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The Effect of Supporting Soil on Seismically Isolated Buildings of Variable Geometric Configurations with and without Shear Walls

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Abstract— **Multi – story reinforced concrete buildings of various geometric configurations (symmetrical, vertically irregular, and horizontally irregular); with and without shear walls; having different base conditions (fixed, isolated using high damping rubber bearing and friction pendulum systems); resting on different soil characteristics (medium dense sand and dense sand), are analyzed by using finite element method under seismic load function (North – South component of the ground motion recorded at a site in El Centro, California in 1940). The bilinear hysteretic model of base isolation system and the Rayleigh damping framework for superstructure and soil are adopted. It is proved that, the base isolation is very effective technique in reducing the earthquake responses and that, the friction pendulum system is more efficient in reducing the earthquake responses compared to the high damping rubber bearing isolators of the same design displacement and fundamental period. Also, including the supporting soil in the analysis will increase the base shear and increasing the soil elastic parameters and angle of internal friction, reduces the base shear considerably for the fixed base structure but, has negligible effects on the base shear for the isolated structures.**

Keywords— Multi-story, vertically irregular, horizontally irregular, isolated building, friction pendulum, high damping rubber bearing, seismic, finite element, soil

I. INTRODUCTION

Isolation shifts the response of the structure to a higher fundamental period and increases the damping, thus reducing the corresponding pseudo acceleration in the design spectrum and attracting smaller earthquake-induced forces, as illustrated in Fig. 1.

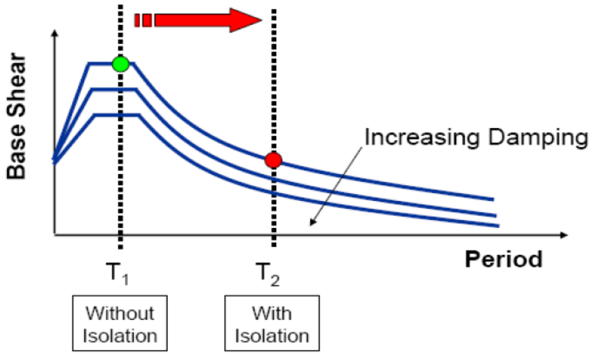


Fig. 1 Design spectrum for fixed-base and isolated base [1].

The main consequences of a seismically isolated structure are [2]:

a. The increase of the fundamental period with the consequent decrease of the structures this effect can be inconsistent or it could also generate bigger design forces.

b. The concentration of the inelastic deformation into the bearings.

c. The dissipation of seismic energy into the isolators, by hysteretic damping in its components, allowing the decrease of shear force and maximum displacement demands.

Gomase and Bakre, 2011[3], investigated the seismic response of fixed base and base isolated three dimensional four story building under three real earthquake time histories [El-Centro (1979), Northridge (1994), and Kobe (1995)]. The force deformation behavior of an isolator was modeled as bilinear hysteretic behavior. In order to investigate the performance of base isolation systems designed according to (UBC-97), nonlinear time history analyses of a four-story base isolated building, located to the specific distance from an active fault, were carried out. The isolation system was composed of high damping rubber bearing. Design displacements were estimated using the (UBC-97) parameters. The results showed that, the (UBC-97) had predicted isolator displacements successfully. Performance criteria were established to check the effectiveness of the isolation system. Those included peak base displacement, peak roof-drift ratio, peak roof top acceleration, and peak base shear. The latter three measures were significantly reduced for the base isolated building, compared to its fixed-base counterpart.

The effect of damping on the response of a (2 bay x 4 bay) eight story base-isolated building was investigated by Ounis and Ounis, 2013 [4]. A parametric study was conducted, taking into account the progressive variation of the damping ratio (8% to 35%) under different types of seismic excitations (El-Centro, Loma Prieta, and Northridge). A time history analysis was used to determine the response of the structure in terms of relative displacement and inter-story drift at various levels of the building. The results showed that the efficiency of the isolator was increased with the assumed damping ratio, provided that the latter is less or equal to (20%). Beyond this value, the isolator became less convenient. Furthermore, a strong deviation of energy capacity by the lead rubber bearing system was recorded.

In this paper two isolator types were used, sliding and elastomeric systems, which represented by the Friction Pendulum System (FPS) and the High Damping Rubber Bearings (HDRB), respectively.

