Al-Azhar University Civil Engineering Research Magazine (CERM)
Vol. (45) No. (1) January 2023

SOIL STRUCTURE INTERACTION EFFECTS ON SEISMIC RESPONSE OF ELEVATED REINFORCED CONCRETE WATER TANKS

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الملخص العربى:

عند دراسه العديد من الحركات الزلزالية السابقة وجد ان السلوك الزلزالي للمنشات الخرسانية يتأثر بشدة ليس فقط بالستجابة الزالزالية للمنشأ ولكن أيضا بالستجابة الزالزلية للتربة أسفل الأساسات. وقد تلاحظ عند دراسه العديد من الابحاث التي اخذت في الاعتبار تأثير التربه الموجودة اسفل الخزانات المياة الخرسانية المسلحة العالية ان رد فعل هذه المنشآت للأحمال الديناميكية عند اعتبار مرونة الاساسات يتناسب عكسيا مع مساحة المسقط الأفقي للمبنى ونوعية التربة أسفل الاساسات. وقد مرت طرق التحليل الإنشائي بمراحل مختلفة وصولا الى ما تم الاستقرار عليه في الاكواد العالمية والتي قسمت طرق التحليل الى طريقتين رئيسيتين. الطريقة الاولى والتي تسمى طريقة التربة التحتية والطريقة الاخرى تعتمد على بناء نموذج للعناصر المحددة لكلا من المبنى والتربة كمحيط متصل لانهائي اخذا في الاعتبار الخصائص الميكانيكية والطبيعية للتربة على النحو المحدد بالمواصفات الفيدرالية الامريكية (FEMA P 2091-2020) . يمكن تلخيص الأهداف الأساسية لهذه الدراسة البحثية على النحو التالي ؛ دراسة آثار تفاعل تربة التأسيس مع المنشأ على الأداء الزلزالي لخزانات المياة الخرسانية المسلحة العالية ، وكذلك دراسة تأثير أنواع التربة المختلفة على تصميم العناصر الإنشائية المقاومة لأحمال الزالزل وتأثيرها ايضا علي القيم الخاصة لمعامل تقليل ردود الأفعال لخزانات المياة الخرسانية العالية التي تم تحليلها مع أخذ التفاعل بين للتربة والمنشأ فى الأعتبار ، و بناء على تحليل نتائج الدراسة يتم اقتراح قيم منطقية لمعامل تقليل ردود الأفعال لخزانات المياة الخرسانية العالية ومقارانتها بالقيم الموجودة في الكود المصري للأحمال.

الكلمات الدالة : تداخل تربة التاسيس ، طيف التجاوب ، قوي القص ، معامل تقليل االستجابة الزالزالية ، معامل تفاعل الطبقة السفلية.

ABSTRACT

An examination of prior earthquakes demonstrates that the seismic behaviour of concrete structures is strongly influenced by the seismic response of the structure and the seismic response of the soil under the foundations. Several studies on the effect of soil structure interaction for elevated water tanks have been carried out, and their findings suggest that the effect of (SSI) is inversely related to the footprint of the foundations, as well as depending on soil stratification, characteristics, and foundation type. The modelling of soil structure interaction (SSI) passes through several stages along the history of research. The up-to-date models consist of two types according to (FEMA P 2091-2020), the substructure approach, and the direct analysis approach. The fundamental objectives of this research study can be summarized as follows: Investigating the effects of soil structure interaction on the seismic performance of reinforced concrete elevated water tanks, Investigating the effect of different soil types on the seismic design of the structural elements and its effect on the values of response reduction factor for the analysed reinforced concrete elevated water tanks, Based on the study results, suggesting adequately reasonable values of the response reduction factor for the analysed elevated tanks when taking soil structural interaction into account and compare it to the values mentioned in the Egyptian Design Code.

KEYWORDS: soil structural interaction, Pushover analysis, Base shear, Response modification factor, Seismic Zones, Spectrum type.

INTRODUCTION

Elevated water tanks are essential in water distribution systems for both regular and emergency uses, such as pressure balancing for water supply networks and pumps. Emergency uses include extinguishing fires. Due to their crucial purpose, storage tanks must be completely functional during natural disasters like earthquakes.

Due to their nature and structural systems, elevated water tanks are less resilient, ductile, and capable of dissipating the dynamic energy delivered by earthquakes than regular buildings. Additionally, the liquids inside the tanks exert hydrostatic forces and momentum on the supporting structure's skeleton and wall surfaces. Due to their limited ductility and redundancy, elevated water tanks' lateral design seismic loads consistently appear to be higher than those of conventional structures with the same dynamic characteristics.

Throughout the past years, it has been found in many literatures that not only the response of the superstructure but also the response of the soil beneath the foundation, has a significant impact on the seismic behaviour of a structure, which has led to the wide adoption of displacement-based techniques, that include nonlinear calculations such as static pushover analysis, allows for the investigation of SSI beyond the elastic limits (FEMA-440 2005) [1], (ASCE 2013) [2]. Using nonlinear analysis techniques made it easier to provide accurate predictions of displacement capacities and seismic drift requirements.

In the United States, academic research taking the SSI into account grew towards the end of the 2000s, and some of them were summarised in the FEMA-440 study [1]. Regulations and expressions are used in this paper to show how SSI may be taken into account in nonlinear static analysis. The findings of these studies were also included in US code specifications (ASCE 2013) [2].

(Somnath Dutta, Aparna Mandal, Sekhar Chandra Dutta 2003) [3] investigated the effect of SSI on two dynamic characteristics: the impulsive lateral period, and the impulsive torsional-to-lateral period ratio and validated the results of analytical formulations used to calculate the two previous characteristics against the FE Model, the findings of the research is that the SSI increases the impulsive lateral period while decreasing the impulsive torsional-to-lateral period ratio and the effect is stronger for elevated tanks supported by alternate frame staging configurations with small- height panels, a larger number of columns, a large column diameter,

and stiffer circumferential beams compared to the columns than in the usual staging configuration. **(Sekhar Chandra Dutta, Somnath Dutta, Rana Roy 2009) [4]** examined the effect of SSI for shaft staging elevated tanks on two characteristics the impulsive lateral period and the impulsive torsional-to-lateral period ratio and it was found that SSI may considerably change the impulsive lateral period and the impulsive torsional-to-lateral period ratio of elevated tanks. Incorporation of this effect increases the first parameter and decreases the second one.

(J Visuvasam, J Simon, J S Packiaraj, R Agarwal, L Goyal, and V Dhingra (2017) [5] Studies

How can taking into consideration SSI affects the base shear force and natural time period for various combinations of tank volumes and type of soils, it was observed from the study that the soil-structure interaction affects the Tf/T ratio by 20% and 10% for soft and medium type soils respectively, The soft and medium soils predict less base resistance because the ratio of base shear of flexible base (Vf) to fixed-base models (V) is less in comparison to hard soil, and The hard soil behaves like a fixed base condition where the Tf/T and Vf/V ratios are confined to unity. **(Kashyap N. Patel, Jignesh A. Amin 2018) [6]** Examined how alternative staging methods and taking soil flexibility into account affect the values of the realistic response modification factor for an RC frame staging elevated water tank that was constructed and designed in accordance with Indian standards. According to the code for water retaining systems IS 1893 (Part-II) [7], four elevated RC frame staging water tanks with capacities of 140, 480, 1000, and 2200 m3 and varying staging heights and patterns were designed. Their base shear capacity and structural ductility were calculated using displacement-controlled nonlinear static pushover analysis according to FEMA-356 [8]. Three distinct types of hard, medium, and soft soils were used in the study to take into consideration the influence of soil flexibility. After performing pushover analysis for the studied tanks, the results show that the impulsive time period of the elevated water tank model increases when the soil spring stiffness decreases from hard to soft soil, and the response reduction factor decreases. This implies that soil flexibility is a function of both the impulsive time period and the response reduction factor.

(R. Livaoglua , A. Dogangunb 2007)[9] using the ANSYS Software to represent the superstructure and the different types of soils selected the study aims to explore the effects of foundation embedment on the seismic behaviour of a fluid-elevated tank-foundation-soil system supported by a structural frame, Their research has shown that The embedment affects the roof displacement considerably and As the soil gets softer, the foundation embedment becomes more effective and influences the system's behaviour more.

(M.R. Kianoush, A.R. Ghaemmaghami 2011) [10] studied the seismic behaviour of a fluid rectangular tank system is explored in terms of ground motion frequency content. The findings demonstrate that as the soil stiffness varies, the maximum impulsive base shear and base moment obtained from the time history analysis of the studied system may grow or decrease. Both shallow and tall tank designs exhibit a definite tendency during low-frequency content earthquakes. As soil stiffness increases, the structural responses go up. (**Asha Joseph, and Glory Joseph 2019) [11]** examined the SSI effect on the impulsive response of circular water tanks, and the influence of frequency content of earthquake and peak ground acceleration (PGA) on the seismic behaviour of water tanks. As a result, the Fundamental impulsive frequency of the SSI system decreases with the decrease in the stiffness of the soil on which the tank rests, and the amplitude of vibration recorded as response displacement of the tank in radial direction increases as soil stiffness decreases for all soil types considered. The impact of soil parameters on response displacement is greater for low-frequency earthquakes with higher PGA than for higher-frequency earthquakes with lower ground acceleration. **(Pranitha Jogi, and B. R. Jayalekshmi 2022)** [12] Compared the seismic response of elevated intze water tanks considering different water levels and different supporting soil conditions. It was found that as the stiffness of the supporting soil decreases, the maximum shell roof displacement also increases, and when the soil stiffness increases, the base shear also increases.

This study investigates the effect of Soil-Structure interaction and the main factors affecting the value of the response modification factor (R) for reinforced concrete elevated water tanks. These factors include the soil type, the tank height, the tank capacity, the seismic zones, and the response spectrum type. 108 models are studied using the finite element program, (SAP2000) [13], considering these parameters to enhance the understanding of the Soil-Structure interaction phenomenon and its impact on the values of the(R)factor.

