Nonlinear Static and Dynamic Analysis of Buildings Considering Soil Structure Interaction

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ABSTRACT:
An attempt has been made during the present study to understand the behavior of reinforced concrete structures considering soil structure interaction. A multistoried frame building subjected to seismic forces are modeled and analyzed through the finite elements software program (SAP 2000 V14) which are primarily designed according to ACI 318M-11) and ASCE 7-10 Code. Both static and dynamic analysis methods are used, which may be linear and nonlinear. Recorded ground motions are used in nonlinear dynamic (time history) analysis. Analyses of frames are carried out to find the lateral displacements, drift ratios, and time period of free vibration motion of structural systems. The study reveals that soil flexibility has significant effect on the response of structures. Soil flexibility led to increase the storey drift and lateral displacement. In addition, it led to increase in neutral lateral time period of structure vibration of frame buildings especially, with soft soil stiffness. The present study also, presents a methodology to protect the structure against earthquake excitation by using rubber isolators, where decreases in the natural frequency of structure building have been observed and the presence of rubber at a location of each column led to decrease the value of axial force and shear base stress as compared with fixed-base case.
Keywords: Building structural system, Finite Elements Method, Nonlinear Dynamic analysis, Soil–structure interaction, Time history analysis.

INTRODUCTION
In any structure, the superstructure and the foundation founded on soil constitute a complete structural system. Structural system is influenced by the type of soil as well as the type of structure; nevertheless most of the designers do not consider the effect of soil structure interaction on structures. The analysis of the superstructure without modeling the foundation system and without considering the rigidity of structure may result in a misleading estimation the real behavior of the structure. Especially, when a structure is subjected to a seismic excitation, since it interacts with the foundation and soil, and thus changes the motion of the ground. Therefore, it is

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increasingly significance and becomes essential to consider the effect of soil structure interaction in the buildings which are located in the earthquake prone, Dutta et al. (2009). Likewise, Abdel Raheem et al. (2014) concluded that if the SSI method is not taken into account in analysis and design properly; the accuracy in assessing the structural safety, facing earthquakes, could not be reliable.

Seismic structure design provisions typically allow structures to undergo inelastic deformations in the event of shaking ground motions. Nevertheless, in most practical design situations only linear elastic analyses are used to estimate the maximum response of the structure. So, it is still considered impractical to carry out nonlinear time history analyses for most practical design situations. Structures suffer significant inelastic deformation under a strong earthquake and dynamic characteristics of the structure change with time, so investigating the performance of a structure requires inelastic analytical procedures accounting for these features. Thus, it was necessary to use basic analysis techniques to estimate the maximum inelastic response of a structure during earthquake ground motions.

Generally, one of the main effects of considering soil structure interaction during the analysis is a decrease in the overall stiffness and an elongation of the overall structural period, which, in general, decreases force demand and increases displacement demand on the structure. So, the modification in fundamental lateral natural period due to the effect of soil–structure interaction must be studied on buildings over raft foundation resting on various soil types’ viz. soft, medium, hard and soft –dynamic simulation. The purpose of earthquake prevention of buildings is to provide the structural safety and comfort by controlling the internal forces and displacement within the particular limits. Base isolation is one of the most widely accepted techniques to protect structures and to mitigate the risk to life and property from strong earthquakes. So, this study is to describe and investigate the influence of considering soil flexibility on the maximum inelastic response of multistoried frame building, and particularly the maximum lateral inelastic displacement, using the results from a linear elastic analysis, and to present a methodology for using rubber isolator in frame system. Inelastic displacement ratios can be described as the ratio of peak inelastic displacement to peak elastic displacement for a system with same damping ratio, Miranda (2000).

Description of the Structural System:

The considered structure is a 3D reinforced concrete frame designed according to the (ASCE) American Code of Seismic design ACI-318-2011 Code. The frame has 4 levels each having a 3 m height and 3 bays with the following dimensions: 4x4x4 m on each direction. It is a symmetrical structure. In order to model the elastic support, elastic springs were considered. The foundation is a square surface mat, made from reinforced concrete. The geometry, loading conditions and all details of the problem are shown in Figure (1). Table (1) presents the dimensions of the all structure models and Table (2) presents the material properties used for the structure. The finite element discretization of the building structure models are carried by (SAP 2000 V14) software.