II. MODELING THE ISOLATED BUILDINGS

The buildings are modeled using the finite element method. A directional material model is used for the superstructure elements, in which uncoupled stress-strain behavior is modeled for one or more stress-strain components. When the state of stress or strain reaches critical value, the concrete can start failing by fracturing. The fracture of concrete can occur in two different ways. One is by cracking under tensile type of a stress state, and the other is by crushing under compressive type of a stress state.

The force-deformation behavior of the two systems of isolators is modeled as non-linear hysteretic represented by the bi-linear model as shown in Fig. 2. The isolator is modeled using six springs. The springs for three of the deformations: axial, shear in the x-z plane, and pure bending in the x-z plane are shown in Fig. 3. The hysteretic models for bearings is used to account for all the energy dissipation, and the viscous damping using the Rayleigh damping framework is used for the superstructure.

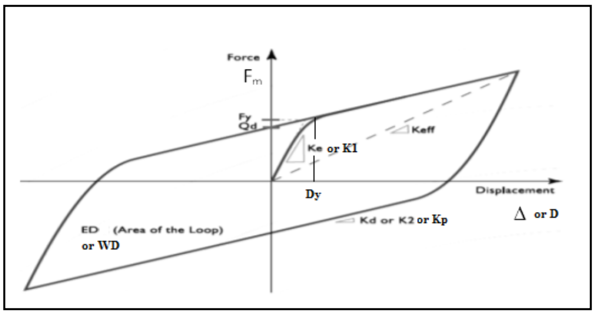


Fig. 2. Parameters of basic hysteresis loop of an isolator for bilinear modeling [5].

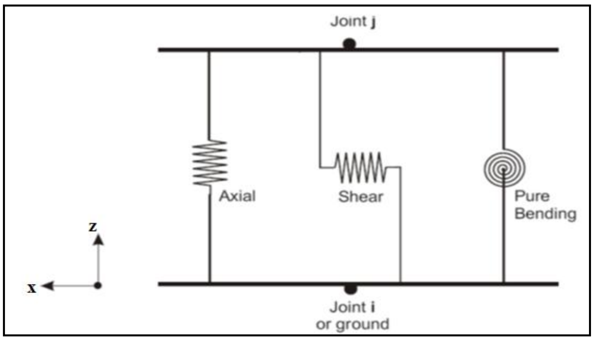
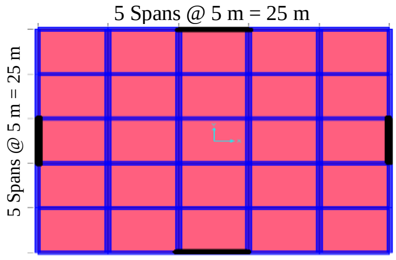
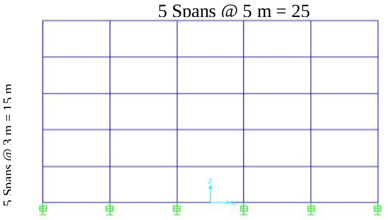


Fig. 3. Three of the six independent springs in a link/support element [6].

The geometric configurations of the superstructures are shown in Fig. 4, 5 and 6. A (150 mm) thick slab and (150 mm) thick shear walls are considered with (400 mm x 600 mm) beam typical sections and column size of (600 mm x 600 mm). The skeleton of the studied cases is illustrated in Table 1.