2. CONCEPT OF SOIL STRUCTURE INTERACTION (SSI)

Soil-structure interaction (SSI) is an analysis of a structure`s dynamic response to soil movement induced by earthquake ground motion, water waves, wind loads, and other loads that might create variations in the characteristics of the soil.

(Reissner 1936) [14] introduced the vibrational foundation theory which marks the start of the SSI investigation. Warburton's research between 1969 and 1972 [15] continues the SSI study, Using Parmelee's soil-structure model, the authors developed some equations for the response of two geometrically similar cylindrical bodies attached to the surface of an elastic half-space. (Veletsos and Meek 1974) [16] demonstrated that because buildings are more flexible when considering the SSI than the corresponding Fixed Base structures, inertial interaction effects for buildings cause a lengthening of the soil-structure system's natural period, as well as an increase in soil-structure system damping brought on by the dissipated energy and waves, radiated back into the soil. (Wolf and Obernhuber 1985) [17] proposed the direct approach for SSI analyses that solves the soil-structure assembly's dynamic equilibrium equation, differentiating the case of a Fixed Base Model compared to a flexible foundation motion model.

In section 6.3 of (the Federal Emergency Management Agency (FEMA) 2020) [18], there are two ways for modelling the SSI. The first way is the rigid foundation and flexible soil (see Figure 1-a), where foundation modelling is based on six formulas for six degrees of freedom (see Table 1). The second way is the flexible foundation and linear flexible soil (see Figure 1-b), in which dispersed springs represent the soil support as a discretized continuous medium, with the springs having a consistent value along the length of the footing. This method is best employed when the flexibility of the foundation's structural parts is explicitly modelled using formula 1 to calculate the unit subgrade spring coefficient (Ks).

$$K_{SV} = \frac{1.3G}{B_f(1-\nu)} \qquad (1)$$

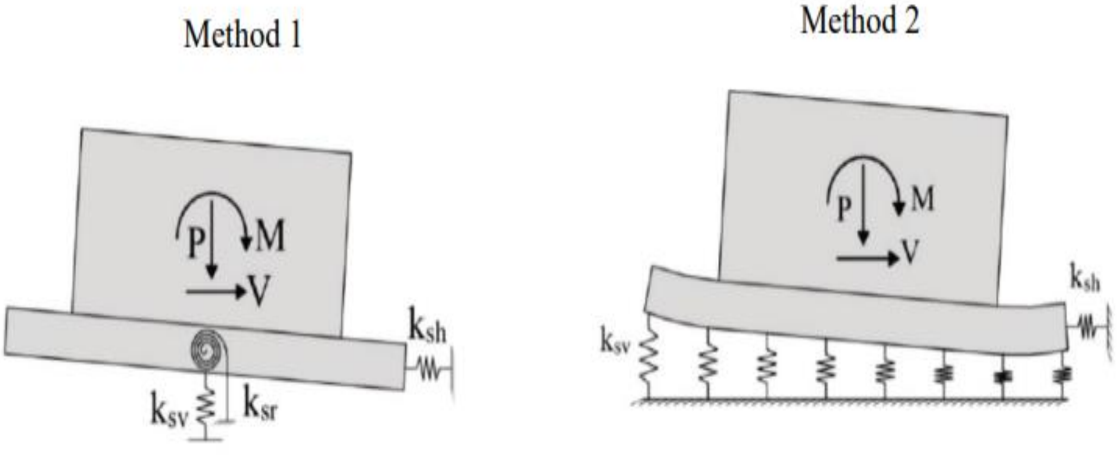


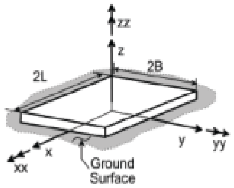
Figure (1-a)

Figure (1-b)

Figure 1: Two methods for foundation modelling approaches with vertical and rotational springs presented in FEMA (2020).

Table 1: the modelling of the foundation depended on six formulas of six degrees of freedom.

Surface Stiffness (FEMA 2020) [16] under Title
“ A Practical Guide to Soil-Structure Interaction”
2BX2L



$$k_{x,sur} = \frac{GB}{2-v}\left[6.8(\frac{L}{B})^{0.65} + 2.4\right]$$

$$k_{y,sur} = \frac{GB}{2-v}\left[6.8(\frac{L}{B})^{0.65} + 0.8\frac{L}{B} + 2.4\right]$$

$$k_{z,sur} = \frac{GB}{1-r}\left[3.1(\frac{L}{B})^{0.75} + 1.6\right]$$

$$k_{xx,sur} = \frac{GB^3}{1-r}\left[3.2(\frac{L}{B})^{1} + 0.8\right]$$

$$k_{yy,sur} = \frac{GB^3}{1-r}\left[3.73(\frac{L}{B})^{2.4} + 0.27\right]$$

$$k_{zz,sur} = GB^2\left[4.24(\frac{L}{B})^{2.45} + 4.08\right]$$

where G = shear modulus, v = Poisson’s ratio for elastic half space, B and L = Half-width and half-length of rectangular foundation.

3. Response Modification Factor

3.1 Methods of Determination of the Response Modification Factor

The most essential design tool for earthquake loads (R) is the response modification factors, which show the expected inelasticity level in structural systems.

Designing a system that can withstand an earthquake without totally collapsing but with considerable damage is the main goal of earthquake engineering. Like this, the structure can withstand far lower base shear pressures than if it were kept elastic during vigorous shaking. The formulation of many over-stretching factor components that may be identified using nonlinear static analysis, as well as the relationship between a structure's base shear and roof displacement are shown in (Figure 2).

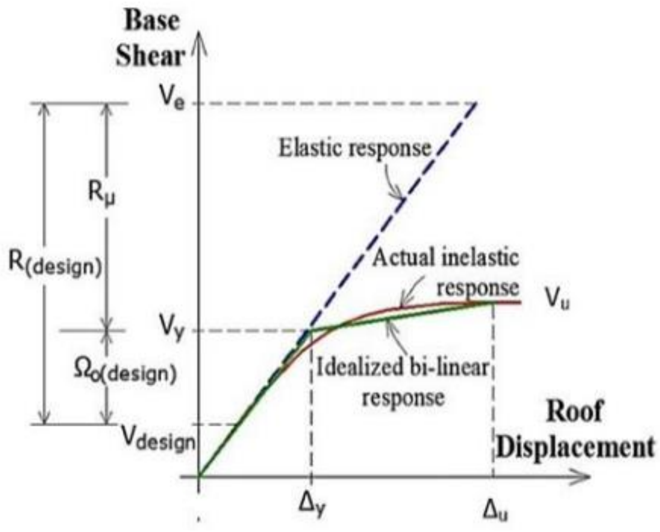


Figure 2: Elastic and inelastic systems' force-displacement responses

The major components of the response modification factor (R) are the ductility factor (Rμ), and the over-strength factor (Ω), The following researchers use different formulations to determine the reduction factor (R), (Newmark and Hall 1969) [19], (Uang 1991) [20], (Miranda and Bertero 1994) [21], Elnashai and Mwafy [22], and (Maheri and Akbari 2003) [23] Thus, the response reduction factor (R) is:

$$R = R\mu \times \Omega \qquad (2)$$

$$\Omega = Vu / Vd \qquad (3)$$

$$\mu = \Delta u / \Delta y \qquad (4)$$

$$R\mu = 1.0 \qquad T \leq 0.03 \qquad (5)$$

$$R\mu = 1 + \frac{(T-0.03)X(\sqrt{(2\mu-1)}-1}{0.09} \qquad 0.03 < T < 0.12 \qquad (6)$$

$$R\mu = \sqrt{(2\mu-1)} \qquad 0.12 \leq T \leq 0.5 \qquad (7)$$

$$R\mu = \sqrt{(2\mu-1)} + 2(T-0.5) \times (\mu-\sqrt{(2\mu-1)}\ ) \qquad 0.5 < T < 1.0 \qquad (8)$$

$$R\mu = \mu \qquad T \geq 1.0 \qquad (9)$$

3.2 Provision of R Factor in International Codes

The value of the response modification factor in different codes and standards varies from 1.8 to 4.74 depending on the type of building and the ductility grade of the structure. As stated in IBC 2000 [24], FEMA 368 [25], ACI 350-3 [26], Eurocode-8 [27], IS 1893-2 [7], and ECP 201[28], the value of the response reduction factor for elevated water tanks is displayed in Table 2.

Table 2: The Values of Response modification adopted in most international codes for Elevated R.C. Water Tanks.

Code	Type of Tank	Response Modification Factor, R
IBC 2000	Supported on Braced and un-Braced legs	3
	Tanks supported on structural towers like buildings	3
FEMA 368	Pedestal supported Tanks	2-3
Euro code 8	Tanks with Low Ductility	1
	Tanks with High Ductility	2
IS-1893, Part2	Supported on R.C. frame staging (OMRF)	2.50
	Supported on R.C. frame staging (SMRF)	4
E.C.P. 201	Supported Framed Structure with limited ductility	1.80
	Supported Framed Structure with sufficient ductility	2.50

4. NONLINEAR STATIC PUSHOVER ANALYSIS

Pushover analysis, a type of nonlinear static analysis, was employed in the current study to assess the global limit states of the RC-MRF (moment-resistant Frames) in terms of drift and force level. In this analysis, the forcing function increases. Performance-based engineering (FEMA 356 and ATC) produces structures with predictable performance within predetermined risk and reliability limits. The main objective is to prevent the construction from fully collapsing. This shows that the upper level can prevent catastrophic collapse. (CP); the sub-level, which contains the vital structures, may sustain only minor damage, and can still be inhabited right away. (IO). There is a situation known as the Life-Safety (LS) level between the lower and upper levels. The nonlinear procedures of FEMA must be followed for defining the nonlinear load-deformation relation. (Figure 3) depicts such a curve.

