International Association
Bridge Earthquake Engineering

The Third International Bridge Seismic Workshop, 3rd IBSW
Seattle, Washington, USA - October 1st to 4th, 2019

The effect of ground deformation and strong ground motion on the damage of a continuous curve viaduct damaged by near-fault ground motion

G. Watanabe(1), R. Takeuchi(2) , K. Magoshi(3), A. Kasai(4)

(1) Associate professor., Yamaguchi University, gakuho.w@yamaguchi-u.ac.jp
(2) B.E., Yamaguchi University, i036@yamaguchi-u.ac.jp
(3) Senior Researcher., Seismic Analysis Research Inc magoshi@sean.co.jp
(4)Associate professor., Kumamoto University, kasai@kumamoto-u.ac.jp

Abstract

In the 2016 Kumamoto earthquake, many bridge structures on Route 28 in Kumamoto prefecture were damaged by strong ground motion and ground deformation caused by fault displacement. Especially at the Ookirihata bridge, in addition to bending damage to the bridge piers and the damage to the rubber bearings, damages that could be related to the collision between the adjacent abutments and the superstructure were observed.

Generally, when a superstructure collides with an adjacent part or superstructure, the impact stress associated with the pounding can propagate into the superstructure and cause local deformation and failure of the structural member. It is known that, in the case of the skewed girder and the curved girder, the bridge girder slides laterally to exhibit rotational behavior about a vertical axis.

In this research, the seismic behavior is analyzed based on the two different nonlinear dynamic response analysis, the effect of the ground deformation and the strong ground motion on the seismic behavior of the bridge structure is verified. As a result, it is found that the shear deformation of the rubber bearings is increased in the parallel direction of the seismic fault. And the local relative displacement between the substructures results in much damage to the superstructures.

Keywords: near-fault ground motion; ground deformation; curve bridge; pounding; dynamic

1. Introduction

In 2016, the Kumamoto earthquake [1, 2] resulted in the fatal damage to the bridge structures along the prefecture route 28 bound for the Aso mountain area. It has been reported that the seismic fault parallelly running to the prefecture route has affected the damage of structures. Ground deformation induced by the fault during an earthquake changes the relative distance between the piers and the abutments supporting the superstructure. As a result, those ground deformations induce the larger failures in the superstructure, the bearings and piers compared to the case where only the seismic force (inertia force) hits the bridge structure. In this research, the effect of the strong earthquake and the ground deformation on the failure of the continuous curve viaduct is evaluated through the simulation of the dynamic response of a continuous curve viaduct.

2. Dynamic analysis of bridge considering the nearfault ground deformation

2.1 Dynamic analysis of structure for strong excitations

In this study, we evaluated the effects of strong ground motion and ground deformation during an earthquake on the superstructure response and its bearing support for a continuous curve viaduct as shown in Fig. 1. When it can be assumed that a strong ground motion uniformly acts on a bridge structure, the structural response $\{u_r\}$ of the bridge during the earthquake can be obtained by solving the following equation of motion.

$$[M]\{\ddot{u}_r\} + [C]\{\dot{u}_r\} + [K]\{u_r\} = -[M]\{I\}\ddot{u}_g$$

On the other hand, in the vicinity of the fault, due to the complex ground behavior, it will be concerned that not only the effect of the multiple earthquake excitations with phase delay but also the ground deformation affects the response of the bridge structure during the earthquake. In such cases, the dynamic response of the bridge as shown in Fig.2 can be obtained by solving the following equation of motion:

$$[M_{ss}]\{\ddot{u}_s\} + [C_{ss}]\{\dot{u}_s\} + [K_{ss}]\{u_s\} = -[M_{sb}]\{\ddot{u}_b\} - [C_{sb}]\{\dot{u}_b\} - [K_{sb}]\{u_b\}$$

Here, $\{u_s\}$ and $\{u_b\}$ represent the absolute responses of the structure and the ground, respectively.

