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Dynamic Time-history Analysis for the Bridges Crossing Fault Based on Ground Motion Records

Kehai WANG
Research professor, Research Institute of Highway Ministry of Transport, China
Email address：kehaiwang@263.net

Yingxin HUI
Ph.D. candidate, Southeast University, China
Email address：huiyx@seu.edu.cn

ABSTRACT: Based on the characteristics of existing ground motion records, the ground motion input model and the corresponding curve simulation method were discussed. IWAN method was adopted in the numerical integration of strong earthquake records and the time variable parameters were analyzed and adjustment. The corresponding displacement time history as a practical engineering earthquake ground motion input. Take a cable-stayed bridge as an example to calculate seismic response of structures using displacement time-history as earthquake input and the results were compared with acceleration time-history. The analysis results showed that the ground motion input method adopting displacement input model can calculate residual deformation and internal force of structure caused the fault rupture, accord with the actual seismic damage characteristic, applied to earthquake motion input of bridges crossing fault.

1. Introduction

Surface rupture caused a significant risk to the bridges crossing or constructed over the active fault zone during the earthquake. Some countries and regions have set the regulations or policies to withstand this risk. Such as: building the new bridges over active faults were forbidden, or a certain safe distance between the structures and the active faults should be set. However, because the limitations of the existing active faults detection technology and calculation method, the actual surface rupture fault trace may neither follow the distribution marked on the geological map, nor occur within the historical earthquake fault zone (Petersene, et al, 2011). So, the damage of the bridge was hard to avert. Recently, several earthquakes showed that strategies of prohibition and setting safe distance could not completely avoid the destruction risk of the bridges over the active faults, which induced great difficulties to the earthquake emergency rescue (Hui, 2014), as in China Taiwan Chi-Chi, China Wenchuan, Turkey Kocaeli and Duzce Earthquake.

In the actual project, some bridges have to be built across or very near active faults due to the restrictions of national defense, topographic and geomorphic conditions, construction costs, construction period, and other objective conditions. Since the damage of bridges directly resulting from a fault rupture was quite few in the past, the study for the bridges crossing fault was very limited. As plenty of road transport infrastructure in high intensity seismic zone have been built in the “immediate vicinity” of seismically active faults, it was important to carry out research into seismic design of the bridges crossing fault.

Based on multi-support excitation displacement input model and characteristics of near-fault strong motion records, ground motion input method for bridges crossing fault was established, which provided a foundation for the design and evaluation of the bridges. Finally the rationality of this method was verified by an example, and seismic response was analyzes.

2. Multiple support excitation displacement input model

Structural responses analysis model under the action of earthquake ground motion could be usually classified into two categories. One was the displacement input model based on the dynamic balance equation of the absolute coordinate system; the other was the acceleration input model under the absolute coordinate system. In traditional seismic response analysis, generally assumed that the earthquake ground motion was the same at each support, the structural internal force was only related to the dynamic displacement, so the acceleration input model has been widely used. However Bridges across the fault had an important influence on dynamic response due to different relative displacement on fault both sides support, and the effect of pseudo static response should be considered.

The equations of motion of the three-dimensional vibration of the bridge when subjected to multiple support excitations can be expressed in a partitioned matrix (Chopra, 2007):

$$\begin{bmatrix} M_{aa} & M_g \\ M_g^t & M_{gg} \end{bmatrix}\begin{bmatrix} \ddot{u}^t \\ \ddot{u}_g \end{bmatrix}+\begin{bmatrix} C & C_g \\ C_g^T & C_{gg} \end{bmatrix}\begin{bmatrix} \dot{u}^t \\ \dot{u}_g \end{bmatrix}+\begin{bmatrix} K & K_g \\ K_g^T & K_{gg} \end{bmatrix}\begin{bmatrix} u^t \\ u_g \end{bmatrix}=\begin{bmatrix} 0 \\ p_g(t) \end{bmatrix} \qquad （1）$$

where the $\ddot{u}^t$, $\dot{u}^t$ and u^t designates vector of non-support node motion； $\ddot{u}_g$, $\dot{u}_g$ and u_g designates vector of known ground motion at absolute coordinates; *M*, *C* and *K* were rectangular mass, damping and stiffness matrices respectively. the subscript *aa*, *gg* and *g* respectively corresponds to degrees of freedom of the bridge model superstructure, supports and coupling term. $p_g(t)$ designates vector of support reaction.

