STRUCTURAL RESPONSE TO HIGH FREQUENCY AND SHORT DURATION IMPULSIVE GROUND MOTIONS

Rajesh Prasad Dhakal[1], Tso-Chien Pan[1] and Shengrui Lan[2]

ABSTRACT: This paper presents a conceptual discussion on structural response to high frequency and short duration impulsive ground motion based on numerical analysis of a single degree of freedom system subjected to explosion-induced ground motion. Parametric study is performed to investigate the effect of impulse duration to natural period ratio on the maximum response of a single degree of freedom system to different types of impulsive loadings. As the loading duration of explosion-induced ground motion is smaller than half of the natural period of most civil engineering structures, maximum displacement response to underground explosion increases with the increase in total impulse, and it generally occurs in the free vibration phase. It is, therefore, necessary to consider longer time domain than the loading duration in the analytical prediction of structural damage due to high frequency and short duration loading. Numerical analyses are carried out on single degree of freedom systems with different natural periods to simulate and investigate the contribution of vibration modes on the overall displacement, velocity and acceleration responses. High frequency vibration modes, which are activated within the forced vibration phase, cause smaller displacement and larger acceleration response. However, free-vibration response is dominated by lower frequency fundamental mode that yields larger displacement and smaller acceleration response. Hence, structures are more likely to undergo displacement-induced damage in the free vibration phase, but relatively larger inertia force due primarily to high acceleration might be detrimental in the forced vibration phase.

KEYWORDS: explosion-induced ground motion, high frequency, short duration, impulse response, single degree of freedom system, free vibration, forced vibration.

1. INTRODUCTION

If the explosives in an underground ammunition magazine accidentally blast, nearby structures are subjected to significant impulsive load that may cause damage or failure depending on the quantity of the explosive and the distance of the structure from the explosion source. Hence, it is necessary to regulate the construction of residential buildings in the neighbourhood of such potential explosion sources. To find the safe *inhabited building distance* IBD in the vicinity of ordnance storage facilities, the response of building structures to *explosion-induced ground motion* EIGM must be well understood.

Studies in the past [1, 2] have revealed that ground motion generated by underground blasting have significantly higher frequency components with larger magnitude and shorter duration. Due to these unique characteristics, the response mechanism of a structure to blasting is much different than that to earthquakes. Few studies [3] have tried to investigate the unique nature of structural response to EIGM, but researches addressing the fundamental issues such as the qualitative influences of each of high frequency, short duration and large magnitude on the structural response to such impulsive ground motions are missing. The authors believe that conceptual guidelines based on the interaction between basic structural parameters and ground motion characteristics will be very much helpful in planning and implementing research strategies for deeper investigations. This paper tries to clarify these basic issues based on the computation of *single degree of freedom* SDOF system response to ground motion with similar characteristics as EIGM.

2. REPRESENTATIVE GROUND MOTION

In this study, analytically simulated *Explosion induced ground motion* EIGM data [1] is used to represent high frequency and short duration impulsive ground motions. The acceleration time history

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[1] Protective Technology Research Centre, School of Civil & Structural Engineering, NTU, Singapore, PhD

[2] Defence Science and Technology Agency, Ministry of Defence, Singapore, PhD

of this representative ground motion and its Fourier spectrum are shown in Figure 1. This ground motion represents the horizontal excitation induced due to a large-scale explosion at 50 m surface distance. Although the simulation is performed for 0.25 sec, the effective duration containing substantial acceleration amplitude is approximately 0.05 sec only. The *peak ground acceleration* PGA and the *peak particle velocity* PPV of this excitation are 1220.19 m/s^2 and 0.978 m/s, respectively. Moreover, it includes significant higher frequency components, the peak Fourier amplitude corresponding to 188.65 Hz.