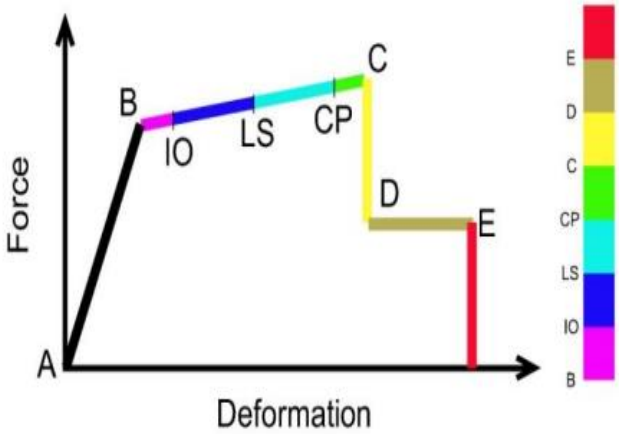


Figure (3) The typical load-deformation relationship, as well as the desired performance levels

Nonlinear static analysis is generally incorporated into the following steps:

1. Construct a three-dimensional finite element model in the program.
2. Apply gravitational forces and static lateral forces or deformations in a way that estimates the comparative frictional forces generated at significant mass sites or when each floor's mass is clustered together in the model.
3. Use the load pattern case from Step 2 and move the structure to the aimed deformation level. (i.e., the destination node's deformation reaches the target deformation).
4. Calculates the forces and deformations of each element at the displacement level that corresponds to the intended displacement.
5. Plot the top displacement versus the base shear.

The FEMA states that the points (A. B. C. D. and E) describe the hinge's behaviour. Three additional requirements—immediate occupancy (IO), life safety (LS), and collapse prevention (CP)—define the approval requirements for the hinge. Numerous performance goals at various levels, including the seismic transition phases, are listed in (ASCE, 2017b) [29].

5. Verification Application

One of the previously studied elevated tanks by Kashyap P, Amin J A [6], who studied this tank through a wide investigation of elevated tanks considering the soil flexibility, is examined in this research to ensure the exact understanding of the algorithm and application of Soil-Structure Interaction and Nonlinear Static pushover analysis to elevated water tanks. The analysed tank has a height of 18 metres, a volume of 140 m3, six columns, and is in seismic zone 3, the used soil types in this study were hard, medium, and soft soils, the full details of the verification case study model data is described in reference [6].

Figure 4 shows the configuration of the Elevated Tank. Elastic soil properties and spring stiffness considered in the studied water tank are illustrated in Table (3).

The comparison between the investigated case findings from [6] and the current SAP2000 application to confirm comprehension of the Pushover Nonlinear Analysis is shown in Figure (5) and Table (4). The values of the response Modification Factor and its components exhibit acceptable agreement, according to the results.

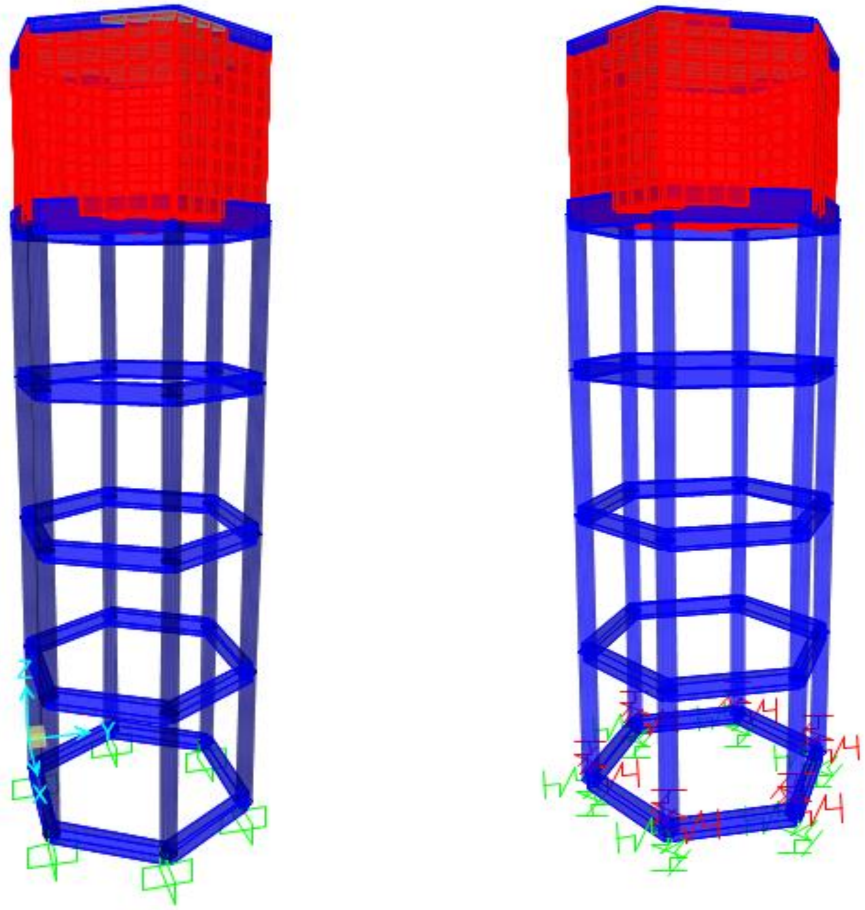


Figure (4-a) Fixed Support Figure (4-b) Elastic Support

Figure (4) Configuration of 140 m3 tank with height 18m

Table (3) Elastic soil properties and spring stiffness considered in the studied water tank.

Type of soil	Degrees of freedom	Spring constant 140 m3 (KN/m/m^2)
Hard	Horizontal	42096.2
	Vertical	63144.3
	Rocking & Torsion	604674.18
Medium	Horizontal	24177.77
	Vertical	36266.66
	Rocking & Torsion	347291.9
Soft	Horizontal	5766.29
	Vertical	8649.68
	Rocking & Torsion	83827.6

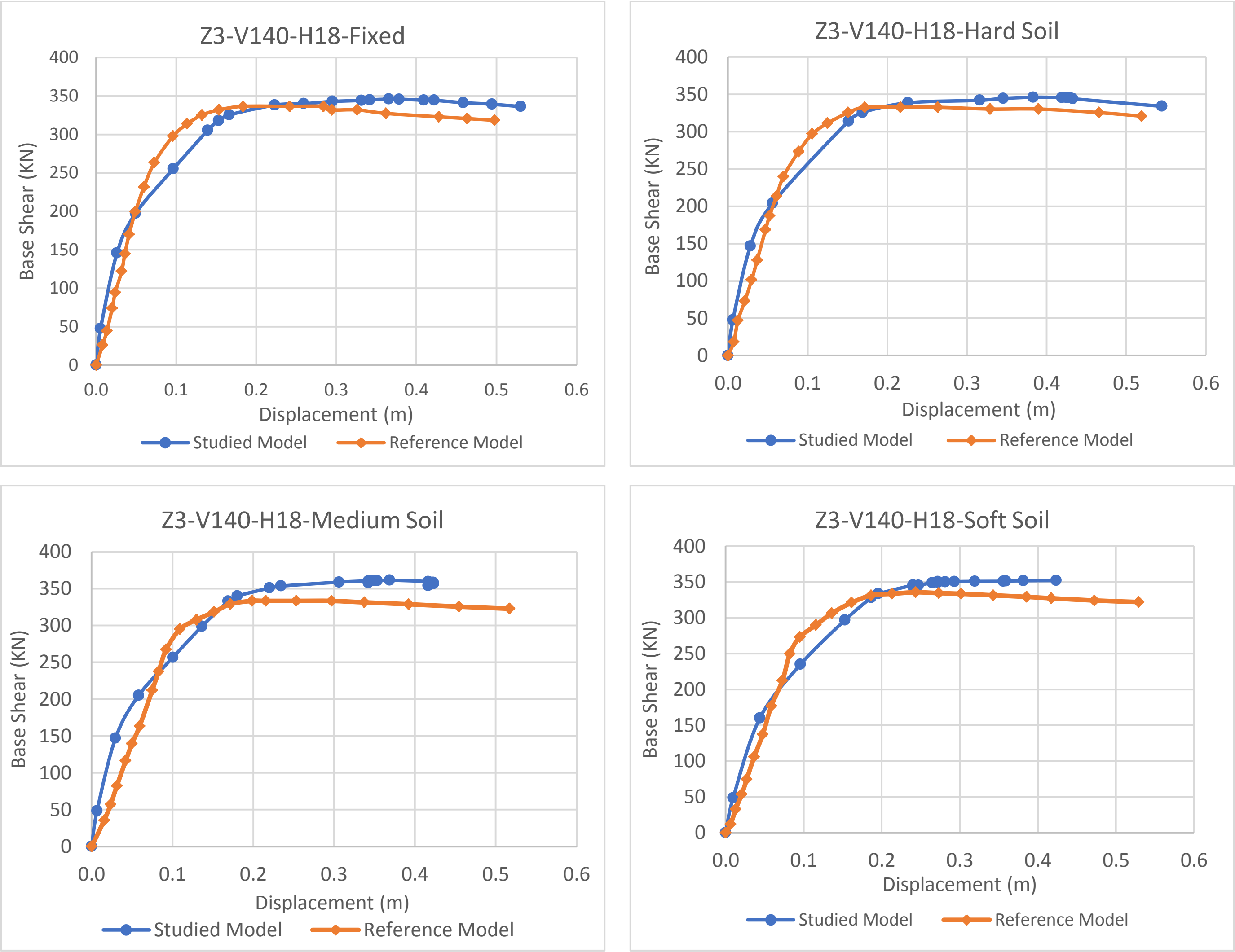


Figure (5) Comparison between Pushover curves for the reference (Kashyap P and Amin J A 2018) and obtained curves by SAP2000 application for Fixed Case, Hard Soil Case, Medium Soil Case, and Soft Soil Case.