Dynamic equilibrium equation with unknown motion vector $\ddot{u}^t$, $\dot{u}^t$ and u^t can be pushed forward from equation 1:

$$M_{aa}\ddot{u}^t + M_g\ddot{u}_g + C\dot{u}^t + C_g\dot{u}_g + Ku^t + K_g u_g = 0 \qquad （2）$$

If using a lumped mass model, there was M_g=0. Because damping matrix C_g *was* difficult to determine and the damping force was far less than inertia force, and can be ignored(Wilson, 2002). Equation 2 can be written as：

$$M_{aa}\ddot{u}^t + C\dot{u}^t + Ku^t = -K_g u_g \qquad （3）$$

Equation 3 was the displacement input model to solution structure response. u_g was the bearing displacement vector of ground motion, $-K_g u_g$ was an absolute coordinates due to the motion of the bearing with the ground forces acting in the upper structure. Displacement input model of the dynamic equilibrium equation was established under the absolute coordinates, can consider the influence of fault on both sides of the support relative movement, not only suitable for uniform excitation input also was suitable for the multipoint excitation input, applies to linear structure can also be applied to nonlinear structure, was the analysis of structural responses under the bridges across the fault more effective model (Tian, 2005).

3. Baseline correction methods to obtain displacement waveform with fault displacement

Different from multiple support excitations acceleration input model, ground motion input information of displacement input model needed for the displacement time history. So when the ground motion input not only involve the ground motion acceleration time history, still need to consider the ground motion displacement time history. Theoretically, the velocities and displacements were obtained by integration of the accelerations. The displacements should reach essentially constant residual values, and the velocities should be around zero after the end of the strong shaking. Unfortunately, due to strong earthquakes recorded by ground tilt, noise and other environmental factors, often severe distortion directly drift velocity and displacement time history obtained strong earthquake acceleration records(Boore, 2005). It were rare that this simple correlation gives these ideal displacement and velocity time histories, a more usual case was shown in Figure 3 (for the E–W component of the motion at TCU052). Therefore, there was a necessity of baseline correction to get the constant residual displacement and zero residual velocity.

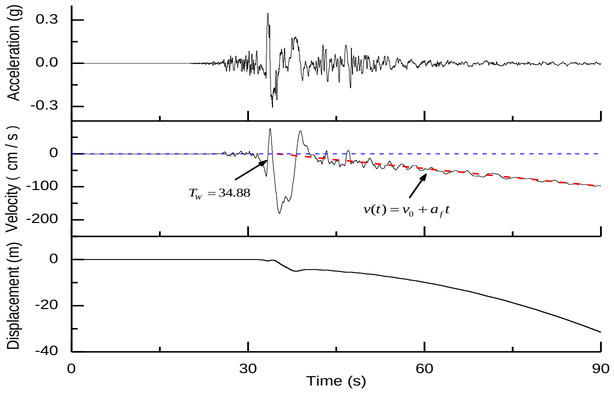


Fig. 1 – Acceleration, velocity and displacement time histories of origin record at TCU052

We adopted the correction algorithm proposed by Iwan et al(Iwan, et al, 1985). In their scheme, the acceleration data was first corrected for the displacement curve offset observed in the data. This was accomplished by performing a time average on only the first one-half of the prevent data in order to eliminate the possibility of including any actual earthquake data. Next, the final offset of the acceleration was determined. Final offset was determined from velocity since it was usually more accurate to estimate the final acceleration offset from the final slope of the velocity record. The overall correction was shown schematically in Fig. 2. In Fig.2, a_m *was* the acceleration to be removed between times t_1 and t_2, and a_f *was* the one to be removed from t_{f1} to the end of the record T. The correlation for the final offset was easily determined by a least squares fit of the final portion between t_{f1} and t_{f2} (=T) of the velocity data, $v(t)$, without correlation. The correction has the form:

$$v(t)=v_0+a_f t \qquad (4)$$

Parameters a_f and v_0 *was* determined by the least squares method. Then, the value of the intermediate range correction acceleration will be:

$$a_m=v(t_2)/(t_2-t_1) \qquad (5)$$

The times t_1, t_2 and t_{f1} may be selected in a number of different way, and the final results were depending on this selection. Different combination of t_1, t_2 and t_{f1} yields different integration result of displacement and velocity.