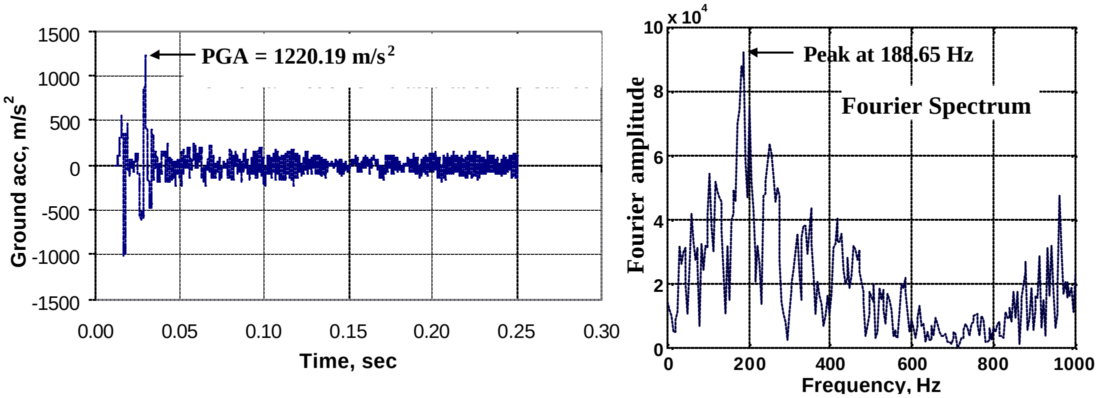

Figure 1. Representative impulsive ground motion with high frequency and short duration

The simulated EIGM is different in some aspects from common seismic excitations recorded during earthquakes. Firstly, it has significant higher frequency content than the seismic excitation. Secondly, it lasts for relatively shorter duration than seismic excitation. Lastly, it has much larger amplitude than that of a seismic excitation. The aforementioned characteristics indicate that EIGM is impulsive in nature, and a review of structural dynamic response to impulsive loads is helpful to understand the structural response to such ground excitations.

3. REVIEW OF STRUCTURAL RESPONSE TO IMPULSIVE LOADS

The main characteristics of an impulsive load are shorter duration and larger magnitude. Structural response to impulsive loading is divided into the forced vibration phase (within the loading duration) and the free vibration phase (after the load is applied). The damping affects the response degradation in free vibration phase but its influence on the maximum response is negligible. Usually due to short loading duration, the structure yields the maximum response in the free vibration phase. Nevertheless, reliable prediction of the response in the forced vibration phase is also important, as the displacement and velocity at the end of this phase will serve as the initial condition for the free vibration phase.

Hereafter, the responses of a *single degree of freedom* SDOF system to impulsive ground excitations of four different shapes (sinusoidal, rectangular, symmetric and asymmetric triangular) are computed by solving the Duhamel Integral [4]. In the computations to follow, the damping ratio is considered to be 5% of the critical damping, and a peak ground acceleration of 1000 cm/s^2 is assumed. SDOF responses are computed for three loading durations t_1 (0.2, 0.1 and 0.04 sec) and six different values of natural period T (5, 2, 1, 0.5, 0.2 and 0.1 sec) so that the ratio t_1/T ranges between 0.008 and 2. It is to be mentioned here that some cases with relatively larger t_1/T ratio may not fall under the category of impulsive loading.

The displacement response histories of SDOF systems with four different natural periods to a rectangular impulsive ground excitation of 0.2 sec duration are shown in Figure 2. For the first two cases (T = 1, 0.5 sec), the maximum response occurs in the free vibration phase, whereas for the third and the fourth cases (T = 0.2, 0.1 sec), displacement response becomes maximum in the forced vibration phase. Note that the maximum response is significantly smaller if it occurs in the forced vibration phase. For all impulse shapes, the responses with different combinations of t_1 and T indicate that the maximum response does not depend separately on t_1 and T, rather it depends on the ratio t_1/T. For symmetrical type of impulsive loading (sinusoidal, rectangular and triangular), the maximum response lies in the free vibration phase if t_1/T is less than 0.5, and this critical ratio is 0.37 for asymmetric triangular impulsive load.

