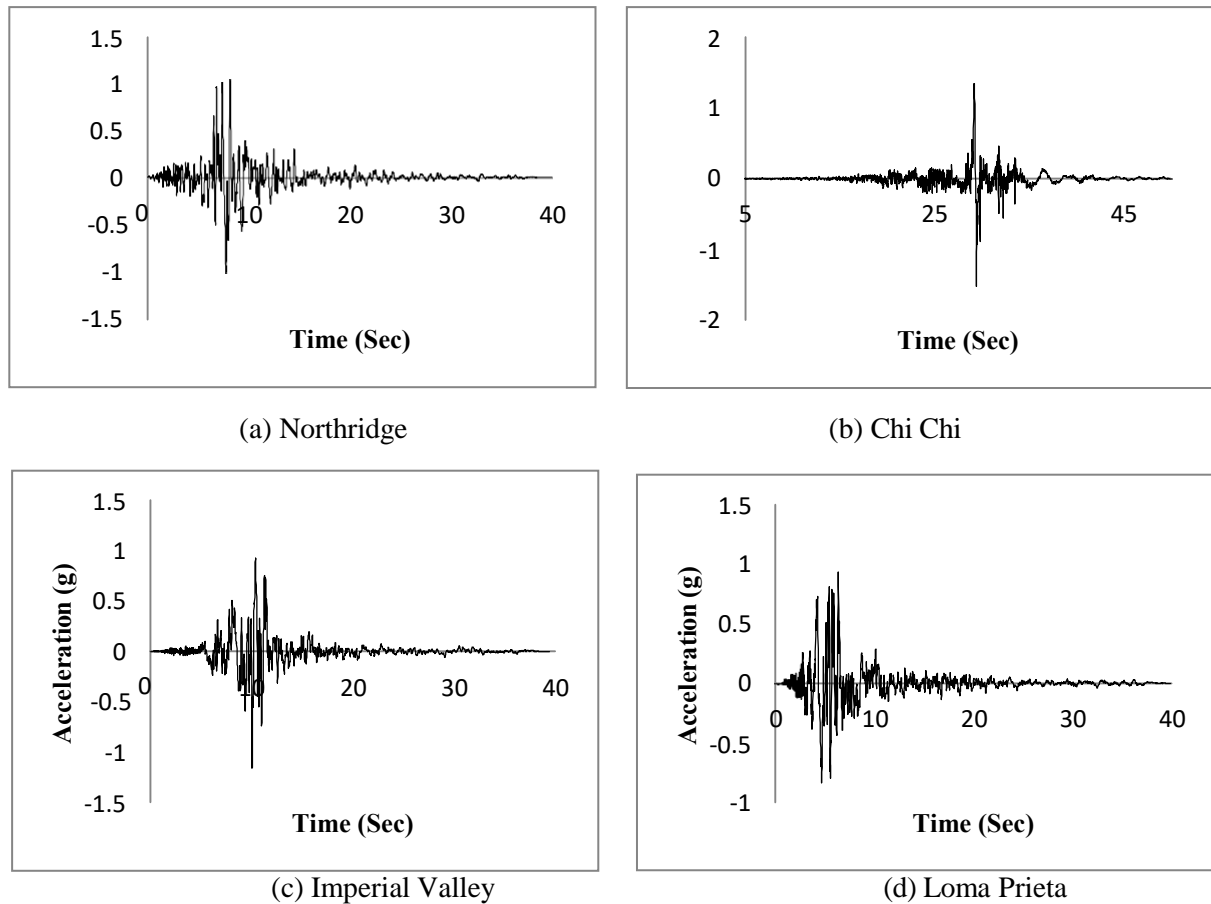
Figure 3. (a), (b), (c) and (d) Scaled ground motions
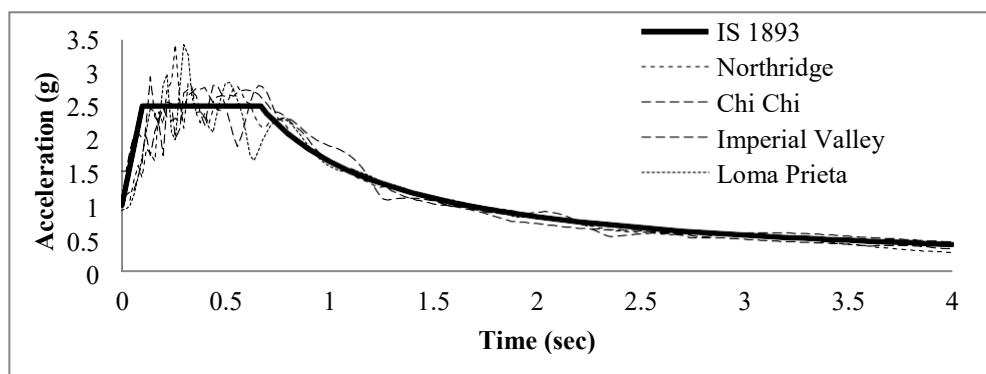
Figure 4. Scaled response spectrum

