SEISMIC ANALYSES OF LONG-SPAN CABLE-STAYED BRIDGES SUBJECTED TO NEAR-FAULT PULSE-TYPE GROUND MOTIONS

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ABSTRACT :

The pulse effect of near-fault ground motions and its effect on engineering structures with fundamental period were investigated in this study. The pulse character of many near-fault ground motions and its causes were introduced briefly. Near-fault ground motions from 8 stations during 1999 Chi-Chi, Taiwan earthquake and four common-used ground motions were selected to investigate the near-fault pulse effect. Response spectrum of these ground motions illustrated that there was abundant long-period component in pulse-type near-fault ground motions. The seismic performance of a constructed long-span cable-stayed bridge was evaluated by time history analysis method. The seismic behavior of the bridge to near-fault with and without pulse effect and common-used ground motions were investigated and compared. It is concluded that pulse-type near-fault ground motions will impose more sever damage potential to engineering structures with long fundamental period. Distinct underestimation of the structural response will be presented if pulse effect of near-fault ground motion is not considered, especially for engineering structures located near an underlying causative fault. Vertical pulse-type near-fault ground shaking should be got more attention in the seismic design and performance assessment of engineering structures in the near-fault region. Parametric study indicated that there is a nearly linear relationship between PGV/PGA ratio, spectral acceleration and spectral velocity of the ground motion and structural response.

KEYWORDS: near-fault ground motion, pulse effect, vertical ground motion, long-span cable-stayed bridge, parametric study

1. INTRODUCTION

Near-fault seismic motions were a prominent research subject and had an outstanding improvement during last several decades, especially after 1999 Taiwan Chi-Chi earthquake. Recordings from recent earthquakes have provided much evidence that seismic ground shaking near a causative fault rupture is characterized by the directivity pulse effect, fling step and hanging wall effect. Many seismologists and civil engineers have addressed in the near-fault seismic characteristics and their effects on engineering structures. Bertero *et al*. (1976; 1978) performed the early attention and research on near-fault effects, especially on pulse-type ground motion in near-fault regions. In recent years, more and more researchers are focusing on this field, including the reason and characteristic of these records from near fault rupture (Malhotra, 1999; Mavroeidis *et al.*, 2004; Mollaioli, *et al*, 2006). These particular near-fault effects revealed on the seismic wave shape, duration, amplitude and frequency aspects may impose different seismic behavior of many engineering structures, compared with far-field ground motions (Hall, *et al.*, 1995; Iwan, *et al.*, 2000; Mollaioli, *et al.*, 2006). But, most researchers always focus on the horizontal component of the near-fault ground motions, in recent years, more and more near-fault recordings were acquired, prominent vertical ground motions in the vicinity of the fault rupture were observed in the earthquake observation and also validated with many theoretical analyses (Papazoglou and Elnashai, 1996). A very highlighted vertical peak ground acceleration of 1.655g was recorded at the El Centro Array #6 station in 1979 Imperial Valley earthquake, with a ratio of 3.77 to horizontal peak ground acceleration at the same station. This remarkable vertical ground motion character also appeared in other earthquakes, for example 1985 Nahanni earthquake, 1989 Loma Prieta earthquake, 1994 Northridge earthquake, 1995 Kobe earthquake and 1999 Chi-Chi earthquake, and the ratio of vertical PGA to horizontal PGA arrive at unit, even larger than unit at many stations in near-fault regions during these events. Up to now, only a few researchers have addressed in the character of vertical peak ground acceleration, vertical response spectra (Bozorgnia and Campbell, 2000; Ambraseys and

Douglas, 2003) and the ratio to that of horizontal component (Dimitriu *et al.*, 1999). Results on the characteristics of the vertical seismic motions have been shown that vertical acceleration response spectra and the ratio of that to horizontal component are profoundly affected by the fault mechanism, distance to fault rupture, site conditions and other factors. Structural dynamic behavior in near-fault region have indicated the significance of vertical ground motions, abnormal high vertical acceleration record by accelerometer and structural damage of modern structures caused by vertical ground motions are investigated in 1994 Northridge earthquake, California, America (Goltz ed., 1994; Hall and Heaton, 1995). After investigation, many researchers pointed out that dominant vertical ground motion in near-fault regions may cause the notable variation of member axial force, and the structure will be at the state of nonlinear behavior, with the lacking ductility of reinforced concrete columns of some frames and local buckling of some steel member, following with the brittle collapse (Papazoglou and Elnashai, 1996; Khairy And Atsuhiko, 2000). Memari *et al.* (2004) showed that the effects of vertical ground motion will cause an increase in the design force for connections of precast heavy cladding panels, especially in near-source region, with the magnitude of the increase dependent on the source-to-site distance.

