# Simplified Dynamic Response Analysis of High-rise Buildings Subjected to Impulse-type Vertical Ground Excitations Including Wave Propagation Effect

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**SUMMARY:**
This study aims at predicting the vertical macro-level responses of high-rise buildings excited by near-fault impulse-type vertical component of earthquake waves by proposed simplified wave propagation method. High-rise buildings are simplified as a continuous solid model with lumped masses and springs, having variable mechanical parameters. The Fast Fourier Transform (FFT) filtering process is applied in the proposed wave propagation analysis in which time delay is taken into account. In addition to the proposed wave propagation method, conventional vibration differential equations and the wave propagation method which is based on difference filter have also been established and analyzed. Comparisons of the computational results from the three methods indicate that wave-propagation-based methods are more competent for predicting structural responses of structures under impulse-type vertical component of earthquake waves which have larger amplitude and shorter duration. It is also shown that less energy can be transferred into the upper part of structures due to significant vertically irregularities in stiffness and mass along structural height. Some preliminary conceptual design ideas from the study for designing high-rise buildings have been advised.

*Keywords: high-rise buildings, wave propagation analysis, impulse-type excitation, vertical earthquake*

## 1. INTRODUCTION

The fluctuation in axial force level of bridge piers occurs when they are subjected to vertical earthquake. It could possibly cause severe degradation in their shear resistance (Kim et al., 2011). When high-rise buildings with non-uniform distribution of axial stiffness in horizontal plane are excited by strong vertical component of ground motions, some horizontal link components, e.g. mega transfer truss, link beams, beam-column joints, etc. could be possibly damaged due to relative vertical displacement (Huang et al., 2009; Hayasi et al., 2009). Some vertical members at certain floor levels are also might be overstressed or even cracked, causing significant reduction in their lateral resistance and amplified lateral responses of the structures under subsequent horizontal component of the motions. Moreover, in near-fault zone, higher value of V/H (the ratio of peak accelerations of horizontal component to vertical component of a ground motion) ratio and impulse-type vertical ground excitations would possibly lead to more unexpected results.

Different methods can be applicable for calculating dynamic responses of high-rise buildings under vertical excitations. Jia and Ou (Jia & Ou, 2010), Zhou et al. (Zhou et al., 2010) analyzed structural dynamic responses under vertical earthquake by time history analysis method, which based on classical vibration mechanics. However, time delay (Li et al., 2010) and propagating wave superimposed effect (Kohler et al., 2007) cannot be included in the vibration method which estimates the vertical response of the structures subjected to impulse-type ground motions. As impulse-type ground motions propagate in the structures in the form of wave, higher vertical vibration modes could be aroused (Iwan et al., 1997). In addition, because of larger height of high-rise buildings, wave propagates from foundation to the top then turn back needs longer time, which makes macroscopic structural vibration lags remarkably behind seismic wave propagation (Todorovska et al., 2001). So it seems to be more reasonable that structural dynamic responses should be predicted by using the wave propagation method.

When vertical seismic wave travels through vertical bearing component into floor, reflection, transmission and diffraction would occur repeatedly and energy dissipates gradually. Complete mechanical analysis and numerical solution of such wave propagation process is rather challenging. Desmond (Desmond, 1999) studied stress waves at a junction of three bars, large amount of numerical iterative have to be applied among the calculation. However, the refined wave method is numerically infeasible and impractical for engineering applications since the macro-level responses of buildings are much of concern. Zhang et al. (Zhang et al., 2011) studied horizontal dynamic responses by modeling columns (or walls) as a series of shear beams with lumped masses at floor levels. Safak (Safak, 1998) calculated structural shear responses by modeling building as a layered medium, similar to soil medium. Todorovska et al. (Todorovska et al., 2001) analyzed horizontal seismic responses of building by modeling wave propagation in 2D structures using finite element analysis. The above simplified calculations focus mainly on horizontal earthquake. Only a few references are available on simplified wave propagation analysis of structures excited by vertical component of earthquakes.

