SEISMIC BEHAVIOR OF VARIOUS REINFORCED CONCRETE BUILDINGS UNDER FLUCTUATING FREQUENCY

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***ABSTRACT:** Earthquake is the result of sudden release of energy in the earth's crust that generates seismic waves. Ground shaking and rupture are the major effects generated by earthquakes. It has social as well as economic consequences such as causing death and injury of living things especially human beings and damages the built and natural environment. In order to take precaution for the loss of life and damage of structures due to the ground motion, it is important to understand the characteristics of the ground motion. The most important dynamic characteristics of earthquake are peak ground acceleration (PGA), frequency content, and duration. These characteristics play predominant rule in studying the behavior of structures under seismic loads.The strength of ground motion is measured based on the PGA, frequency content and how long the shaking continues. Ground motion has different frequency contents such as low, intermediate, and high. The response of the buildings due to the ground motions in terms of story displacement, story velocity, story acceleration, and base shear are found. The responses of each ground motion for each type of building are studied and compared. The results show that low-frequency content ground motions have significant effect on both regular as well as irregular RC buildings. However, high-frequency content ground motions have very less effect on responses of the regular as well as irregular RC buildings.*
***Keywords:** Reinforced concrete building, ground motion, peak ground acceleration, frequency content, time history analysis, gravity load, building material properties.*

I. INTRODUCTION

An earthquake is the result of a rapid release of strain energy stored in the earth's crust that generates seismic waves. Structures are vulnerable to earthquake ground motion and damages the structures. In order to take precaution for the damage of structures due to the ground motion, it is important to know the characteristics of the ground motion. The most important dynamic characteristics of earthquake are peak ground acceleration (PGA), frequency content, and duration. These characteristics play predominant rule in studying the behavior of structures under the earthquake ground motion. Severe earthquakes happen rarely. Even though it is technically conceivable to design and build structures for these earthquake events, it is for the most part considered uneconomical and redundant to do so. The seismic design is performed with the expectation that the severe earthquake would result in some destruction, and a seismic design philosophy on this premise has been created through the years. The objective of the seismic design is to constraint the damage in a structure to a worthy sum. The structures designed in such a way that should have the capacity to resist minor levels of earthquake without damage, withstand moderate levels of earthquake without structural damage, yet probability of some nonstructural damage, and withstand significant levels of ground motion without breakdown, yet with some structural and in addition nonstructural damage. [2]

Origin of Project

A few research is carried out to study the frequency content of the ground motion. Cakir [3] studied the evaluation of the effect of earthquake frequency content on seismic behavior of cantilever retaining wall including soil-structure interaction. Also, Nayak & Biswal [4] studied seismic behavior of partially filled rigid rectangular tank with bottom-mounted submerged block under low, intermediate, and high-frequency content ground motions.

Research Significance

The earth shakes with the passing of earthquake waves, which discharge energy that had been confined in stressed rocks, and were radiated when a slip broke and the rocks slid to release the repressed stress. The strength of ground quaking is determined in the acceleration, duration, and frequency content of the ground motion.
The responses of RC buildings are strongly dependent on the frequency content of the ground motions. Ground motions have different frequency contents such as low, intermediate, and high. Low, mid, and high-rise reinforced concrete buildings show different response under low, intermediate, and high-frequency content ground motions

Objective and Scope

The purpose of this project is to study the response of low, mid, and high-rise regular as well as irregular three-dimension RC buildings under low, intermediate, and high-frequency content ground motions in terms of story displacement, story velocity, story acceleration and base shear preforming linear time-history analysis using STAAD Pro [1] software.
From the three dynamic characteristics of ground motion, which are PGA, duration, and frequency content, keeping PGA and duration constant and changing only the frequency content to see how low, mid, and high-rise reinforced concrete buildings behave under low, intermediate, and high-frequency content ground motions.