The long-span bridge possess longer horizontal and vertical fundamental period than common buildings, so the pulse-type near-fault ground motions which characterized by large amplitude and long period pulse effects may imposed more sever damage potential on this type structure. In this study, pulse-type characteristic of near-fault ground motions will be introduced firstly and then the horizontal and three-dimensional seismic response of a constructed cable-stayed bridge subjected to near-fault ground motion records and common-used ground motions is simulated, the effect horizontal and vertical near-fault seismic motions on the long-span cable-stayed bridge was evaluated the comparison between horizontal and three-dimensional excitations was also performed, and analyses and conclusions ware presented at the end of this study.

2. RECORDS AND STRUCTURAL MODEL USED IN THIS STUDY

Time history analysis method usually is used to evaluate the performance of important engineering structures, and the selection of input excitations play a very dominant role in this method, affecting the assessment of the structural performance directly. But, the method of the selection of the input motions adequately is not presented in most of structural seismic codes and guidelines. The input ground motion records were required to accord with the seismic design spectrum, but most of these design spectrums haven't considered the effect of the near-fault effect, except only in a few seismic codes and guidelines. The long-span bridges which have longer fundamental period may exhibit distinctive performance under the ground motion excitation near a causative fault.

2.1 Pulse Characteristic of Near-fault Ground Motion

Pulse effect is one of the most prominent attributes of near-fault ground motions. Many recordings from recent earthquake events have provide evidence that ground motion record near a fault rupture is characterized by a limited number of obvious pulses with very high energy input, this pulse often contains large long-period (2s-6s), this phenomenon often appeared in horizontal and vertical ground motions. It can be generated by two fault rupture movement, (I) The fault rupture propagate toward a site with a velocity close to shear wave velocity, and the fault rupture energy will be assembled in a short time, with a following single large long-period pulse of motion that occurs at the beginning of the record (Somerville et al., 1997), which is called fault rupture forward directivity effect. This radiation pattern of the shear dislocation on the fault cause the large pulse to be oriented in the direction perpendicular to the fault, causing the peak velocity of normal component to be larger than that of parallel component(Somerville, 1998). (II) Fault rupture movement generates the permanent offset of the ground surface; fling-step effect is used to describe this near-fault seismic motion attribute. To distinguish these two near-fault effects, “directivity effect” and “fling-step effect” are use for the fault rupture directivity and elastic rebound effects, respectively. For strike slip fault, rupture directivity effect occurs on the component of motion perpendicular to the fault rupture plane, but fling-step effect occurs along the direction of the fault rupture propagation with a significant surface offset. For the dip-slip fault, directivity pulse effect and fling-step effect can be combined on the same component of ground motions. Near-fault pulse-type attribute is a well-known phenomenon in seismology (Somerville and Graves, 1993), yet only recently the impact of the pulse-type effect has been attracted more attention and considered by engineers in a limited number of seismic codes (UBC1997).

Abundant near-fault recordings are captured from recent severe earthquake events, and many recordings have presented pulse character in the velocity traces, even in the acceleration trace, including horizontal component and vertical component of ground motion records in the vicinity of a causative fault rupture. Figure 1 portrays the North-South component and vertical component of acceleration and velocity traces at TCU052 station during 1999 Chi-Chi earthquake, Taiwan, respectively. The closest distance from this station to the surface projection of rupture is 0.24km. There are many other recordings at some stations near the fault rupture reveal this attribute in seismic motion traces. In these traces, the large amplitude, long-period pulse shape is obvious in the velocity even in the acceleration time history. The wave shape, amplitude and frequency character of this typical shaking have been studied extensively in last decades, but it is noted that many researches focus on near-fault horizontal ground motions, with no sufficient attention on vertical component, this pulse effect in vertical component of ground shaking should also be attracted more attention and study.