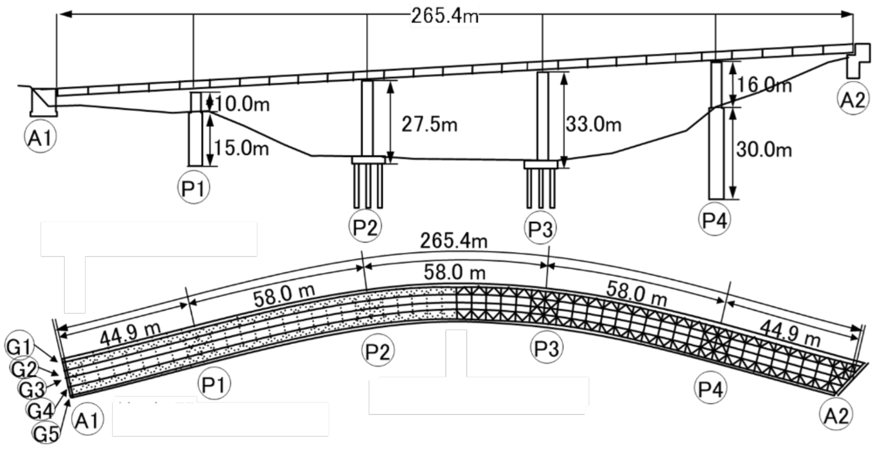


Fig. 1 The target bridge in this anlysis

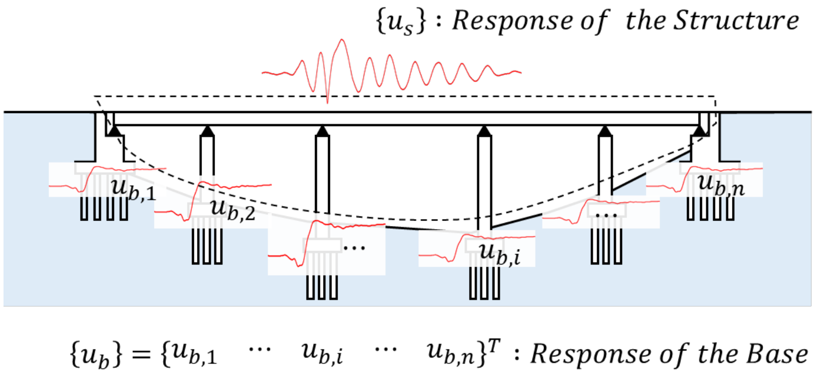


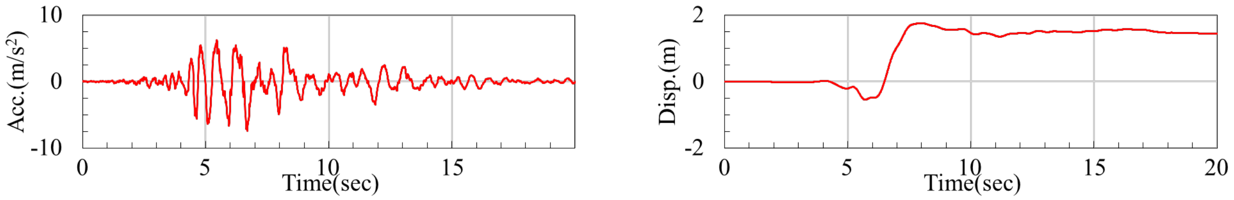
Fig. 2 The dynamic response of bridge structure

2.2 Input ground motion and the ground deformation

In the vicinity of this bridge, strong ground motion including residual ground deformation was observed as shown in Fig.3, so the strong ground motion is used to analyze the seismic response of the bridge structure. To consider the difference of the ground motion at each location, the effect of the intensity and phase delay of the ground motions should be a concern in the analysis. Based on the assumption of the less effect of the phase delay on the seismic response, the above recorded ground motion is used by changing the intensity of the ground motion at each base.

In accordance with the result of the detailed survey after the earthquake shows that the substructures had undergone the relative displacement deformation between each other as shown in Fig.4, respectively. The input intensity of ground motion at each base was adjusted so that the relative displacement between the substructures matched the survey results as shown in the Table.1 and Figu.5.

In the analysis of multi-point excitations considering the deformation of the ground, the total energy of the input ground motion is reduced to about 83% of the that of the uniform input analysis.



(a) Acceleration (b) Displacement

Fig.3 Strong ground motion including residual ground deformation

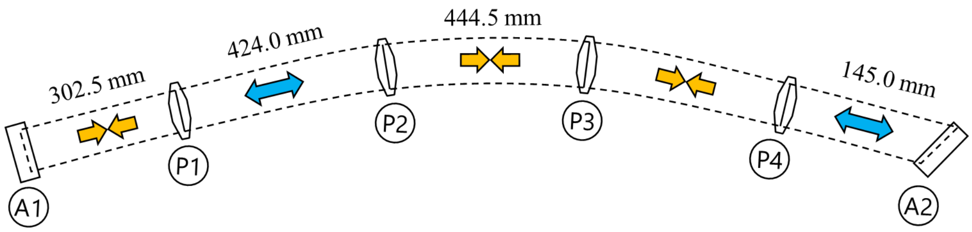


Fig.4 The relative displacement of ground deformation

Table 1 The input intensity of ground motion at each base in the analysis of multi-point excitations