Description of the Proprieties of Soil:

In the present case study, three types of soil are adopted to study the influence of soil structure interaction. The simulation of soil has been done by develops Winkler's Model as a three dimensional springs, These expressions were developed in such a form that springs located below at each (0.5m2) of the raft foundation surface area, the three degrees of freedom can account for the flexible behavior of soil below the entire raft in the equivalent sense by two cases:

1- Static Behavior for soft, medium, and hard soils:

An equivalent linear approach is adopted to identify the spring by for three different values of modulus of subgrade reaction 'K' relating to different soil types as shown in Table (3). It was considered as fixed base condition as well as considering flexible-base condition resulting from soil flexibility. A 5% of critical damping which is reasonable for concrete structures is considered. The plate load test (PLT) has been a traditional in situ test to estimate the modulus of subgrade reaction, Terzaghi (1995). PLT is a direct test to determine both KS and ES. It is a direct measurement of the compressibility and bearing capacity of the soil.

2- Dynamic Behavior for Soft Soil:

Table (4) represents the value of spring constant optioned by using the frequency independent foundation stiffness relations given by New mark Rosenblueth, which are depicted in Table (5). This stiffness permits the estimate and the control of the foundation impedances, foundation soil damping and natural frequency of the structure, Davidovici (1999).

In Table (5), G is the effective shear modulus of the soil, and ν Poisson's soil ratio, A is a foundation area; βz, βx and are coefficients that depend on the Poisson's ratio value and on the value of the ratio between the foundation dimensions.

Properties of Rubber Isolator:

In the present study the same previous two models of buildings (frame building and frame plus shear wall building) one is without base isolation and the other is with base isolation was analyzed in two cases:

1- Rubber isolator at just outside columns.
2- Rubber isolator at all columns.

Also, load cases were used in the analysis like previous load cases for live, dead, and seismic by Lacc-North time history earthquake. The properties for rubber isolator are shown in table (6), which provided from the manufacturer the stiffness (K) was 1751000 (kN/m2) in two direction (x, y) and its mass was 0.45*10-4 (ton).

Time History Analysis:

The time history analysis is very handful for multi storey building with a symmetrical plan. The dynamic load is applied on all models of structure; LACC NORTHDAGE earthquake record in CENTURY city – 1994 (0.020 Sec. and PGA is 0.18g (sap 2000 v14)) as shown in figure (2), which is used for linear and nonlinear dynamic analysis (direct integration method). These records are used from (Sap 2000 time history file) ground motion levels of intensity were performed for X direction in each analysis. A constant damping ratio of 5% has been taken for RC buildings. Linear and nonlinear time history analyses were totally applied. It was selected because of its PGA that is close to PGA of IRAQ category which have the value nearly o.15 g.

Discussion of Results:

There are various parameters which are taken into account in present study, loading type, support type, soil type. In all case studies, the reference which compared with all results is the bare frame building with fixed support and there is no soil structures interaction under static loading. In the traditional design for structural system not including the soil structure interaction and assumed that according to the type of support recommended by soil investigation and simulated by any structural software as affixed if the type of support is pile cup or raft and pin contacted with tied beams in case of separate footing.

Effect of Soil Structure Interaction:

This study aims to quantify the effect of Soil-Structure Interaction and foundation flexibility on the structural response demands of multistoried frame buildings. So that, Lateral displacements, drift, and lateral natural frequency are obtained for all the modes and are tabulated in the table (6). The profiles of lateral displacement along longitudinal direction for static and dynamic method are shown in figure (3).

The result showed that, the storey displacements of flexible-base structures are considerably more than that of structures modeled as fixed base. Such a big difference in storey displacements and drifts is not negligible; thus, the effect of soil–structure interaction must be taken into account in static analyses as shown in figure (3) and figure (4). The results of the present study show clearly that, the lateral displacement on (bare frame model was higher than 1.75 times of fixed base case.

Dynamic Behavior of Building Considering SSI:

- **Effect of SSI on lateral natural period:**

From results of the models analyses it can be noticed the importance of considering soil structure interaction as it affects the natural period of the structure and its frequency in case soft soil stiffness's principally, it was 11%, and there is no change when soil is hard, these results are also plotted in Figure (7), for the sake of wholeness. And considering SSI, decreased because of the stiffness of structural elements decreased according to support types with constant masses.