In this paper, the building is simplified as a continuous solid model with lumped masses and springs with variable parameters (Fig. 1.1, MDOF denotes multiple degrees of freedom). On the basis of the reference (Safak, 1998), which focused on shear wave, reflection and transmission coefficients of longitudinal wave through lumped mass are determined by combining wave mechanics with vibration mechanics. Time delay and FFT frequency filtering are applied in the proposed wave analysis method. The method is not only simple but able to consider wave propagation effect. And then the comparisons are made with wave propagation method based on difference filtering and the vibration method. Finally, vertical impulse-type seismic waves are selected to calculate structural dynamic responses and compared with vertical non-impulse seismic waves. Equivalent impulse models (Menun & Fu, 2001) are adopted for subsequent parametric analysis.

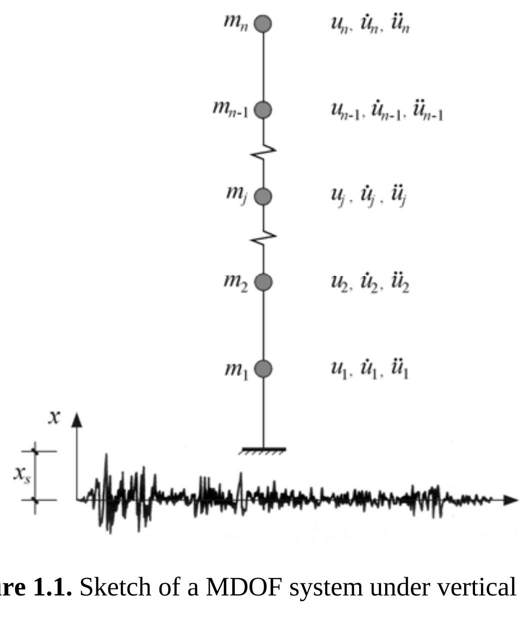


**Figure 1.1.** Sketch of a MDOF system under vertical motion

## 2. MODELING OF LONGITUDINAL WAVE PROPAGATION IN STRUCTURES

### 2.1. Vertical Seismic Wave Propagation in Structures

On the basis of the simplified structure in Fig. 1.1, according to traditional vibration analysis, the earthquake effect is treated as inertial force and is moved to the right side of the vibration differential equation, and then structural responses can be obtained by modal superposition method or step-by-step integration method.

In the view of wave analysis, vertical seismic wave travels into the structure from the foundation. After that, reflection and transmission occur at every lumped mass as shown in Fig. 2.1, i.e. the incident wave is divided into reflection wave and transmission wave. The downgoing reflection wave is divided into the upgoing reflection wave and the downgoing transmission wave at lower lumped mass again; the upgoing transmission wave is also divided into the downgoing reflection wave and the upgoing transmission wave at upper lumped masses. At the top and the bottom of the structure, vertical seismic waves are reflected completely, but the vibration direction of seismic wave is changed at the bottom. So, dynamic response of each lumped mass is the superposition of all upgoing waves and downgoing waves through the lumped mass.

