Asymmetry of Seismic Displacement Response of Highway Bridge Supported by Spread Foundation

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SUMMARY:
This paper discusses the causes of the asymmetric response of superstructures using the elasto-plastic model by considering the influence of the P-Δ effect and the modified wave of real ground motion records. Since the inelastic behavior subjected to the input earthquake motion is very complicated, in this paper we estimated it to modify the ground motion. We established a simple seismic design method that considered the asymmetric response and investigated the nonlinear response characteristics using four types of nonlinear models. The superstructure itself is idealized as a single degree freedom system attached to a rigid spread foundation with two degrees of freedom that is flexibly supported. We determined that modified waves are effective to explore the asymmetry of response. The response behavior and the residual displacement differ with each period of the models.

Keywords: Asymmetric response, Asymmetric coefficient, P-Δ effect, Ductility factor, Elasto-plastic earthquake response

1. INTRODUCTION

A great number of highway bridge structures in route 3 of the Hanshin expressway were severely damaged by the Hyogoken-Nanbu earthquake in 1995. For that reason, the specifications for highway bridges were improved from specification based to performance based designs. However, the specific and setting methods of the performance are now different for every structure. We must devise evaluations with high accuracy and apply them for the dynamic behavior of concrete and steel structures in the plasticity zone and ultimate strength (for example, Japan Association for Earthquake Engineering, 2006).
Moreover, when the load exceeding design for external force acts on a structure, an "asymmetric response" may occur whose motion converges in one way on the great plastification level. It is experientially easy to produce a phenomenon of a pulse epicentral earthquake that resembles the Hyogoken-Nanbu earthquake that can cause serious damage. However, little research has examined its cause and mechanism (Marubashi *et al*., 2006). We must also investigate the influence of the decrease of the restoring forces by the P-Δ effect on the asymmetric response. The earthquake resistant design of bridges can disregard the influence of the P-Δ effect by considering a design that expects the motion performance of a plastic zone from the anticipating motion behavior or the regulation of the residual displacement to consequently lower the limit in Japan. However, the plastic response is complicated. The motion progresses to one side as a result, and a structure may collapse.
This paper introduces, the "asymmetric coefficient" (Mukai *et al.*, 2000) and considers the maximum plasticity rate in relation to the mean plasticity. The objective of this paper is achieved by conserving the question of the asymmetric response mechanism of structures in the plasticity zone. The rocking single degree of freedom (R-SDOF)(Yamashita *et al*., 2003), which specifically addresses the resistance decrease after the yield by the P-Δ effect, and the general SDOF treat the horizontal vibration of the shearing deformation (S-SDOF). We also assume that the highway bridge supported by the spread foundation on the basis of 48 cases using three degree of freedom models (R-3DOF and S-3DOF) modeled the rigid spread foundation (two degree of freedom). One source of the input

earthquake motions is the Kobe Marine Observatory of the 1995 Hyogoken-Nanbu earthquake of the NS component wave (JMA Kobe), which was significantly affected by the main three or four pulses (Sakai *et al.*, 1997). Another wave shape is a rectangular one (modified wave) that Nakayama *et al.* (1998) deem effective and an easy method to predict the size of the maximum plastic flow. We analyzed the elastic-plastic earthquake response and considered the influence with the period and the height of the superstructure that provides the asymmetric coefficient and the ductility factor, and studied the relation of the asymmetric coefficient, the ductility factor, and the residual displacement. We compared the displacement response waves of each period and addressed the asymmetric earthquake responses based on them.

2. EQUATIONS OF MOTION

2.1. Sdof model

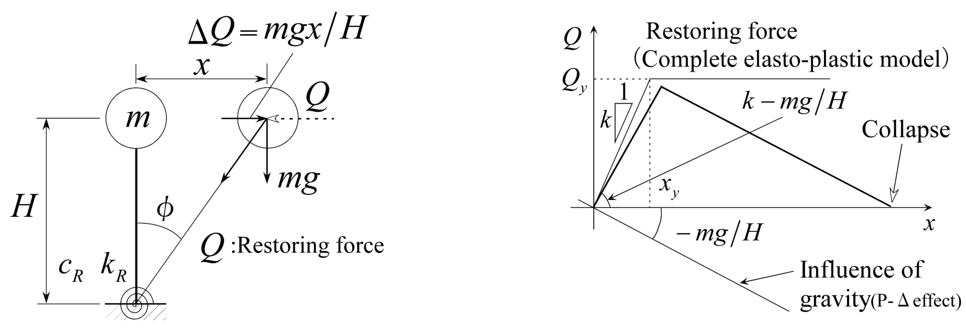
We assume that small displacement occurs in a superstructure (Figure 1), and create a balance equation from it. We perform a geometric approximation and model, the equation of motion of R-SDOF, which is denoted by the following equation:

