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Soil-Structure Interaction Effect on Seismic Response Modification Coefficient of Dual System Using Substructure Approach

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Abstract;

Soil mainly affects the dynamic response of structures. Soil-Structure interaction (SSI) is effectively important in case of shear walls according to many international codes. This research aims to study the effect of (SSI) on the dynamic response of dual systems resting on raft foundations using the numerical software engineering program SAP2000. The research methodology relies on studying linear dynamic behavior for models using parameters (number of stories, earthquake frequency, soil type) and using substructure approach in modelling soil to see it's impact on the overall response and design forces of these systems. Then perform pushover analysis to see the effects of parameters on the response modification coefficient (R). The study showed an increase in the natural period, lateral deflection, internal bending moment in columns of the structure, and a reduction in base shear value compared to the fixed base. The (R) value is different according to the number of stories and type of soil. It is not constant as is mentioned in the Syrian Arab code and ASCE. It increases by 20% in the case of four stories and sand soil compared to codes. The (SSI) increases designing requirements (elements section and analysis time) so it's a higher cost.

Keywords: Dynamic Response, Pushover Analysis, soil-structure interaction, Dual system. Substructure Approach.

تأثير التفاعل المتبادل بين التربة والمنشأ على معامل تعديل الاستجابة الزلزالية للجمل الثنائية باستخدام طريقة Substructure Approach

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الملخص:

تؤثر التربة بشكل أساسي على الإستجابة الديناميكية للمنشأت. يعتبر التفاعل المتبادل بين التربة والمنشأ SSI مهماَ في حالة جدران القص وفقاَ للعديد من الكودات العالمية. يهدف البحث إلى دراسة تأثير التفاعل المتبادل على الاستجابة الديناميكية للجمل الثنائية المستندة إلى حصيرة باستخدام برنامج SAP2000. تعتمد منهجية البحث على دراسة السلوك الخطي الديناميكي للنماذج باستجدام متغيرات (عدد الطوابق ، تواتر الهزة، ونوع التربة) وفق طريقة Substructure Approach في نمذجة التربة لمعرفة انعكاس أثرها على الاستجابة الكلية والقوى التصميمية لهذه الجمل. ثم إجراء تحليل الدفع الجانبي الستاتيكي اللاخطي لمعرفة تأثير المتغيرات على معامل تعديل الاستجابة الزلزالية R. أظهرت الدراسة زيادة في الدور الطبيعي والانحراف الجانبي وعزم الانعطاف الداخلي في الأعمدة، وانخفاض في قيمة القص القاعدي مقارنة بحالة الوثاقة. تختلف قيمة معامل تعديل الاستجابة R باختلاف عدد الطوابق ونوع التربة وهي ليست ثابتة كما هو مذكور في الكود العربي السوري والكود ASCE ؛ حيث يزيد بمقدار 20% في حالة أربعة طوابق وتربة رملية مقارنة بقيم الكودات. يزيد التفاعل المتبادل من المتطلبات التصميمية (مقاطع العناصر ، وزمن التحليل) لذلك فهو أكثر كلفة .

الكلمات المفتاحية: الاستجابة الديناميكية، تحليل الدفعي الجانبي الستاتيكي اللاخطي، التفاعل المتبادل بين التربة والمنشأ SSI، الجمل الثنائية، Substructure Approach.

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Introduction:

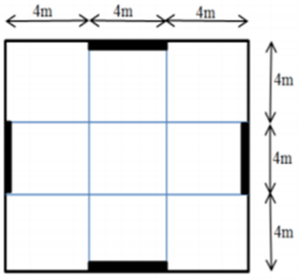
Soil mainly affects the response of structures. The dynamic response of the structure resting on solid soil is nearly to the response of fixed case. If the soil is soft the response will be different due to soil properities and this is called soil-structure interaction (NEHERP, 2012). The soil-structure interaction (SSI) depends on properties of the underlying soil, type of structure, and nature of excitation (Chowdhury et al., 2009). SSI effects are categorized as inertial interaction effects, kinematic interaction effects, and soil-foundation flexibility effects. It can be studied by two theories: Direct or Substructure Approach. In substructure approach, the SSI problem is partitioned into separate parts that are combined to formulate the complete solution. The importance of SSI comes from the need to build important structures in locations with less favorable geotechnical conditions like seismically active regions. Although the SSI reduces base shear which is beneficial, it also causes additional displacements to the overall structure which has detrimental effects.
Bashar Al-Farah studied the nonlinear soil skeleton structures interaction under seismic loading via mathematical programming. It was found that the maximum translation in the case of the plastic-elastic analysis is less than in the case of the elastic analysis. The plastic-elastic translations increased when entering (SSI), but in the elastic analysis, the translations were in some cases less when entering (SSI) (Al Farah, 2012).
Chinmayi, and Jayalekshmi studied effects of SSI on the seismic response of reinforced concrete buildings with shear walls. They found that period and lateral deflection increase and base shear decreases as the soil becomes softer compared with the fixed case (Chinmayi et al., 2013).
Chinmayi, and Jayalekshmi studied effect of soil stiffness on the seismic response of reinforced concrete buildings with shear walls. They found that lateral deflection is the smallest in the case of shear walls at the core for all soils. The period increases with decreases in the hardness of the soil by at least 23% compared to the fixed. The best location for shear walls is in the corners for soil Vs ≥300 m/s and in the core for soils Vs ≤ 300 m/s where the base shear is minimal (Chinmayi et al., 2016).
Bakhtyar studied effect of soil-structure interaction by using earthquake analysis of a 12-Story building and three type of soil. He found an increase in the response values in general (maximum shear force, drift, displacement, and maximum bending moment) compared with the fixed case for different type of soil (Bakhtyar ,2017).