II. LITERATURE REVIEW

Ground motion at a specific site because of earthquakes is influenced by source, local site conditions, and travel path. The first relates to the size and source mechanism of the earthquake. The second defines the path effect of the earth as waves travel at some depth from the source to the spot. The third describes the effects of the upper hundreds of meters of rock and soil and the surface topography at the location. Powerful ground motions cause serious damages to made-up amenities and unluckily, From time to time, induce losses of human lives. Factors that affect strong ground shaking are magnitude, distance, site, fault type, depth, repeat time, and directivity and energy pattern. [11]

Rathje, et al. [12] studied three simplified frequency content, which are mean period (Tm), predominant period (Tp), and smoothed spectral predominant period (Tp). They computed the frequency parameters for 306 motion records from twenty earthquakes. They used the data for developing a model to describe the site reliance, magnitude, and distance of the frequency content parameters. Model coefficients and standard error terms are evaluated by means of nonlinear regression analyses. Their results show that the conventional Tp parameter has the highest uncertainty in its prediction and the earlier correlation suggested predicting Tp are unreliable with their current data set. Moreover, the best frequency content characterization parameter is Tm.

The stochastic method is a basic and powerful method for simulation of ground motions. It is specified as adjustment of combination of parametric or functional description of the amplitude spectrum of ground motion with a random phase spectrum such that the motion is distributed over a time span related to the earthquake magnitude and to the distance from the source. This method is useful for simulation of higher-frequency ground motions (e.g. 0-1 Hz) and when the recordings of the potentially damaging earthquakes are not accessible, it is used to predict them. [13]

strong ground motion may not be defined by Tp . They developed empirical relationships that predict three parameters (Tm, Tavg, and To) as a function of earthquake magnitude, rupture directivity, site to source distance, and site conditions. They claim that new relationships update those early ones. Their results show that three site classes, which classify between rock, deep soil, and shallow soil present better prediction of the frequency content parameters and minor standard error terms than traditional “rock” and “soil” site classes. The frequency content parameters, particularly Tm and To are increased noticeably due to forward directivity, at distances less than 20 km. Among the frequency-content parameters, Tm is the preferred one because the frequency content of strong ground motions is best distinguished by means of it.

Pankaj & Lin [20] carried out material modeling in the seismic response analysis for the design of RC framed structures. They used two alike continuum plasticity material models to inspect the impact of material modeling on the seismic response of RC frame structures. In model one, reinforced concrete is modeled as a homogenized material using an isotropic Drucker-Prager yield condition. In model two, also based on the Drucker-Prager criterion, concrete and reinforcement are included independently; the later considers strain softening in tension. Their results indicate that the design response from response history analyses (RHA) is considerably different for the two models. They compared the design nonlinear static analysis (NSA) and RHA responses for the two material models. Their works show that there can be important difference in local design response though the target deformation values at the control node are near. Likewise, the difference between the mean peak RHA response and the pushover response is dependent on the material model.

Habibi & Asadi, 2013 [24], have studied seismic performance of RC frames irregular in elevation designed based on Iranian seismic code. They designed several multistory Reinforced Concrete Moment Resisting Frames (RCMRFs) with different types of setbacks, as well as the regular frames in elevation, corresponding to the requirements of the Iranian national building code and Iranian seismic code for the high ductility class. They carried out inelastic dynamic time-history analysis on all frames subjected to ten ground motions. Their outcomes show that when setback occurs in elevation, the provision of the life safety level are not fulfilled. They have also indicated that the parts close to the setback undergo the highest damage. Therefore, it is necessary to reinforce these elements by proper technique to comply with the life safety level of the frames.