3.2. Behaviour of fixed base water tanks
Moslemi et al. [7], performed finite element seismic analysis of elevated conical shaped liquid storage tanks. The sloshing and impulsive forces of water are not considered in this analysis. The structural

analysis program SAP2000 is used for seismic analysis of fixed base overhead staged water tanks. The Ritz method of modal analysis was performed to observe the natural fundamental time periods of all the models. The scaled ground motions are used for the linear modal time history analysis to investigate the behaviour of water tanks.

Table 3. Base shear and Natural Time Period Values of Fixed Base Water Tanks

Location	M1	M2	M3
Time Period (Sec)	0.28	0.68	0.84
Northridge (kN)	276.71	898.88	1599.93
Chi-Chi (kN)	224.18	973.17	1851.13
Imperial Valley (kN)	197.35	776.05	1708.23
Loma Preita (kN)	243.50	820.83	1318.44

The non-linearity of the framing elements and water tanks are ignored in this study. The motion is applied only in x-direction as the structure is symmetric in both directions. The base shear values from seismic analysis performed using various ground motions are noted and presented. It is seen from the Table 3 that all the values of time periods increasing as the height of the system increases. Similarly, the base shear values of all the models increase as the seismic weight of the structures increase. It is clear from the results that the frequency content of ground motions also has certain effect on the base shear values as they are varying with respect to varying ground motions. The same kind of results is reported in Kianoush and Ghemmaghami [5] that the behaviour of the fluid-tank-soil system is highly sensitive to frequency characteristics of the earthquake records.

3.3. Behaviour of flexible base water tanks

The importance of soil structure interaction in various types of structures during seismic excitation is clearly explained by researchers [16-23]. Dutta et al. [22] investigated the effect of soil structure interaction on dynamic behaviour of elevated water tanks and presented the design recommendations. The analysis of structures considering soil-structure interaction (SSI) shall be performed either by direct or indirect approach. In the former, the entire structure, foundation and soil systems are modelled as a single unit and analysis is carried out, but in the latter case, impedance functions of the foundation systems [37] are found considering soil and foundation characteristics. The soil stiffness properties are calculated using the formulae suggested by Gazetas [37]. The stiffness in horizontal and vertical direction as translation in x, y and z directions and rocking about lateral and longitudinal and torsion as rotation about x, y and z directions are calculated as per Table 4. The calculated values are modelled as springs at the columns base using SAP2000.

4. Effect of soil flexibility

4.1. Time Period of structures

The Indian standard [29] provides empirical formula to find fundamental natural time period of the structures. The code is silent for time period of the liquid storage tanks. The effect of soil-structure interaction also not clearly defined. From Figure 5, it is clear that the ratio of time period of flexible base (T_f) to fixed base (T) varies with respect to various soil types. In all types of soils, the T_f/T ratio is almost linear and equal, which is not depending on tank capacity. Out of all the soil types, the ratio is high in case of soft soil. The values are almost 20% and 10 % high in comparison to hard and medium soil types respectively. The hard soil behaves similar to fixed base condition where the ratio confined to unity. Hence, the consideration of SSI is essential for seismic analysis of elevated water tanks particularly they are founded on soft soils.