1. Research Methodology:

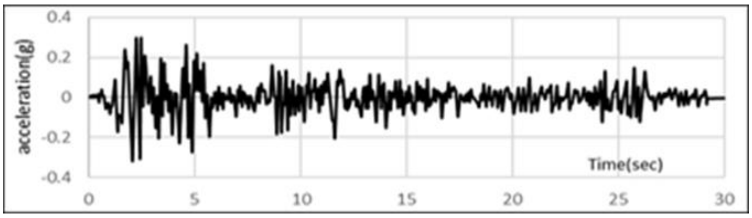
The research aims to study the linear dynamic behavior of dual system on mat considering soil-structure interaction by studying its effects on the main response (period, base shear and lateral deflection). Then parametric study includes three types of soil (rock, conglomerate, sand), as well as changing the number of stories of the building, i.e.,4,8 and 16. Using three seismic records of different specifications. Then appear its effects on the internal forces and design values. After that, calculating the seismic response modification coefficient using substructure approach.

1.1. Ingredients of the System:

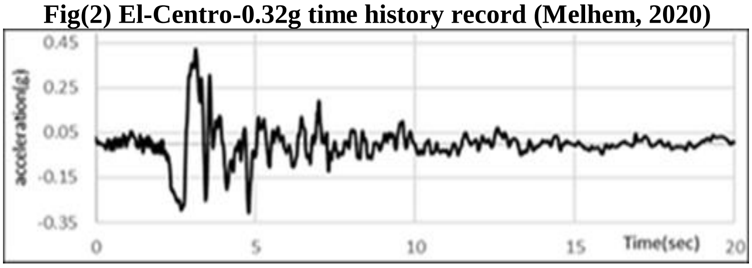
To study dynamic behavior accounting the effect of soil structure interaction with dual system of (4-8-16) stories. Slab thickness was chosen as 0.15m. The slab of the mat foundation was 0.3m. The story height was chosen as 3m for domestic or small office buildings. The dimensions of components of buildings have arrived at the basis of design. The materials of elements were C20 concrete and Fe 415 steel. Mass density and Poisson’s ratio of reinforced concrete were taken as 25 kN/m3 and 0.15 respectively. Plan of a typical 3 bay x 3 bay and location of shear wall in the building is represented schematically in Fig. 1. The time history records in Figs. 2, 3 and 4. Soil properties [3] in Table 1. Member's dimensions of the system in different cases in Table 2. Values of stiffness and damping Coefficient as Gazetas (1991) in Table 3. The model in (SAP2000) in Fig. 5.



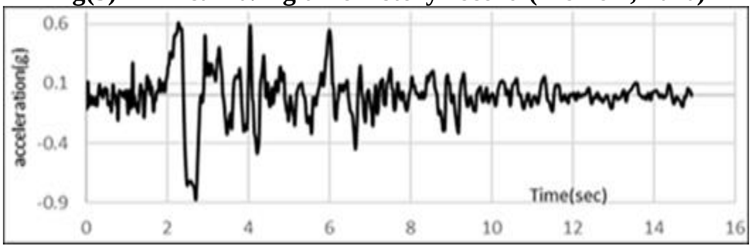
Fig(1) Location of shear wall



Fig(2) El-Centro-0.32g time history record (Melhem, 2020)



Fig(3) Erzincan-0.42g time history record (Melhem, 2020)



Fig(4) Northridge-0.87g time history record (Melhem, 2020)

Table(1) Properties of soil (Chinmayi et al., 2013).