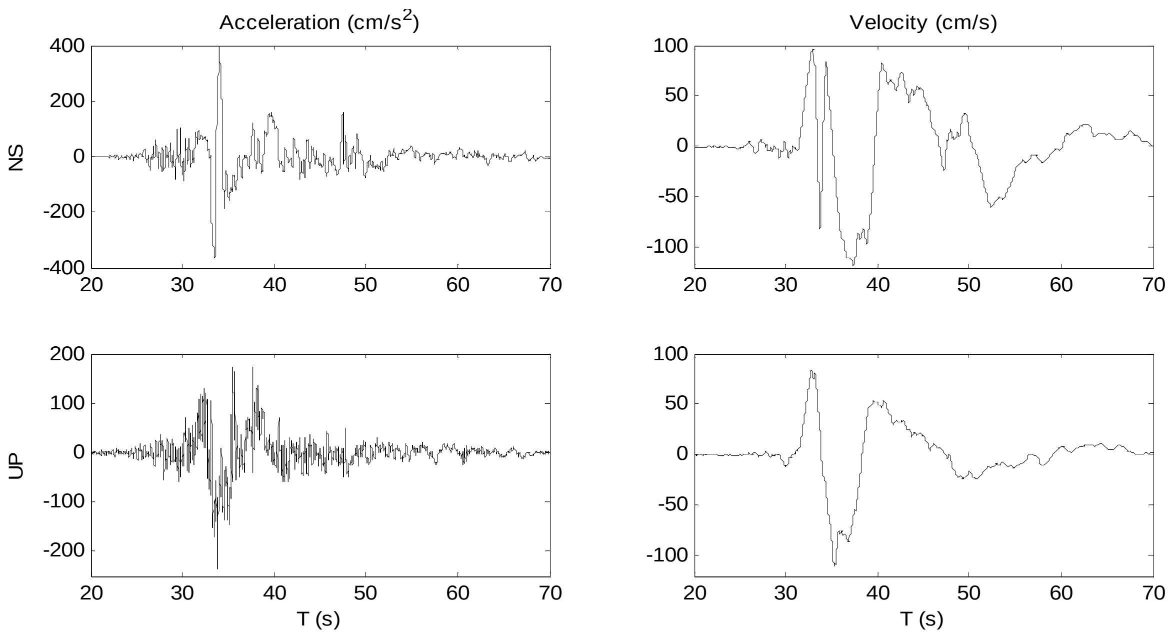

Figure 1 North-south and vertical component of the acceleration (left), velocity (right) time histories recorded at the TCU052 station, respectively, during the September 21, 1999 Chi-Chi earthquake, Taiwan

2.2 Ground Motion Records and Structural Model Used in This Study

Abundant recordings captured in 1999 Chi-Chi, Taiwan earthquake (M_W7.6), provide a paramount opportunity to study the character of near-fault ground shaking. The ground motion recording recorded by the accelerometers at 8 stations shown in Table 1 during this event was selected to evaluate the performance of a long-span bridge. The name of these stations and peak ground acceleration (PGA), peak ground velocity (PGV) and the PGV/PGA ratio of the horizontal component and vertical component records at these stations, the closest distance from this station to the surface projection of rupture were listed in this table, the maximum horizontal PGA and its corresponding PGV at the same component were selected. The site-to-fault distance of these recordings from this event is from 0.24 km to 15km. Three categories of ground motion records is used in this study, all of the first and second category used herein are captured in Chi-Chi earthquake, and the third category in Table 1 includes three common-used recordings, which is belonged to 1940 Imperial Valley earthquake (M_W7.0), 1952 Kern County earthquake (M_W7.4), 1976 Tangshan earthquake (M_W7.6), respectively. There is also a Shanghai artificial ground motion used in the third category.

