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Comparison of Ground Motion Pulse Models for the Acceleration Response of Seismically Isolated Buildings

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Abstract

An important objective of seismic isolation is to minimize floor accelerations for protecting sensitive contents. In this regard, the success of seismic isolation has been proven by many research studies and by the observed acceleration responses under real earthquakes. However, concerns with regard to the success of seismic isolated buildings have been declared by researchers who noted the long-period large-amplitude velocity pulses that appeared in the latest ground motion records, which may be harmful to such long-period structures. Consequently, acceleration responses of seismically isolated buildings subjected to near-fault earthquakes have been an important research subject in the last two decades. In the absence of adequate number of historical near-fault ground motions, there is need for simple analytical ground motion pulse models which are capable of simulating the effects of pulse-like earthquakes; particularly for conducting parametric studies. Among others, analytical ground motion pulse models developed by Makris (1997) and Agrawal & He (2002) are the popular ones used in research studies previously. In order to determine the capability of these models in representing the effects of real pulse-like earthquakes on the acceleration responses of seismically isolated buildings, in this study a benchmark seismic isolated building is subjected to historical near-fault earthquakes and their synthetically developed counterpart Makris (1997) and Agrawal & He (2002) pulse models. Floor accelerations are reported in a comparative fashion. Results show that the level of success of the pulse models in representing historical near-fault earthquakes in terms of acceleration response varies with respect to the earthquake and the isolation system characteristics.

Keywords: Acceleration response, earthquake engineering, seismic isolation, near-fault earthquake, ground motion pulse model.

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Introduction

An important objective of seismic isolation is to reduce floor accelerations compared to fixed-base buildings (Komodromos, 2000). While successful in case of far-fault earthquakes, seismically isolated buildings are particularly challenged by the near-fault earthquakes with long period and large amplitude velocity pulses (Providakis, 2009; Heaton et al., 1995; Makris and Chang, 2000).

Being a core performance criteria, floor acceleration responses of seismically isolated buildings were the subject of various previous research studies. The effect of superstructure flexibility on the acceleration response of a seismically isolated multi-story shear frame was reported by Matsagar and Jangid (2004). Providakis (2009) assessed the effects of near-fault ground motions and additional damping on the acceleration responses of base-isolated buildings. Jangid and Kelly (2001) investigated the optimum isolation damping for minimizing floor accelerations of base-isolated buildings under near-fault ground motions. Alhan and Gavin (2005) investigated the reliability of base isolation in protecting vibration-sensitive equipment in case of near-fault earthquakes that may produce high floor accelerations. Effect of equivalent linear modeling on the floor acceleration responses of multi-story buildings was investigated by Alhan and Şahin (2011). Öncü and Alhan (2012) reported peak floor acceleration profiles of a benchmark five-story shear frame under synthetic near-fault earthquakes of various magnitudes and fault distances in order to investigate the acceleration performance of seismically isolated buildings under such earthquake loadings.

As the researchers are still actively investigating various aspects of this issue, apparently there is a need for synthetic ground motion pulse models in the absence of adequate number of historical ground motions including near-fault effects. To this end, several researchers (Alavi and Krawinkler, 2000; Menun and Fu, 2002; Makris, 1997; Makris and Chang, 2000; Agrawal and He, 2002; He and Agrawal, 2008) proposed several analytical pulse models that approximate pulse-like near-fault earthquakes. Alavi and Krawinkler (2000) used piecewise-linear equivalent velocity pulses and investigated elastic and inelastic responses of frame structures subjected to these pulses. Makris (1997) developed forward and forward-and-backward equivalent pulse motions. Thereafter, Makris and Chang (2000) added a third type -a multiple pulse model- and examined the performances of various damping systems. Menun and Fu (2002) defined a piece-wise model by nonlinear regression analysis and conducted time history analysis of linear and nonlinear single degree of freedom systems using this model. Agrawal & He (2002) proposed closed-form approximation of pulse-like ground motions and compared the dynamic responses of single degree of freedom systems subjected to the recorded motions and their counterpart pulse models, which was also used in other studies (Dicleli and Buddaram, 2007; Öncü and Alhan, 2012).