Table (4) Comparison Between Response Modification Factor (R) Values obtained from SAP2000 reference (Kashyap P and Amin J A 2018) [6]

		T	Vo (KN)	Vd (KN)	Rs	Δm	Δy	μ	Rμ	R
Fixed Support	Reference Study	1.22	340	70	4.85	211	92	2.29	2.67	12.94
	Present Study	1.19	336	76.6	4.39	211	72.5	2.91	3.38	14.8
Hard Soil Case	Reference Study	1.31	336	66	5.09	211	103	2.05	2.34	11.93
	Present Study	1.25	335	67	5.00	211	90	2.35	2.73	13.65
Medium Soil Case	Reference Study	1.36	336	84	4.01	209	107	1.97	2.23	8.92
	Present Study	1.3	347	88.8	3.91	208	90	2.31	2.69	10.5
Soft Soil Case	Reference Study	1.64	335	85	3.94	211	110	1.91	2.29	9.02
	Present Study	1.57	336	89	3.77	208	90	2.31	2.75	10.36

6. Numerical Study for Seismic Performance For R.C Elevated Water Tanks Considering SSI

The main purpose of this study is to discuss seismic performance for elevated reinforced concrete water tanks considering SSI. The analysis was performed using the sap 2000 program, which determined the period of vibration (T) using its empirical equation. Nonlinear pushover static analysis (P.O.A) was used to determine the condition of plastic hinges at yield and ultimate states, followed by the computation of the response modification factor 'R' for reinforced concrete elevated water tanks with different stagging heights and capacities.

6.1 Geometrical Description of Models

The investigated elevated rectangular tank models consist of 3 different soil types, 3 different stagging heights,3 different capacities, 2 different seismic zones, and one response spectrum function as per the Egyptian code of loads, ECP201,2012. The main characteristics and parameters of the studied tanks in the present work are summarized in Table (5) and Figure (6).

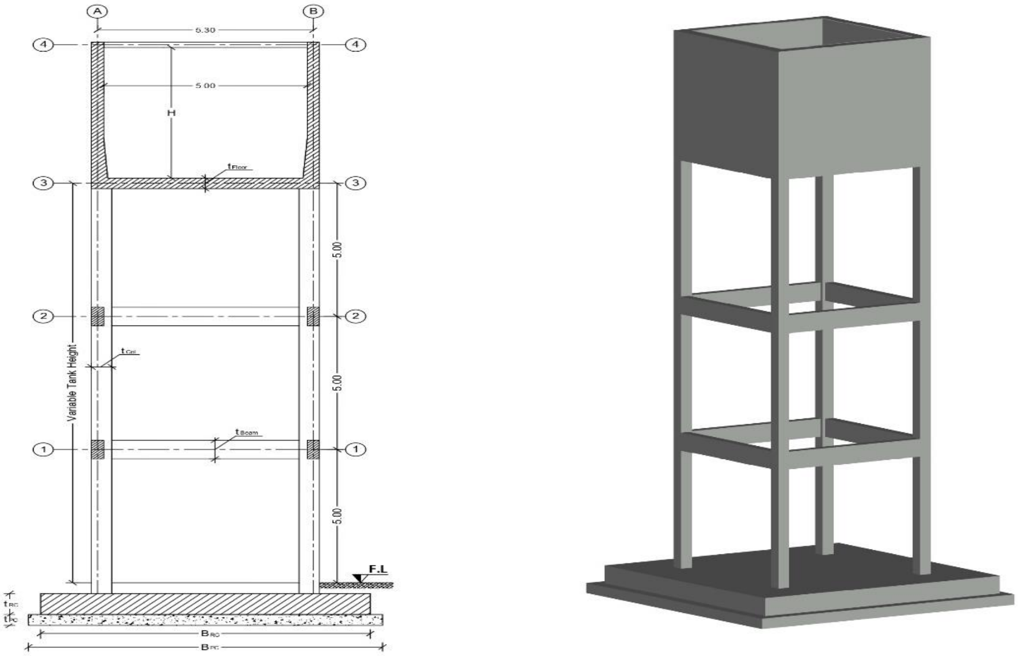


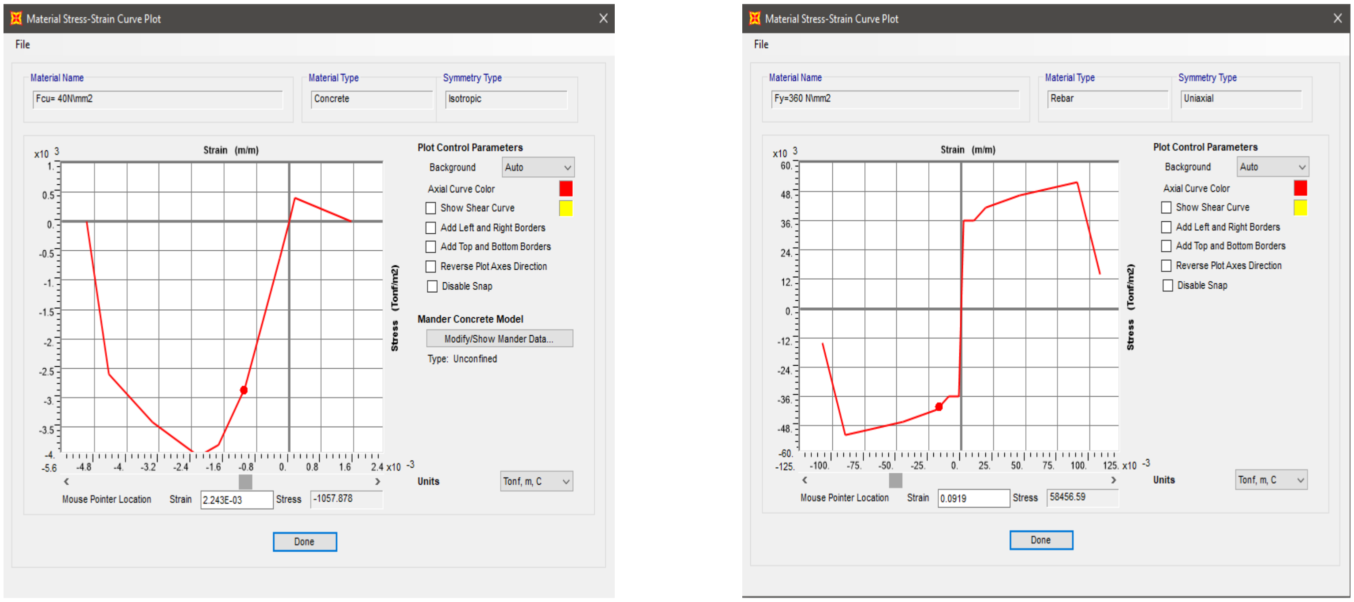
Figure (6) Configuration of Vertical shape elevated water Tank.

Table (5) Different Parameters of the Studied Elevated Tanks.

Number of studied Models	Soil Types	Seismic Zones	Tanks Capacities (m^3)	Heights - H (m)	Supporting system
108	Hard – Medium - Soft	Z3 – Z5	75 – 125 – 175	10 – 15 – 30	Fixed -Flexible Soil

6.2 Design Criteria and Assumptions.

The mechanical properties of the used materials as well as the loading assumptions and the Finite Elements Modelling types for beams and columns are summarized in Table (6). The material's nonlinear data for both concrete and steel are demonstrated in Figure (7) for both concrete and steel respectively.



Material Name: Fcu= 40N\mm2
Material Type: Concrete
Symmetry Type: Isotropic

Plot Control Parameters
Background: Auto
Axial Curve Color: 🟥
☐ Show Shear Curve 🟨
☐ Add Left and Right Borders
☐ Add Top and Bottom Borders
☐ Reverse Plot Axes Direction
☐ Disable Snap

Mander Concrete Model
Type: Unconfined

Units: Tonf, m, C

Mouse Pointer Location Strain 2.243E-03 Stress -1057.878

Material Name: Fy=360 N\mm2
Material Type: Rebar
Symmetry Type: Uniaxial

Plot Control Parameters
Background: Auto
Axial Curve Color: 🟥
☐ Show Shear Curve 🟨
☐ Add Left and Right Borders
☐ Add Top and Bottom Borders
☐ Reverse Plot Axes Direction
☐ Disable Snap

Units: Tonf, m, C

Mouse Pointer Location Strain 0.0919 Stress 58456.59

(a) Stress-strain curve for concrete (b) Stress-strain curve for steel bar.

Figure (7) Stress-strain curves introduced in SAP2000 (Computer & Structures Inc., 2018) [13]

Table (6) Design Parameters and Assumptions.

Modelling Assumptions		
		Assumptions
Material	Concrete	Compressive strength [fcu=4000 ton/ m2]
	Steel rebar material	Young's Modulus [21000000 ton/ m2] Yield strength [36000 ton/ m2]
	Stress - Strain relationship	Concrete [Confined and unconfined according to Mander et al (1988)]
Loading	Self-weight of members	Weight per unit volume [2.5 ton/m3]
	Effective weight	(Total dead load) + (Full water load)
	Lateral load	Static load pattern as per Eurocode8 2004 spectrum type (2)
	Analysis Program	SAP2000 2020 v20.2.0
Modelling	Element modelling	Frame elements for beams and columns with plastic hinges as per ASCE 41-13 assigned at start and end relative distances of 0.05 and 0.95.
		Shell elements for slabs.

6.3 Design of Structural Elements

The analysed factors matrix for this parametric study produces 108 models with all potential combinations taking into account the SSI effect. The 108-case study with different parameters was designed according to the Egyptian codes for all the load combinations.

6.3.1 Design of Superstructure

To achieve an ideal design with a stress ratio between demands and a maximum capacity of approximately (0.80-0.90). The side dimensions of square columns vary from 400 mm to 950 mm according to the height, tank volume, soil type, and seismic zone. To achieve the best design, it was also necessary to change the bonding beams, the floor thickness, the wall thickness, and the reinforcement ratio. According to ECP 201 [28], each of these tanks was designed to endure both gravitational and seismic loads. The average characteristic values for all the design data for the 108 tank study Cases are listed in Table (7).