The medial standardized acceleration response spectrum of the three categories of ground motions was shown in figure 2. It is illustrated that these three types of ground motion possess different characteristics. Abundant long period component exits in the first group ground motion with the distinct long-period pulse in velocity traces, when the period is large than 0.5s. The medial response spectrum of the common-used seismic excitations is close to that of near-fault ground motions without distinct long-period pulse, and they have abundant moderate period component. From the standardized acceleration response spectrum, it is demonstrated that these near-fault ground motions with distinct long-period pulse characteristic may impose more severe damage potential on the long-span and space engineering structures, which may also possess long fundamental period.

Finite element model shown in figure 3 of the constructed Binzhou yellow river highway bridge in Shandong province, China, was used herein to investigate the seismic behavior of the large-span cable-stayed bridge to near-fault ground motions with pulse and without pulse character. Three towers, double cable planes and 200 cables are designed in this prestressed reinforced concrete bridge, whose main span is 768 meters and span collocation is 84m+300m+300m+ 84m，the height of central tower is 123.25 m and the side tower is 75.78m. According to the seismic design information, this bridge located in 6-degree basic intensity place can be designed for 7-degree basic intensity due to its significance, the equivalent shear wave velocity is between 140m/s and 250 m/s. Nonlinear behavior of the reinforce concrete material was not considered in this finite element model, but geometric nonlinear effect was taken into account. Block Lanczos method was utilized to perform the modal analysis and the first three vertical modal periods are 4.3 sec, 2.2 sec and 1.7sec, respectively.

Table 1 Parameters of vertical ground motion excitations

Category	Station	Horizontal			Vertical			Distance
		PGA(g)	PGV(cm/s)	PGV/PGA	PGA(g)	PGV(cm/s)	PGV/PGA	
pulse	TCU052	0.241	110.5	0.47	0.419	118.4	0.288	0.24
	TCU068	0.486	187.3	0.39	0.566	176.6	0.318	1.09
	TCU087	0.108	61.5	0.581	0.128	40.8	0.325	3.18
	TCU101	0.169	55.2	0.333	0.251	49.4	0.201	2.94
no-pulse	CHY006	0.202	25	0.126	0.364	55.4	0.155	14.93
	TCU072	0.279	35.8	0.131	0.489	71.7	0.150	7.36
	TCU074	0.286	24	0.086	0.597	73.3	0.125	13.67
	TCU079	0.388	25.3	0.067	0.742	61.2	0.084	10.04
usual	El Centro	0.205	10.7	0.053	0.313	29.8	0.097	12
	Taft	0.109	6.6	0.062	0.178	17.5	0.100	42
	Tianjin	0.075	4.43	0.06	0.149	18.3	0.125	65
	Artifical	0.036	9.93	0.28	0.036	9.93	0.28	—