$$mH^2\ddot{\phi} + c_R\dot{\phi} + k_R\phi - mgH\phi = -mH^2\ddot{u}_G \tag{2.1}$$

where m is the mass of SODF, c_R is the damping coefficient, $M(\phi)$ is the restoring moment, ϕ is the rotational angle of the pier (which is assumed to be rigid, and equal to the nonlinear plastic hinge at its bottom), H is the pier height, g is the gravity acceleration, and $\ddot{u}_G$ is the horizontal input earthquake motion. The spring coefficient receiving R-SDOF and S-SDOF is k. When we use the relation of $k = k_R/H^2$, the equations of the motion of S-SDOF are denoted by the following formula:

$$m\ddot{x} + c\dot{x} + kx - k_{p\Delta}x = -m\ddot{u}_G \tag{2.2}$$

where $k_{p\Delta}$ is the volume decrease of the restoring force by the P-Δ effect and $k_{p\Delta} = mg/H$. When we consider $Q(x) = kx$, $M(\phi)$ is the restoring moment of this model. The yield strength is $Q_y = mgC_y$ since C_y is the yield seismic coefficient. When $Q(x)$ equals 0, namely, when the structure's restoring force equals the additional shearing force by the P-Δ effect, the model collapses (ultimate condition) (Figure 1(b)).



(a) R-SDOF (b) Influence of P-Δ effect

Figure 1. Relation between SDOF and P-Δ effect

2.2. 3dof model

We replaced the highway bridges supported by the spread foundation with R-3DOF (Figure 2(a)), which has the locking motion of superstructures and the sway and rocking motions of the foundations. To determine a coordinate system of the vibration model that excludes such damping terms (Figure

2(b)), we used vibration Eq.2.3 after ignoring the term coupled the sway and the rocking in the restoring force of the foundation-soil system.

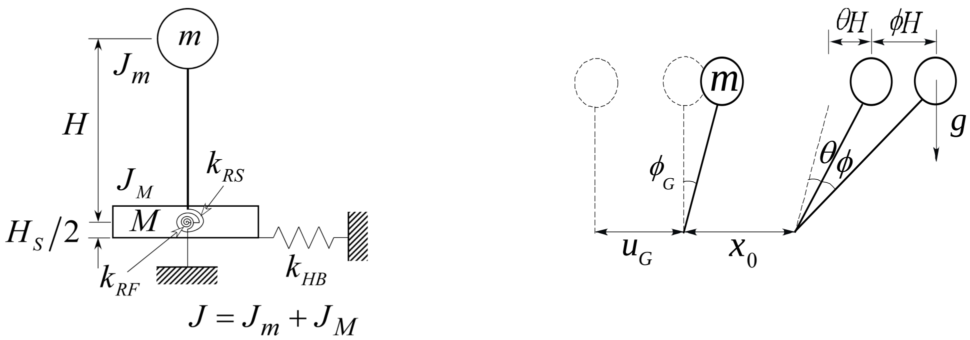
$$[M]\{\ddot{y}\}+[K]\{y\}=-[M]\{I\}\ddot{u}_G \tag{2.3}$$

where

$$[M]=\begin{bmatrix} mH^2 & mH & mH^2 \\ mH & m+M & mH \\ mH^2 & mH & mH^2+J \end{bmatrix},\quad \{y\}=\begin{Bmatrix} \phi \\ x_0 \\ \theta \end{Bmatrix},\quad \{I\}=\begin{Bmatrix} 0 \\ 1 \\ 0 \end{Bmatrix}$$

$$[K]=\begin{bmatrix} k_{RS}-mHg & 0 & -mHg \\ 0 & k_{HB} & -k_{HB}H_S/2 \\ -mHg & -k_{HB}H_S/2 & k_{RF}-mHg+k_{HB}H_S^2/4 \end{bmatrix}$$

where, m and M are the mass of the superstructure and the foundation, and a mass moment of inertia $J=J_m+J_M$ with respect to the centroid of the rigid spread foundation. k_{RS}, k_{HB}, and k_{RF} are the spring coefficients, which are the rocking springs of the superstructure, the sway spring at the bottom of the foundation, and the rocking spring of the rigid spread foundation. ϕ, x_0, and θ are the deformations, which are the rotational angle of the superstructure, the horizontal displacement, and the rotational angles of the foundation, and $\ddot{u}_G$ is the input earthquake motion. $[K]\{y\}$ is the restoring force term of the superstructure and the foundation. As restoring force characteristics, the horizontal spring of the superstructure and the foundation are the elasto-plastic hysteresis loop, and the rocking spring of the foundation is a trilinear hysteresis loop. We induce the equation of motion to S-3DOF using the relationship between the sway and the rocking spring of SDOF in the superstructure.