Table 4. Spring Stiffness as per Gazetas [37]

| Degree of Freedom	Stiffness of equivalent soil
Vertical	$\left[2GL/(1-v)(0.73+1.5\chi^{0.75}) \right]$
Horizontal (lateral direction)	$[2GL/(2-V)](2+2.5\chi^{0.85})$
Horizontal (longitudinal direction)	$[2GL/(2-V)](2+2.5\chi^{0.85})-[0.2/(0.75-v]GL[1.(B/L)$
Rocking (about longitudinal)	$[G/(1-V)I_{bY}^{0.75}(L/B)[2.4+0.5(B/L)]$
Rocking (about lateral)	$[3G/(1-V)]I_{bY}^{0.75}(L/B)^{0.15}$
Torsion	$3.5GI_{bZ}^{0.75}(B/L)^{0.4}(I/B^4)^{0.2}$

Table 5. Base shear and Natural Time Period values of Flexible Base Models

| Location	Model-1			Model-2			Model-3		
	Soft	Medium	Hard	Soft	Medium	Hard	Soft	Medium	Hard
Time Period Tf (Sec)		0.34			0.82			1.03	
Northridge (kN)	215.84	229.67	246.27	719.10	755.06	826.97	1295.94	1375.94	1495.94
Chi-Chi (kN)	156.93	168.14	186.07	768.80	807.73	895.32	1684.53	1740.06	1814.11
Imperial Valley (kN)	153.93	161.83	177.62	682.92	713.97	752.77	1605.74	1639.91	1656.98
Loma-Prieta (kN)	211.85	219.15	228.89	722.33	746.96	779.79	1199.78	1219.56	1278.89

4.2. Base shear
The base shear is the resistance offered by the structures against lateral forces. For analysis and design of structures, the base shear values shall be distributed parabolically along the height of the structures. The higher the external storey shears forces, the higher should be base resistance. In other words, the base shear is higher; the design external forces also shall be higher. The various elevated tank models are subjected to four scaled ground motions. The ratio of base shear for flexible base models (V_f) to fixed base models (V) is presented based on capacity of tanks in Figure 6. It is seen from the Fig.6 that V_f/V ratio is nearly equal to unity in case of hard soil for all ground motions. Similarly, the medium soil predicts lesser base shear values in comparison with hard soil followed by soft soil. The ratio values are nearly 20 % and 10% less for soft and medium soils respectively compared to hard soil
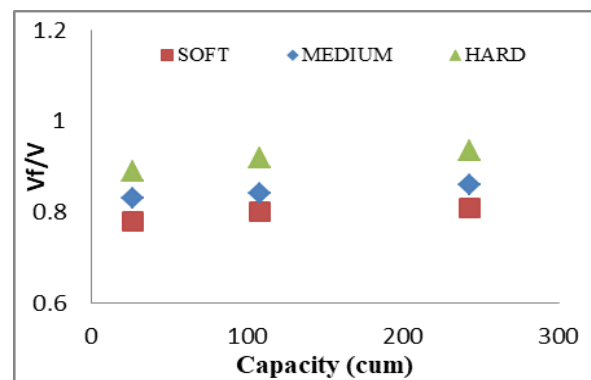
condition. It is because of the time period values of both soft and medium soil conditions are less and hence design the acceleration values.
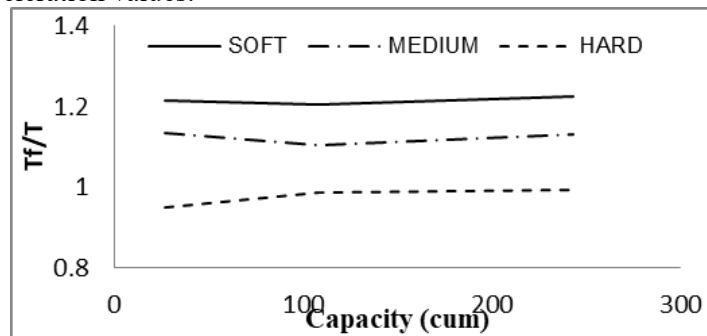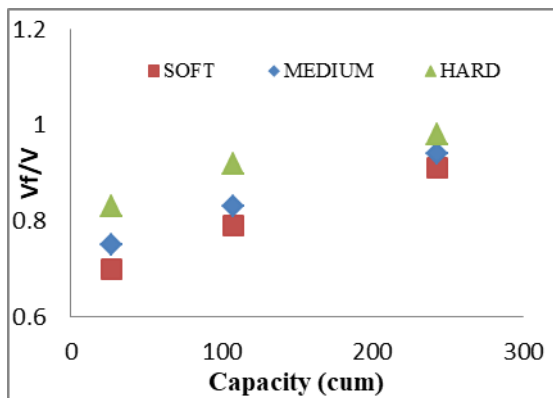