III. METHODOLOGY & RESEARCH WORK

The following six ground motion records, which have low, intermediate, and high-frequency content, have been considered for the analysis:

- 1979 Imperial Valley-06 (Holtville Post Office) H-HVP225 component [5]
- IS 1893 (Part1) : 2002 (Artificial ground motion) [6]
- 1957 San Francisco (Golden Gate Park) GGP010 component [7]
- 1940 Imperial Valley (El Centro) elcentro_EW component [8]
- 1992 Landers (Fort Irwin) FTI000 component [9]
- 1983 Coalinga-06 (CDMG46617) E-CHP000 component [10]

Ground motion record (1), (3), (5), and (6) are selected from Pacific Earthquake Engineering Research Center (PEER) Next Generation Attenuation (NGA) database. The ground motion record (2) is the compatible time-history of acceleration as per spectra of IS 1893 (Part1) [6] for structural design in India. The ground motion (4) is the 1940 El Centro east west component.

All the above six ground motions duration is 40 s. In order to have same PGA, the above ground motions are scaled to magnitude of 0.2 g. Two, six, and twenty-story RC buildings, which are considered as low, mid, and high-rise reinforced building are modeled as three-dimension regular and irregular reinforced concrete buildings in STAAD Pro [1]. Then the ground motions are introduced to the software and linear time history analysis is performed.

The basis of the present work is to study the behavior of reinforced concrete buildings under varying frequency contents. This study shows how low, mid and high-rise reinforced concrete buildings behave in low, intermediate, and high-frequency content ground motions.

Here, the story displacement, story velocity, story acceleration, and base shear of low, mid, and high-rise regular and irregular reinforced concrete buildings due to the six ground motions of low, intermediate and high-frequency content are obtained. The methodology, which is conducted, is briefly described as below:

- Ground motion records are collected and then normalized.
- Linear time history analysis is performed in STAAD Pro [1].
- Building response such as story displacement, story velocity, story acceleration, and base shear are found due to the ground motions.
- The results of the three regular and irregular RC buildings are compared with respect to the six ground motions.

Regular RC Buildings

Two, six, and twenty-story regular reinforced concrete buildings, which are low, mid, and high-rise, are considered. The beam length in (x) transverse direction is 4m and in (z) longitudinal direction 5m. Figure 3.1 shows the plan of the three buildings having three bays in x-direction and five bays in z-direction. Story height of each building is assumed 3.5m. Figure 3.2-3.4 shows the frame (A-A) and (01-01) of the twenty, six, and two-story RC building respectively. For simplicity, both the beam and column cross sections are assumed 300 mm x 400 mm

Irregular RC Buildings

Two, six, and twenty-story irregular reinforced concrete buildings, which are low, mid, and high-rise, are considered. The beam length in (x) transverse direction is 4m and in (z) longitudinal direction 5m. Figure 3.5 shows the plan of the three buildings having five bays in x-direction and five bays in z-direction. Story height of each building is assumed 3.5m. Figure 3.6, 3.8, and 3.10 shows frame (01-01) and (06-06) of the twenty, six, and two-story irregular RC buildings respectively. Figure 3.7, 3.9, and 3.11 shows frame (A-A) and (F-F) of the twenty, six, and two-story irregular reinforced concrete building respectively. For simplicity, both the beam and column cross sections are assumed 300 mm x 400 mm.

Gravity Loads

Slab load of 3 kN/m2 is considered for the analysis and wall load of 17.5 kN/m is applied both on exterior and interior beams of the RC buildings as per IS 875. Live load of 3.5 kN/m2 is provided in accordance to IS 875 (Part2) [29]. Table 3.1 shows the gravity loads.

For seismic weight, total dead load and 50 percent of live load is considered as per Table 8 of IS 1893 : 2002. For calculation of seismic weight, no roof live load is taken.

Table gravity load which are assigned to the RC building

Gravity Load	Value	
Slab load (dead load)	3	(kN/m^2)
Wall load (dead load)	17.5 (kN/m)	
Live load	3.5	(kN/m^2)

Structural Elements

Linear time history analysis is performed on two, six, and twenty-story regular and irregular reinforced concrete buildings and six ground motions of low, intermediate, and high-frequency content are introduced to STAAD Pro [1]. In order to compare the results, for simplicity beam and column dimensions are assumed 300 mm x 400 mm. Height of the story is 3.5m and beam length in transverse direction is taken 4m and in longitudinal direction 5m. These dimensions are summarized in Table The thickness of the wall is assumed 250 mm.