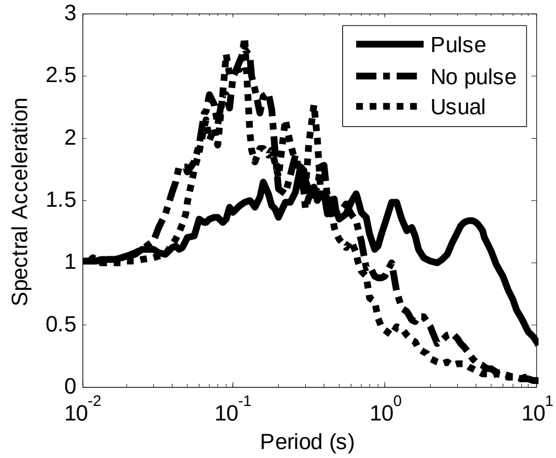

Figure 2 Standardized Response spectrum of these

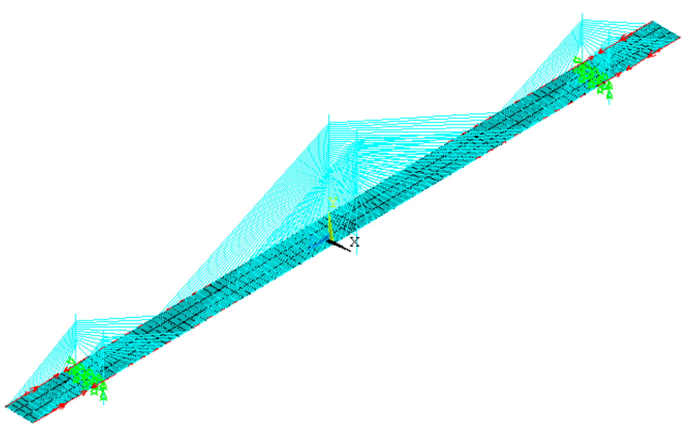

Figure 3 The long-span cable-stayed bridge finite

3. RESPONSE OF THE LONG-SPAN CABLE-STAYED BRIDGE TO SEISMIC EXCITATIONS

Predominant impulsive character of the near-fault ground motions impose the severe damage potential on these structures located in near-fault region, abundant transmission energy have to be absorbed and dissipated in a short time at the beginning of the earthquake occurs. The influence of the large amplitude, long-period pulse on the structural seismic response was first presented by Bertero *et al.*(1976). Recent concern about damage potential of near-fault pulse-type ground motions has attracted more attention on the nature of this kind of excitation and its impact on structural performance. It is demonstrated that near-fault records with pulse-type attribute can be represented by equivalent pulses defined on the basis of a limited number of ground motion parameters, such as, pulse duration, pulse amplitude, shape factors and so on (Alavi and Krawinkler, 2000). The effect of the pulse-type ground motion may requires consideration in the design process for structures located in the near-fault region, which is usually assumed to extend about 20 km from the fault rupture. The damage potential of pulse-type near-fault ground motions to the structure with long fundamental period should be investigated further for the application in the structural seismic design and assessment.

3.1 Structural Response for Horizontal Excitations

Time history analysis method was used to evaluate the horizontal performance of the long-span cable-stayed bridge in this study. The two horizontal component ground motions were considered as input excitation at the same time and the gravity effect also was included. According the seismic design code of China, the amplitude of the input excitation along the length of the bridge was scaled to 220 gal, and that of the other horizontal component which is perpendicular to the length direction was 0.85 times of foregoing amplitude. A finite element software package was used to perform this time history analysis, only considering the geometry nonlinearity and without consideration of material nonlinearity.

The lateral displacement of the central tower was calculated under every pair of horizontal ground motion excitation. The medial lateral displacement of these three group ground motions along the height of the tower was illustrated in figure 4. Under the pulse-type near-fault ground motion excitations, the lateral displacement in the parallel direction to the length of the bridge was larger than that of the other two situations, without pulse-type near-fault ground motions and common-used ground motions, especially above the middle location of the tower, with an increase by 60%. It is noted that the lateral displacement under the common-used ground motion is close to that under the no pulse-type near-fault ground motion, resulting in underestimation of the damage potential of the earthquake ground shaking, especially for the near-fault region.

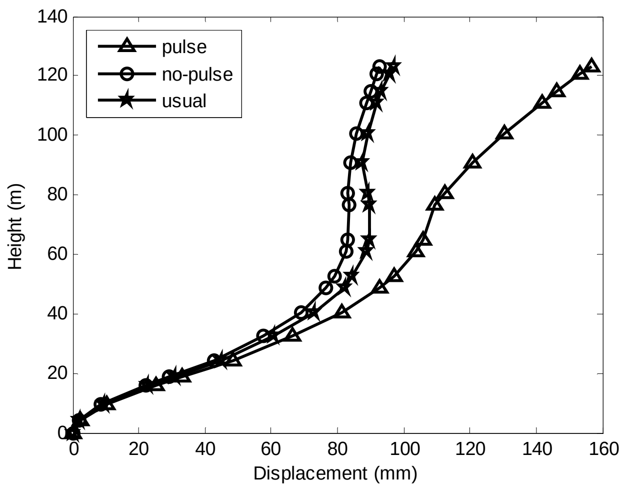

Figure 4 The medial lateral displacement of the central tower under the three group excitations