Abutment 1	Pier 1	Pier 2	Pier 3	Pier 4	Abutment 2
1.00	0.764	1.095	0.748	0.643	0.756

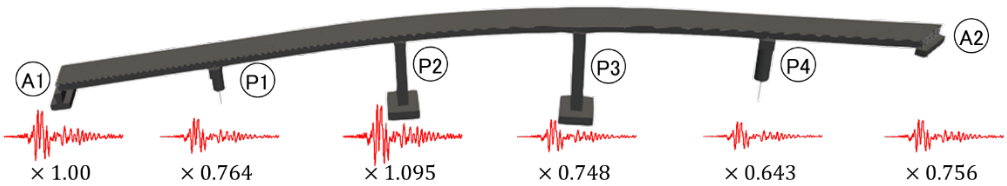


Fig.5 The input intensity of ground motion at each base

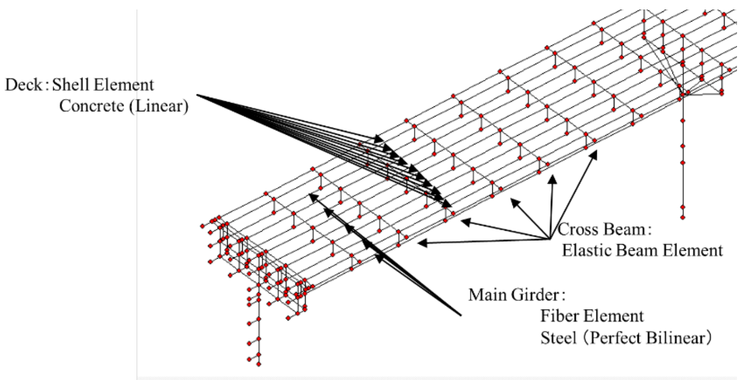
2.3 Idearlization of the pounding phenomena of the girder deck with the adjucent abutmens

In recent years, the damage caused by earthquakes has gradually decreased due to the upgrading of the seismic performance of bridge structures. On the other hand, the elongation of the natural period due to the adoption of the continuous superstructure and elastic rubber bearings produces the large displacement of the superstructure during an earthquake. It may cause superstructure collisions between adjacent abutments, causing local buckling of the main girder, and resulting in new damage mode not seen before. In Kumamoto earthquake, some of the bridges over the prefecture route 28 suffered damage due to this effects. To evaluate the effect of the pounding effect on the bridge dynamic behavior, the impact spring model [3] as shown in Fig.5 is installed in the target bridge model between the abutment and the superstructure.

3. Results and Discussions

3.1 The amplification of the dynamic response of the bearings in the fault parallel direction

Fig. 6 (a) shows the dynamic response of the rubber bearing in the horizontal plane obtained by dynamic analysis with uniform input. The larger bearing responses on A1 and P1 are obtained in the longitudinal direction, and the larger bearing responses on P2, P3, P4 and A2 are obtained in the transverse direction. On the other hands, although the total input energy is decreasing, the 1.5 times larger dynamic response of bearings on A1, P1, P4 and A2 are obtained rather than that of response in the uniform input analysis as shown in Fig.6 (b). Thus, it is considered that the bearing's dynamic response has been amplified in the fault parallel direction by the effect of ground deformation during the earthquake.