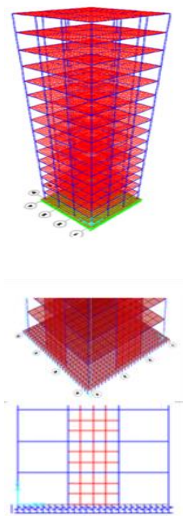
Soil Type	Shale ROCK (SB)	CONGLOMERATE (SC)	SAND (SE)
Shear wave velocity V_s (m/sec)	1200	600	150
Poisson's ratio μ	0.3	0.3	0.4
Unit weight γ (Kn/m3)	22	20	16
Shear modulus G (Mpa)	$3.23 * 10^3$	$7.34 * 10^2$	$3.67 * 10^1$
Young Modulus E (Mpa)	$8.4 * 10^3$	$1.91 * 10^3$	$1.03 * 10^2$

Table(2) Member's dimension of the system in different cases

No. stories	Up to 3 stories	Above 3 stories	Shear wall thickness
4	0.35*0.35	0.35*0.35	0.15
8	0.40*0.40	0.35*0.35	0.2
16	0.6*0.6	0.5*0.5	0.25

Table(3) Values of stiffness and damping Coefficient as Gazetas

stiffness	KX	KY	KZ	rx	ry	rt	cx	cy	cz	crx	cry	crz
Rock	$1.11x10^8$	$1.11x10^8$	$1.36x10^8$	$4.52x10^9$	$4.49x10^9$	$7.31x10^9$	$2.14x10^6$	$2.09x10^6$	$2.69x10^6$	$7.03x10^7$	$7x10^7$	$1.14x10^8$
Distributed values/m	$6.58x10^5$	$6.58x10^5$	$8.06x10^5$	$1.9x10^6$	$1.89x10^6$	$1.54x10^6$	$1.27x10^4$	$1.24x10^4$	$1.59x10^4$	$2.95x10^4$	$2.94x10^4$	$2.39x10^4$
Conglomerate	$2.53x10^7$	$2.53x10^7$	$3.09x10^7$	$1.01x10^9$	$1x10^9$	$1.65x10^9$	$5.79x10^5$	$5.57x10^5$	$7.4x10^5$	$1.58x10^7$	$1.56x10^7$	$2.57x10^7$
Distributed values/m	$1.49x10^5$	$1.49x10^5$	$1.83x10^5$	$4.26x10^5$	$4.21x10^5$	$3.46x10^5$	$3.43x10^3$	$3.29x10^3$	$4.38x10^3$	$6.64x10^3$	$6.57x10^3$	$5.39x10^3$
Sand	$1.34x10^6$	$1.33x10^6$	$1.7x10^6$	$5.53x10^7$	$5.27x10^7$	$7.86x10^7$	$5.81x10^4$	$5.34x10^4$	$8.85x10^4$	$9.54x10^5$	$9.14x10^5$	$1.33x10^6$
Distributed values/m	7939.3	7859.9	10145.8	23220.9	22128.4	16514.5	343.7	316.0	523.4	400.9	384.0	278.9

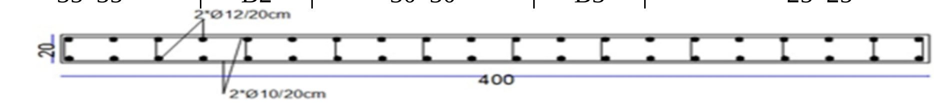
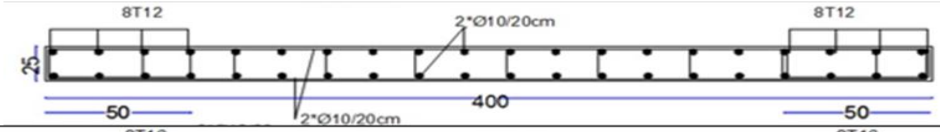
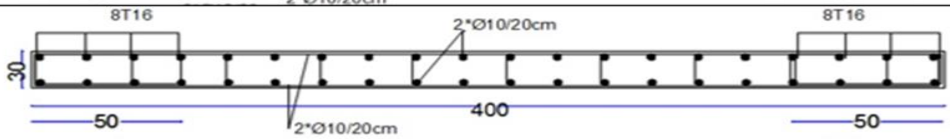


Fig(5) The model in SAP2000

1.2. Seismic Rresponse Modification Coefficient:

The Seismic Response Modification Coefficient is a seismic design tool that determines the expected level of plasticity in structural systems during an earthquake (ATC-19, 1995),(Priestley, 2007). It reflects a structure's ability to dissipate energy through inelastic behavior and is used to reduce earthquake-resistant design forces and calculate damping, power dissipation capacity, and increased strength of structure. We will first design the structural system for building according to the seismic requirements of Damascus city according to the developed static method [12], where soil section is SE in three cases (4-8-16) stories, in order to obtain a model that achieves a point performance in all cases. The dimensions of sections and their reinforcement are as shown in the following Tables 4, 5 and 6. Then a pushover analysis will be done for models (ATC-19, 1995).