- **Effect of SSI on lateral displacement and drift ratio:**

Time history analysis effects on building as linear and non-linear according to the type of supports are taken into account and discussed. From Figure (7) and Table (6); it is noted that the decreasing in soil stiffness's led to increased lateral displacements for model bare frame.

For frame building BF Figure (6) depicts the obvious impression of the lateral displacements of (the four floors with ground level in longitudinal direction) behavior of the building during the time of the earthquake with each type of flexible foundation in addition to the fixed base.

The maximum lateral displacement was increased in case of SSI because of there are no full interaction between the full elements and the flexibility of soil make the super structure more displaced.

- **Effect Of Rubber Isolator On Frame Structure Behavior:**

Table (7) represents the ratios of simulation for existence of rubber isolator in two cases: 1) rubber in all columns, 2) rubber in outside columns to fixed base for bare frame model. From these values of ratios for axial force, it can be noticed that the reduction in axial force ratio for the lower the value is the better and has an economic benefit and as observed from that the value of axial force for rubber case to each columns led to a reduction by 85.9% and to 40.33% for frame model than it is in the case of fixed-base.in partial representation, and full representation case respectively.

It can be noted that the presence of rubber isolator allowed causing a horizontal displacements in the lowest point and this led to decrease rigidity of the building, which reduce the stresses resulting from base shear. Therefore, the resulted increase in displacement at the top floor point is clearly identified because the increase has been become cumulative and this behavior is obvious in the figure (8). And it can be noticed the reduction in the frequency which leads to absorb more energy and elongate the period time of the natural frequency for the structure.

CONCLUSIONS:

Based on the findings and the discussion of the different loading and stiffness's of soil, the following conclusions can be made:

- The results of the dynamic analysis are intended to represent mean values for the applied earthquake exaction. There is a considerable scatter about the mean. Consequently it is appropriate to investigate likely building performance under extreme load conditions that exceed the design values. This can be achieved by increasing the target values of displacement.
- The response of superstructure, foundation and soil mass are significantly altered due to the effect of soil-structure interaction. For accurate estimation of the design force quantities, the interaction effect is needed to be considered.
- When taking into account the shear modulus (G) in the soil simulation of analysis of the building led to different results from using subgrade modulus (K) in simulation of the soil flexibility.
- By using the rubber isolator, the drift ratio between the floors of a building is minimized and axial force is reduced.

Notation:

Frame model = BF

Linear = L

Nonlinear = NONL

Lat. dis.= lateral displacement

TH = time history

Fixed-base = fb

Soft soil = S_s

Medium soil = S_m

Hard soil = S_h

dynamic simulation of soil = S_d

Table (1): Dimensions of the structure model.

Name of model	Column (mm)	Reinforcement Ratio for (%)		Beam (mm)		Slab (mm)	Raft (mm)
		Column	Beam	Depth	Width		
Frame	300x300	1	0.9	300	500	150	600

Table (2): Material properties for concrete in the basic problem.

	Symbol	Definition	Value
Concrete	f'_c	Cylinder compressive strength (MPa)	30
	E_c	Young's modulus (MPa)	25743
	f_r	Modulus of rupture (MPa)	3.3958
	υ	Poisson's ratio	0.2*
	ρ_c	Density (kg/m3)	2500*

Note: * Assumed value;

$E_c = 4700\sqrt{\acute{f_c}}$ and $f_r = 0.62\sqrt{\acute{f_c}}$ as per ACI-2014 Code.

Where:

K_s: modulus of subgrade reaction to be evaluated from appropriate tests on soil (kN/m^3)

$$k = \frac{(1-\sin(3.14159*\theta/180))}{(1-\sin(3.14159*\theta/180))}$$

And, $K_{s\ Horizontal} = k * K_{s\ Vertical}$

$K_{s\ Vertical}$ is the value of vertical modulus of subgrade reaction, and

Table (3): Values of modulus of subgrade reaction 'K' pertaining to different soil types.