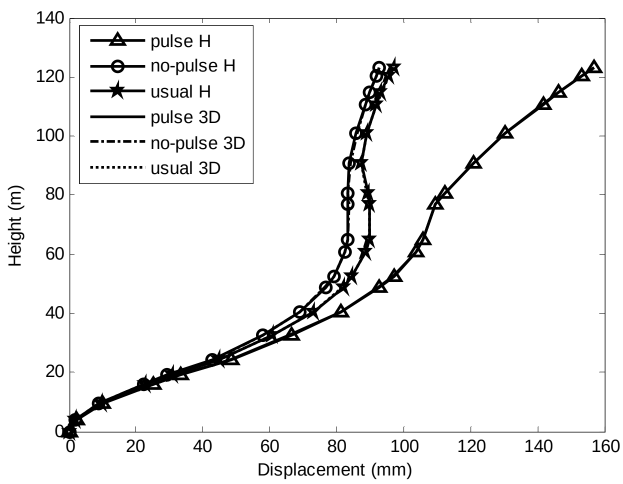

Figure 5 Comparison of the medial displacement of the central tower under horizontal and 3-D excitations

3.2 Structural Response for Three-dimensional Excitations

Three-dimensional time history analysis was performed to evaluate the seismic performance of the long-span bridge under three-dimensional excitations. In three-dimensional time history analysis, the three component ground motions were scale by 1:0.85:0.65, the peak amplitude of vertical component is 0.65 times to that of horizontal ground motion parallel to the bridge length direction. The three-dimensional seismic response analysis is carried out to investigate the effect of the vertical ground motions on the horizontal and vertical response, including with and without pulse-type characteristic and the common-used ground motions.

The comparison of the medial displacement of the central tower under horizontal and three-dimensional excitations was shown in figure 5. It is shown that the lateral displacement under three-dimensional excitation is nearly the same as that only under horizontal excitation, the effect of the vertical ground motion on the horizontal response is negligible. Figure 6 illustrated that the medial axial force along the height of the central tower. The axial force at the bottom of the central tower is increased by about 10% under the pulse-type near-fault ground motions, compared with that under the other two group excitations. The axial force under common-used ground motions is very close to that under without pulse-type near-fault ground motions, underestimation of the axial force will be induced when the pulse characteristic of the vertical ground motion is not considered. The medial maximum absolute vertical displacement of the main beam along the bridge length direction is portrayed in figure 7. The vertical displacement under pulse-type near-fault ground motions is more than 2 times and 3 times of that under common-used ground motions and without pulse-type near-fault ground motions, respectively. The effect of pulse character of vertical near-fault ground motions on the vertical response of the structure is revealed markedly. If only the common-used ground motions are considered in the seismic analysis, the vertical seismic response, including axial force and vertical displacement, may be underestimated distinctively, especially for the vertical displacement.

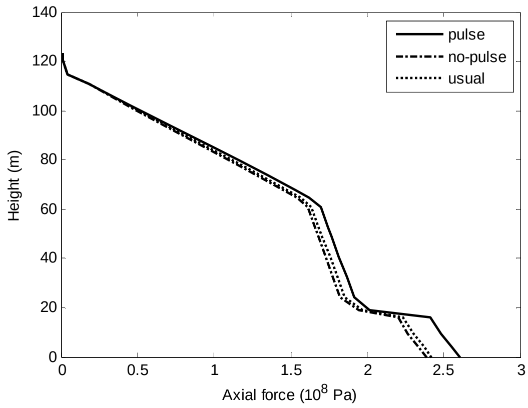

Figure 6 The medial axial force along the height of the central tower

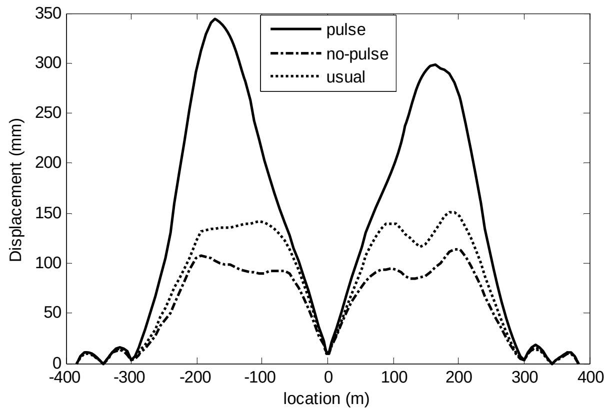

Figure 7 The medial vertical displacement of the main beam along the bridge length

4. Parametric study

The objective of parametric study is to investigate which parameter of the near-fault ground motion will affect the dynamic behavior of engineering structures predominantly. 12 selected ground motions mentioned above were used as input ground motions for this purpose. The main aim of this parametric study is to present the relationship between parameters of vertical ground motions and the maximum vertical displacement of the main beam.