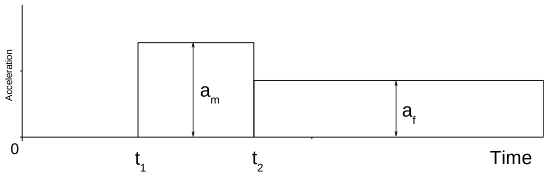


Fig. 2 – Schematic diagram of Iwan baseline correction method

We applied Iwan's correlation algorithm to correct the acceleration records of the nearest 10 strong motion observation stations (less than 5km away from the Chelungpu fault) during the 1999 Chi-Chi Earthquake. The station distribution and displacement time histories after baseline correction were shown in Figure 3. For comparison, the residual displacement observed by GPS station was also shown in Fig.3. The figure shows that the residual displacement of displacement time histories after baseline correction was roughly identical to the corresponding GPS station record, which suggests that Iwan's correlation algorithm was appropriate.

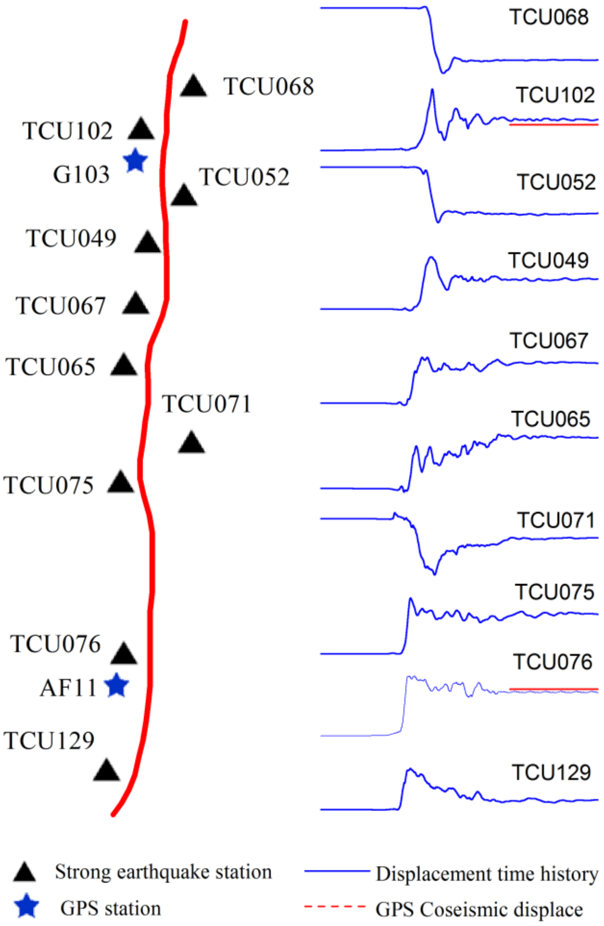


Fig. 3 – Displacement time histories after baseline correction

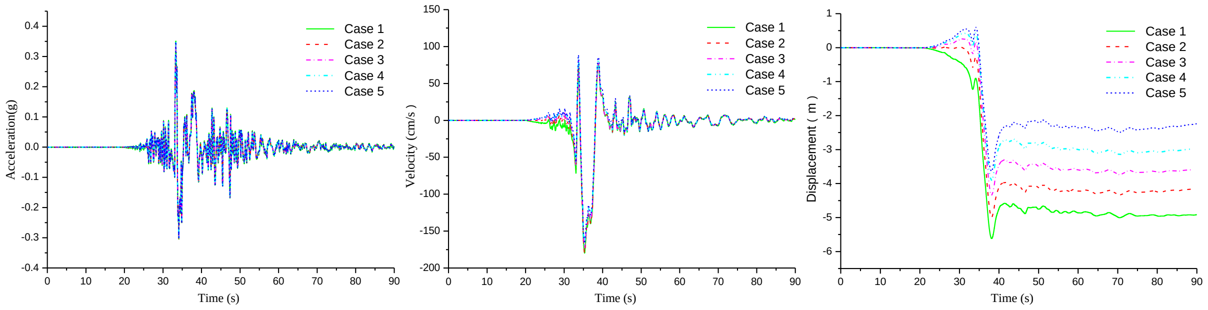
4. Estimation of time history of fault displacement