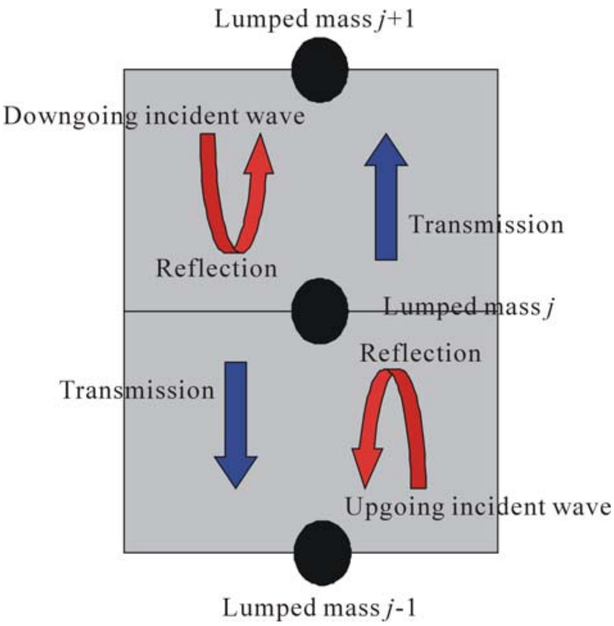


**Figure 2.1.** Longitudinal wave propagation at lumped mass *j*

## 2.2. Determination of Reflection Coefficient and Transmission Coefficient

For the reasons mentioned above, reflection and transmission coefficients of longitudinal wave through lumped masses need be determined to obtain structural vertical responses. Some assumptions adopted herein are that, i.e. 1) Structure always behaves linearly elastic; 2) The size of lumped masses, lateral strain of vertical components, strain rate effect and wave diffraction could be ignored. Lumped mass *j* and its two adjacent members (see Fig. 1.1), vibrate only in longitudinal direction (as shown in Fig. 2.2) with no lateral displacement. The bottom of the structure is subjected to an upgoing incident wave of a specified frequency and unit amplitude. Then the vibration differential equation of lumped mass *j* is listed as

$$F_j + G_j + f_j + f_{cj} = 0 \tag{2.1}$$

Where, $F_j$ denotes inertia force; $f_j$ denotes restoring force; $f_{cj}$ denotes damping force; $G_j$ denotes gravity.

Vertical displacement wave equations (Safak, 1998) are also listed as

$$u_a(x,t,f) = T_{u,j} \bullet e^{-i \bullet 2\pi f \left(x/V_j - t\right)} \tag{2.2}$$

$$u_b(x,t,f) = e^{-i \bullet 2\pi f \left(x/V_j - t\right)} + R_{u,j} \bullet e^{+i \bullet 2\pi f \left(x/V_j - t\right)} \tag{2.3}$$

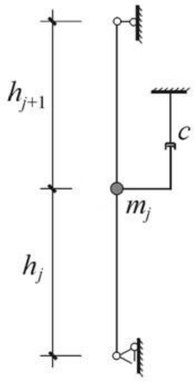


**Figure 2.2.** Sketch of lumped mass j

Where, $u_a$ denotes the absolute displacement at upper surface of lumped mass $j$ and equals to transmission component of the incident wave; $u_b$ denotes the absolute displacement at lower surface of lumped mass $j$ and its value is the sum of reflection wave and incident wave; $x$ denotes the distance from the lumped mass; $R$ and $T$ denote reflection and transmission coefficients respectively; $V$ denotes longitudinal wave velocity; $f$ denotes natural frequency.

Reflection and transmission coefficients can be determined by combining vibration mechanics with wave mechanics, i.e. Eqns 2.1, 2.2 and 2.3 are solved simultaneously.

$$R_{u,j}=\frac{1-a_j-b_j\left(1-e^{i\bullet 2\pi f\sqrt{\frac{M_{w,j}h_j}{E_jA_j}}}\right)-i\bullet 2\pi fc_j}{1+a_j+b_j+i\bullet 2\pi fc_j} \tag{2.4}$$

$$T_{u,j}=\frac{2+b_je^{i\bullet 2\pi f\sqrt{\frac{M_{w,j}h_j}{E_jA_j}}}}{1+a_j+b_j+i\bullet 2\pi fc_j} \tag{2.5}$$

Where, $E$ denotes the modulus of elasticity; $A$ denotes sectional area; $h$ denotes story height; $c$ denotes damping coefficient which can be obtained by equivalent single degree of freedom (SDOF) system, i.e. lumped mass $j$ and its two neighbouring members are treated as SODF systems; Coefficients, $a_j$ ,$b_j$ and $c_j$, depend on structural parameters; $M_w$ denotes floor mass; $f$ denotes natural frequency.