Figure 5. Effect of soil stiffness on time period
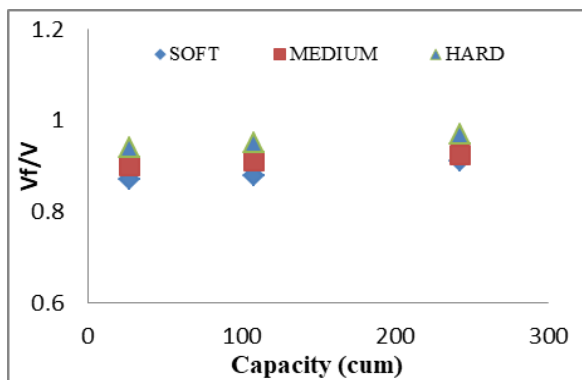
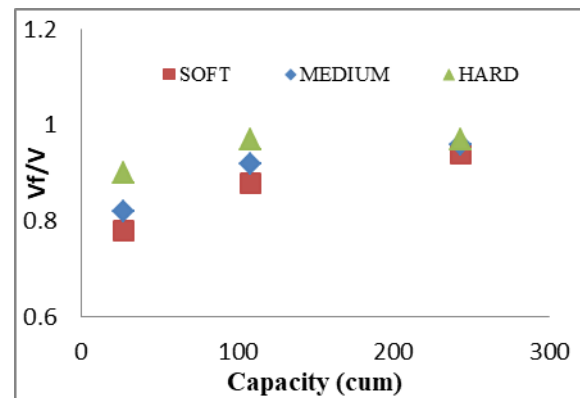
(a) Loma Prieta   (b) Northridge

(c) Chi Chi   (d) Imperial Valley

Figure 6. Effect of soil stiffness on base shear

Thus, the models analysed and designed considering fixed base condition overestimate the design values. Although, it is important to consider SSI during analysis and design of elevated rectangular water tanks especially in soft soils, the rocking of foundations also necessarily is noted.

5. Conclusion

The following main points are observed from the study carried out on seismic performance of elevated reinforced concrete rectangular water tanks considering soil structure interaction.

- The ratio of fundamental time period of flexible base (T_f) to fixed base (T) behaves linearly in case of all types of soils such as soft, medium and hard. There is no much variation with respect to capacity of water tanks.
- The soil structure interaction affects the T_f/T ratio by 20% and 10% for soft and medium type soils respectively.
- The soft and medium soils predict less base resistance. The ratio of base shear of flexible base (V_f) to fixed base models (V) is less in comparison to hard soil.
- The hard soil behaves similar to fixed base condition where the T_f/T and V_f/V ratios confined to unity.
- The models analysed and designed considering fixed base condition overestimate the design values.