Table Beam and column length and cross section dimension

Structural Element	Cross section (mm x mm)	Length (m)
Beam in (x) transverse direction	300 x 400	4
Beam in (z) longitudinal direction	300 x 400	5
Column	300 x 400	3.5

Table Direct and indirect effects of earthquake

Direct Effects	Indirect Effects
Ground shaking, ground cracking, ground lunching, differential ground settlement, Soil liquefaction, lateral spreading, landslide, rock falls, vibration of structures, falling objects, structural damage, and structural collaps	Landslides, tsunamis, seiches, avalanches, rock falls, floods, fires, and toxic Contamination

Six ground motions are taken for the study purpose. The first ground motion is the 1979 Imperial Valley-06 (Holtville Post Office) H-HVP225 component, second ground motion is the IS 1893 (Part1) : 2002, the third ground motion is 1957 San Francisco (Golden Gate Park) GGP010 component, the fourth ground motion is 1940 Imperial Valley (El Centro) elcentro_EW component, the fifth ground motion is 1992 Landers (Fort Irwin) FTI000 component, and the last one is 1983 Coalinga-06 (CDMG46617) E-CHP000 component. Each ground motion is explained in section 4.3 and the corresponding velocity and displacement versus time are obtained.

Ground Motion Records

Buildings are subjected to ground motions. The ground motion has dynamic characteristics, which are peak ground acceleration (PGA), peak ground velocity (PGV), peak ground displacement (PGD), frequency content, and duration. These dynamic characteristics play predominant rule in studying the behavior of RC buildings under seismic loads. The structure stability depends on the structure slenderness, as well as the ground motion amplitude, frequency and duration. [23] Based on the frequency content, which is the ratio of PGA/PGV the ground motion records are classified into three categories [38]:

1.	High-frequency content	PGA/PGV > 1.2
2.	Intermediate-frequency content	0.8< PGA/PGV< 1.2
3.	Low-frequency content	PGA/PGV < 0.8

The ratio of peak ground acceleration in terms of acceleration of gravity (g) to peak ground velocity in unit of (m/s) is defined as the frequency content of the ground motion. [38]

IV. LINEAR TIME HISTORY ANALYSIS

Time history analysis is the study of the dynamic response of the structure at every addition of time, when its base is exposed to a particular ground motion. Static techniques are applicable when higher mode effects are not important. This is for the most part valid for short, regular structures. Thus, for tall structures, structures with torsional asymmetries, or no orthogonal frameworks, a dynamic method is needed.

In linear dynamic method, the structures is modeled as a multi degree of freedom (MDOF) system with a linear elastic stiffness matrix and an equivalent viscous damping matrix. The seismic input is modeled utilizing time history analysis, the displacements and internal forces are found using linear elastic analysis. The playing point of linear dynamic procedure as for linear static procedure is that higher modes could be taken into account.

Two, six, and twenty-story regular as well as irregular RC buildings are modeled as three-dimension. Material properties, beam and column sections, gravity loads, and the six ground motions listed in Table 4.3 are assigned to the corresponding RC buildings and then linear time history analysis is performed. The linear time-history analysis results for regular and irregular RC buildings are shown in chapter 5 and 6 respectively.

V. RESULTS & DISCUSSION

The base shear of twenty-story regular RC building due to ground motion GM1, GM2, GM3, GM4, GM5, and GM6 is shown in Figure 4.15. Figure 4.15 (a) shows that the building has maximum base shear of 6,437.29 kN due to1940 Imperial Valley (El Centro) elcentro_EW component and minimum base shear of 355.83 kN due to 1957 San Francisco (Golden Gate Park) GGP010 component ground motion in x-direction. Figure 4.15 (b) shows that the building has maximum base shear of 6,538.69 kN due to 1940 Imperial Valley (El Centro) elcentro_EW component and minimum base shear of 338.98 kN due to 1957 San Francisco (Golden Gate Park) GGP010 component ground motion in z-direction

The maximum and minimum values of story displacement, story velocity, story acceleration, and base shear of two, six, and twenty-story regular RC building due to GM1-GM6 in x and z-direction are summarized in Table 4.1.