## 2.3. Numerical Solution Strategy

Reflection and transmission coefficients not only depend on structural parameters but also vary with frequency. They are similar with linear time invariant system function in signal processing field and have a feature of high frequency filtering. So, reflection and transmission waves can be obtained by filtering of system functions, $R$ and $T$, when a vertical seismic wave is treated as a transmit signal.

Different filter types can be adopted. Firstly, reflection and transmission coefficients might be equivalent with digital filter. Reflection and transmission waves are obtained by corresponding finite difference format in which difference coefficients are merely associated with structural parameters. Secondly, the frequency filter is adopted based on FFT. The filter form not only can consider structural parameters but also can filter for the signal of specified frequency. The second strategy is more accurate for vertical seismic wave containing high frequency components, especially near-fault impulse-type vertical seismic wave, because it is based on frequency filter and overcome the shortage of the difference filter in which difference coefficients are constants.

Then, single reflection and transmission at each lumped mass can be decided according to proposed solution strategy in Fig. 2.3. The complete calculation is going on along the height of the structure. Superposition principle is adopted to predict dynamic responses of lumped masses, so the method is limited in elastic range. But ductility behaviour of axial member is typically small because of that axial stiffness of the structure is large. Meanwhile, soil-structure interaction is ignored, i.e. seismic wave is input directly from the bottom of the structure.

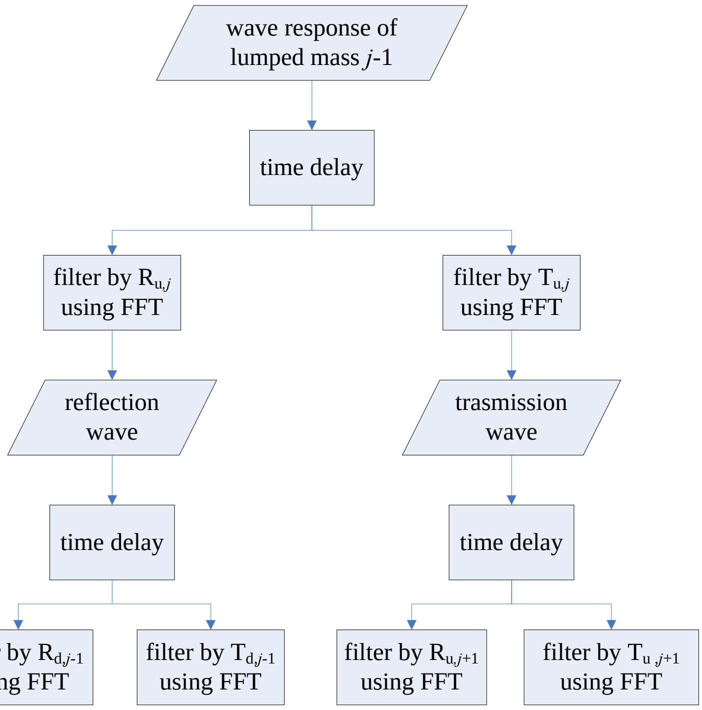


**Figure 2.3.** Solution strategy at lumped mass *j*

## 3. APPLICATION AND ANALYSIS

According to Fig. 1.1, some structural parameters are chosen to check and analyse the above solution strategy. Story height, $h$=4m; The sectional area of all vertical bearing components at the base floor, $A$=100m$^2$, which decreases 5m$^2$ every 10 stories; Density, $\rho$=25kN/m$^3$; Floor mass equals to story mass, but more than 1.5 times at variable cross-section; The modulus of elasticity, $E$=4.0×10$^{10}$N/m$^2$. The height of the structure is 200m with 50 lumped masses (50 stories). The vertical fundamental period is 0.2766sec. Two vertical seismic waves (see Table 1) are selected among Chi-Chi seismic waves from PEER database (PEER, 2012), i.e. one is an impulse-type and other is a non-impulse-type. Their response spectra are plotted in Fig. 3.1. A wave slot containing PGA (peak ground acceleration) is taken out as input for computational simplicity. PGA is scaled to 0.1 g, and then the spectral acceleration of the structure is 0.1012g and 0.1283g respectively. The above three methods are adopted to predict structural responses. The absolute accelerations of lumped mass 10 (at first variable cross-section) from different methods are made comparisons.