Three important vertical ground motion parameters, the PGV/PGA ratio, spectral acceleration and spectral velocity are studied to explore their effect on the vertical seismic response of the large-span cable-stayed bridge. The PGV/PGA ratio of every vertical record used in this study are listed in table 1, and the spectral accelerations and spectral velocities are calculated with the period 4.3 sec for the analytical model, which is the vertical fundamental period of the analyzed cable-stayed bridge. Figure 8 shows the relationship between the maximum vertical displacement at the middle location of the mid-span and the PGV/PGA ratio, spectral acceleration and spectra velocity for the cable-stayed bridge subjected to the selected 12 near-fault ground motion records. The black straight line is the result of linear curve fitting. It is suggested that the maximum vertical displacement of the bridge will increase with the increase of the PGV/PGA ratio, spectral acceleration and spectral velocity.

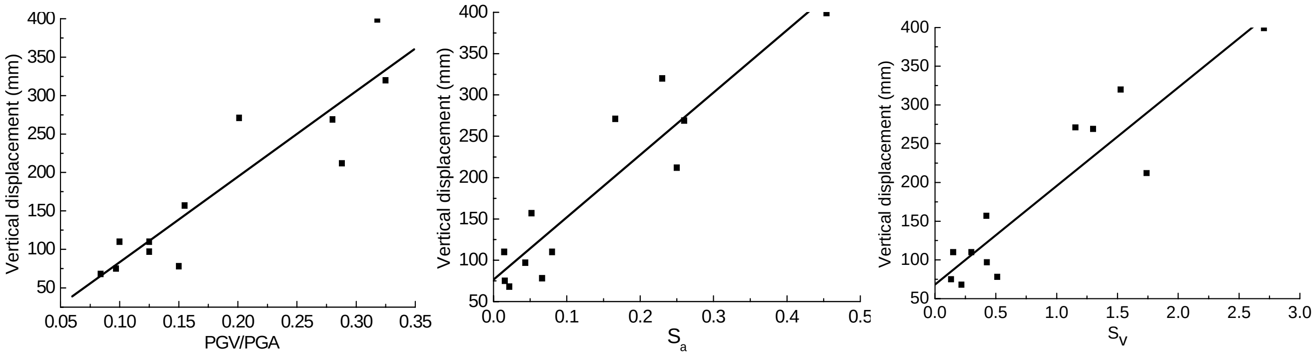

Figure 8 Relationship between the vertical displacement of the main beam and the PGV/PGA (left); spectral acceleration (center), and spectral velocity (right)

5. CONCLUSIONS

The pulse character of near-fault ground motion records from 1999 Taiwan Chi-Chi earthquake was introduced primarily on the basis of time history and response spectra, and two causes of this phenomenon was also explained briefly. Horizontal and vertical records from 8 stations during this event and 4 common-used ground motions in other earthquakes were utilized to investigate the horizontal and three-dimensional seismic behavior of a large-span cable-stayed bridge. Some conclusions can be got as follows:

Near-fault pulse effect not only exists in horizontal component at the near-fault ground motion records, but also vertical component, which indicate that abundant long-period component in near-fault ground motions. The vertical acceleration response spectra of common-used ground motions is very close to that of no pulse-type near-fault motions, but evidently lower than that of pulse-type near-fault motions, which is very important for the long fundamental period engineering structures.

The horizontal and vertical seismic responses of the cable-stayed bridge to three group ground motions were evaluated by time history analysis method. Lateral displacement of the central tower under horizontal excitation of pulse-type near-fault motions is particularly larger than that under the no-pulse near-fault and common-used ground motions, with an increase by 60%. The attendance of vertical excitation will affect the horizontal seismic response negligibly, axial force at the bottom of the tower and maximum vertical displacement of middle location of mid-span under vertical pulse-type near-fault motions have an increase by 10% and 200%, respectively, compared with that under no-pulse near-fault motions. So, if only the common-used ground motion was utilized in time history analysis, predominant underestimation of the damage potential of the earthquake shaking will be induced for the horizontal and vertical excitation, especially for the vertical displacement.