(a) Modeling (b) Coordinate system

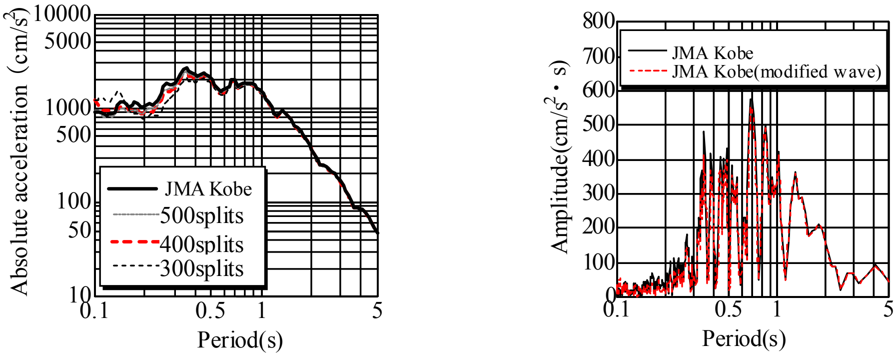
Figure 2. Mathematical models for non-linear response history analysis

3. ELASTO-PLASTIC EARTHQUAKE RESPONSE ANALYSIS

3.1. Analysis condition

Elasto-plastic earthquake response analysis uses the incremental method ($\beta=1/6$), and the minute time was measured to 0.001 s by linear interpolation. The input earthquake motion uses the NS component of JMA Kobe. We created a modified wave that divides the 20 s durations of JMA Kobe into 300-500 splits. The absolute acceleration response spectrum of the modified wave and JMA Kobe are shown in Figure 3(a). We used 400 split modified waves that have little influence at the natural periods (0.712～1.388 s) of the superstructure and a small division of waves because the long interval

has constant acceleration.
The Fourier spectrum of JMA Kobe and the modified wave is shown in Figure 3(b). The modified wave spectrum is smaller than the JMA Kobe spectrum in short periods. In addition, when we verify the asymmetric ratio (Marubashi *et al.*, 2006) which is the rate of the absolute values of the maximum acceleration, and when the maximum value of the positive and negative domains to evaluate the asymmetry of the JMA Kobe is modified, JMA Kobe is 1.42 and the modified wave is 1.35.



(a) Response spectrum (b) Fourier spectrum
Figure 3. JMA Kobe (NS component)

For various superstructure and foundation constants, there are four pier height (period) types: 11 m (0.712 s and 0.965 s), 12 m (0.812 s and 1.100 s), 13 m (0.917 s and 1.242 s), and 14 m (1.026 s and 1.389 s). Table 3.1 shows, 12 of the 48 cases of the various constants of the superstructure and the foundation (11 m cases), The yield seismic intensity is 0.2, the unit weight of the ground is 17.6 kN/m^3, Poisson's ratio is 0.3, the adhesive force is 0 kN/m^2, the N-values are 40 (according to the specifications for highway bridges, the shear velocity is 273.6 m/s, and internal frictional angle is 39.5 degree), and the damping ratios of the superstructure and the foundation are 0.05 and 0.1.

Table 3.1. Various superstructure and foundation constants (case of 11 m)

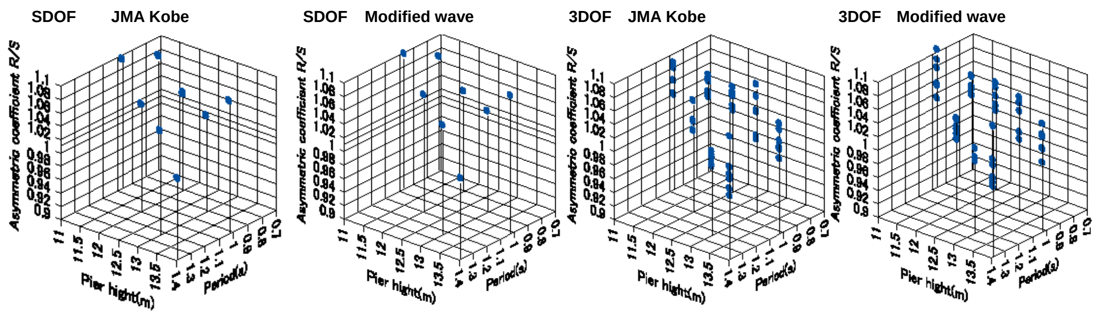
Case	Period	Pier hight	Superstructure		Foundation			Rotational moment of inertia
			Bridge girder wight	Pier wight	Hight	Radius	Mass	
	T (s)	H (m)	Wu (kN)	Wp (kN)	H_S (m)	a (m)	M (kN • s^2/m)	J (kN • m^2)
1	0.712	11	10744.7	1119.7	2	4	235.94	288267.0
2	0.712	11	10744.7	1119.7	2	4.5	298.61	288869.1
3	0.712	11	10744.7	1119.7	2	5	368.66	289703.3
4	0.712	11	10744.7	1119.7	2.5	4	294.93	288583.4
5	0.712	11	10744.7	1119.7	2.5	4.5	373.26	289350.7
6	0.712	11	10744.7	1119.7	2.5	5	460.82	290409.9
7	0.965	11	20070.4	1119.7	2	4	235.94	529188.7
8	0.965	11	20070.4	1119.7	2	4.5	298.61	529790.8
9	0.965	11	20070.4	1119.7	2	5	368.66	530625.0
10	0.965	11	20070.4	1119.7	2.5	4	294.93	529505.1
11	0.965	11	20070.4	1119.7	2.5	4.5	373.26	530272.4
12	0.965	11	20070.4	1119.7	2.5	5	460.82	531331.6