In this study, in order to assess the capability of Makris (1997) and Agrawal & He (2002) pulse models in representing the effects of real pulse-like earthquakes on the acceleration responses of seismically isolated buildings, a benchmark building is subjected to historical near-fault earthquakes and their synthetically developed counterparts. Here, floor accelerations are reported in a comparative fashion, while the inter-story drift response part of the problem is presented in a companion paper by Gazi, et al. (2013).

Near-Fault Ground Motions and Synthetic Pulse Models

Near fault ground motions are typically characterized by long period and large amplitude velocity pulses. These ground motion records are typically observed within 10 km distance from the fault. As observed in the near-fault records of recent large magnitude earthquakes, such as the 1999 Kocaeli Earthquake, the 1999 Chi-Chi Earthquake, the 1992 Landers Earthquake and the 1994 Northridge Earthquake, serious damage to the buildings may come into scene. Several closed-form analytical models for simulating such pulse-like near-fault ground motions were proposed by various researchers and a complete review of these models can be found elsewhere (Öncü, 2011). Two of these models, namely one developed by Makris (1997) and another one developed by Agrawal & He (2002), are the popular ones used in various research studies previously.

Makris (1997) Approximation

The long period pulses in pulse-like ground motions were classified as Type A, Type B by Makris (1997). Type C_n pulse was further defined by Makris and Chang (2000). Type A, Type-B, and Type C_n pulse models exhibit a forward pulse, a forward-backward pulse, and n-main pulses in its displacement time history, respectively. In this study, we make use of Type-A and Type-B models only and thus only these types are summarized below.

The analytical expressions for Type-A are as follows:

$$a(t) = \omega_p (v_p / 2) \sin(\omega_p t) \qquad 0 \le t \le T_p \qquad (1)$$

$$v(t) = (v_p / 2) - (v_p / 2) \cos(\omega_p t) \qquad 0 \le t \le T_p \qquad (2)$$

$$u(t) = (v_p / 2) t - (v_p / 2\omega_p) \sin(\omega_p t) \qquad 0 \le t \le T_p \qquad (3)$$

where a(t) is the ground acceleration, v(t) is the ground velocity, and u(t) is the ground displacement. The analytical expressions for Type-B are given as follows:

$$a(t) = \omega_p v_p \sin(\omega_p t + \pi / 2) \qquad 0 \le t \le T_p \qquad (4)$$

$$v(t) = -v_p \cos(\omega_p t + \pi / 2) \qquad 0 \le t \le T_p \qquad (5)$$

$$u(t) = (v_p / \omega_p) - (v_p / \omega_p) \sin(\omega_p t + \pi / 2) \qquad 0 \le t \le T_p \qquad (6)$$

The parameters of the pulse models given in Equations (1)-(6) are the amplitude of the velocity pulse, v_p , and the frequency of the sinusoid, ω_p. The pulse period, T_p is then calculated as $T_p=2\pi/\omega_p$.

Agrawal & He (2002) Approximation

In this model, the displacement and the velocity functions of the ground motion pulse are decaying sinusoids expressed as follow:

$$u(t) = \left[se^{\alpha t} \left[\alpha \sin(\beta t) - \beta \cos(\beta t) \right] + s\beta \right] / \omega_p{}^2 \tag{7}$$

$$v(t) = se^{\alpha t} \sin(\beta t) \tag{8}$$

Differentiating Equation (8), the acceleration of the pulse is obtained as:

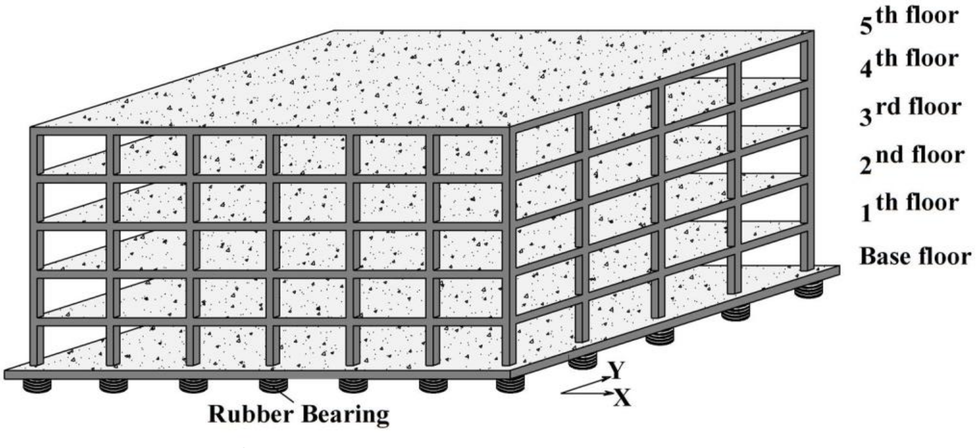
$$a(t) = se^{\alpha t} \left[\alpha \sin(\beta t) + \beta \cos(\beta t) \right], \qquad \alpha = -\zeta_p \omega_p\,, \;\; \beta = \omega_p \sqrt{1 - \zeta_p{}^2} \tag{9}$$

where the damping factor of the decaying sinusoid, ζ_p, the initial amplitude of the pulse, s, and the frequency of the sinusoid, ω_p, are parameters of the closed form approximation.

Mathematical Modeling

A 5-story seismically isolated benchmark building with a rectangular plan composed of 4 bays in Y-direction and 6 bays in X direction with a bay width of 5 m is considered. The three dimensional view of the benchmark building is shown in Figure 1. The floor heights are 3.0 m, and the dimension of the columns and beams are 45 cm x 45 cm and 30 cm x 50 cm, respectively. For all structural members, the concrete class is taken as C30. The mass of each floor and the isolation floor are assumed as 650 kNs^2/m.

Figure 1. *Three Dimensional View of the Benchmark Building*



The modeling of seismically isolated building is carried out in two stages:

i. The superstructure is modeled as a fixed-base moment resisting frame in SAP2000 (CSI, 2011). Then, modal information of the building, which are eigenvalues and eigenvectors, are obtained from the modal analyses carried out in this software.

ii. The modal information obtained in stage (i) is used as input for the super-structure modeling in 3DBASIS (Nagarajaiah et al., 1991). Then, the isolation elements that exist under each column are connected by a rigid slab at base. For the mathematical modeling of the isolation system, the yield force, F_y, the yield displacement, D_y, and the post-yield to pre-yield stiffness ratio, α of the isolation elements are input to 3DBASIS.

In this study, the isolation systems with two different isolation periods (T_0= 3s and 5s) based on the post-yield stiffness K_2, yield strength ratios of Q/W = 5% and 10% and, combinations of these are considered. The properties of the isolation systems used, for a yield displacement of D_y = 40 mm, are presented in Table 1.

Table 1. *Properties of the Seismic Isolation Systems*

Isolation Label	**T_0 (s)**	**Q/W (%)**	**α (-)**	**F_y (kN)**
T03QW5	3	5	0.26	72.15
T03QW10	3	10	0.15	125.29
T05QW5	5	5	0.11	59.98
T05QW10	5	10	0.06	113.12

Historical Ground Motions and their Counterpart Pulse Models

In this study, two historical pulse-like near-fault earthquakes are used. One of them is RRS228 component of the 1994 Northridge Earthquake at the Rinaldi Receiving Station, which is retrieved from the PEER Strong Motion Database (2005). The other one is N90 component of the 1992 Landers Earthquake at the Lucerne Valley Station, which is retrieved from COSMOS Virtual Data Center (2013). The synthetic pulses that approximate the aforementioned earthquakes are generated using Equations (1)-(9) and the ground motion parameters which are reported in Table 2. Pulse model parameters of RRS228 are taken from the studies of Makris and Chang (2000) and Agrawal & He (2002), whereas the parameters of N90 are taken from the studies of Makris (1997) and Agrawal & He (2002).