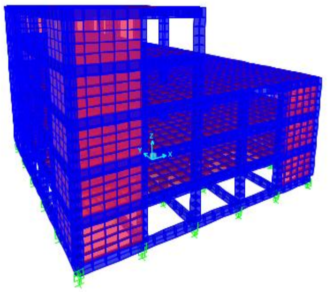


a. Plan

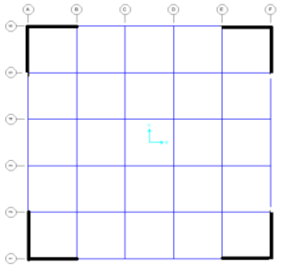


b. section

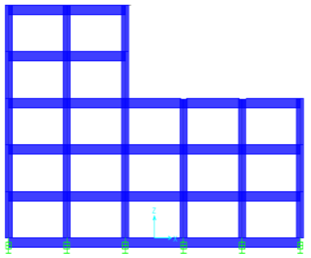
Fig. 4. Symmetrical building



a. 3D view

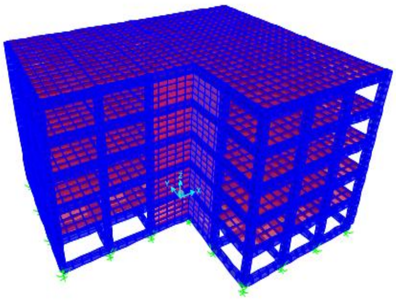


b. Plan

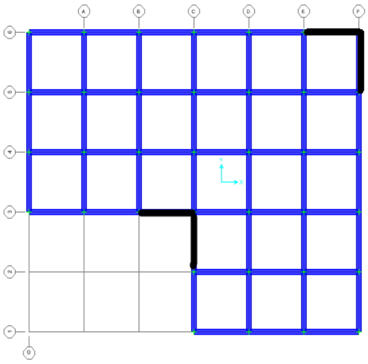


c. Section

Fig. 5. Vertically irregular building



a. 3D view



b. Plan

Fig. 6. Horizontally irregular building

TABLE 1 SKELETON OF THE STUDIED CASES

Case study No.	Type of base	Type of soil	Type of reinforced concrete superstructure
1	Fixed High damping rubber bearing Friction pendulum	Medium dense sand dense sand	Symmetrical building
2	Fixed High damping rubber bearing Friction pendulum	Medium dense sand dense sand	Symmetrical building with shear walls
3	Fixed High damping rubber bearing Friction pendulum	Medium dense sand dense sand	Vertically irregular building
4	Fixed High damping rubber bearing Friction pendulum	Medium dense sand dense sand	Vertically irregular building with shear walls
5	Fixed High damping rubber bearing Friction pendulum	Medium dense sand dense sand	Horizontally irregular building
6	Fixed High damping rubber bearing Friction pendulum	Medium dense sand dense sand	Horizontally irregular building with shear walls

III. THE EFFECT OF SOIL TYPE

Two different types of the supporting soil were considered for the fixed base and isolated buildings. The soil properties are listed in Table 2. The soil medium is assumed as homogenous, isotropic Mohr - Couomb elasto-plastic half space. It is modeled using solid finite elements. Fixed boundary conditions are assumed along all external sides of the soil block except the top (ground surface), which is remained free. The dimensions of soil domain are (51 m (about twice the building width) x 51 m x 30 m depth). Beyond these dimensions, a negligible effect of boundaries is recorded.

TABLE 2 PROPERTIES OF SOILS

Type of soil	Modulus of elasticity (Es) (MPa)	Density (ρ_s) (kg/m^3)	Friction angle Ø (degree)	Dilation angle ?? (degree)	Poison's ratio (ν_s)	Damping ratio (ζ_s)
Medium dense sand	30	1800	30	20	0.30	0.02
Dense sand	70	1800	38	25	0.35	0.02

IV. MESH SIZE

Numerical distortion of the propagating wave can occur, in dynamic analyses, as a function of the modeling conditions. Both the frequency content of the input wave and the wave-speed characteristics of the system will affect the numerical accuracy of wave transmission. For an accurate representation of wave transmission through a model, the element size must be smaller than approximately one-tenth to one-eighth of the wavelength associated with the highest frequency component of the input wave [7] i.e.,

$$\Delta l \leq \frac{\lambda}{10} \qquad 1$$

Where

Δl : The element size

λ : The wave length associated with the highest frequency component that contains appreciable energy.

Expressing Δl in the form of shear wave velocity, (Vs) and the highest frequency introduced to the system (f_{max}) Eq. 1 can be written as:

$$\Delta l \leq \frac{V_s}{10.f_{max}} \qquad 2$$

This requirement necessitated a fine mesh and a corresponding small time step.

Fig. 7, shows the discretized soil medium using (1m x 1m x 1m) solid elements, which are small enough to transmit all the frequency components of the input motions. It should be mentioned that; this size is tested against (0.5 m x 0.5 m Ax 0.5 m) elements and it is found that the results have minor changes of about (0.01%).