Table (7) Average Dimensions and Reinforcement of superstructure structural elements

Structural Element	Dimensions & RFT.	Seismic Zone (3)			Seismic Zone (5)		
		H=10	H=15	H=30	H=10	H=15	H=30
Columns	Dimensions (mm)	450 X 450 550 X 550 650 X 650	450 X 450 550 X 550 650 X 650	400 X 400 450 X 450 550 X 550	600 X 600 700 X 700 950 X 950	600X600 700 X 700 900 X 900	550 X 550 650 X 650 800 X 800
	Reinforcement	18T16 22T16 28T18	14T16 20T16 28T18	12T16 14T16 22T18	28T18 34T18 42T22	26T18 32T18 38T22	22T18 30T18 28T22
	Stirrups	Y8 @100	Y8 @100	Y8 @100	Y8 @100	Y8 @100	Y8 @100
Beams	Dimensions (mm)	300 X 700 300 X 800 300 X 900	300 X 700 300 X 800 300 X 900	300 X 700 300 X 800 300 X 900	300 X 800 300 X 900 300 X 1000	300 X 800 300 X 900 300 X 1000	300 X 700 300 X 800 300 X 900
	Reinforcement	8T16 8T16 9T18	7T16 8T16 8T18	6T16 6T16 8T16	9T18 7T22 10T22	8T18 6T22 9T22	8T16 7T18 7T22
	Stirrups	T 8 @150	T 8 @150	T 8 @150	T 8 @150	T 8 @150	T 8 @150
Tank Floor	Dimensions (mm)	300	400	500	300	400	500
	Reinforcement	6T16/m′	7T16/m′	6T18/m′	7T16/m′	8T16/m′	8T18/m′
Tank Wall	Dimensions (mm)	300	400	500	300	400	500
	Vertical RFT.	6T16/m′	8T16/m′	7T18/m′	7T16/m′	9T16/m′	9T18/m′
	Horizontal RFT.	6T12/m′	6T12/m′	6T12/m′	6T12/m′	6T12/m′	6T12/m′

6.3.2 Design of Foundations

After performing the seismic analysis and designing the structural elements of studied tanks, to include the effect of Soil-Structure Interaction in the analysis of the studied tanks the foundations of tanks must be properly designed to withstand gravitational loads, water pressure, and seismic loads according to ECP (203) code.

The foundation dimensions as shown in Figure (8) had to be modified as the tank capacity, tank height, soil type, and seismic zone changed throughout the current study. Table (8) summarizes the average dimensions and RFT of designed foundations.

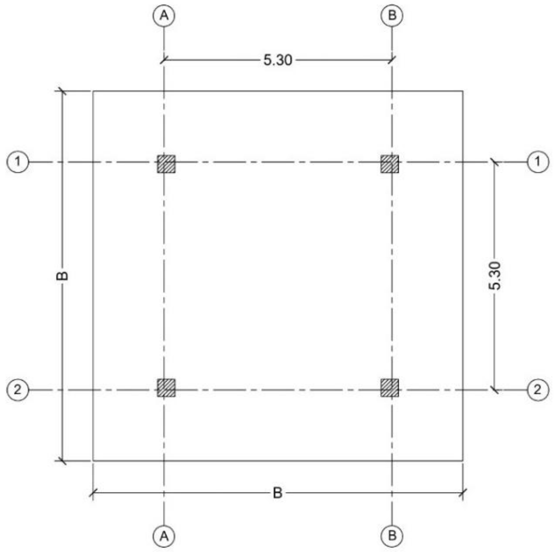


Figure (8) Foundation Plan Configuration of studied R.C. Elevated Tank

Table (8) Average Dimensions and Reinforcement of Foundations

Soil Type	Dimensions & RFT.	Seismic Zone (3)			Seismic Zone (5)		
		V=75 m^3	V=125 m^3	V=175 m^3	V=75 m^3	V=125 m^3	V=175 m^3
Hard Soil	Dimensions (m)	6.5*6.5*0.8	7.5*7.5*0.8	8.0*8.0*0.8	8.5*8.5*1.0	9.0*9.0*1.0	9.5*9.5*1.0
	Reinforcement	7T16/m	7T16/m	7T16/m	7T18/m	7T18/m	7T18/m
Medium Soil	Dimensions (m)	7.0*7.0*0.8	8.0*8.0*0.8	8.5*8.5*0.8	8.7*8.7*1.0	9.3*9.3*1.0	10*10*1.0
	Reinforcement	8T16/m	7T16/m	7T16/m	7T18/m	7T18/m	7T18/m
Soft Soil	Dimensions (m)	9.5*9.5*0.8	11*11*0.8	12*12*0.9	11.5*11.5*1	13*13*0.8	13.5*13.5*1
	Reinforcement	9T16/m	9T16/m	9T16/m	9T18/m	7T18/m	9T18/m

The soil flexibility can be simulated using a set of elastic springs with equivalent translation, rocking and torsional elastic stiffnesses based on soil properties and using equations mentioned in Table (1).

According to ATC-40 and FEMA 356, performance-based design is used for elevated tanks and nonlinear static pushover analysis is performed using SAP2000 Package. According to ASCE 41-13, plastic hinges with (M3) type for beams and (P-M2-M3) type for columns are placed where yielding is anticipated under seismic stresses at both ends of the beams and columns with start and end relative distances of 0.05 and 0.95, respectively. The mass source that results from the gravity loads (Dead Load + Super Dead Load + Live Load) is used in the nonlinear static gravity load situation, which has full values for each of its own weight, super dead load, and live load with zero initial condition. Nonlinear static pushover load cases in global X-Direction with static lateral load pattern are applied to the structure starting from the end of the nonlinear gravity load case with target displacement equal to 4% of the total building height.

7. Results and Discussion

For each one of the 108 studied tanks, after performing the optimum design cycle followed by the pushover analysis for the fixed support case then followed by another pushover analysis cycle using elastic supports to include the effect of SSI.

7.1 Fundamental Natural Periods of The Tanks.

The Fundamental Natural period obtained from SAP2000 (v20.1) is outlined according to ECP 201 (2012) for the studied tank cases in the following Figures from (9) to (14).

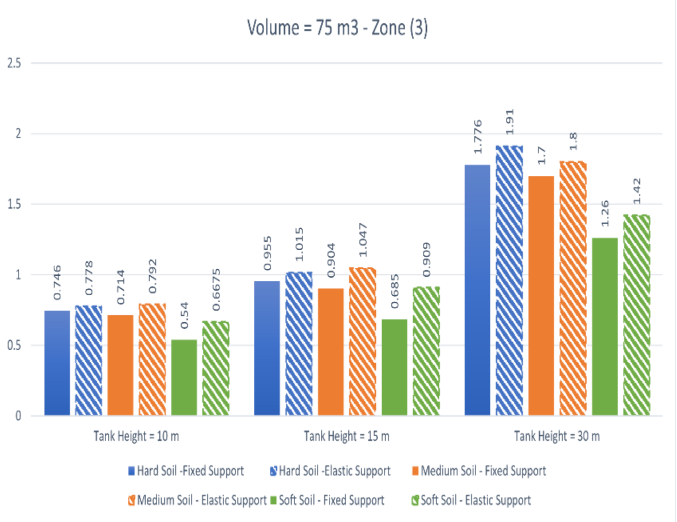


Figure (9) Fundamental Natural period for different types of supports for 75 m^3 Tank, and seismic zone (3).

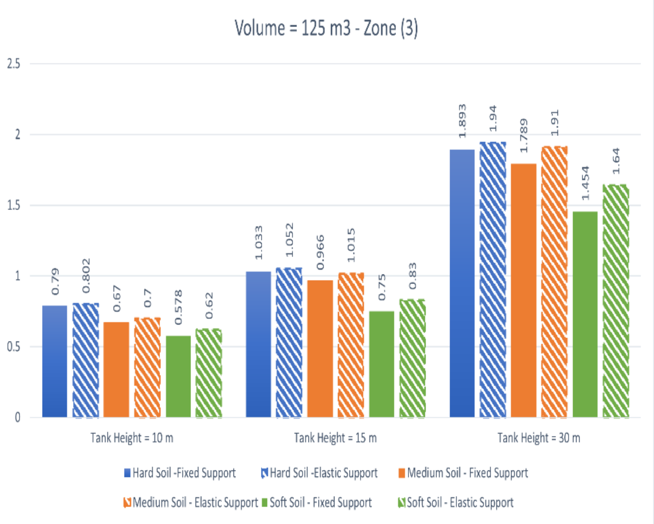


Figure (10) Fundamental Natural period for different types of supports for 125 m3 Tank, and seismic zone (3).

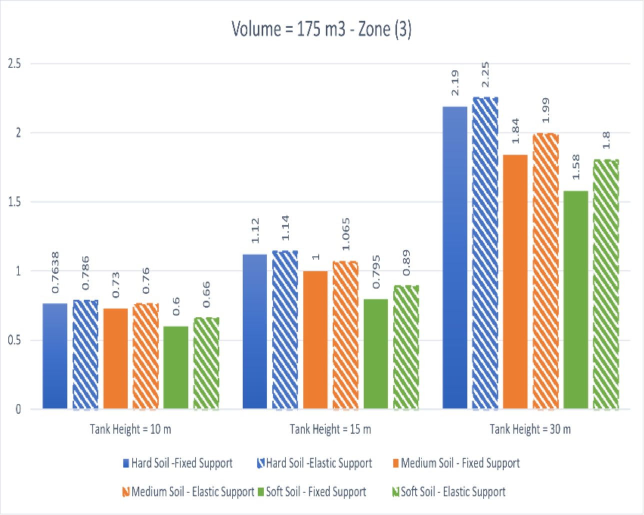


Figure (11) Fundamental Natural period for different types of supports for 175 m^3 Tank, and seismic zone (3).