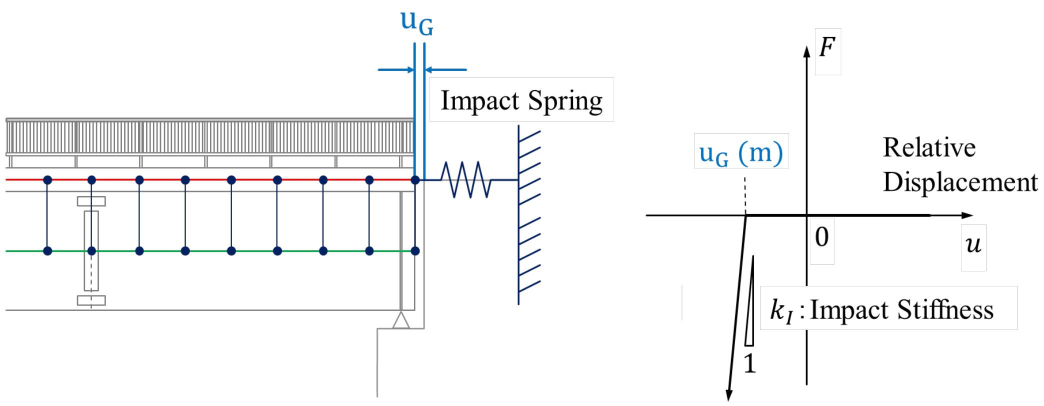


Fig.6 The impact spring model installed in the adjacent strucutres

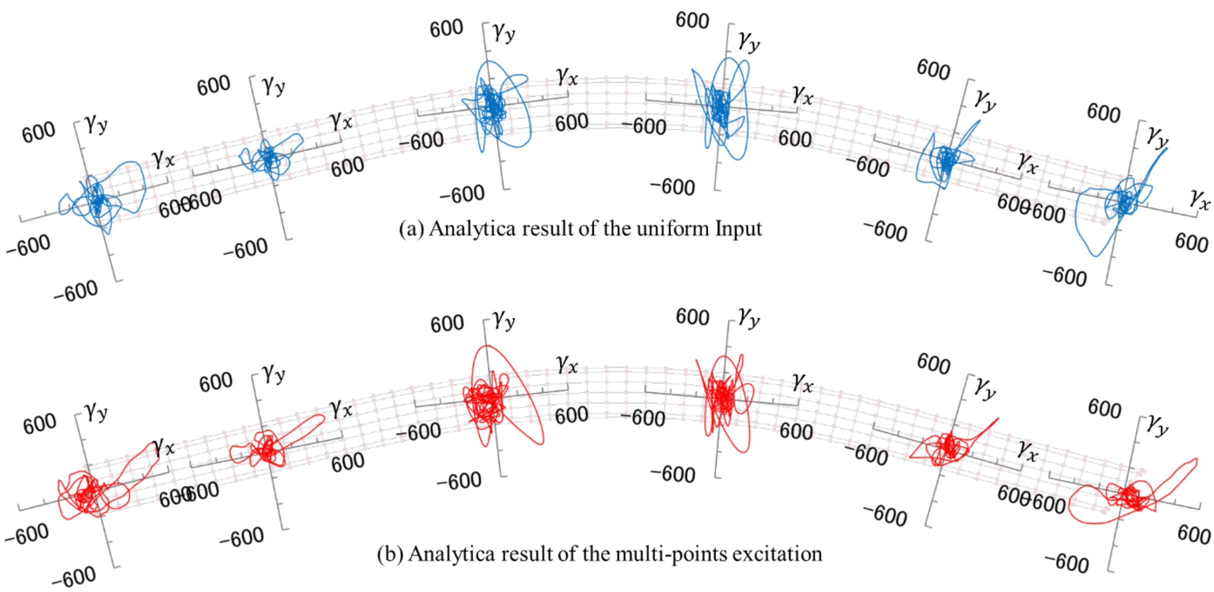
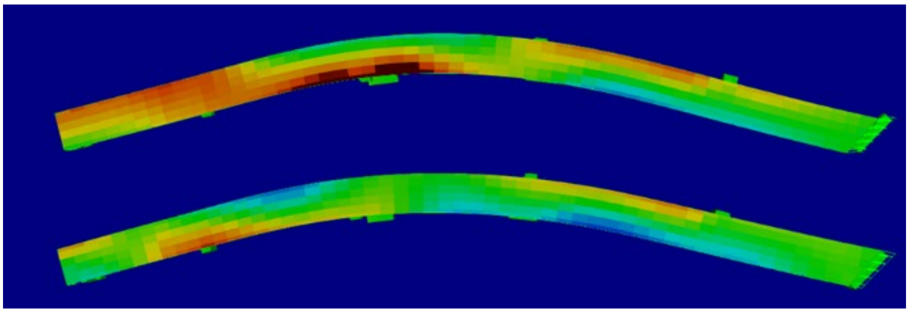


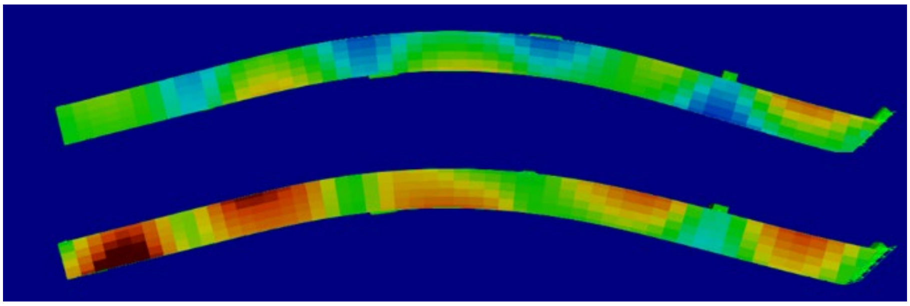
Fig.7 The dynamic response of the rubber bearing in the horizontal plane