**Table 1.** Selected Vertical Seismic Waves

| Classify | Station | PGV (cm/s) | PGA (g) | PGV/PGA (s) | Rrup (km) | Mag. |
|---|---|---|---|---|---|---|
| Impulse-like record | TCU104 | 23.3301 | 0.0828 | 0.29 | 12.9 | M7.62 |
| Non-impulse-like record | CHY041 | 9.8542 | 0.1227 | 0.08 | 19.8 | M7.62 |

The computational results are illustrated in Figs. 3.2 and 3.3. The absolute vertical acceleration from the wave propagation method is larger than that from the vibration method. Especially, the closer to the top the lumped mass is, the larger its acceleration is. The reason is the superimposition effect from reflection wave at the top. The predictions from the rule are in good accordance with the measured results in the reference (Bozorgnia et al., 1998). And time delay is also represented by the wave propagation method.

Because structural spectrum acceleration is predominant in vibration method, the absolute acceleration (0.1030g) of lumped mass under non-impulse-type ground motion is larger, as the results show, than impulse-type ground motion (0.0996g). But in view of wave propagation method based on proposed solution strategy, its conclusion is on the contrary, i.e. the acceleration (0.1039g) of lumped mass under non-impulse-type ground motion is smaller than impulse-type ground motion (0.1305g). It is determined by a feature of wave propagation analysis representing the spread of energy.

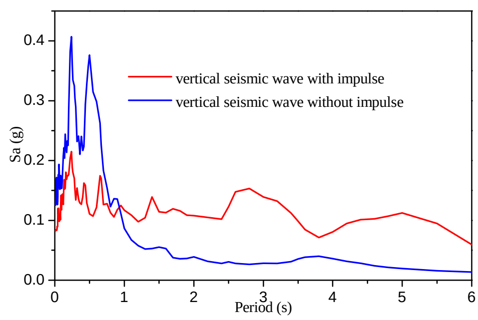


**Figure 3.1.** Response spectrum of selected vertical seismic waves

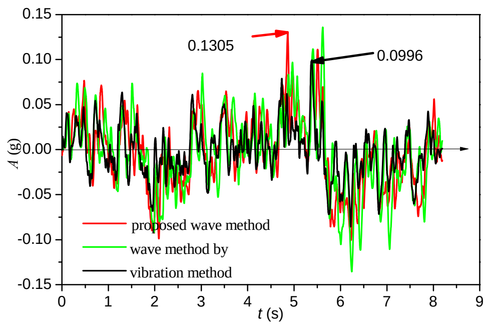


**Figure 3.2.** Acceleration of lumped mass 10 under vertical earthquake wave with impulse

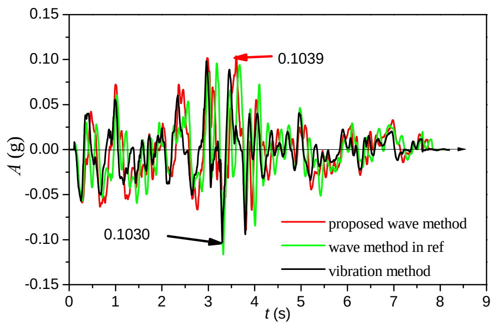


**Figure 3.3.** Acceleration of lumped mass 10 under vertical earthquake wave without impulse

Thus it can be seen that wave analysis method is more competent in calculating structural macro-level responses under vertical impulse-type seismic waves. Time delay and wave superposition are represented by the method. Although more time is needed and data points are limited, FFT filter not only avoids calculating time delay of difference filter but also can be specific to seismic wave of specified frequency.