Table(4) Dimensions and sections reinforcement used in the study

column	Col1	Col2	Col3	Col4	Col5	Col6	Col7	Col8
dimension	30*30	35*35	40*40	40*40	50*50	60*60	80*80	90*90
reinforced	1%	1.5%	1.5%	2.3%	2%	2.5%	2.3%	2.3%
Beam1	35*35		B2	30*30		B3	25*25	
Wal1								
Wal2								
Wal3								

Table(5) Dimensions and sections reinforcement used in case of 16 stories.

No.of stories	Corner col.	Central col.	Side col.	Shear Wall
16-15-14-13	Col2	Col5	Col5	Wal1
12-11-10-9-8-7	Col3	Col6	Col6	Wal1
6-5-4-3	Col5	Col7	Col7	Wal2
2-1	Col7	Col8	Col8	Wal3

Table(6) Dimensions and sections reinforcement using in case of 8 stories.

No.of stories	Corner col.	Central col.	Side col.	Shear Wall
8-7-6-5-4	Col2	Col2	Col2	Wal1
1-2-3	Col3	Col3	Col4	Wal1

Table(7) Dimensions and sections reinforcement used in case of 4 stories

No.of stories	Corner col.	Central col.	Side col.	Shear Wall
4	Col1	Col1	Col1	Wal1
1-2-3	Col3	Col3	Col3	Wal3

2. Results and discussions

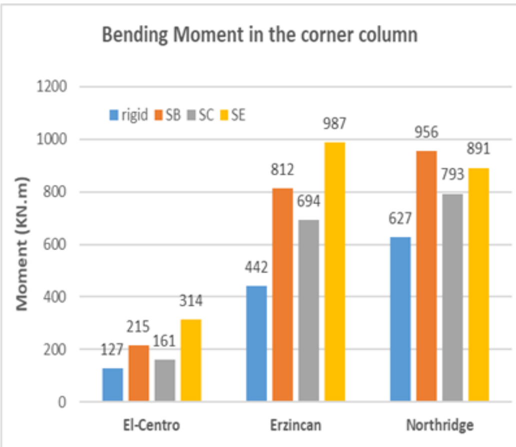
2.1. Case 16 stories model:

Table 8 Indicates that period increases in all soil types (maximum difference from rigid case 40% in sand), lateral deflection increase (maximum difference 62% in sand) and base shear decreases (maximum difference 58% in sand).

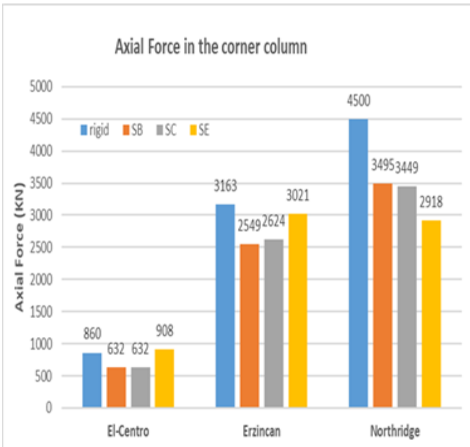
It was found that the peripheral frame next to the shear walls is the most dangerous frame in terms of internal forces. Axial force in the corner column decreased in varying proportions in rock and conglomerates soils with all earthquakes, Fig.7. Internal bending moments increased with decreasing soil hardness and in different proportions according to earthquake frequency, the largest was in sand soil with earthquake Erzincan (123%), Fig. 6.

Table(8) Main parameters compared with fixed case.

parameter	Earthquake record	rigid	substructure			Relative difference from rigid		
			Rock	conglomera	sand	Rock	conglomera	sand
(Period) sec	El-Centro	1.59	1.66	1.74	2.22	4%	9%	40%
	Erzincan							
	Northridge							
Lateral defl(m)	El-Centro	0.24	0.266	0.295	0.352	11%	23%	47%
	Erzincan	0.61	0.929	0.96	0.99	52%	57%	62%
	Northridge	0.63	0.86	0.96	0.82	37%	52%	30%
Base Shear (KN)	El-Centro	4840	4031	3655	3404	-17%	-24%	-30%
	Erzincan	13069	10972	10890	8951	-16%	-17%	-32%
	Northridge	19265	12721	11180	8141	-34%	-42%	-58%



Fig(6)Moment comparison in column with a different type of soil and support for each earthquake (16 stories)



Fig(7) Axial force comparison in column with a different type of soil and support for each earthquake (16 stories)

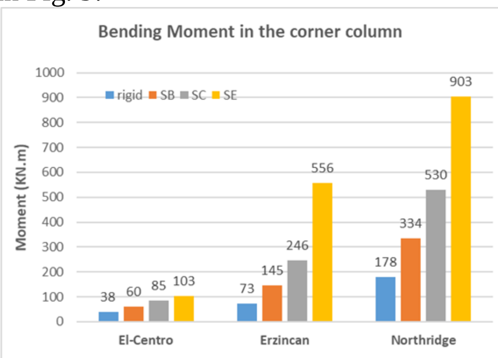
2.2. Case 8 stories model:

Table 9 shows that period increases in all soil types (maximum difference 73% in sand soil), lateral deflection increased in sand (maximum difference 34%) and base shear decreases in all soil types (maximum difference 50% in sand).