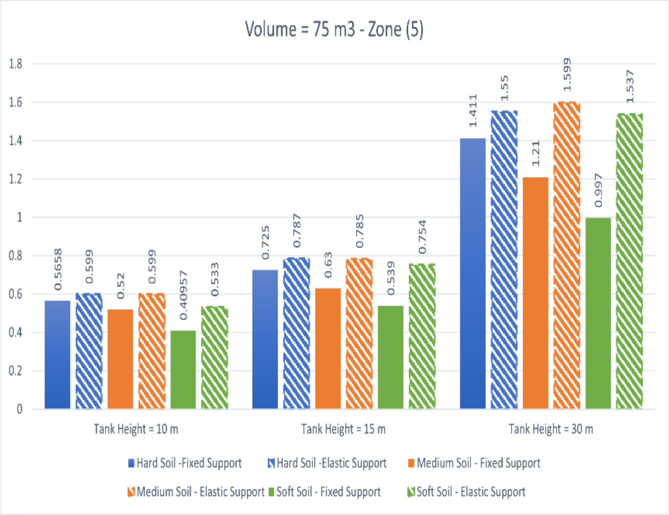


Figure (12) Fundamental Natural period for different types of supports for 75 m^3 Tank, and seismic zone (5).

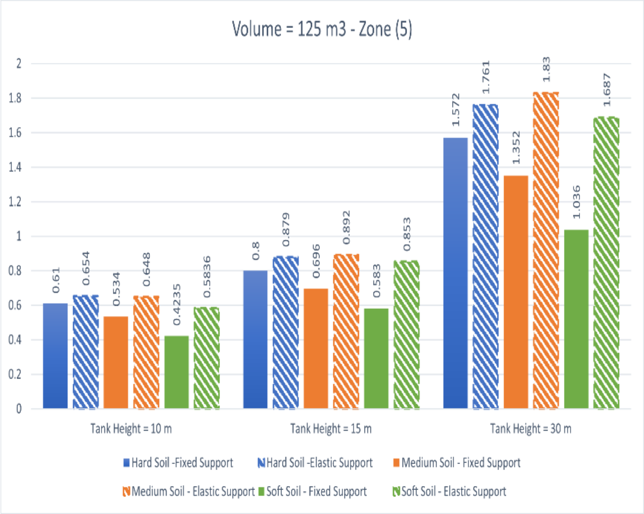


Figure (13) Fundamental Natural period for different types of supports for 125 m^3 Tank, and seismic zone (5).

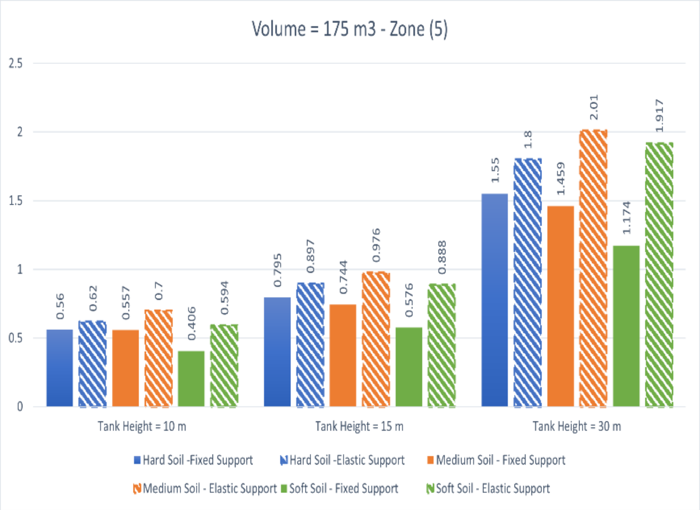


Figure (14) Fundamental Natural period for different types of supports for 175 m^3 Tank, and seismic zone (5).

From Figures 9 to 14 it was found that:

1- The fundamental time period for 75, 125, and 175 m^3 elevated water tanks is higher in the case of the SSI system compared to the fixed base type.
2- The fundamental time period value increases considering SSI with soil types (medium and soft soils). The highest value in the fundamental time period is for soft soil makes it a critical condition.
3- The fundamental time period of the studied elevated tanks increases by a greater percentage When soil gets softer, as the increasing percentage reaches 8,16, and 32% for Hard, medium, and soft soils respectively for seismic zone 3 and 16, 38, and 64% for hard, medium, and soft soils respectively for the seismic zone (5).
4- Fundamental time period value increases with increasing the elevated tank height.

7.2 The Pushover Curve (P.O.C.) For the Studied Tanks.

In the next figures from Figure (15) to Figure (32), The pushover curves for the 75 m^3, 125 m^3, and 175 m^3 elevated tanks, tank heights of 10 m, 15 m, and 30 m, spectrum type (1), and (seismic zone pressure 0.15 g and 0.25 g) from ECP 201 (2012) are depicted in the following figures from SAP 2000 v20.1. The Y-axis represents base shear in KN, and the X-axis represents top displacement in millimetres, for each elevated tank the pushover curve was plotted twice to include the effect of SSI by comparing the case of fixed support against the case of elastic support.

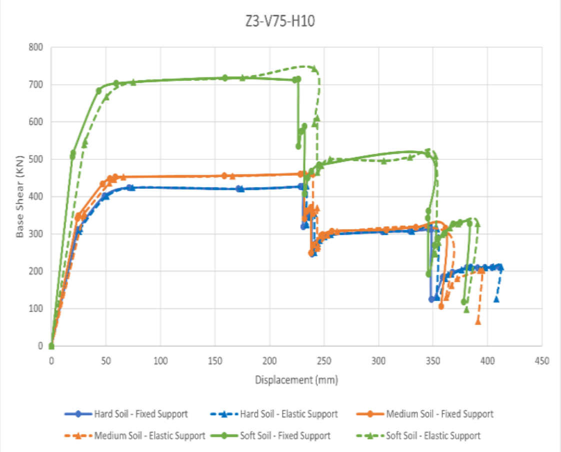


Figure (15) Pushover Curves zone (3), (V=75m^3), and (H=10 m).

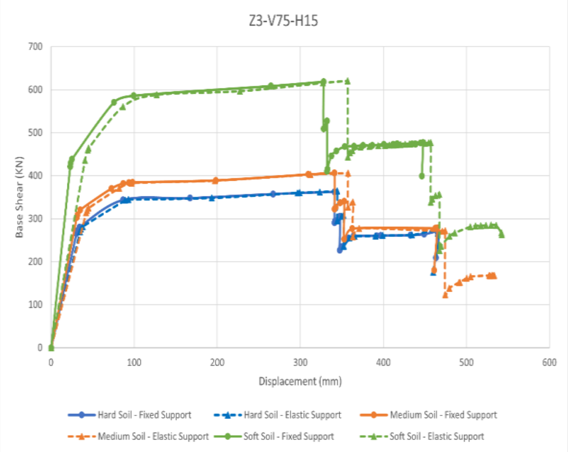


Figure (16) Pushover Curves zone (3), (V=75m^3), and (H=15 m).

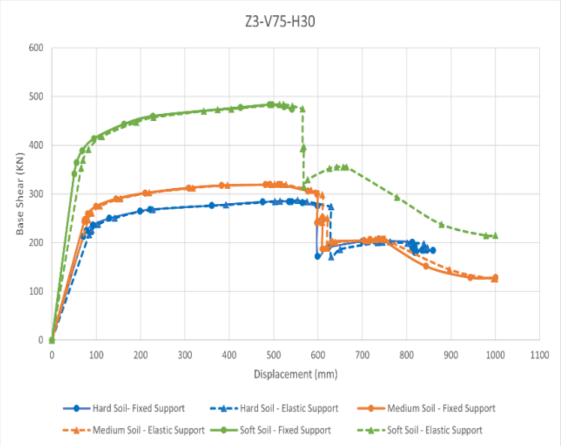


Figure (17) Pushover Curves zone (3), (V=75m^3), and (H=30 m).

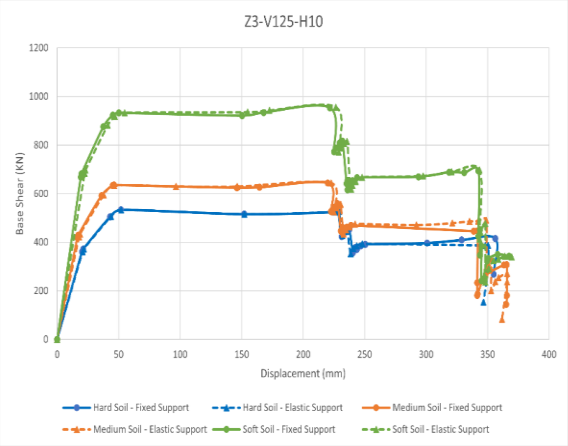


Figure (18) Pushover Curves zone (3), (V=125m^3), and (H=10 m).

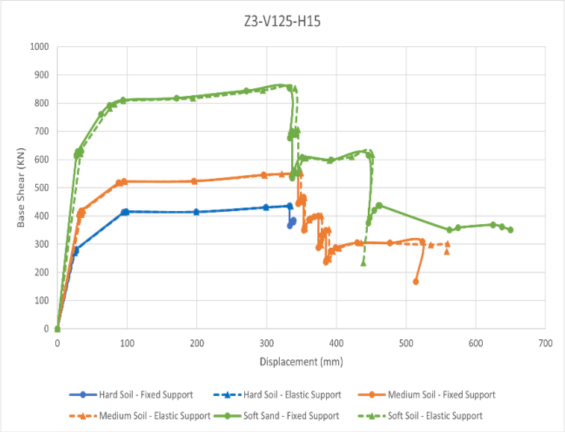


Figure (19) Pushover Curves zone (3), (V=125m^3), and (H=15 m).

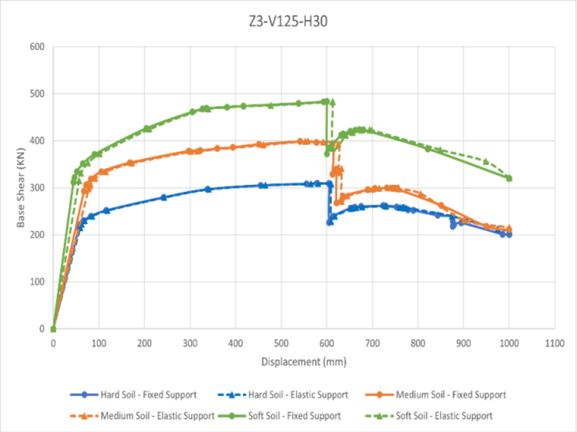


Figure (20) Pushover Curves zone (3), (V=125m^3), and (H=30 m).