Table 2. *Ground Motion Parameters for the Pulse Models*

Earthquake Parameter	**Earthquake Parameter**	**Pulse Models**		**Earthquake Parameter**	**Pulse Model**
		Type-A	Type-B		Agrawal & He
RRS228	**T_p(s)**	0.800	1.300	**ω_p(s)**	6.080
	v_p(m/s)	1.750	1.300	**s(m/s)**	2.000
N90	**T_p(s)**	3.100	4.877	**ω_p(s)**	1.360
	v_p(m/s)	1.153	1.153	**s(m/s)**	1.740

In order to illustrate compatibility between the recorded historical earthquakes and their synthetically developed counterparts, acceleration, velocity, and displacement time histories of the ground motions are shown in Figures 2 and 3 for the RRS228 record and the N90 record, respectively. The pulses are generated using Equations (1)-(9) and the ground motion parameters reported in Table 2.

Figure 2. *Acceleration, Velocity and Displacement Time Histories: Rinaldi Receiving Station - RRS228 Record, the 1994 Northridge Earthquake*

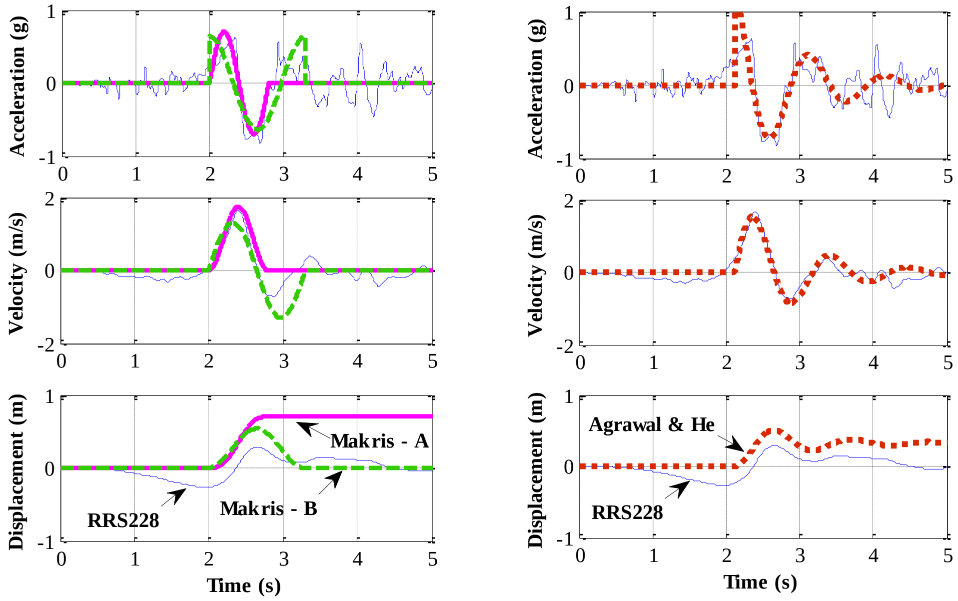
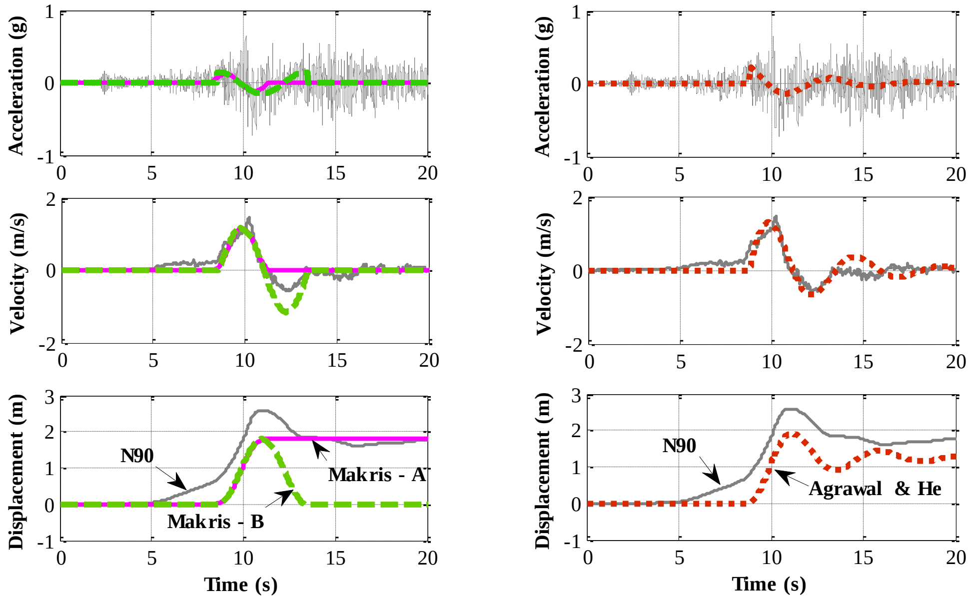