Type of soil	Angle of friction θ (Deg.)	γ	K_{factor}	$K_{s\ Vertical}$ (kN/m^3)	$K_{s\ Horizontal}$ (kN/m^3)
Soft	30	19	0.3333	10000	3333
Medium	35	20	0.271	64000	17343
Hard	45	22	0.1716	84000	14823

$K_{s\ Horizontal}$ is the value of horizontal modulus of subgrade reaction, and k factor to obtain the horizontal modulus of subgrade reaction.

Table (4): Values of dynamic spring pertaining to soft soil types.

Type of soil	E Modulus of elasticity MPa	υ	G MPa	Velocity m/sec	Foundation area (m^2)	K_v kN/m	K_h kN/m
Soft	13.317	0.45	4.5921	150	169	108540	173121

Table (5): Dynamic spring constant for a rectangular surface mat foundation, ASCE (2010)

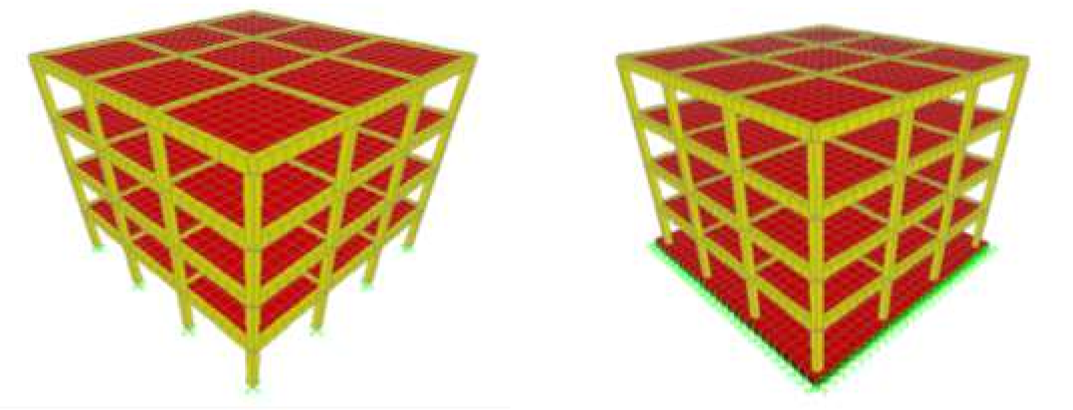
Movement	Foundation Stiffness
Vertical	$K_v = \frac{G}{1-v} \beta_Z \sqrt{A}$
Horizontal Sliding	$K_h = 2(1+v)G \ \beta_\chi \sqrt{A}$

Table (6): Values of maximum displacement with time at top floor by linear and nonlinear analyses in addition to model analysis and natural frequency for all building models

Model Type	Lat. disp. Linear (m)	Time (sec)	Lat. disp. Non Linear (m)	Time (sec)	Model (m)	Time of period (sec/2Π)	Time of lateral natural period (T) (sec)	Variation in natural period
BF-fb	0.8922	2.6	0.827	4.8	0.0665	0.5963	0.5963	reference case
BF-Sh	0.9289	2.6	0.9017	5.6	0.0664	0.6093	0.6093	2.23%
BFSm	0.9247	1.6	0.8928	5.6	0.0664	0.6105	0.6105	3.9%
BF-Ss	1.063	9.4	1.178	8.7	0.0662	0.6549	0.6549	11.01%
BF-Sd	0.9036	2.6	0.8504	5.6	0.0665	0.5999	0.600	1.069%

Table (7): the ratio of model (frame and frame-shear wall) (outside rubber and all rubber) to fixed base case.

Axial force Ratio	Dynamic linear analysis(rubber/fixed)	Dynamic nonlinear analysis (rubber/fixed)
($BF_{\text{outside rubber.}}$/BF-fb)	0.8256	0.8593
($BF_{\text{full rubber}}$/BF-fb)	0..803	0.4039



a) frame system-fixed-base b) frame system with SSI

Figure (1): A finite-element discretization of four-story frame Building.