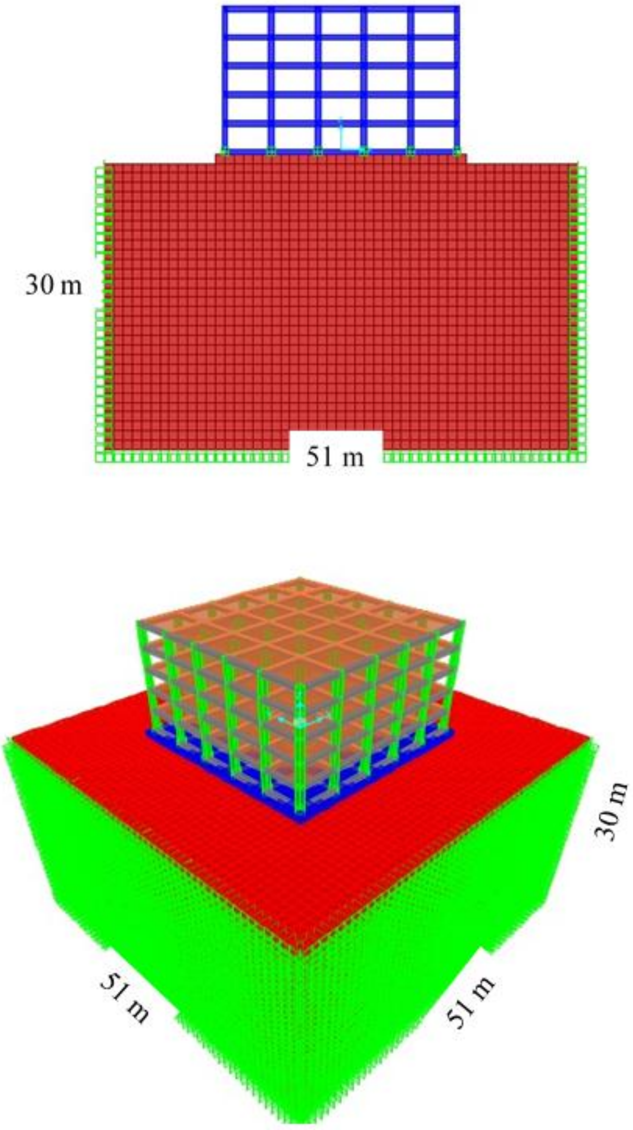


Fig.7 The three-dimensional finite element mesh adopted in the analyses.

The characteristics of superstructure materials and the design parameters of the isolation systems are summarized in Tables 3 and 4.

TABLE 3 THE SUPERSTRUCTURE MATERIAL PROPERTIES.

Symbol	description	unit	Value
f'_c	The cylinder ultimate compression strength of concrete	N/mm^2	25
f_y	The yield stress of steel reinforcement	N/mm^2	410
E_c	The modulus of elasticity of concrete	N/mm^2	23000
ρ_c	The concrete density	kg/m^3	2400
ν_c	Poisson's ratio of concrete	---	0.15

TABLE 4 DESIGN PARAMETERS OF ISOLATORS.

data	Parameter and unite	Value for HDRB	Value for FPS	Nomenclature
Input	T (sec)	2.5	2.5	Design period
	β (%)	20	20	Effective damping
	D (mm)	200	200	Design displacement
	W (kN)	2000	2000	maximum vertical load in service condition including seismic action
	μ	----	0.02	friction coefficient
Output	K_{eff} (kN/m)	1500	1370	Effective stiffness
	Q (kN)	88	40	Short term yield force
	K_2 (kN/m)	1200	1150	Inelastic stiffness
	K_1 (kN/m)	12000	115000	Elastic stiffness
	D_y (mm)	8.1	0.4	Yield displacement
	R (mm)	----	1700	radius of curvature

V. APPLIED LOADS

The reinforced concrete buildings are analyzed for dead, live, and earthquake functional loads. The minimum design dead load on each floor consists of loads due to floor slab, beams, columns and portion walls. The floor live load is taken as (3 kN/m²) and the roof live load is taken as (1.5 kN/m²). The North-South component of the ground motion recorded at a site in El Centro, California in 1940, shown in Fig. 8, is applied to the building. All of the dead load and only (25%) of the live load is considered in the seismic analysis [IBC 2012][8].