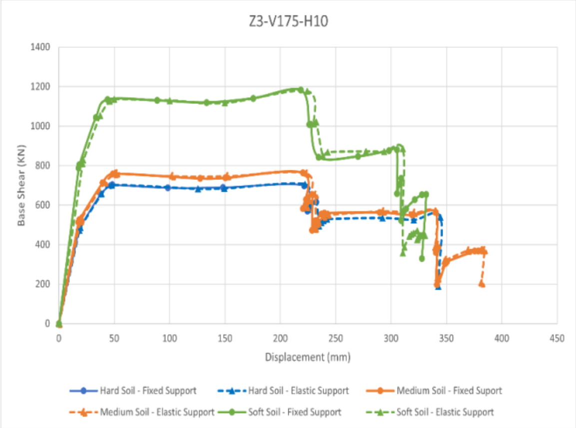


Figure (21) Pushover Curves zone (3), (V=175m^3), and (H=10 m).

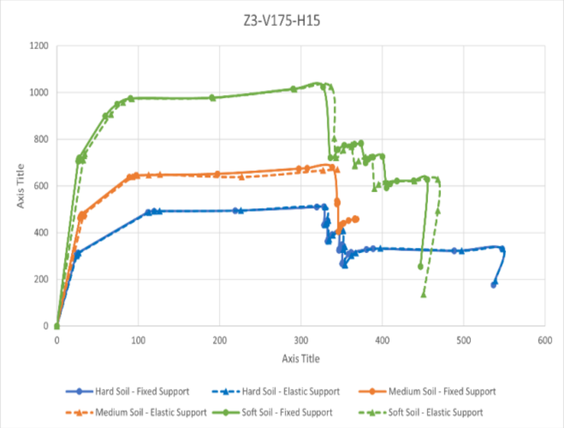


Figure (22) Pushover Curves zone (3), (V=175m^3), and (H=15 m).

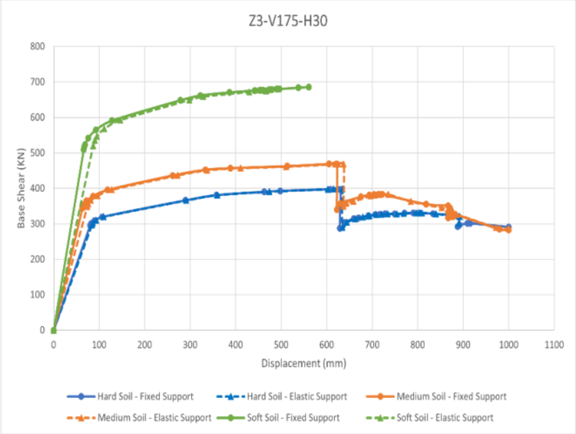


Figure (23) Pushover Curves zone (3), (V=175m^3), and (H=30 m).

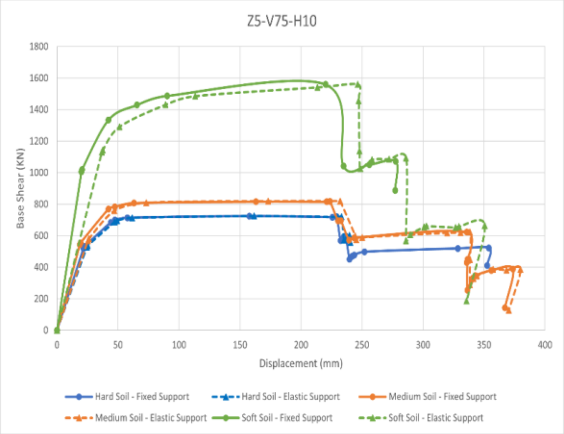


Figure (24) Pushover Curves zone (5), (V=75m^3), and (H=10 m).

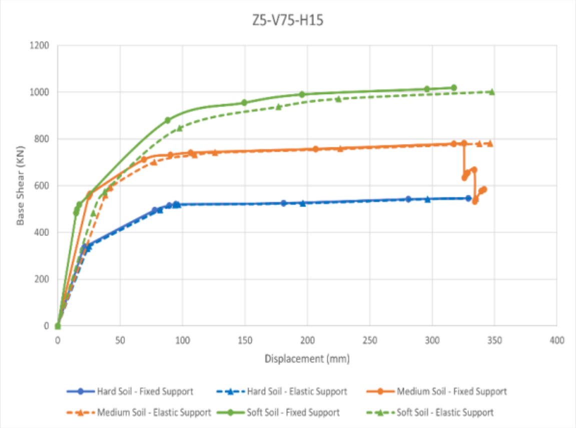


Figure (25) Pushover Curves zone (5), (V=75m^3), and (H=15 m).

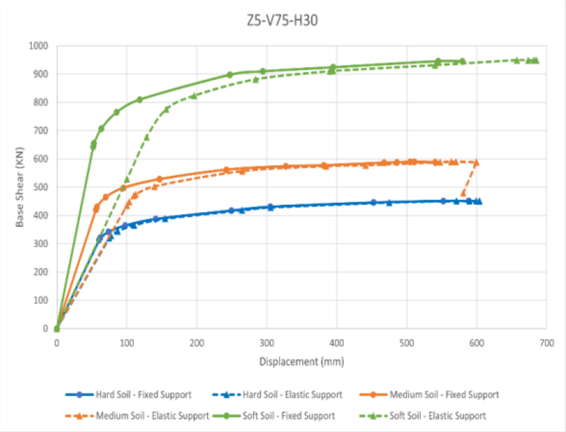
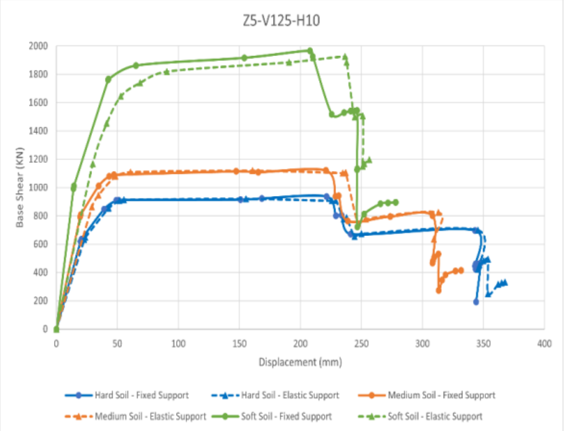


Figure (26) Pushover Curves zone (5), (V=75m^3), and (H=30 m).



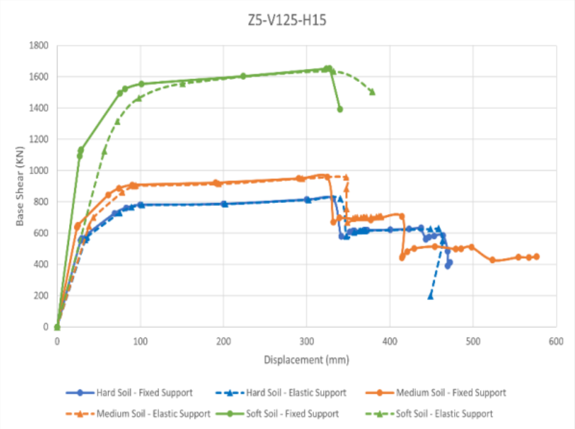


Figure (27) Pushover Curves zone (5), (V=125m^3), and (H=10 m).

Figure (28) Pushover Curves zone (5), (V=125m^3), and (H=15 m).

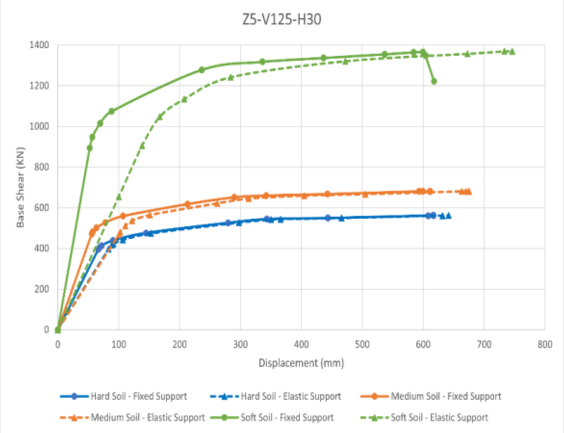


Figure (29) Pushover Curve Zone (5), (V=125 m^3), and (H=30 m).

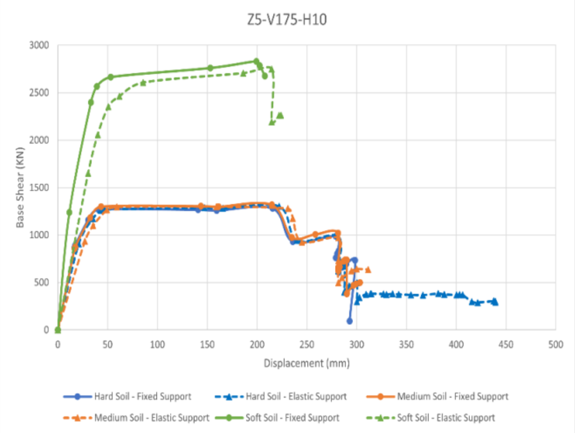


Figure (30) Pushover Curve Zone (5), (V=175 m^3), and (H=10 m).