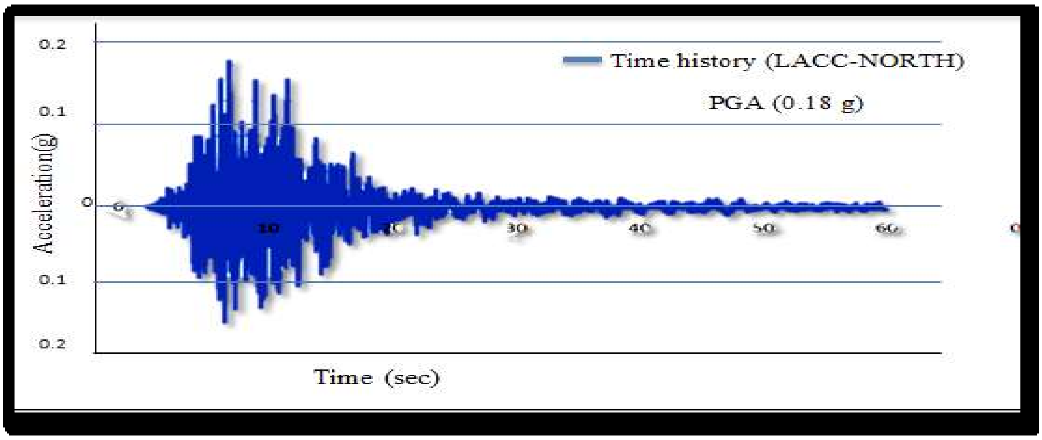


Figure (2): Time history – LACC- NORTH earthquake record (obtained using SAP 2000)

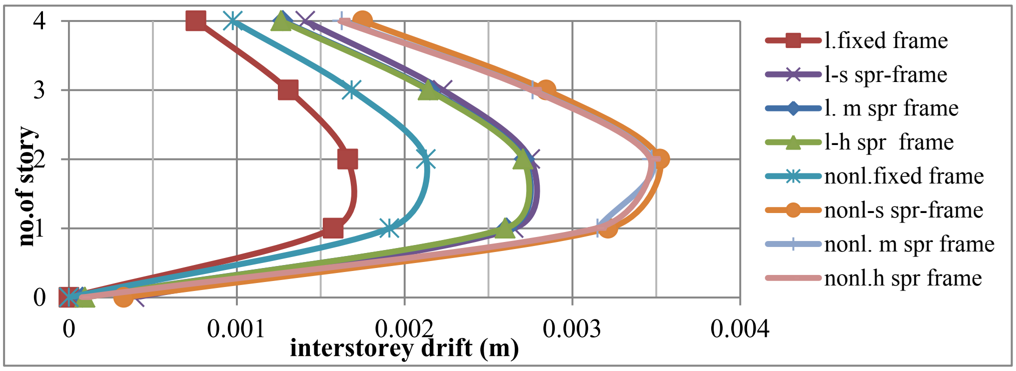


Figure (3): Storey drifts for linear and nonlinear static analyses with SSI (Ss, Sm, Sh) compared to without SSI (fb) for bare frame, and Ss compared to with and without SSI (fb)

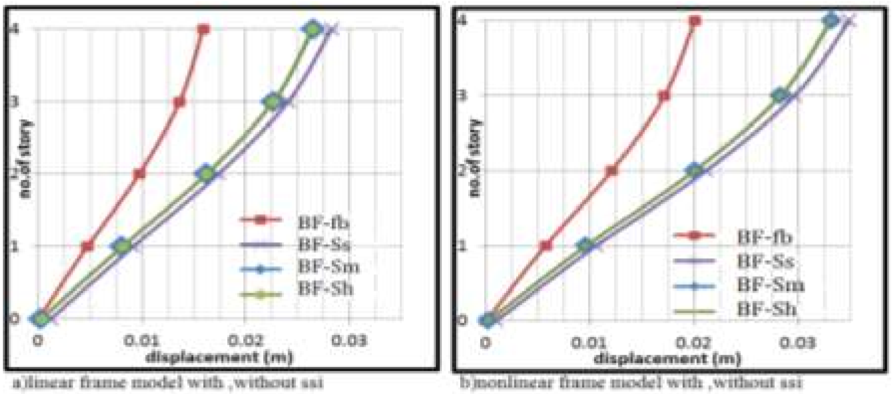


Figure (4): Effect of SSI on the result of lateral displacement of building models (linear and nonlinear) static analysis.