Table 4.1: Two, six, and twenty-story regular RC building responses due to GM1-GM6 in x and z-direction

RC Building		Two-Story				Six-Story				Twenty-Story		
GM (x, z)	GM (x)*		GM (z)**		GM (x)		GM (z)		GM (x)		GM (z)	
Maximum/ Minimum	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
Story displacement	4	3	4	3	4	3	4	3	1	3, 6	1	3, 6
Story Velocity	2	3	4	3	4	3, 6	4	6	1	3, 6	4	3, 6
Story Acceleration	2	3, 6	4	3	5	6	4	6	4	3, 6	4	3, 6
Base Shear	4	3	4	3	4	3	4	3	4	3	4	3

The base shear of twenty-story irregular RC building due to ground motion GM1, GM2, GM3, GM4, GM5, and GM6 is shown in Figure 4.30. Figure 4.30 (a) shows that the building has maximum base shear of 8,187.92 kN due to 1940 Imperial Valley (El Centro) elcentro_EW component and minimum base shear of 535.41 kN due to 1957 San Francisco (Golden Gate Park) GGP010 component ground motion in x-direction. Figure 6.15 (b) shows that the building has maximum base shear of 9,138.61 kN due to 1940 Imperial Valley (El Centro) elcentro_EW component and minimum base shear of 422.90 kN due to 1957 San Francisco (Golden Gate Park) GGP010 component ground motion in z-direction

The maximum and minimum values of story displacement, story velocity, story acceleration, and base shear of two, six, and twenty-story irregular RC building due to GM1-GM6 in x and z-direction are summarized in Table 4.2.

Table 4.2: Two, six, and twenty-story irregular RC building responses due to GM1-GM6 in x and z-direction

RC Building		Two-Story				Six-Story				Twenty-Story		
GM (x, z)	GM (x)*		GM (z)**		GM (x)		GM (z)		GM (x)		GM (z)	
Maximum/ Minimum	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
Story displacement	2	3	4	3	4	3	4	3	1	3, 6	1	3, 6
Story Velocity	2	3	4	3	4	3	4	6	1	3, 6	4	3, 6
Story Acceleration	2	3	4	3	4	3, 6	4	6	4	3, 6	4	3, 6
Base Shear	2	3	4	3	4	3	4	3	4	3	4	3

VI. CONCLUSIONS

Following conclusions can be drawn for the two, six, and twenty-story regular RC buildings

- Two-story regular RC building experiences maximum story displacement due to low-frequency content ground motion in x and z-direction
- Two-story regular RC building experiences minimum story displacement due to high-frequency content ground motion in x and z-direction
- Two-story regular RC building experiences maximum story velocity due to intermediate-frequency content ground motion in x-direction and low-frequency content ground motion in z-direction
- Two-story regular RC building experiences minimum story velocity due to high-frequency content ground motion in x and z-direction
- Two-story regular RC building experiences

maximum story acceleration due to intermediate-frequency content ground motion in x-direction and low-frequency content ground motion in z-direction

- Two-story regular RC building experiences minimum story acceleration due to high-frequency content ground motion in x and z-direction
- Two-story regular RC building experiences maximum base shear due to low-frequency content ground motion in x and z-direction
- Two-story regular RC building experiences minimum base shear due to high-frequency content ground motion in x and z-direction
- Six-story regular RC building undergoes maximum story displacement due to low-frequency content ground motion in x and z-direction
- Six-story regular RC building undergoes minimum story displacement due to high-frequency content ground motion in x and z-direction

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