Figure 3. *Acceleration, Velocity and Displacement Time Histories: Lucerne Valley Station - N90 Record, the 1992 Landers Earthquake*



Results

Acceleration Profiles

Nonlinear time history analyses of the seismic isolated buildings with different seismic isolation systems (T03QW5, T03QW10, T05QW5, and T05QW10) are carried out for the RRS228 and N90 records and their synthetically developed counterpart ground motion pulse models via 3DBASIS.

The acceleration profiles, given in Figures 4 and 5 for RRS228 and N90, respectively, show the peak total floor accelerations along the height of the benchmark building with different isolation systems. For comparison purposes, the acceleration profiles obtained from analyses under synthetic ground motion pulse models approximating the actual records are also shown in the same plots. In the plots, 0 indicates the base floor.

It is observed from Figure 4 that the peak floor acceleration profiles corresponding to the actual RRS228 record matches well with the acceleration profiles corresponding to the pulse model of Makris, Type-A and the pulse model of Agrawal & He for all seismic isolation systems. However, there is a considerable deviation for the T03QW5 and T03QW10 for Makris, Type-B model. Overall, the best match for all pulse model responses is observed for the long period and low damping T05QW5 system. Another observation from Figure 4 is that the level of match varies along the height of the building.

It is seen from Figure 5 that although the acceleration profiles corresponding to the actual N90 record does not match to the acceleration profiles corresponding to the pulse models *as well as it was observed for the RRS228 case*, still, the *general trend* of the actual acceleration profiles are captured -both quantitatively and qualitatively- by the acceleration profiles corresponding to the pulse models. In particular, Makris, Type-A model captured the actual acceleration profile in T03QW5 case and Makris, Type-B and Agrawal & He captured the actual acceleration profile in T05QW10 case, well. Again, the level of match between the peak floor accelerations corresponding to the actual record and those corresponding to the approximate pulse models vary along the height of the building. In this case, no typical trend was observed in terms of the relation between the characteristics of the isolation system and the capability of the pulse models in representing the actual earthquake record in terms of the acceleration response.

Error Rates for Pulse Models

In order to quantify the level of match between the acceleration profiles corresponding to the actual earthquake records and those corresponding to the approximate ground motion pulse models, error rates given by

$$e = \left(\frac{a_{\text{pulse}} - a_{\text{recorded}}}{a_{\text{recorded}}}\right) \times 100 \qquad (10)$$

are calculated for all cases and for all floors. Here, e is the error rate (%) for the ground motion pulse model considered, a_{pulse} and a_{recorded} are the peak total floor acceleration corresponding to the ground motion pulse model and corresponding to the actual recorded ground motion, respectively.