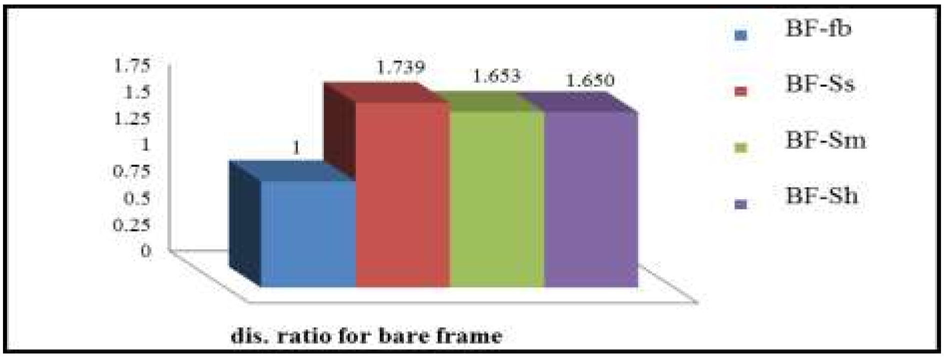
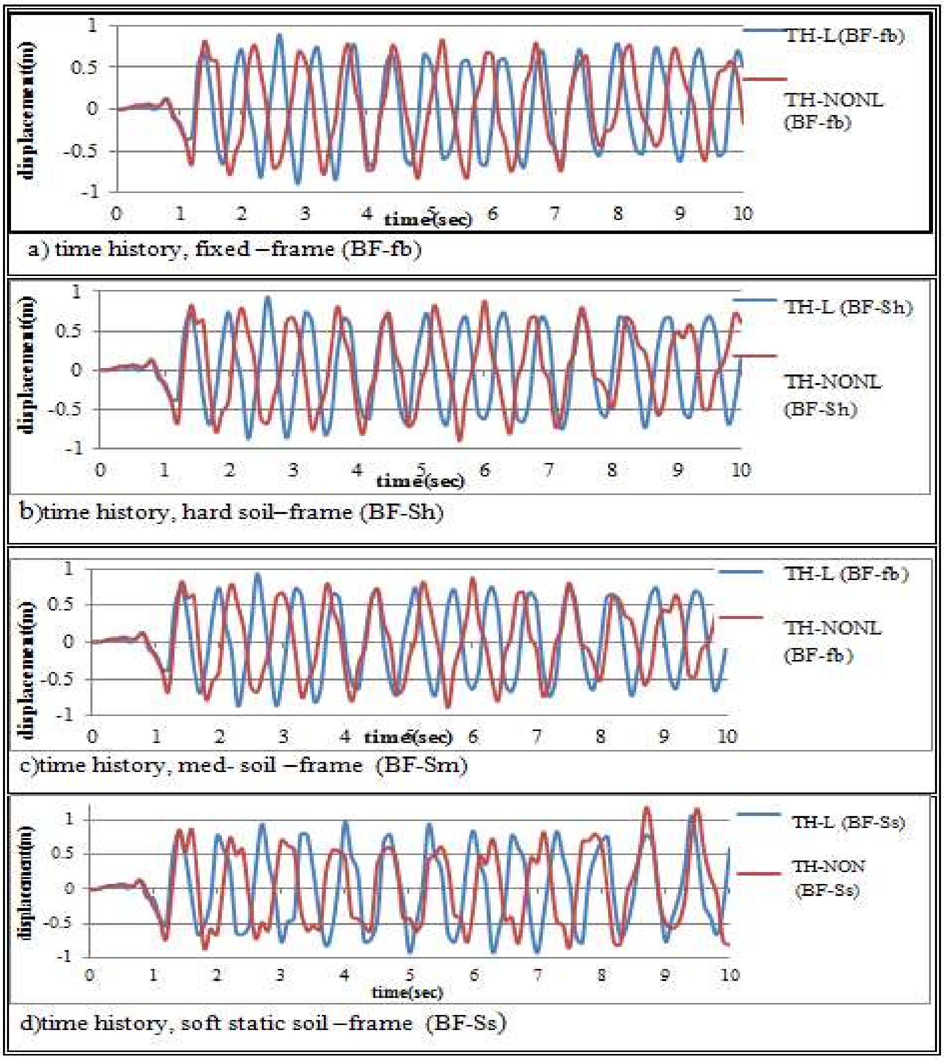


Figure (5): Lateral displacement ratio of SSI (flexible-base) for soil types to fixed-base models of building for nonlinear static structure analysis.