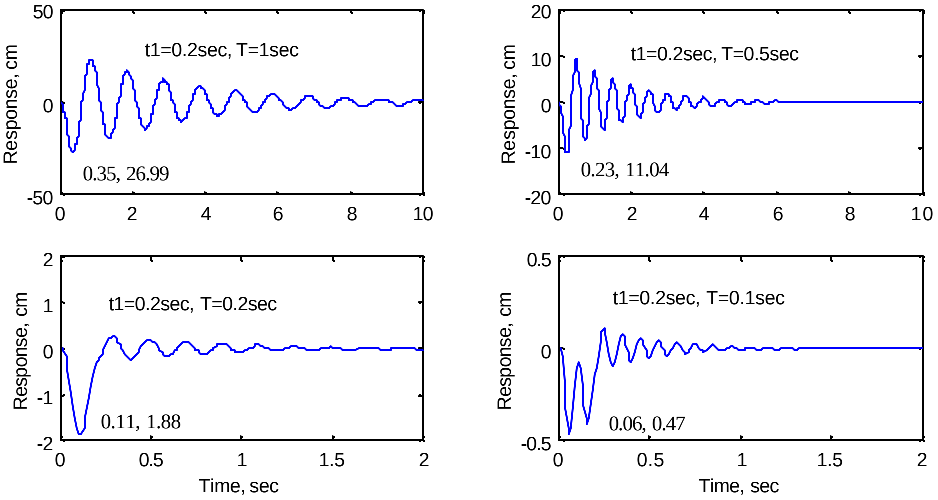

Figure 2. SDOF Response to rectangular impulse of duration 0.2 sec

As different values of natural period T correspond to different mass and/or stiffness, the absolute displacement responses are expected to differ in each of the above cases. Hence, a generalized parameter called the maximum response ratio R_{max}, which is defined as the ratio of maximum dynamic response to the static response, is used for mutual comparison of different cases. For all impulse shapes, the relationships between R_{max} and t_1/T, also called shock spectra, are drawn in Figure 3.

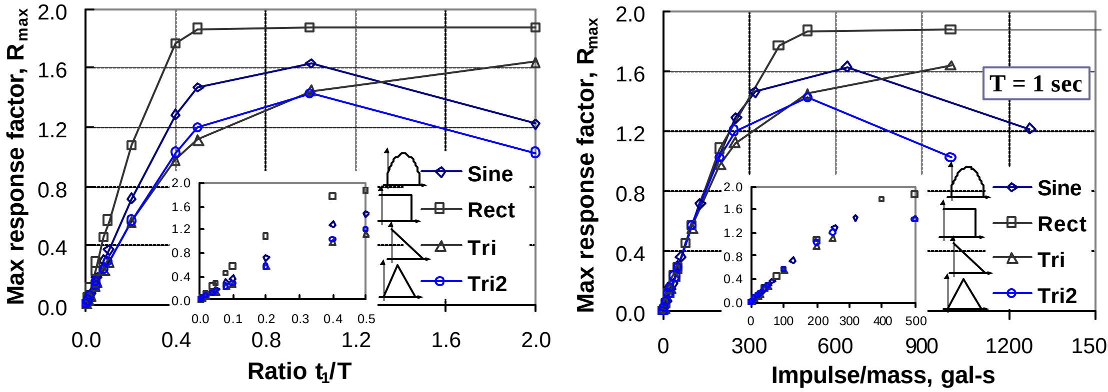

Figure 3. Effect of t_1/T and impulse on the SDOF response to different impulse shapes

As expected, the shock spectra corresponding to different impulse shapes are different from each other. If t_1/T is more than the critical ratio, the maximum response factor is almost independent of t_1/T. For smaller t_1/T ratio, the maximum response factor R_{max}, though small, is very sensitive to t_1/T. In other words, the response of a structure to a short-duration impulsive excitation depends primarily on the loading duration or the total impulse. For further clarification, the maximum response factor R_{max} is plotted against the total input impulse normalized with respect to the mass of an SDOF system with natural period of 1 sec in Figure 3. Regardless of the impulse shape, the R_{max}-impulse relationship follows a common path until t_1/T is smaller than the critical ratio. Nevertheless, this unique relationship no longer exists for larger values of t_1/T.