There were differences in the permanent ground displacement between seismic safety evaluation of engineering sites and integral of strong earthquake acceleration records. Therefore, how to make the actual displacement value of strong earthquake records consistent with value of the seismic safety evaluation was the key to application in engineering. As mentioned earlier, different combination of t_1, t_2 and t_{f1} yielded different integration velocity, displacement time histories. Time parameters t_2 had a great effect on permanent ground displacement, because permanent ground displacement usually occured in the end section of strong records. So, it may consider adjusting t_2 to achieve desired permanent ground displacement.

We considered 5 cases with different combination of these parameters as shown in Table 1. The acceleration, velocity, displacement time histories of observation station TCU049 and TCU052 after baseline correlation were shown in Fig.4 and Fig.5. The figure showed that difference in the acceleration was very small, but that in the displacement was very large. Fig.6 and Fig.7 indicated the response acceleration and response displacement spectra. No marked difference was found for natural period shorter than 5 sec. From the above analysis, permanent ground displacement of the seismic safety evaluation were obtained by adjusting numerical integration time parameter and apply to ground motion displacement input for bridge engineering crossing fault.

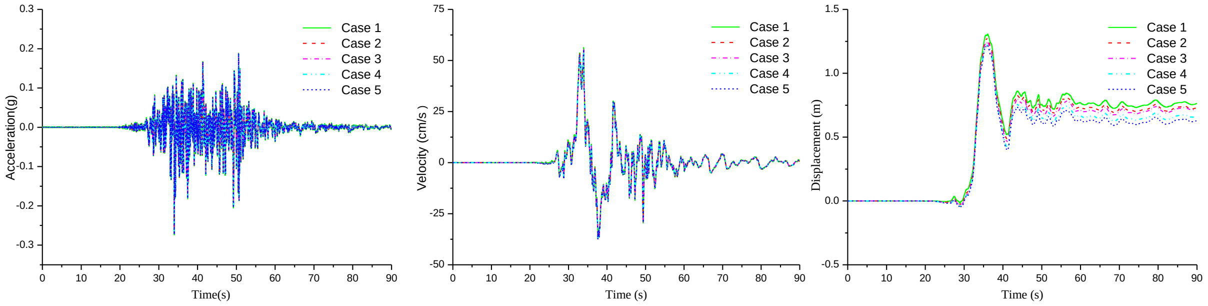
Table 1 – Parameter combinations and corresponding permanent ground displacement

Case	Time parameters				TCU052	TCU049
	t_1(s)	t_2(s)	t_{f1}(s)	t_{f2}(s)	Permanent displacement(m)	Permanent displacement(m)
Case 1	20	30	65	90	-4.91	0.76
Case 2	20	35	65	90	-4.15	0.73
Case 3	20	40	65	90	-3.58	0.696
Case 4	20	45	65	90	-2.97	0.663
Case 5	20	50	65	90	-2.37	0.629



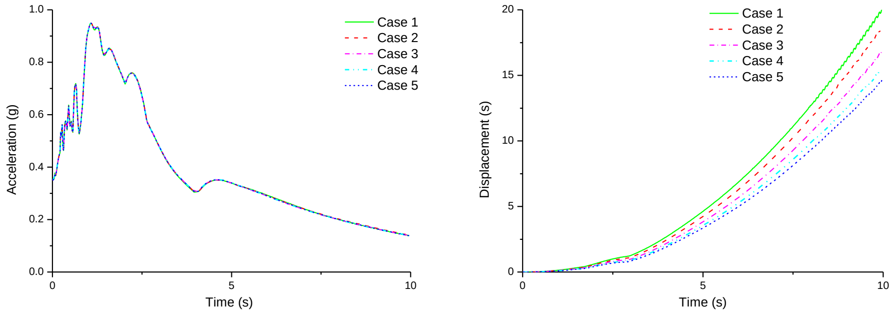
(a) (b) (c)

Fig. 4 – Time histories at TCU052（EW）station: (a) acceleration, (b) velocity, and (c) displacement