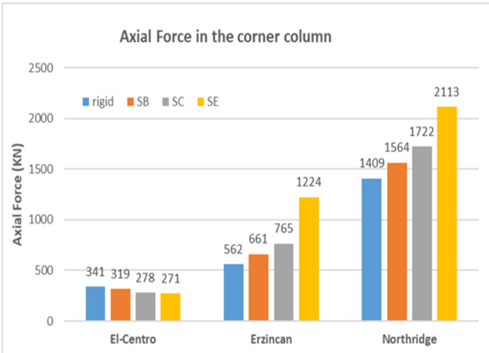
Table(9)Main parameters compared with the fixed case in case 8 stories

parameter	Earthquake record	rigid	substructure			Relative difference from rigid		
			Rock	conglomera	sand	Rock	conglomera	sand
Period) sec(	El-Centro	0.62	0.66	0.73	1.07	6%	18%	73%
	Erzincan							
	Northridge							
Lateral defl (m)	El-Centro	0.208	0.264	0.254	0.255	27%	22%	23%
	Erzincan	0.526	0.528	0.543	0.703	0%	3%	34%
	Northridge	0.668	0.644	0.65	0.796	-4%	-3%	19%
Base Shear (KN)	El-Centro	3881	3534	2771	1954	-9%	-29%	-50%
	Erzincan	7030	6880	6552	6844	-2%	-7%	-3%
	Northridge	17060	15380	14270	10900	-10%	-16%	-36%

The behavior of the column differed with the decrease in the number of stories, as the axial force began to increase in different proportions according to the type of soil and earthquake. Internal bending moments increased with the decrease of soil hardness and in different proportions according to the earthquake frequency, the largest was in sand soil with Northridge earthquake (400%) as in Fig. 8 and (50%) for axial force as in Fig. 9.



Fig(8) Moment comparison in column with a different type of soil and support for each earthquake (8 stories)



Fig(9) Axial force comparison in column with a different type of soil and support for each earthquake (8 stories)

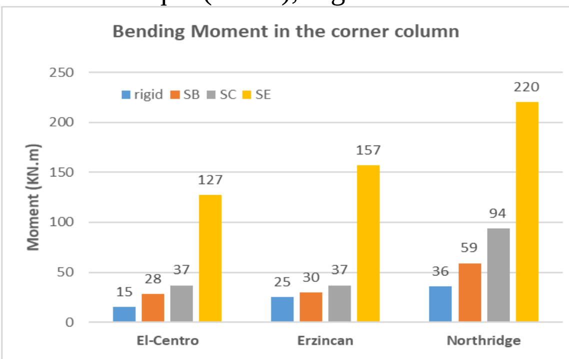
2.3. Case 4 stories model:

Table 10 shows that period increases in all soil types by maximum difference 204% in sand, lateral deflection increased in sand by maximum difference 38% and base shear decreases in all soil types by maximum difference 37% in sand.

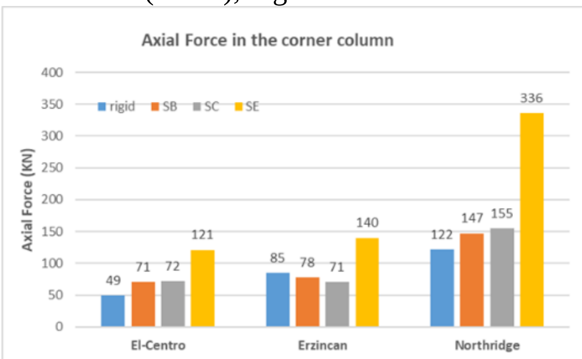
Table(10) Main parameters compared with the fixed case in case 4 stories

parameter	Earthquake record	rigid	substructure			Relative difference from rigid		
			Rock	conglomera	sand	Rock	conglomera	sand
Period) sec(	El-Centro	0.23	0.232	0.26	0.7	1%	13%	204%
	Erzincan				0.6			161%
	Northridge				0.59			157%
Lateral defl (m)	El-Centro	0.16	0.215	0.219	0.22	34%	37%	38%
	Erzincan	0.42	0.418	0.423	0.443	0%	1%	5%
	Northridge	0.397	0.389	0.396	0.429	-2%	0%	8%
Base Shear (KN)	El-Centro	2194	2155	1784	1620	-2%	-19%	-26%
	Erzincan	3762	2737	2390	2382	-27%	-36%	-37%
	Northridge	5498	5076	5181	5387	-8%	-6%	-2%

Internal moments increased with the decrease in soil hardness and in different proportions according to the earthquake frequency, the largest was in sand soil with Northridge earthquake. Northridge earthquake led to an increase in torque (512%), Fig.10 and an increase in axial force (165%), Fig.11.