As the effective duration of impulsive excitation such as EIGM is short enough (usually less than 0.1 sec) to ensure that t_1/T is less than the critical ratio for most civil engineering structures (fundamental frequency lower than 5 Hz), the maximum response of a structure to underground explosion occurs in the free vibration phase. This fact advocates for the need to consider longer time domain than the actual ground excitation period in analysing the structural response to blast-type loading. Moreover, the free vibration maximum response depends on the total impulse applied to the structure, which in turn depends on the duration of the ground excitation.

4. CONTRIBUTION OF DIFFERENT MODES IN STRUCTURAL RESPONSE

Basically, structural response is a combination of several modes and each of these modes corresponds to a different frequency. Depending on the structural properties and loading characteristics, some modes have larger contribution in the overall structural response. It is reported [5] that high frequency vibration modes dominate the structural response to high-frequency ground excitation such as EIGM. However, this is true if the high frequency ground motion is of sufficiently long duration, and when the response in the forced vibration phase is of main concern. The authors believe that in spite of higher frequency modes (closer to the dominant frequency in the input ground excitation) dominating the structural response within the loading duration, vibration mode with lower frequency (closer to the fundamental frequency of the structure) governs the response in the free vibration phase that is more important in case of short duration ground excitations. In other words, two important characteristics of structural response to high frequency and short duration ground motions are high frequency modes dominating the forced vibration response and fundamental structural mode governing the free vibration response. It is, therefore, necessary to understand qualitatively the relative contributions of vibration modes with different frequencies before converging to deeper conclusions.