Figure 6 depicts the error rates calculated for all floors, all seismic isolation systems and for both RRS228 and N90 records. Error rate plots for Makris Type-A, Makris Type-B, and Agrawal & He pulse models are shown separately.

At a glance, it is seen that Agrawal & He model generally produces the lowest error rates, followed by Makris Type-A model in case of RRS228 record. For this record, the highest error rates were 24.95% and 21.41% for the Makris Type-A model and Agrawal & He model, respectively. The representativeness capability of Makris Type-B model was poorer for this RRS228 record. The error rates were generally higher compared to two other models and the highest error rate for this model was 52.98%.

The error rate plots corresponding to N90 records show that in general, the error rates higher than those obtained in RRS228 case. Still, among all models, all seismic isolation systems and all floors, the highest error rate was 53.56%, which may still be interpreted as acceptable considering that a complex earthquake record was approximated by simple analytical pulse models. For this N90 record, error rates considerably vary between the pulse models depending on the seismic isolation system type. For T05QW10, the error rates are less than about 10% for Makris Type-B and Agrawal & He models, showing a notable success. Similarly, the error rates are less than 10% for Makris Type-A model in case of T03QW5. On the other hand, the error rates for the Makris Type-B model are higher than 40% for all floors in case of T05QW5.

Conclusions

Simple analytical pulse models approximating near-fault pulse-like ground motions are very useful in investigating the behavior of seismically isolated buildings. Of those, Makris (1997) and Agrawal & He (2002) pulse models are the popular ones and were used in various research studies in the seismic isolation area. In this study, the capability of these models in representing the acceleration response behaviors of seismically isolated buildings is investigated. For this purpose, peak floor acceleration responses of benchmark buildings equipped with different seismic isolation systems under actual recorded ground motions (RRS228 and N90) are compared to those under aforementioned ground motion pulse models representing these actual records.

Based on the parametric analyses conducted here, it is concluded that the level of success of the pulse models in representing historical near-fault earthquakes in terms of the acceleration response varies with respect to the earthquake and the isolation system characteristics. Furthermore, this success also varies along the height of the building.

Even though the percent errors introduced by the approximate pulse models may be high in some cases, they may still be interpreted as acceptable considering that complex earthquake records are approximated by simple analytical pulse models. In many cases, the general trend of the actual acceleration profiles are captured both quantitatively and qualitatively.