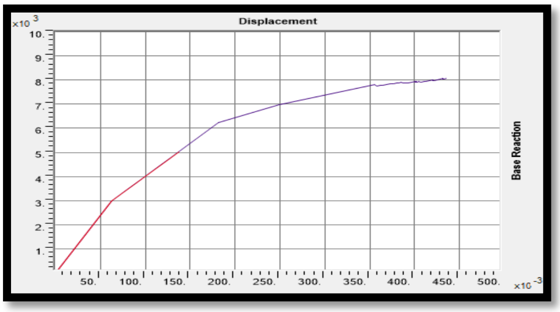
Fig(10) Moment comparison in column with a different type of soil and support for each earthquake (4 stories)

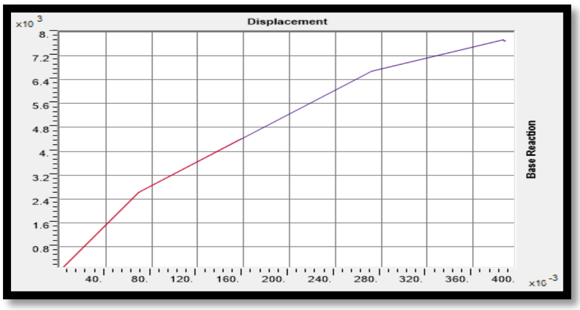


Fig(11) Axial force comparison in column with a different type of soil and support for each earthquake (4 stories)

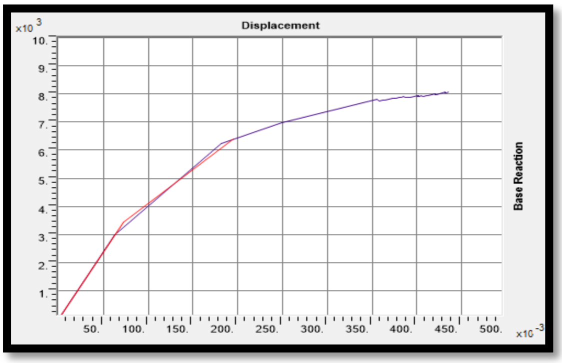
2.4. Calculation of the seismic Response Modification Coefficient:

The following Figs. show the change in coefficient values with the change of soil type for each model of the stories separately, and the result are summarized in Fig. 15, and Fig. 16.