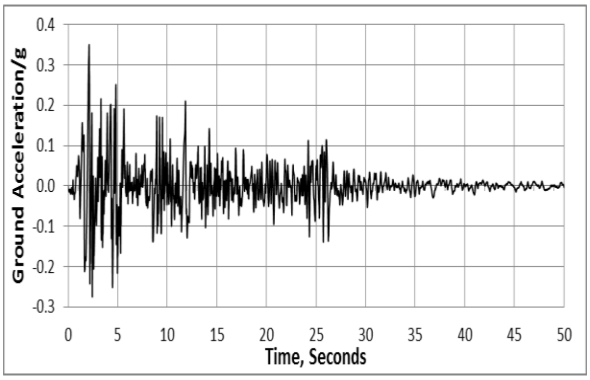
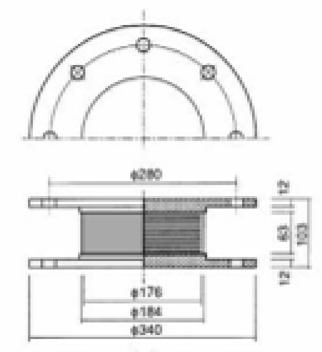


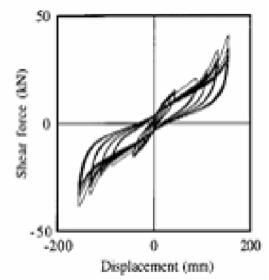
Fig. 8. El Centro, California in 1940 earthquake [9].

VI. DESIGN OF BASE ISOLATORS

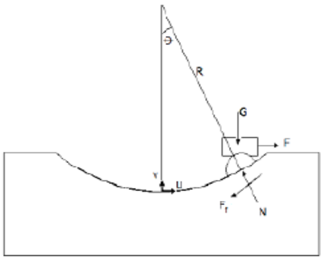
The isolators are designed according to the procedures described in the UBC-97 [10]. The characteristics of high damping rubber bearing system are illustrated in Fig. 9-a,b whereas, the mechanism of friction pendulum system is shown in Fig. 9-c.



a. High damping rubber bearing used in the earthquake simulator tests with dimensions in mm[11].



b. Corresponding force-deformation hysteresis for HDRB [11].



c. Mechanism of the friction pendulum system [12].

Fig. 9. The characteristics of isolation systems.

VII. NONLINEAR DIRECT INTEGRATION METHOD

The nonlinear direct integration method is used to analyze the building cases under El Centro earthquake motion for different supporting soils.

The results are shown in Table 5.

TABLE (7.9) EFFECT OF SOIL TYPE ON TOTAL BASE SHEAR UNDER EL CENTRO EARTHQUAKE.

No. of case study	Case Study	Type of soil	Base shear (kN)			Percentage of base shear reduction %	
			fixed base	HDRB	FPS	HDRB	FPS
1	Symmetrical building	Medium dense sand	2787.7	391.8	188.4	85.9	93.2
		Dense sand	2000.3	375.2	170.1	81.2	91.5
2	Symmetrical building with shear walls	Medium dense sand	2368.0	388.1	185.3	83.6	92.2
		Dense sand	1609.1	370.6	179.4	77.0	88.9
3	Vertically Irregular building	Medium dense sand	2641.8	340.6	171.9	87.1	93.5
		Dense sand	1733.8	330.7	168.7	80.9	90.3
4	Vertically Irregular building with shear walls	Medium dense sand	2068.1	334.2	190.8	83.8	90.8
		Dense sand	1437.3	325.4	184.9	77.4	87.1
5	Horizontally Irregular building	Medium dense sand	2806.7	395.1	198.2	85.9	92.9
		Dense sand	2032.8	380.3	179.6	81.3	91.2
6	Horizontally Irregular building with shear walls	Medium dense sand	2506.6	386.5	210.4	84.6	91.6
		Dense sand	1751.5	372.1	205.8	78.8	88.3

VIII. CONCLUSIONS

a. Increasing the soil elastic parameters and angle of internal friction, reduces the base shear considerably for the fixed base structure but, has negligible effects on the base shear for the isolated structures for all cases.

b. The inclusion of the supporting soil in the analysis will increase the base shear for all cases.

c. The deformations of buildings with supporting soil have shown a considerable increase compared to the fixed base case. This would in turn increase the base shear of the whole building.

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