3.2. Analysis results

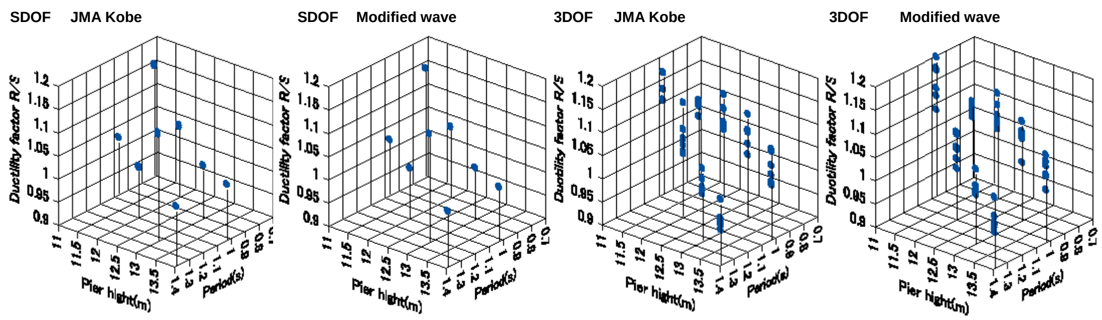
Next we show the asymmetric coefficient ($d = \mu_{max} / \mu_{average}$) and the ratio of the ductility factor (rocking/sway) when we input JMA Kobe and the modified wave to spread the foundation-superstructure system of 48 cases in Figure 4. In the models using SDOF, the value of the ratio became equal when the pier height and the bridge girder present an equal weight because they do not consider the foundations.
The asymmetric coefficient of JMA Kobe and the modified wave in Figure 4(a), in the SDOF, and the ratio of the modified wave is greater than that of JMA Kobe in 6 of 8 cases (36 of 48 cases). In 3DOF, the ratio of the modified wave is greater in 23 of 48 cases than JMA Kobe. Except for the period of 1.026 s, the ratio tends to become great, the period becomes short, and the pier becomes low.

For the ductility factor of JMA Kobe and the modified wave in Figure 4(b), in the SDOF, the ratio of the modified wave became greater in 6 of 8 cases (36 of 48 cases) than JMA Kobe, and in the 3DOF, the ratio of the modified wave became greater in 23 of 48 cases. If the periods become short, the ratios of the ductility factor tend to become great, like the asymmetric coefficient ratio.

The positive and negative (absolute value) maximum displacements which are plotted for each period, are shown in Figure 5. The diagonal lines are not asymmetrical about positive and negative maximum displacements. The trends related to positive maximum displacements are often larger than negative ones, except the period of 1.389 s in Figure 5. When we compare the values of Figure 5(a) and (b), the