3.2 The axial stress response induced in the girder deck due to the effect of the ground deformation

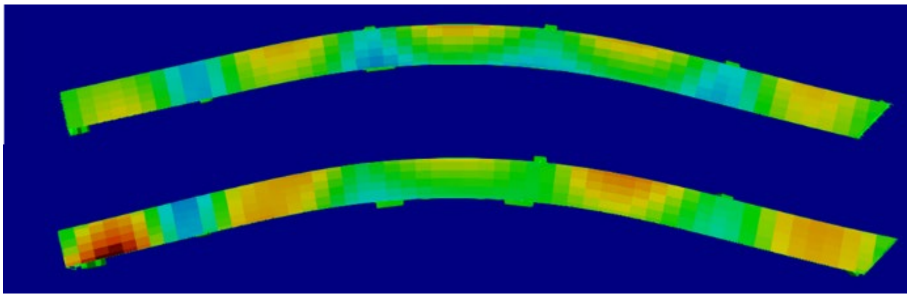
Fig. 7 shows the distribution of the maximum bending moment induced in the superstructure along the longitudinal axis. About 1.5 times larger bending moment is obtained in the positive side.



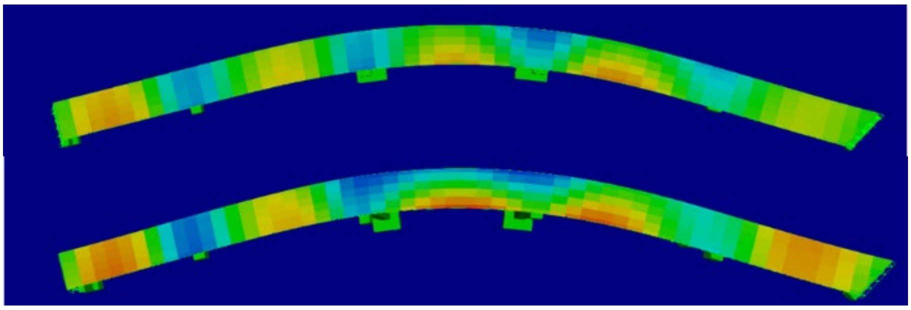
(a) 6.453 (s)



(c) 6.573 (s)



(c) 8.178 (s)



(d) 9.472 (s)

Fig.8 (1) Dynamic response of the axial stress induced in the superstructure (Upper : uniform input Lower : Multi-Points Excitaion)

Fig.8 shows the dynamic response of the axial stress induced in the superstructure at the representative time step during the earthquake. Due to the effect of the pounding occured between the superstructure and the abutment A1 at 6.4 second, the axial stress induced in the superstructure is travelling from the side of abutment A1 to the opposite side along the longitudinal axis in the analysis of the uniform input.

On the other hands, the significant amplification of the axial stress is not observed due to the stress wave induced in the superstructure by the pounding between the adjacent structures in the analysis of multi-point input. The local amplification of the axial stress, however, occurs at the bridge deck. This is because the transverse bending moment induces in the curved superstructure by the relative displacement of the substructures.

4. Conclusions

In this research, the seismic behavior of the continuous curve bridge was carefully analyzed based on the two different nonlinear dynamic response analysis. And the effect of the ground deformation and the strong ground motion on the seismic behavior of the bridge structure was investigated. As a result, it is found that due to the ground deformation, the shear deformation of the rubber bearings is amplified in the fault parallel direction, and this may cause much damage to the bearing supports. Also, the local relative displacement between the substructures induces the further axial stress in the superstructure due to the accompany of the bending moment.

5. References

[1] https://ewww.kumamoto-u.ac.jp/dept/earthquake/

[2] S. Bhattacharya, M. Hyodo, G. Nikitas, B. Ismael, H. Suzuki, D. Lombardi, S. Egami, G. Watanabe, K. Goda.: Geotechnical and infrastructural damage due to the 2016 Kumamoto earthquake sequence, Soil Dynamics and Earthquake Engineering, Elsevier, Volume 104, pp.390-394, 2018.

[3] Watanabe, G. and Kawashima, K., Numerical Simulation of Pounding of Bridge Decks, Proc. of 13th World Conference on Earthquake Engineering, Paper No. 884, Vancouver, Canada, 2004.8.