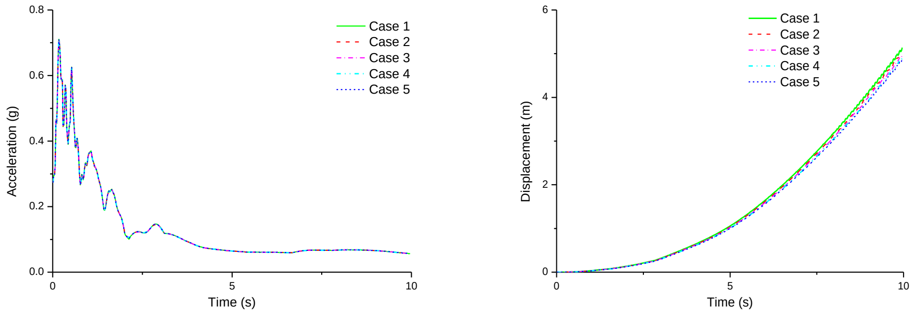
(a) (b) (c)

Fig. 5 – Time histories at TCU049（EW）station: (a) acceleration, (b) velocity, and (c) displacement



(a) (b)

Fig. 6 – Response spectra at TCU052（EW）station：(a) acceleration and (b) displacement



(a) (b)

Fig. 7 – Response spectra at TCU049（EW）station: (a) acceleration and (b) displacement

5. Analysis of engineering example

An analysis of cable-stayed bridge was shown as analysis example and assumed that the active fault crossed the bridge between piers P1 and P2 as shown in figure 8. The response of the bridge model under fault-rupture was calculated using OpenSees（Mazzoni, 2007）. Then, used the direct integral calculus method of Newmark to solve solution, and get each node and element's displacement and internal force time history. In view of the ground motion attenuation laws of both sides of fault was different, the displacement of TCU052 and TCU049 （as shown figure 3）were selected respectively as the input displacement on the hanging-wall side and the footwall side. On the basis of fault on both sides of the hypothesis of permanent ground displacement, corresponding displacement can be obtained by adjusting the time parameter. Fig.8 shows an example of inputting fault displacement waveforms to a cable-stayed bridge in dynamic analysis. Fig.8 indicates that the displacement time history of cases 1 for TCU052 was input at the bottom of pier P1, and cases 3 for TCU049 was input at the bottom of piers P2 and piers P3 in Table 1. In addition，the displacement time history in the displacement input model corresponding to the acceleration time history as earthquake excitation of acceleration input model, the seismic responses of the structure were compared.

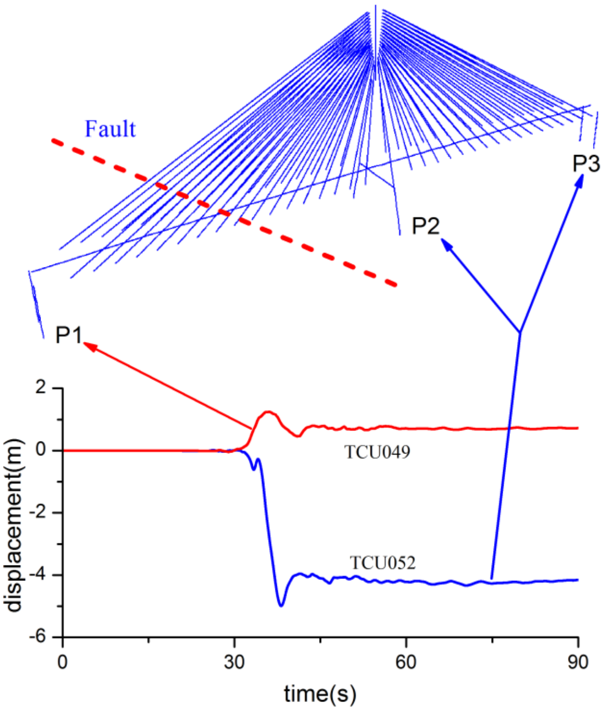
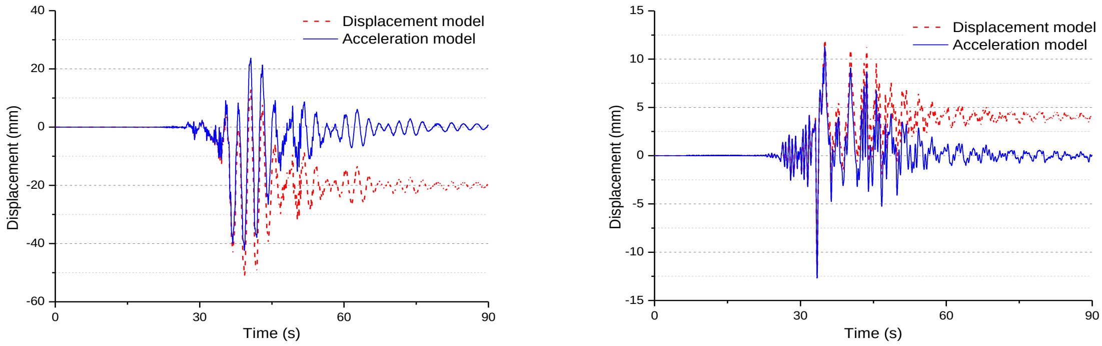