Figure 4. *Floor Acceleration Profiles for RRS228 Record and Pulse Models*

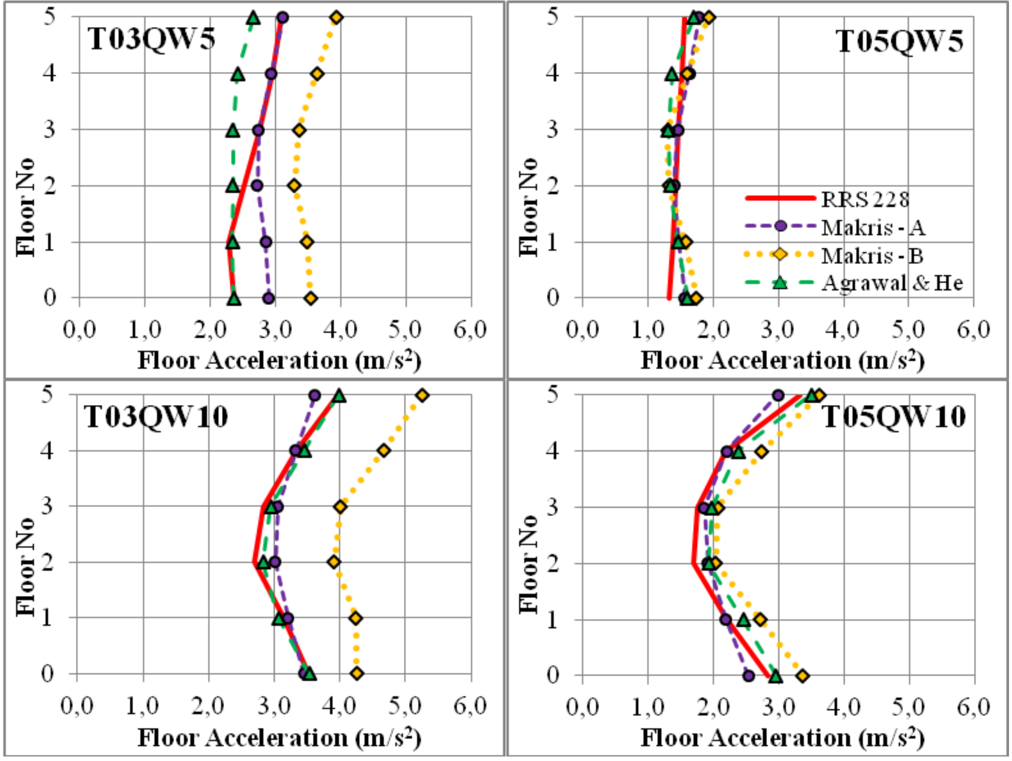


Figure 5. *Floor Acceleration Profiles for N90 Record and Pulse Models*