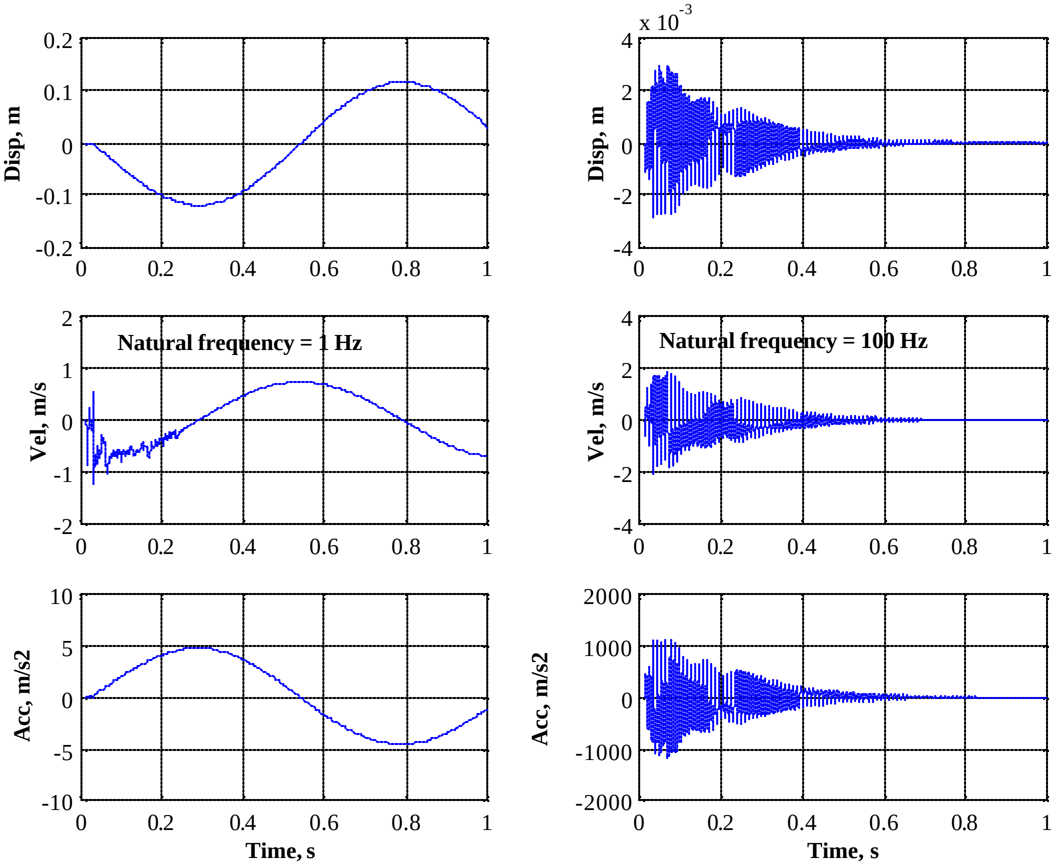

Figure 4. Response histories of SDOF systems with natural frequencies of 1 Hz and 100 Hz

To investigate the relative contribution of different modes, responses of SDOF systems with different natural periods to the EIGM representing short duration and high frequency ground excitations are computed hereafter. To cover all possible vibration modes, the natural frequencies of the six SDOF systems are selected to range between 0.3 Hz and 300 Hz. In one case, the fundamental frequency of the SDOF system is assigned equal to the frequency at the peak of the Fourier amplitude of the representative ground motion (188.65 Hz) to qualitatively represent the resonance condition. For all computations to follow, damping is assumed to be 1% of the critical. The displacement, velocity and acceleration responses of two SDOF systems with normal and high natural frequencies (1 Hz and 100 Hz) are shown in Figure 4. The acceleration responses shown in the figure are the absolute value and not relative to the ground acceleration. That is why compared to the flexible structure with normal period (1 Hz frequency), rigid structure with short natural period (100 Hz frequency) shows larger acceleration that is closer to the applied ground acceleration.

Supporting the earlier arguments, the maximum responses of structure with 1 Hz fundamental frequency occurred in the free vibration phase, and those with 100 Hz occurred in the forced vibration phase because the effective loading duration is less than 0.2 sec. The maximum displacement response of structure with 1 Hz natural frequency is significantly larger than that of 100 Hz structure. In contrast, the maximum acceleration response is much larger in case of 100 Hz structure than in 1 Hz structure.

The response histories corresponding to other values of natural frequencies are not illustrated in figure, but the maximum values of the responses for all six cases are shown in Table 1. Moreover, the variations of maximum displacement, maximum velocity and maximum acceleration with SDOF natural frequency are illustrated in figure 5. Note that the maximum velocity and maximum acceleration responses are normalized with respect to PPV and PGA, respectively to get corresponding dynamic amplification factors. As the natural frequency of the SDOF system increases, the maximum displacement decreases. In spite of resonance with high frequency ground excitation, the displacement response of SDOF system with high natural frequency is very small. However, he velocity and acceleration responses increase with the increase in natural frequency.

Table 1. Effect of SDOF natural frequency on maximum responses

Response parameter	**Natural frequency of SDOF system,** w					
	0.3 Hz	**1.0 Hz**	**10 Hz**	**100 Hz**	**188.65 Hz**	**300 Hz**
Maximum Displacement	414.2 mm	119.4 mm	9.2 mm	3.0 mm	3.1 mm	0.65 mm
Maximum Velocity	1.226 m/s	1.224 m/s	1.123 m/s	2.025 m/s	3.731 m/s	1.203 m/s
Maximum Acceleration	1.472 m/s^2	4.717 m/s^2	36.30 m/s^2	1176.4 m/s^2	4328.2 m/s^2	2331.0 m/s^2