a) time history, fixed –frame (BF-fb)

b)time history, hard soil–frame (BF-Sh)

c)time history, med- soil –frame (BF-Sm)

d)time history, soft static soil –frame (BF-Ss)

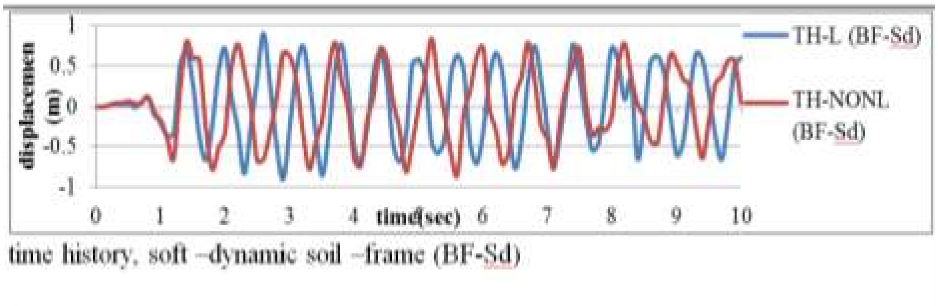


Figure (6): Max lateral displacement in structure model BF (bare frame) at top floor respective with time (linear and nonlinear analysis).

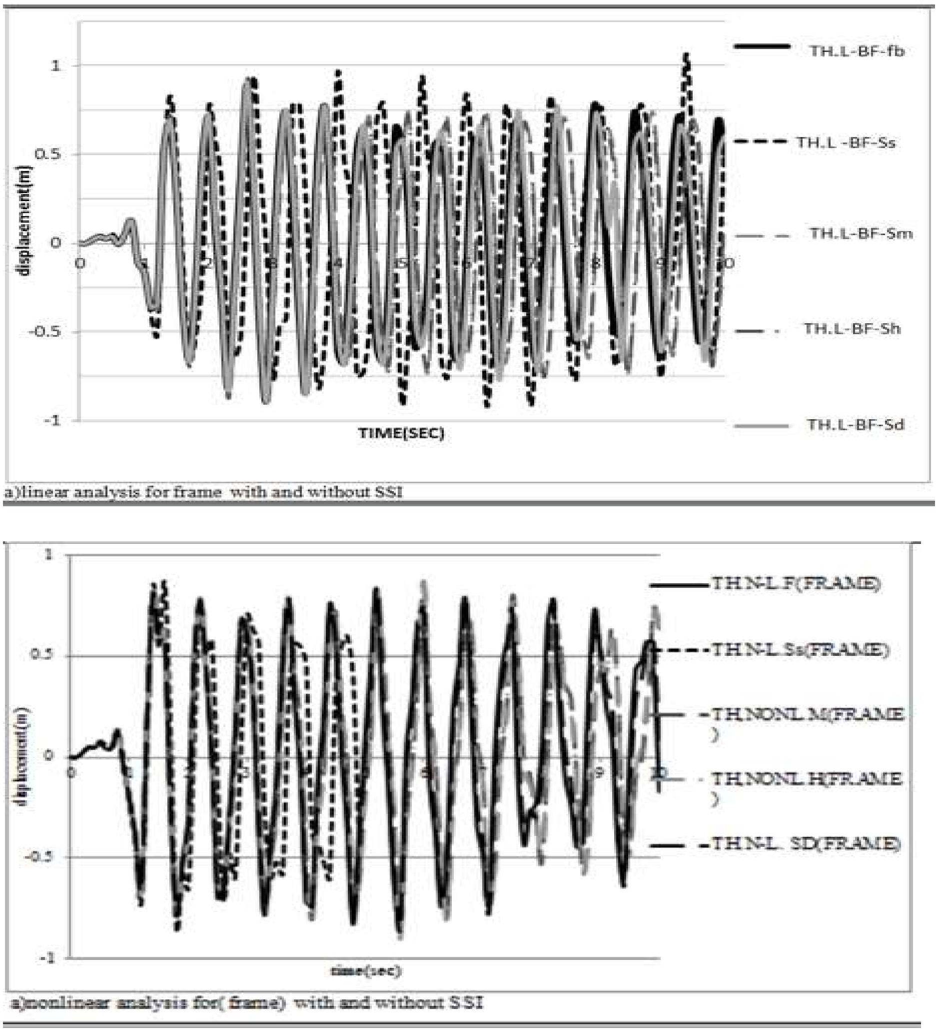
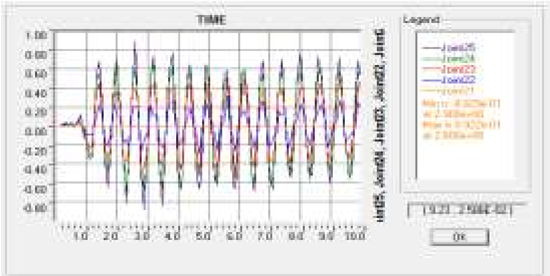
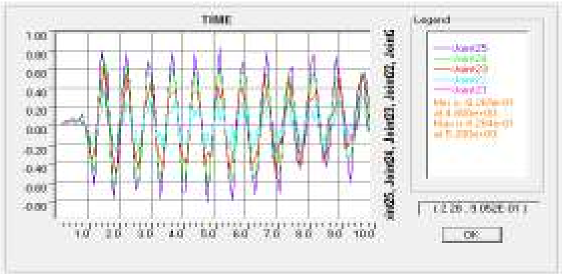