Fig. 8 – Example of multi-supports displacement input to bridges crossing fault

Displacement time history of pier top relative to the bottom at pier P1 and pier P2 in two input model was shown in Fig.9. The displacement response demonstrated that the peak displacement pier top relative to the bottom were very close for two input model. The value and shape of displacement were identical basically before fault dislocation; the displacement value of displacement input model increased after fault dislocation; residual deformation were found and the relative deformation value in acceleration input model tending to zero after the earthquake ground motion.

Bending moment time history of pier bottom at pier P1 and pier P2 in two input model was shown in Fig.10.The bending moment response demonstrated that displacement input model almost completely enveloping acceleration input model to corresponding to the bending moment curve. Residual bending moment was found and the corresponding value in acceleration input model tending to zero after the earthquake ground motion.

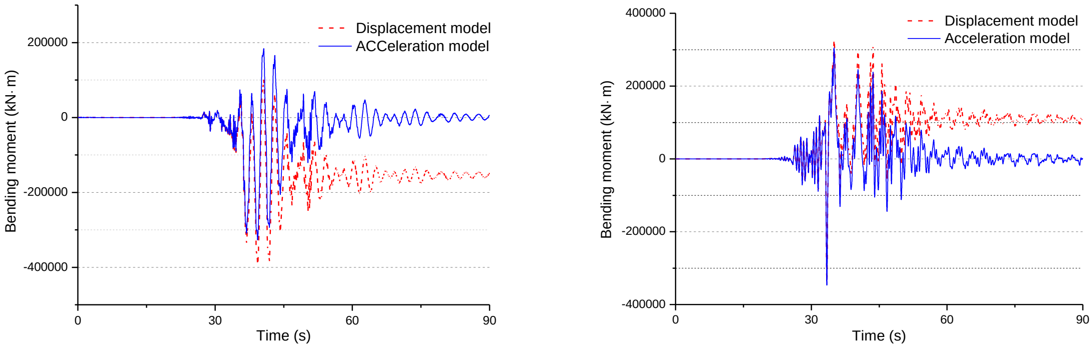
The analysis results showed that the ground motion input method adopting displacement input model can calculate residual deformation and internal force of structure caused the fault rupture, accord with the actual seismic damage characteristic, applies to bridges crossing active fault earthquake input. And acceleration input model cannot reasonable estimate the residual deformation and internal force of piers after fault dislocation, may leading to unreliable results.



(a)

(b)

Fig. 9 – Relative displacement history form pier top to bottom: (a) P1 and (b) P2



(a)

(b)

Fig. 10 – Bending moment history of pier bottom: (a) P1 and (b) P2

6. Conclusion

(1) Multiple support excitation displacement input model was the analysis of structural responses under the Bridges across the fault more effective model, and can consider the influence of fault on both sides of the support relative movement.

(2) Target permanent ground displacement of the seismic safety evaluation were obtained by adjusting numerical integration time parameter and apply to ground motion displacement input for bridge engineering crossing fault.

(3) The analysis results show that the ground motion input method adopting displacement input model can calculate residual deformation and internal force of structure caused the fault rupture, accord with the actual seismic damage characteristic.

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