## 4. PARAMETRIC ANALYSIS

Simplified impulses are capable of representing their effects on structural responses (Sehhati et al., 2011). In this section, simplified impulses are input to get the effect on structural macro-level responses from variable model parameters and variable structural parameters. The velocity time history expression of the selected simplified impulses model (Menun & Fu, 2001) is

$$\dot{u}(t;\theta)=\begin{cases} V_p \exp\left[-n_1\left(\frac{3}{4}T_p - t + t_0\right)\right]\sin\left[\frac{2\pi}{T_p}(t-t_0)\right] & t_0 < t < t_0+\frac{3}{4}T_p \\ V_p \exp\left[-n_2\left(t - t_0 - \frac{3}{4}T_p\right)\right]\sin\left[\frac{2\pi}{T_p}(t-t_0)\right] & t_0+\frac{3}{4}T_p < t < t_0+2T_p \end{cases}$$

Where, $\theta$=[$V_p$, $T_p$, $t_0$, $n_1$, $n_2$]$^T$, it is a vector about model parameters. $V_p$ controls the amplitude of velocity impulse; $T_p$ controls the duration time of velocity impulse; $t_0$ is the starting time of the impulse; $n_1$ and $n_2$ controls the shape of the velocity impulse. So, different types of velocity impulses can be got by changing the value of $n_1$ and $n_2$. For cases of $n_1$=0.5, $n_2$ =4 and $n_1$=4, $n_2$ =4, their time-velocity diagrams can be seen in plotted in Figs. 4.1 and 4.2.

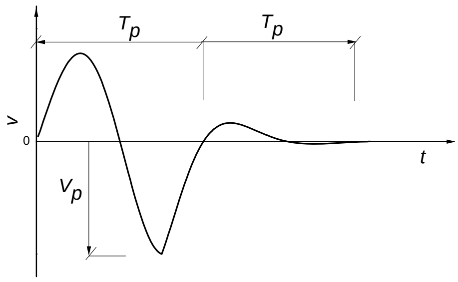


**Figure 4.1.** Velocity time history of model 1

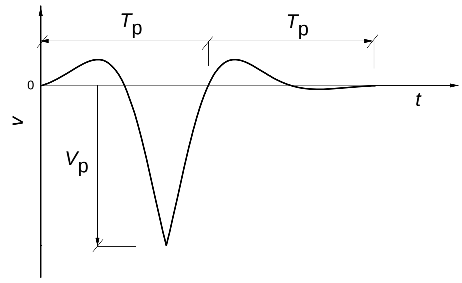


**Figure 4.2.** Velocity time history of model 2

The coincidence between the simplified impulses model and actual seismic waves have already been discussed in the reference (Menun & Fu, 2001). This paper, the qualitative analysis is implemented with the above structural parameters and two simplified impulses model, and the analysis mainly focuses on structural vertical responses for different parameters.

The normalized absolute peak accelerations of lumped mass 10 are plotted in Figs. 4.3 and 4.4. The responses at other lumped mass have the same law. The law is also similar between two different impulse models. The larger the values of $V_p$ are, the larger the structural responses are, and the larger the values of $T_p$ are, the smaller the structural responses are. From the energy point, the larger the values of $V_p$ is, the more energy seismic wave contains, and the larger the values of $T_p$ is, the shorter time that the same amount of energy is input into structure needs. This situation is more unfavourable to the structures. Where duration $T_p$ is more critical factor when the amplitude is in a smaller extent. Especially once $t_p$ not greater than 0.2 sec, as shown in the example, the peak responses increase significantly. So, during the design of high-rise buildings, the vertical impulse-type ground motion of large amplitude and short duration should be considered seriously.