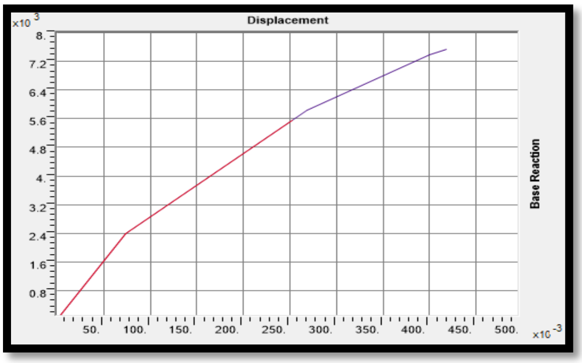




FIX-SB , R=5.87 **SPRING-SB . R=5.53**



FIX-SC , R=7.5

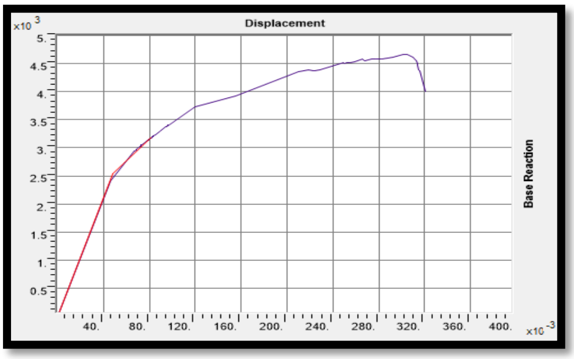


SPRING-SC , R=6.5

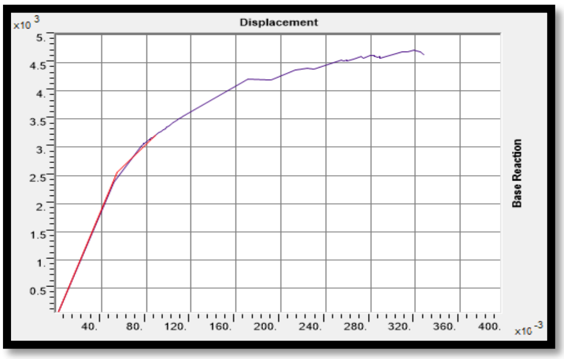
FIX-SE , R=7.57

SPRING-SE , R=4.5

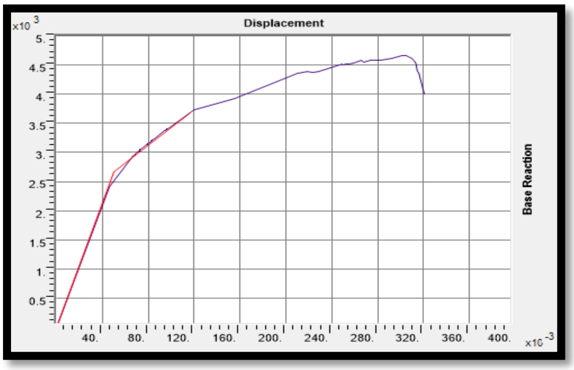
Fig(12) Pushover diagram for case 16 stories)



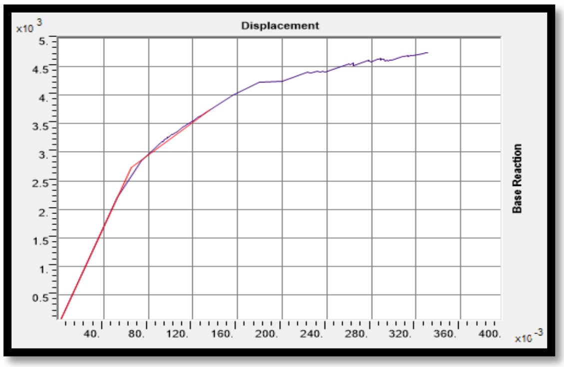
R=6.08 , FIX-SB



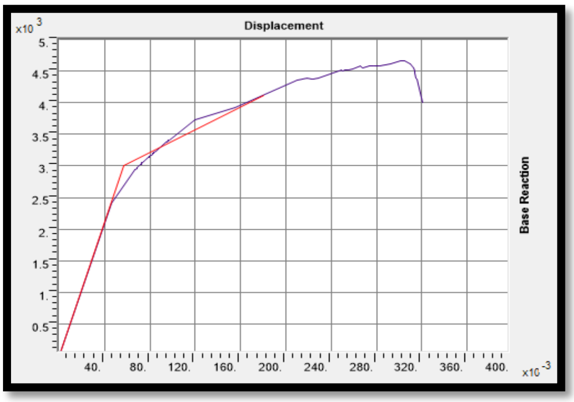
SPRING-SB , R=6.75



FIX-SC , R=5.64



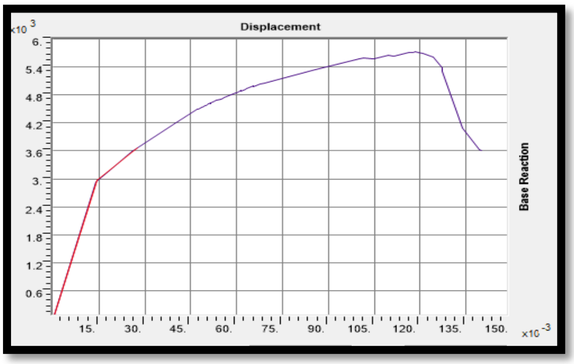
SPRING-SC , R=6.76



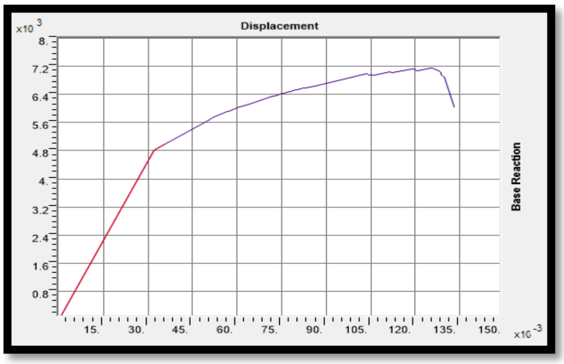
FIX-SE , R=5.7

SPRING-SE , R=5.05

Fig(13) Pushover diagram for case 8 stories)