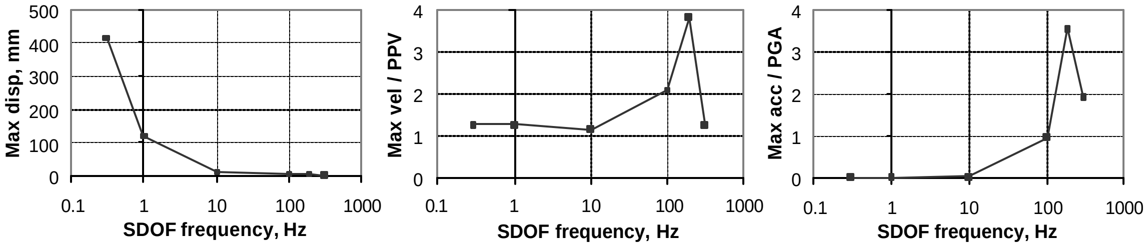

Figure 5. Variation of maximum responses with SDOF natural frequency

Although real nonlinear structures are better represented by multi degree of freedom system with distributed mass idealization, an SDOF response can be fairly assumed to be qualitatively equivalent to overall structural response, where all modes except the one with frequency equal/close to the natural frequency of the SDOF system are suppressed. The above results, therefore, indicate that the velocity and acceleration are large and displacement is small if the higher frequency modes contribute more, as in the forced vibration response to high frequency and short duration ground motions. Similarly, the acceleration becomes smaller and the displacement becomes larger if the overall structural response is governed by lower frequency modes, as in the free vibration response. Large velocity/acceleration generate significant damping/inertia force, causing the base shear to increase considerably. On the other hand, large displacement causes larger strain that damages the structure through cracking, yielding etc. Hence, a structure subjected to high-frequency ground excitation such as EIGM may not undergo severe damage during the forced vibration phase because the displacement is small, but may be subjected to significant shear force. However, the possibility of damage cannot be ruled out in the free vibration phase because of the non-negligible displacement response.

5. CONCLUSIONS

The fundamental concepts of structural dynamics are applied to explain qualitatively the structural response to high frequency and short duration impulsive ground motions. Parametric study based on the response of simplified structural model to a typical ground excitation generated by underground blasting is carried out to highlight the influence of shorter duration and higher frequency of the input ground motion in various structural response parameters. Due to the short duration such impulsive ground motions, the maximum displacement response occurs after the ground motion is applied; i.e. in the free vibration phase. Hence, the time domain considered in the numerical computation of structural response to short duration ground excitations must be a few times larger than the loading duration. The computation only within the loading duration cannot capture the maximum response and hence will underestimate the displacement. The maximum displacement response of a structure to short duration impulsive loading is proportional to the total impulse (area of load-time curve) applied to the structure, but this unique interrelationship no longer exists once the loading duration becomes longer than half of the natural period of structure.

The forced vibration response to a high frequency ground excitation is dominated by higher frequency vibration modes, whereas the free vibration response in mainly governed by the lower frequency vibration mode. Higher frequency modes cause smaller displacement but larger velocity and acceleration, thus causing less displacement-induced damage but high shear force in the forced vibration phase. The lower frequency modes cause larger displacement and smaller acceleration, thus increasing the possibility of damage in the free vibration phase. This study provides only the conceptual idea how the general structures might behave under high frequency and short duration impulsive ground excitation such as that generated by underground blasting. More extensive studies should be conducted before drawing more general conclusions.

6. REFERENCES

[1] Ma, G., Hao, H. and Zhou, Y.X., "Modelling of Wave Propagation Induced by Underground Explosion", *Computers and Structures*, 1998 (3-4), Vol. 22, pp. 283-303.

[2] Dowding, C.H., *Construction Vibrations*, Prentice-Hall, Englewood Cliffs, NJ, 1996.

[3] Ma, G., Hao, H. and Zhou, Y.X., "Assessment of Structural Damage to Blasting Induced Ground Motions", *Engineering Structures*, 2000, Vol. 22, pp. 1378-1389.

[4] Clough, R.W. and Penzien, J., *Dynamics of Structures*, McGraw-Hill, 1993, Second Edition.

[5] Lu, Y., Hao, H., Ma, G. and Zhou, Y., "Simulation of Structural Response Under High-Frequency Ground Excitation", *Earthquake Engineering and Structural Dynamics*, 2001, Vol. 30, pp. 307-325.