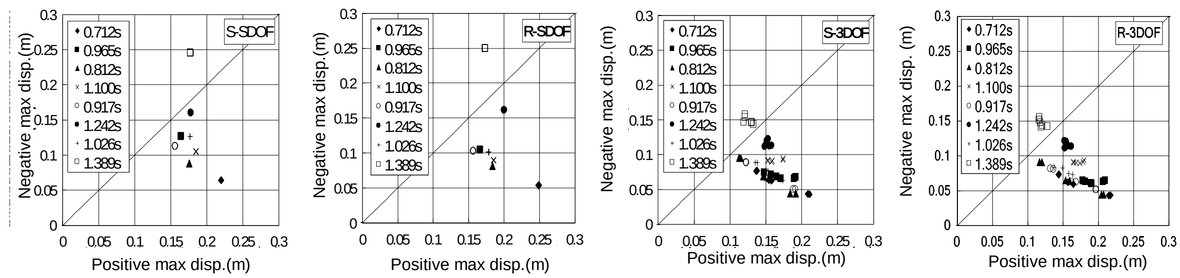


(a) Asymmetric coefficient

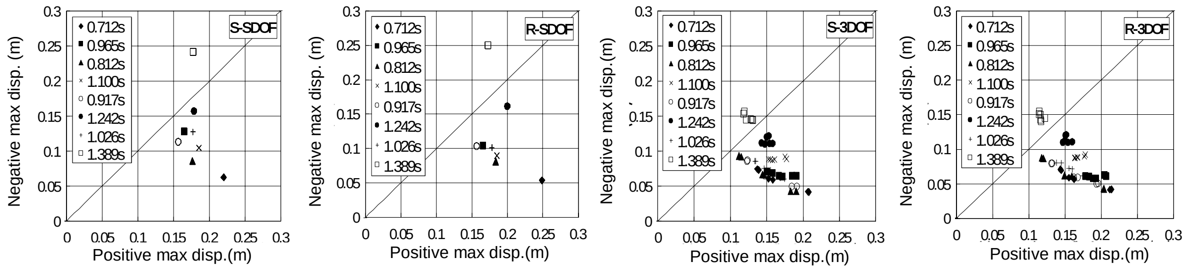


(b) Ductility factor

Figure 4. Ratio of asymmetric coefficient and ductility factor : rocking/sway



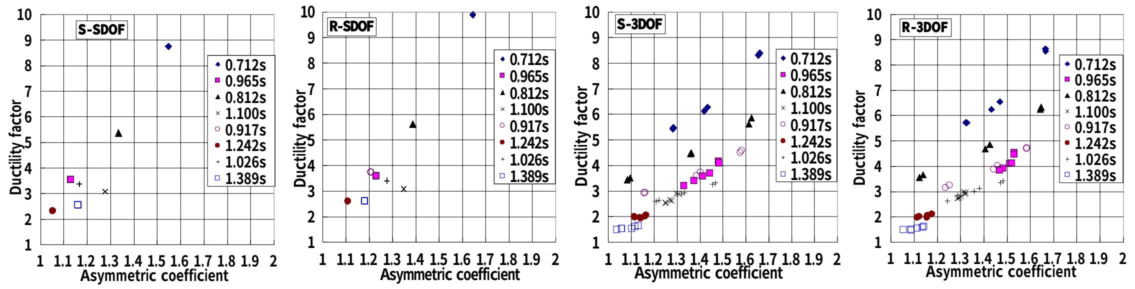
(a) JMA Kobe



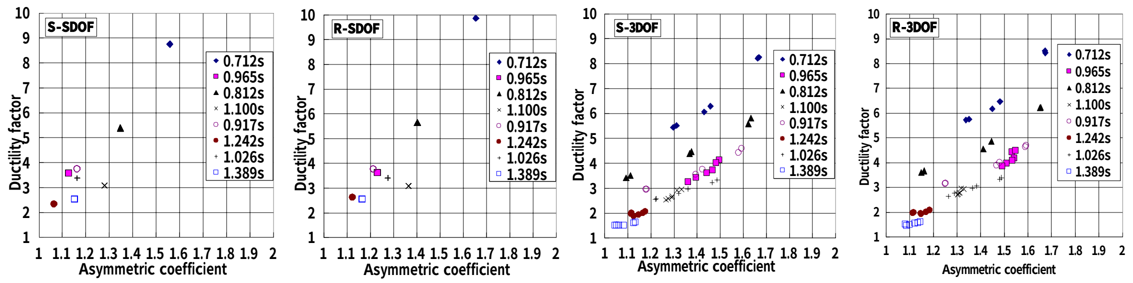
(b) Modified wave

Figure 5. Positive and negative (absolute value) maximum displacement

modified wave values are greater than JMA Kobe in 7 of 8 cases (42 of 48 cases) of positive maximum displacement and 1 case (6 cases) of negative maximum displacement in R-SDOF. Similarly, the values of the modified wave are greater than JMA Kobe in 8 cases (48 cases) in relation to the positive maximum displacement and in 2 cases (12 cases) in relation to the negative maximum displacement in S-SDOF. If SDOF acts in the domain of the modified wave, the maximum displacements tend to positively increase. For the SDOF value in Figure 5, the R-SDOF values are greater than the S-SDOF values in 7 of 8 cases (42 of 48 cases), and JMA Kobe was input in 6 of 8 cases (36 of 48 cases).