Parametric study demonstrated that the seismic response of the structure is related to parameters of the ground motions. The PGV/PGA ratio, spectral acceleration and spectral velocity at the fundamental period of the structure will affect the seismic response behavior of the large-span cable-stayed bridge, with a nearly linear proportion relationship. But remarkable difference of the relationship between the structural response and these three parameters were not found in this study.

The pulse-type near-fault ground motion imposes a significant effect on the horizontal and vertical structural response, especially for the long fundamental period structures. So, pulse effect should be considered in many important engineering structures located near a causative fault. Material nonlinearity was not considered in this study, it will be considered in the following research to evaluate the structural nonlinear performance accurately.

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REFERENCES

Alavi, B. and Krawinkler, H. (2000). Consideration of near-fault ground motion effects in seismic design. Proceedings of the 12th world conference on earthquake engineering, Auckland New Zealand, 30 January-4 February 2000, Paper No.2665.

Ambraseys, N.N. and Douglas, J. (2003). Near-field horizontal and vertical earthquake ground motions. *Soil Dynamics and Earthquake Engineering*, **23:1**, 1-18.

Bertero, V.V, Herrera, R.A. and Mahin, S.A. (1976). Establishment of design earthquake-evaluation of present methods, Proceedings of the international symposium on earthquake structural engineering, St. Louis, Mo., **1**, 551-580

Bertero,V.V, Mahin, S.A. and Hrrera, R.A. (1978). A seismic design implication of near-fault San Fernando earthquake records, *Earthquake Engineering and Structural Dynamics*, **6:1**, 31-42.

Bozorgnia, Y.M., Campbell, K.W. and Niazi, M. (2000). Observed spectral characteristics of vertical ground motion recorded during world earthquakes from 1957 to 1995. Proceedings of the 12th world conference on earthquake engineering, Auckland New Zealand, 30 January-4 February 2000, Paper No.2671.

Dimitriu, P., Kalogeras, I. and Theodulidis, N. (1999). Evidence of nonlinear site response in horizontal-to-vertical spectral ratio from near-field earthquakes, *Soil Dynamics and Earthquake Engineering*, **18:6**, 423-435.

Goltz, J.D., ed. (1994). The Northridge, California earthquake of January 17, 1994: General reconnaissance report", Technical Report NCEER-94-0005.

Hall, J.F., Heaton T.H., Halling, M.W., Wald, D.J. (1995). Near-source ground motion and its effects on flexible buildings. *Earthquake Spectra*, **11:4**, 569-605.

Iwan, Wilfred. D., Huang Ching-Tung, Guyader Andrew C. (2000). Important features of the response of inelastic structures to near-field ground motions, Proceedings of 12WCEE. Auckland, New Zealand, Paper No.1740.

Khairy, H.A. And Atsuhiko M. (2000). Effect of vertical motion of earthquake on failure mode and ductility of RC bridge piers. Proceedings of the 12th world conference on earthquake engineering, Auckland New Zealand, 30 January-4 February 2000, Paper No.0463.

Malhotra, P.K. (1999). Response of buildings to near-field pulse-like ground motions. *Earthquake Engineering and Structural Dynamics*, **28:11**, 1309-1326.

Memari A.M., Maneetes H. and Bozorgnia Y. (2004). Study of the Effect of near-source vertical ground motion on seismic design of precast concrete cladding panels. *Journal of Architectural Engineering*, **10:4**, 167-184.

Mollaioli, F., Silvia, B., Luis, D. D. and Giuliano F.P. (2006). Characterization of the Dynamic Response of Structures to Damaging Pulse-type Near-fault Ground Motions. Meccanica, **41:1**, 23-46.

Papazoglou A.J. and Elnashai A.S. (1996). Analytical and field evidence of the damaging effect of vertical earthquake ground motion. *Earthquake Engineering and Structural Dynamics*, **25:10**, 1109-1137.

Somerville P.G. (1998). Development of an improved ground motion representation for near-fault ground motions. In: SMIP98. Seminar on Utilization of Strong-Motion Data: Oakland, California, September 15, 1998. Proceedings, California Division of Mines and Geology, Sacramento, CA, 1-20.