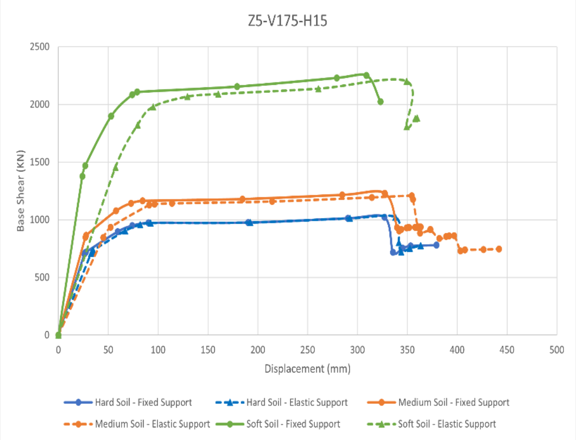


Figure (31) Pushover Curve Zone (5), (V=175 m^3), and (H=15 m).

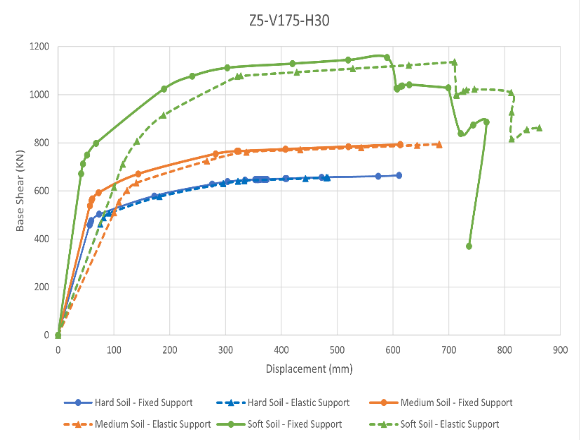


Figure (32) Pushover Curve Zone (5), (V=175 m^3), and (H=30 m).

From the previous Figure, it is clear that the SSI is affecting the performance of the seismic:

1. The shape of the pushover curve of 75 m^3,125 m^3, and 175 m^3 Tanks are less in the case of the SSI system, compared to the fixed base type.
2. With respect to soil type, the harder the soil the less effect of The SSI on seismic response and Pushover Curve.
3. When compared to the Fixed support case, the yield displacement values rose due to the SSI effect, as it was discovered that the increasing percentage elevates when the soil softens, and the seismic zone increases.
4. With respect to seismic zones, the change in the shape of the pushover curve in the case of the SSI system is more pronounced for higher seismic zones.
5. Concerning tank height, the lowest shape of the pushover curve in the case of the SSI system is for the tank with the greatest height and hardest soil.

7.3 ESTIMATION OF RESPONSE MODIFICATION FACTOR (R)

The Response modification factor (R) values for the investigated cases are gathered on the bar charts shown in the following Figures from Figure (33) to Figure (38) to illustrate the impact of the SSI, the seismic zone, tank volume, and tank height on the obtained results.

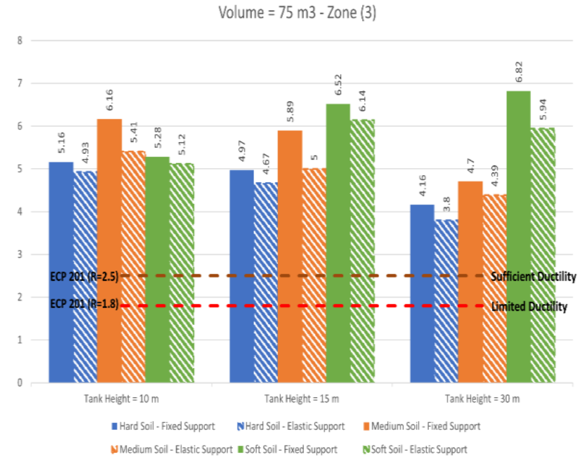


Figure (33) Response Modification factor (R) for 75m^3 tank, seismic zone (3), and different tank heights.

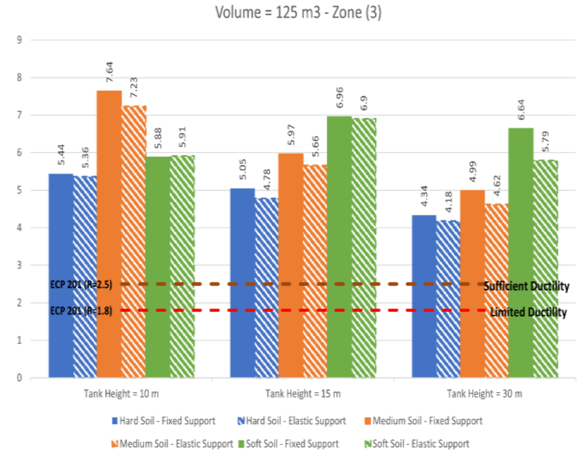


Figure (34) Response Modification factor (R) for 125m^3 tank, seismic zone (3), and different tank heights.

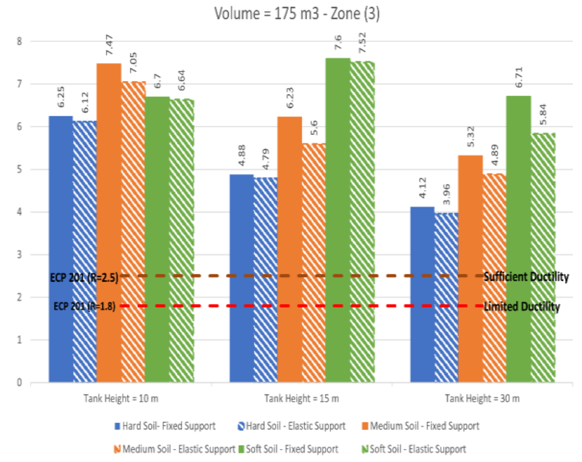


Figure (35) Response Modification factor (R) for 175m^3 tank, seismic zone (3), and different tank heights.

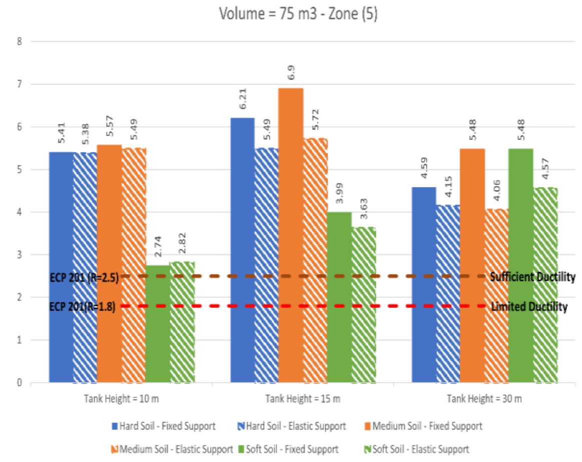


Figure (36) Response Modification factor (R) for 75m^3 tank, seismic zone (5), and different tank heights.

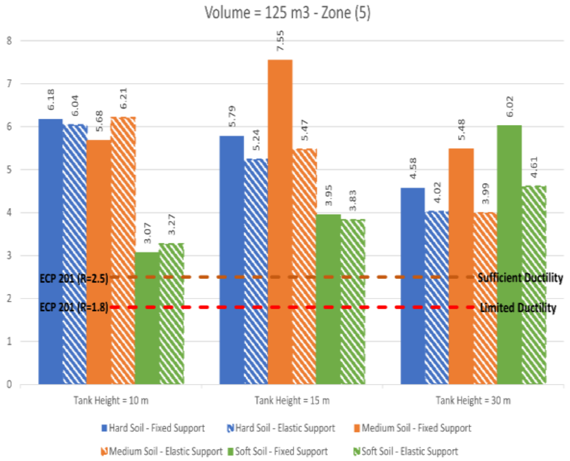


Figure (37) Response Modification factor (R) for 125m^3 tank, seismic zone (5), and different tank heights.

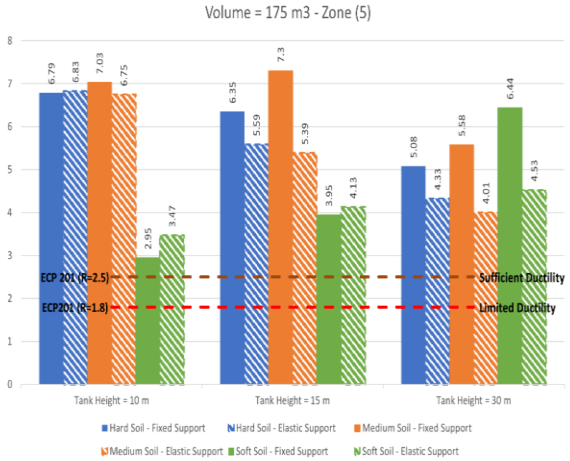


Figure (38) Response Modification factor (R) for 175m^3 tank, seismic zone (5), and different tank heights.

8. Summary and Conclusions

The impacts of SSI on the seismic performance of R.C Elevated water tanks: -

1. When assessing the performance of RC elevated tanks, especially when they are constructed on soft soils, the SSI effects should be taken into consideration.
2. The seismic performance of buildings is affected by changes in soil properties, with taller structures and softer soil profiles seeing more significant changes.
3. As the soil spring stiffness decreases from hard to soft soil, the fundamental time period of the elevated water tank model increases. This means that the fundamental time period is a function of soil flexibility.
4. Consideration of the flexibility of medium and soft soils during analysis increases the yield and ultimate displacement compared to that of the fixed base model.
5. In terms of internal forces, the SSI influences the structure of internal forces such as bending moment and axial forces, altering the plastic hinge development of the structural element.
6. For the studied cases of 75 m^3,125 m^3, and 175 m^3 Tanks taking into consideration the effect of SSI decreases the Response modification factor compared to the fixed support case.
7. The maximum reduction in (R) because of taking into account the SSI effect reached 9% for hard soil, 16% for medium soil, 14% for soft soil for seismic zone (3) and 15% for hard soil, 28% for medium soil, and 30% for soft soil for seismic zone (5).

8. The given value of the (R) factor at ECP-201(2012) equals 1.80 for limited ductility and 2.5 for sufficient ductility class of R.C Elevated Water Tanks, which is an exaggerated value as the accurate value of R-factor the study is higher, resulting in uneconomic structure design.
9. For some studied cases it was found that the (R) Value is in the same range of the codes (Ranging from 2-4) which explains the conservative values of R Factors recommended by most of the national and international codes.

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