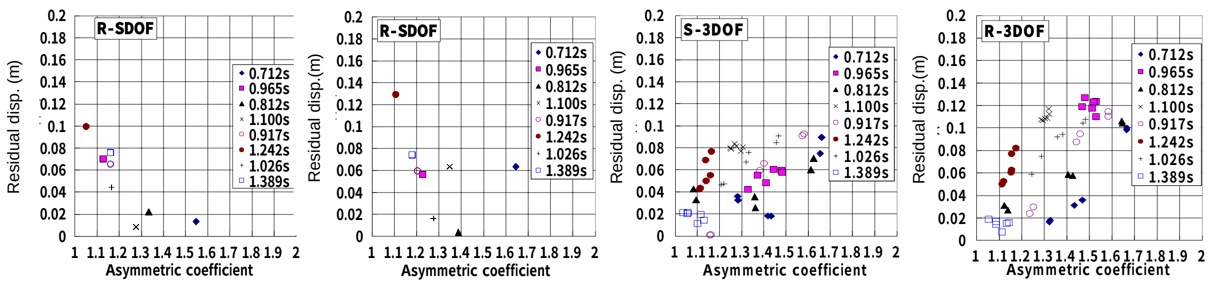


(a) JMA Kobe

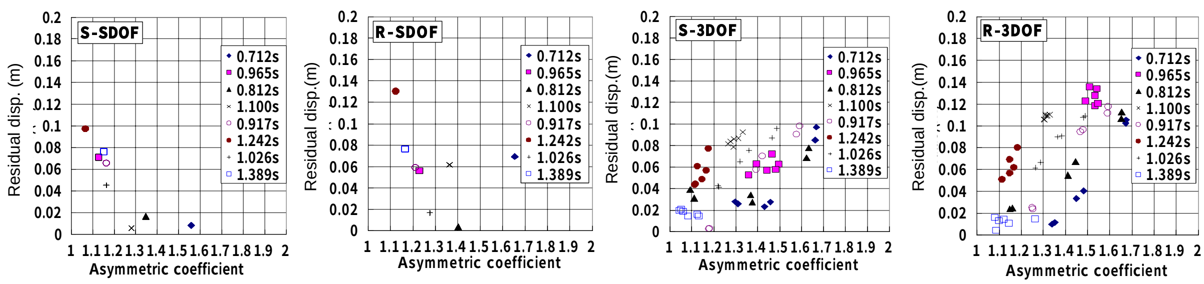


(b) Modified wave

Figure 6. Relations of ductility factors and asymmetric coefficient



(a) JMA Kobe



(b) Modified wave

Figure 7. Relations of absolute values of residual displacement and asymmetric coefficient

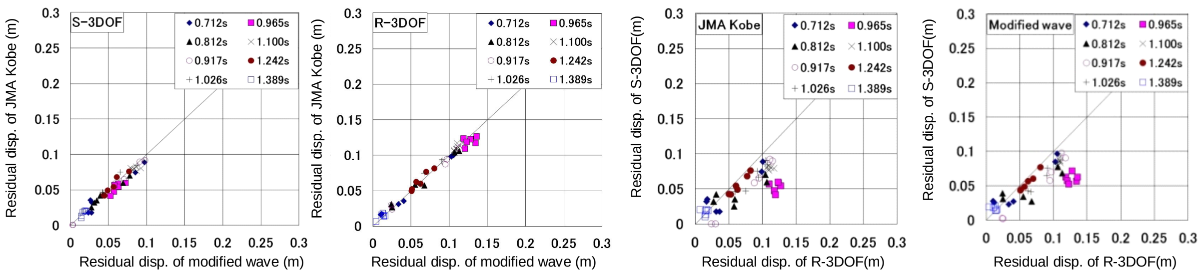
When 3DOF was input into JMA Kobe, the positive maximum displacements of R-3DOF exceeded S-3DOF. In 41 of 48 cases, and when it was a modified wave, a similar trend was seen in 39 of 48 cases. However, the negative value of R-3DOF has a greater S-3DOF in 13 of 48 cases when JMA Kobe was used. The models of period 0.712 s present greater disparity than the values of the positive and negative maximum displacements, For both JMA Kobe and the modified wave, the positive values are about 3.4 times greater than the negative values when S-SDOF was used, about 4.6 times when R-SDOF was used, about 4.6 times when S-3DOF was used, and about 5.0 times when R-3DOF was used.

The relations of the ductility factor and the asymmetric coefficient of each period are shown in Figure 6. We can see the trend expanding in Figure 6. There are correlations between the ductility factors and the asymmetric coefficients resulting from their interaction. Both the ductility factor and asymmetric coefficient are greater when the period is shorter.

The relation of the absolute values of the residual displacement and the asymmetric coefficient of each period is shown in Figure 7. Except for period 0.712 s, Figure 7 shows the correlation of the falling right shoulder in the SDOF domain. We compared periods 0.712 s of R-SODF and S-SDOF. R-SDOF became 5.0 cm greater than S-SDOF with JMA Kobe input. R-SDOF became 6.1 cm greater than S-SDOF with modified wave input (Figure 7(b)). When both JMA Kobe and modified wave input are R-3DOF, the periods of 0.965 s are 6.8 cm greater than S-3DOF.