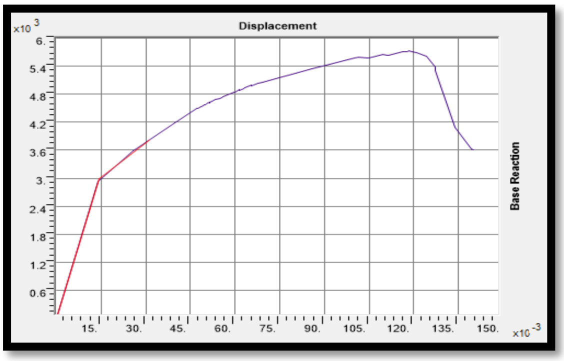


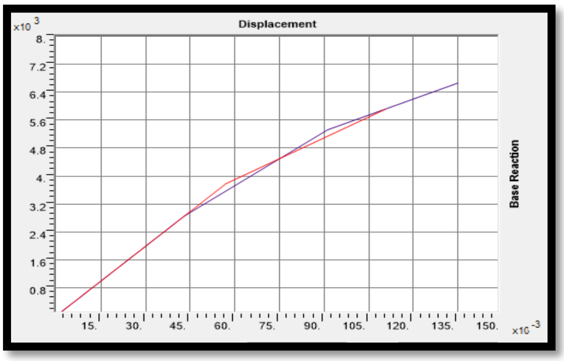
FIX-SB , R=6.9



SPRING-SB , R=5.9

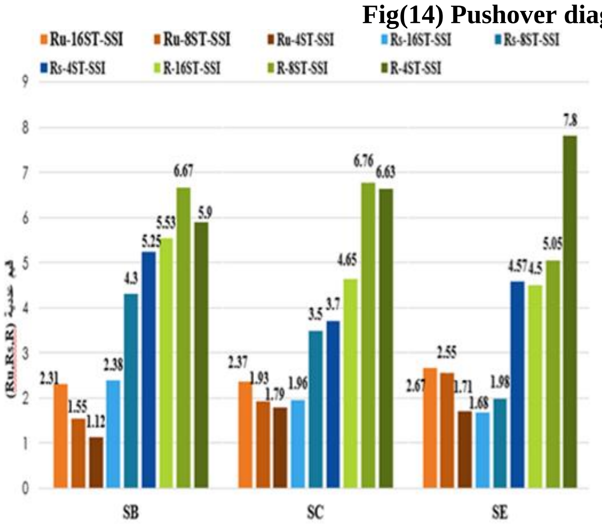
FIX-SC , R=7.56 **SPRING-SC , R=6.63**



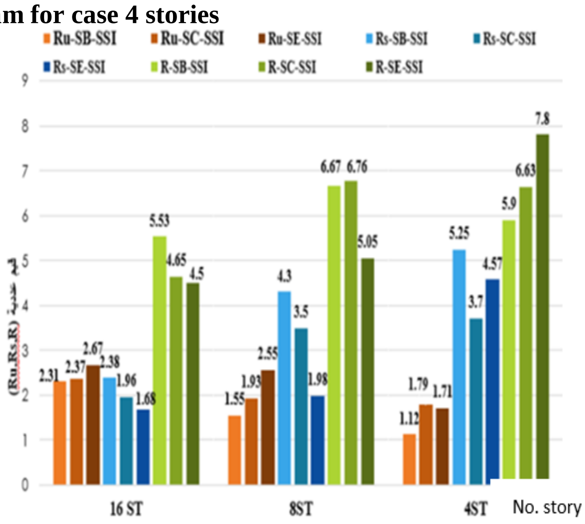


FIX-SE , R=8.25 **SPRING-SE , R=7.8**

Fig(14) Pushover diagram for case 4 stories



Fig(15) Comparing the R component in different cases of soil and different stories



Fig(16) Comparing the R component in different cases of soil and stories

Fig. 15 shows the effect of difference in the number of stories on (R) with the stabilization of the soil type. In case of rock and conglomerate soils, the case of 8 stories gave the largest value of (R) (6.67) and (6.76), respectively. While in sand soil, the number of stories 4 gave the largest value of the coefficient (7.8) difference percentage of code (20%), (ASCE 7-10. 2010), (Syrian Arabic Code, 2013). Fig. 16 shows effect of different soil types on (R) with stabilization of the number of stories. In case of 16 stories rock soil gave the largest value (5.53) but all values was less than code one (6.5). In 8 stories case conglomerate soil gave the largest value (6.76) and only sand gave value (4.5) less than code. In 4 stories the sand gave the largest value (7.8) and only rock (5.9) gave value less than code.

3. CONCLUSION:

- Effect of SSI is as great as possible when there is a discrepancy between the soil hardness and the structure (flexible structure - hard soil and vice versa) of the state of sand soil.
- Effects of SSI is clearer in case of buildings with low stories and weak soils (sand soil has a lower hardness coefficient and therefore large rotations in the foundation).
-The international codes considered one value for the response modification coefficient for dual systems (in the Syrian Arab and ASCE codes, R= 6.5) (ASCE 7-10. 2010), (Syrian Arabic Code, 2013) regardless of the characteristics of the structure, the number of stories and the nature of the depreciation (fix or soil) which is not sufficient because its values differ according to these characteristics of the one type of systems.
-The introduction of SSI in the study increases the design requirements and its impact cannot be neglected, where neglecting it gives a design far from reality, as it increases the wholesale sections and therefore it has a higher cost.

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