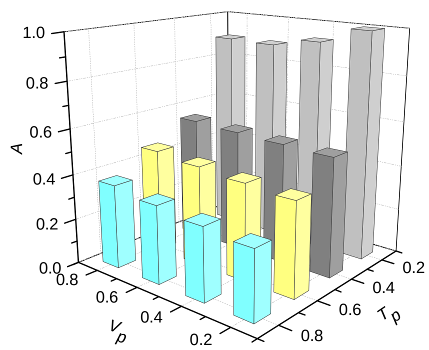


**Figure 4.3.** Peak responses of lumped mass 10 under model 1

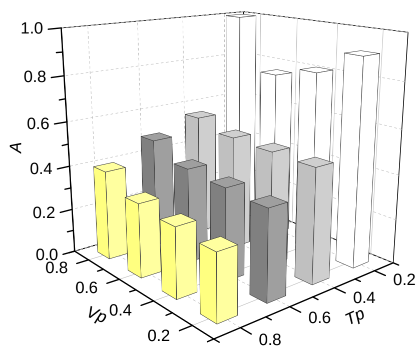


**Figure 4.4.** Peak responses of lumped mass 10 under model 2

The effect on structural responses from structural parameters is analyzed under impulse model 1. Structural acceleration responses are analyzed when significant vertically irregularity in stiffness occurs at the third variable cross-section. Normalized peak accelerations are plotted in Fig. 4.5. It can be seen that smaller responses of upper lumped masses when the stiffness gets smaller. That means less energy is input into the upper structure. It might be imagined that more energy will be concentrated at lower part of the structure, if the stiffness of the lower story gets smaller, and this situation is seriously destructive. The relative vertical displacement between the inner core cube and outer frame column might be found because of that the axial stiffness of the both have large gap, especially different vertically irregularities in stiffness along the height. Because of that, more serious results might occur, e.g. that the outriggers are sheared and stress concentration is presented at the joint. Similarly, the situation is also presented when lumped mass gets bigger as shown in Fig. 4.6. So, significant vertically irregularities in stiffness and mass should be paid more attention under vertical earthquake during the design of high-rise buildings.

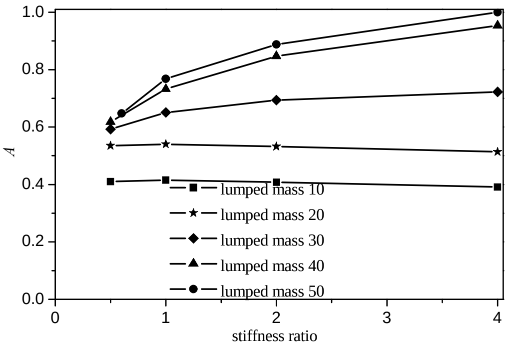


**Figure 4.5.** Peak responses for different stiffness ratios

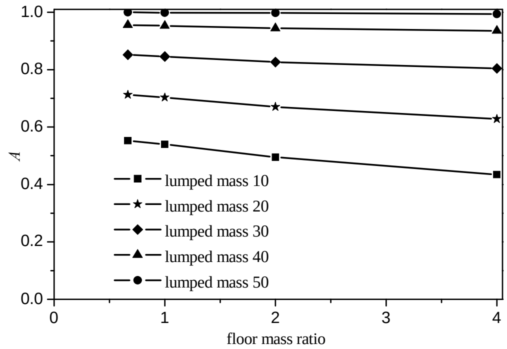


**Figure 4.6.** Peak responses for different mass ratios

## 5. CONCLUSIONS

The wave propagation method considering wave effects proposed herein is used to conduct qualitative analysis on macro-level responses of high-rise buildings excited by impulse-type strong vertical ground motions. Some conclusions could be reached from the analysis as follows,

(1) When compared to the vibration method, wave propagation method based on proposed solution strategy can reflect wave effects and is more competent in calculating structural macro-level responses under vertical impulse-type seismic wave;

(2) High-rise buildings might experience more serious damage under vertical impulse-type ground motion with larger amplitude and shorter duration;

(3) In contrast with vertically regular structural systems, significant vertically irregularities in stiffness and mass along structural height prevent much more seismic energy transferred into upper structure which could give rise to some serious problems, e.g. stress concentration and damage for the lower component, relative displacement between vertical components, shear damage for girder, stress concentration at the joint.

Only qualitative analysis is implemented by using the proposed simplified wave propagation method. Further investigation is needed for quantitative discussions.

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