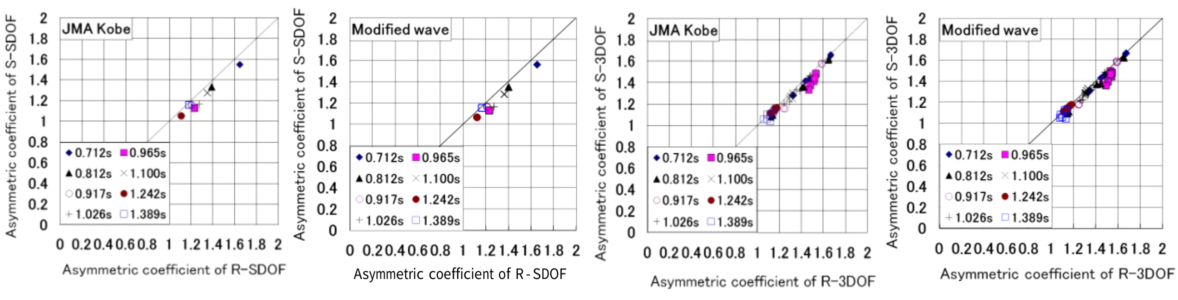
The relation of the residual displacement (absolute value) between JMA Kobe and the modified wave is shown in Figure 8(a). The modified wave values are greater than JMA Kobe in 25 of 48 cases when R-3DOF is used, and in 32 of 48 cases when S-3DOF is used. These results show that the modified wave's residual displacement become greater than cases with modified wave values. When comparing R-3DOF and S-3DOF, the average values of period 0.965 s are the most different of the eight periods. If JMA Kobe is input, the R-3DOF value is about 2.3 times greater than the S-3DOF value, and if the modified wave is input, it is about 2.1 times. The relation of the residual displacement for R-3DOF and S-3DOF is shown in Figure 8(b). The R-3DOF values that were input into JMA Kobe and the modified exceed the S-3DOF value in 40 of 48 cases. From this result, R-3DOF which considered the P-Δ effects, tends to have residual displacements that are greater than S-3DOF.

The relations of the asymmetric coefficient between R-SDOF and S-SDOF are shown in Figure 9(a) and those between R-3DOF and S-3DOF are shown in Figure 9(b).



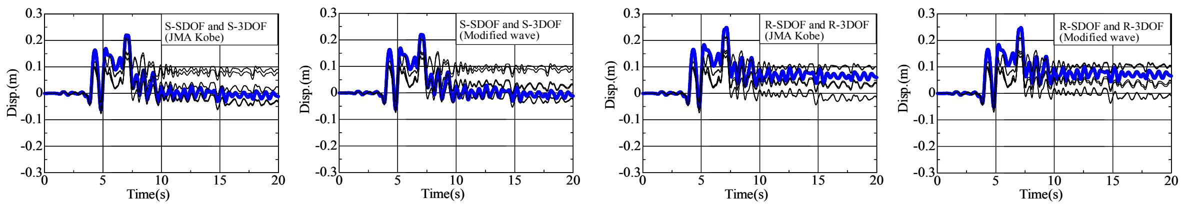
(a) JMA Kobe and modified wave (b) R-3DOF and S-3DOF

Figure 8. Relation of residual displacement (absolute value)

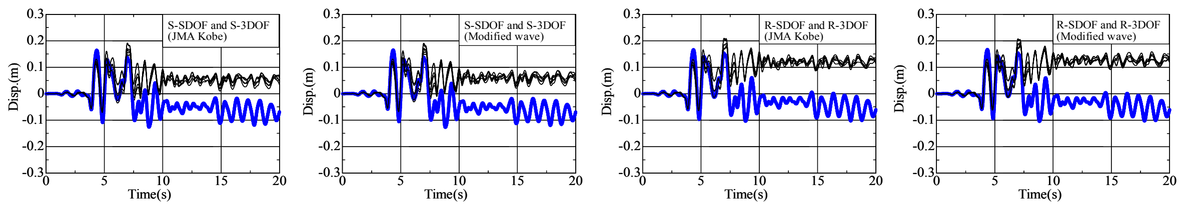


(a) S-SDOF and R-SDOF (b) S-3DOF and R-3DOF

Figure 9. Comparison of asymmetric coefficient



(a) Period 0.712 s



(b) Period 0.965 s

Figure 10. Displacement response waves of superstructures

The R-SDOFs, which were based on the influence of the P-Δ effects, became asymmetric coefficients and exceeded the S-SDOFs in all cases. When comparing the modified wave and JMA Kobe, the modified wave, which had R-SDOF and S-SDOF input, were greater in 6 of 8 cases (36 of 48 cases).