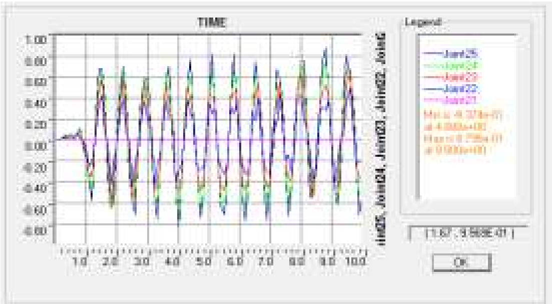
Figure (7): Maximum lateral displacements of top floor of multistoried building of nonlinear analysis for fixed with and without soil structure inter action.



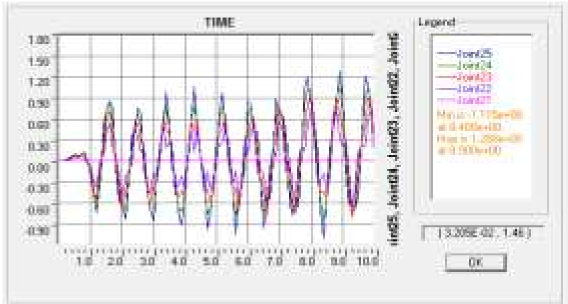
a)fixed –base frame(linear)



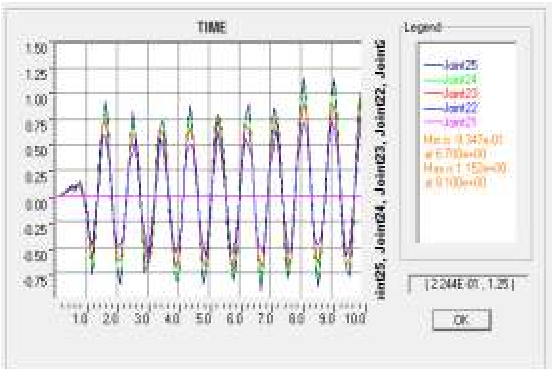
b)fixed base frame(non linear)



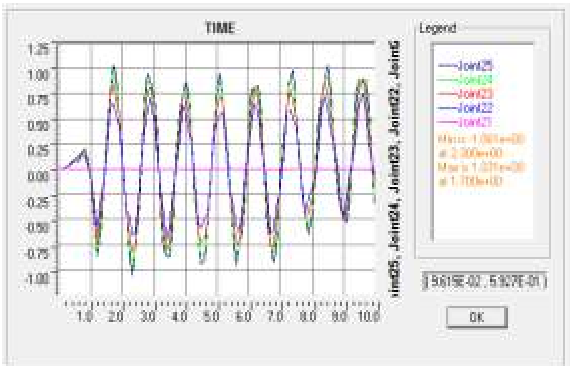
c) outside rubber frame(linear)



d) outside rubber frame(nonlinear)



e) full rubber frame(linear)



f) full rubber frame(nonlinear)

Figure (8): the influence of existence of rubber isolator on lateral displacement with time (time history analysis) by sap2000 V14.

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