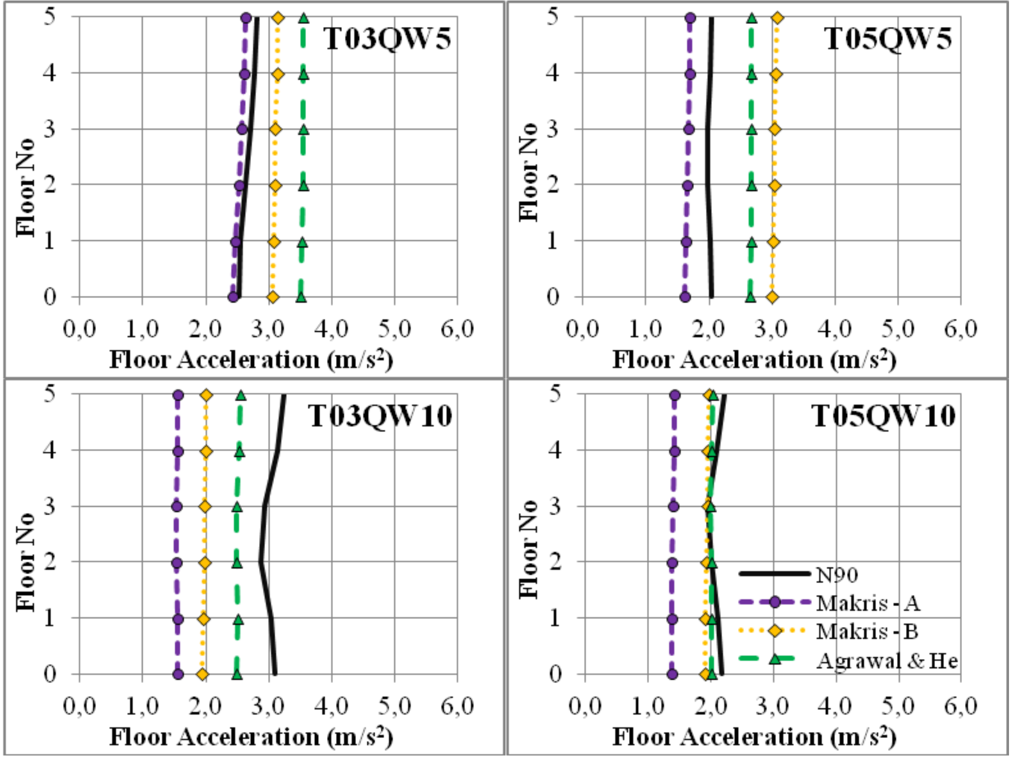
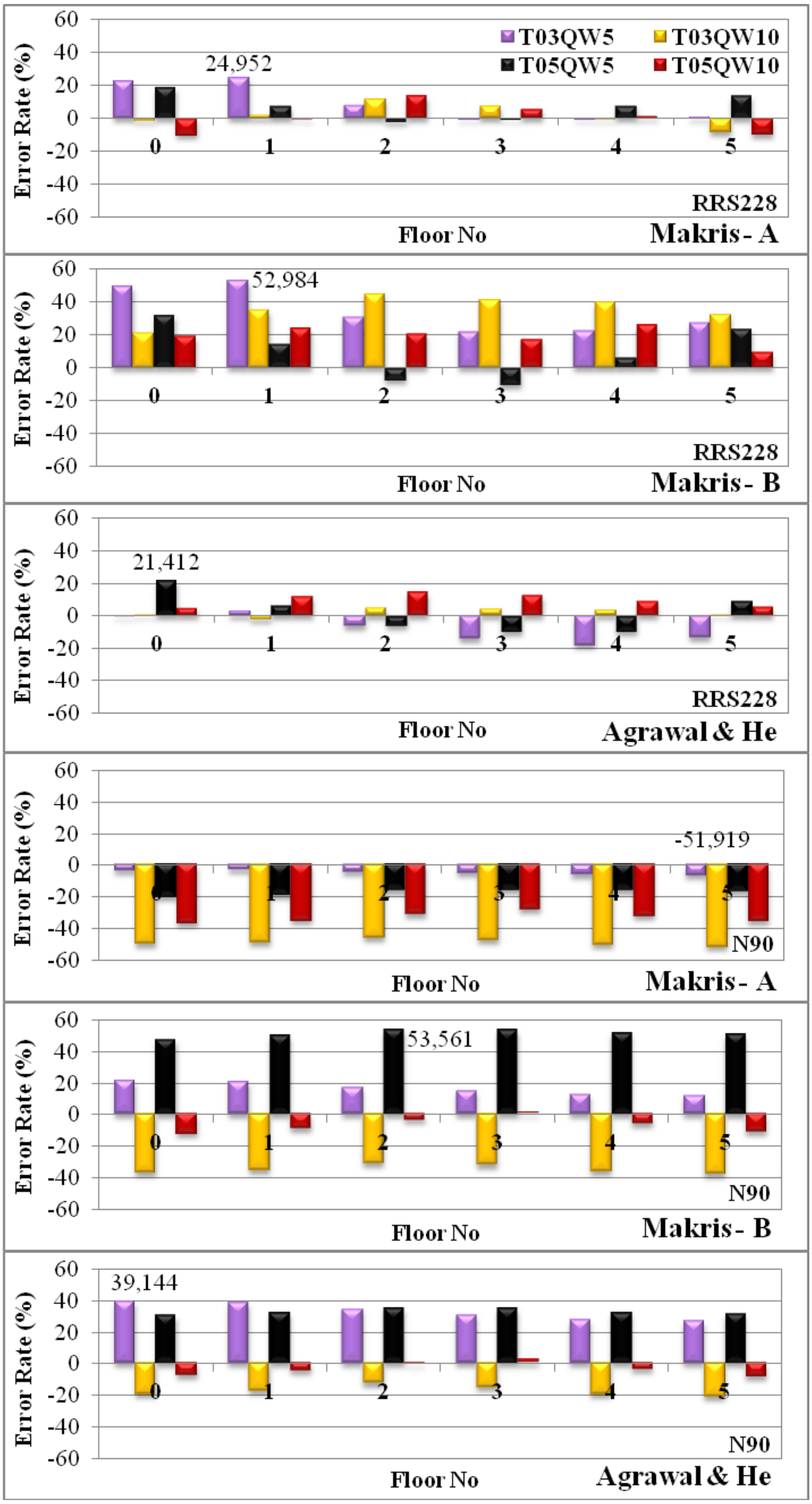


Figure 6. *Error Rates*



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