References

[1]   D. C. Rai, *Proc. Indian Acad.Sci. (Earth Planet. Sci.)*, Sept. 2003. **112, No. 3**, pp. 421-429.
[2]   E. C. Knoy, 1995. *AWWA Annual Conference & Exhibition*.
[3]   J. K. Sudhir, and U. S. Sameer, December, 1990. *Ninth Symposium on Earthquake Engineering*, **vol. 1**, pp. 113-120,
[4]   J. Z. Chen, and M. R. Kianoush, 2005. *Can. J.   Civ. Eng.,* **vol. 32**, pp. 739–752,
[5]   M. R. Kianoush, and A. R. Ghaemmaghami, 2011. *Engineering   Structures* **33**, pp. 2186-2200.
[6]   S. Soroushnia, S. T. Tafreshi, F. Omidinasab, 2011. N. Beheshtian, and S.Soroushnia, *Procedia Engineering* **14**, pp. 3076-3087.
[7]   M. Moslemi, M. R. Kianoush, and W. Pogorzelski, 2011. *Engineering   Structures* **33**, pp. 2074-2084.
[8]   U. Chaduvula, D. Patel, and N. Gopalakrishnan, 2013. *Procedia Engineering* **51**, pp. 84-91.
[9]   R. Livaoglu, and A. Dogangun, April 2007. *Indian Journal of Engineering & Materials Sciences*, **vol. 14**, pp. 133-145.
[10]   A. Dogangun, A. Durmu, and Y. Ayvaz, *Computers & Structures*, 1996. **vol. 59**, No. 3, pp. 547-552.
[11]   M. R. Kianoush, H. Mirzabozorg, and M. Ghaemian, 2006. *Can. J. Civ. Eng.*, **vol. 33**, pp. 501-507.
[12]   M. R. Kianoush, and J. Z. Chen, 2006. *Engineering Structures* **28**, pp. 704–715.
[13]   A. R. Ghaemmaghami, and M. R. Kianoush, April 2010. *Journal of Structural Engineering*, **136(4)**, pp. 441- 451,
[14]   M. R. Kianoush, and A. R. Ghaemmaghami, 2011.*Engineering Structures* **33**, pp. 2186-2200.
[15]   S. Hashemi, M. M. Saadatpour, and M. R. Kianoush, 2013.*International Association for Earthquake Engineering & Structural Dynamics*, **DOI: 10.1002/eqe.2291**.
[16]   A. S. Veletsos, and Y. Tang, *Earthquake Engineering and Structural Dynamics*, , 1990. **vol. 19**, pp. 473-496.
[17]   M. A. Haroun, and M. K. Temraz, 1992.*Soil Dynamics and Earthquake Engineering* **11**, pp. 73-86.
[18]   P. Chatterjee, and B. Basu, 2001. *Earthquake engineering and structural dynamics* **30**, pp. 1419-1437.
[19]   S. Dutta, A. Mandal, and S. C. Dutta, 2004. *Journal of Sound and Vibration* **277**, pp. 825-853.
[20]   R. Livaoglu, and A. Dogangun, 2006. *Journal of fluids and structures* **22**, pp. 421-439.
[21]   R. Livaoglu, 2008. *Soil dynamics and earthquake engineering* **28**, pp. 132-146.
[22]   S. C. Dutta, S. Dutta, and R. Roy, 2009. *Engineering Structures* **31**, pp. 2617-2629.
[23]   M. R. Kianoush, and A. R. Ghaemmaghami, 2011. *Engineering Structures* **33**, pp. 2186-2200.
[24]   R. Livaoglu, and A. Dogangun, 2006. *Journal of fluids and structures* **22**, pp. 421-439.
[25]   R. Livaoglu, and A. Dogangun, 2007. *Soil dynamics and earthquake engineering* **27**, pp. 855-863.

[26]   R. Livaoglu, 2008. Soil *dynamics and earthquake engineering* **28**, pp. 132-146

[27]   S. C. Dutta, S. K. Jain, and C. V. R. Murty, 2000. *Soil Dynamics and Earthquake Engineering* **19**, pp. 183-197.

[28]   S. C. Dutta, S. K. Jain, and C. V. R. Murty, 2001. *Journal of Sound and vibration* 242 (1), pp. 151-167.

[29]   IS 1893(Part-1):2002. Criteria for Earthquake Resistant Design of Structures. Bureau of Indian Standards, New Delhi, India.

[30]   SAP2000. Structural and Earthquake Engineering Software, Computers and Structures. Inc.

[31]   IS 3370 (Part 1): 2009. Concrete Structures for storage of liquids – code of practice. General requirements. Bureau of Indian Standards, New Delhi, India.

[32]   IS 3370 (Part II): 2009. Concrete Structures for storage of   liquids   –   code   of   practice. Reinforced Concrete Structures. Bureau of Indian Standards, New Delhi, India.

[33]   IS 3370 (Part IV): 1967. Code of practice for concrete structures for the storage of liquids. Design Tables. Bureau of Indian Standards, New Delhi, India.

[34]   IS 3370 (Part II): 2009. Concrete Structures for storage of   liquids   –   code   of   practice. Prestressed Concrete Structures. Bureau of Indian Standards, New Delhi, India.

[35]   IS 456: 2000. Plain and Reinforced Concrete – Code of Practice. Bureau of Indian Standards, New Delhi, India.

[36]   SEISMOMATCH 2016. Earthquake Engineering Software Solutions. Italy.

[37]   G. Gazetas. 1990. *Journal of Geotechnical Engineering*, **119(9).**