When looking at Figure 9(b), the R-3DOFs are greater than S-3DOF in 44 of 48 cases in JMA Kobe and the modified wave. When comparing the values between JMA Kobe and the modified wave, the modified wave became greater than JMA Kobe in 42 of 48 cases, because the asymmetric coefficients of the modified wave are greater than JMA Kobe. We compared S-SDOF or R-SDOF and S-3DOF or R-3DOF by asymmetric coefficients in Figure 9(a) and (b). When we input JMA Kobe, R-3DOF was greater than R-SODF in 29 of 48 cases, and S-3DOF was greater than S-SODF in 31 of 48 cases. Similarly, when we input the modified wave, R-SODF was greater in 27 of 48 cases, and S-3DOF was greater than S-SODF in 34 of 48 cases. From this result, based on the influence of spread foundation and the foundations, 3DOFs became asymmetric coefficients and exceeded SDOF.

The displacement response waves of periods 0.712 s and 0.965 s show traits Figure 10(a) and (b). In Figure 10, SDOF is shown in bold lines and 3DOF in thin lines. We can sort the residual displacements of 3DOF into three lengths:7.6～10.6 cm, 2.3～4.7 cm, and -4.5～-0.4 cm in Figure 10(a).

There are waves in cases 1 and 4, cases 2 and 5, and cases 3 and 6 in Table 3.1. The response wave of period 0.712 s involves radius foundation, and the influence of the foundation mass is also suggested.

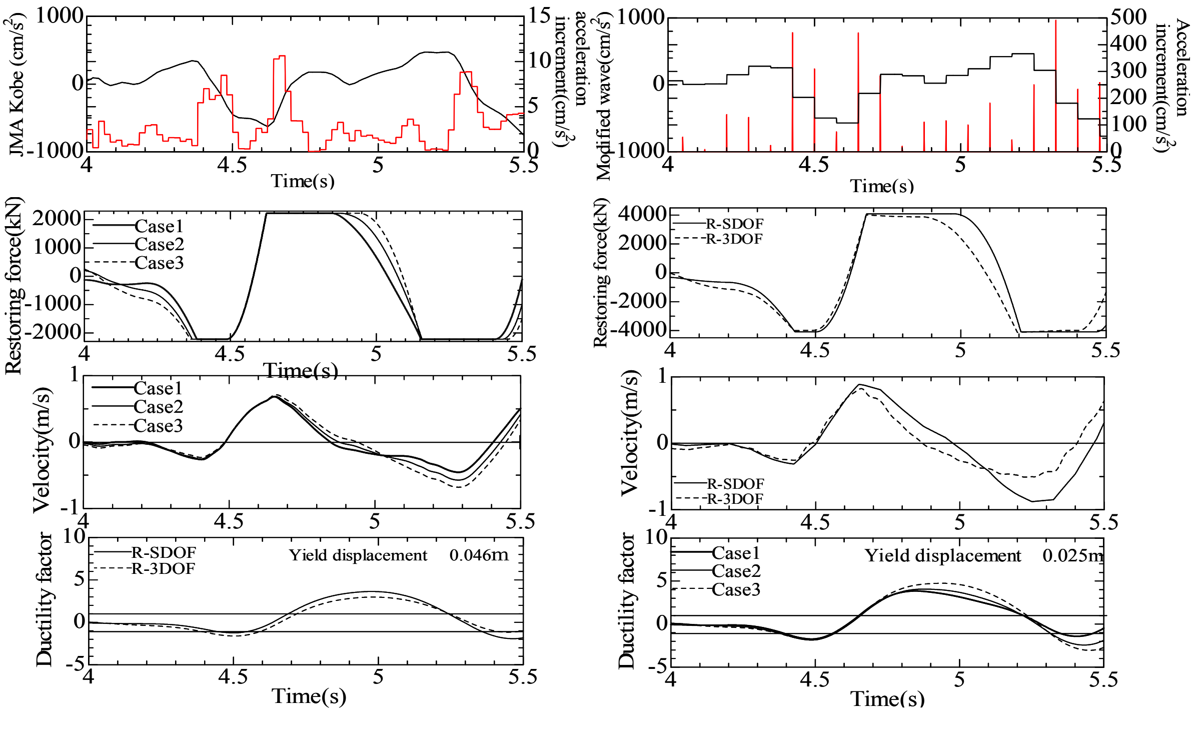
The response waves of SDOF and 3DOF fork at nearly 4 s, and residual displacements become negative and positive in Figure 10. The SDOF amplitude tends to decrease around 14 s with a maximum increase at 9.9 cm.

For detailed analysis into the cause of the different responses in period 0.712 s (Figure 10), JMA Kobe and the increments from 4.5～5.5 s, and the time history of the restoring force, the velocity and the ductility factor of cases 1～3 of S-3DOF were input into this wave (Figure 11(a)). Similarly, for period 0.965 s, the modified wave and the increment, and the waves of case7 of R-SODF and R-3DOF were input into this wave (Figure 11(b)). JMA Kobe is linearly interpolated for analysis at 0.001 s time intervals from 0.02 s of the observational data. The increments don't change between 0.02 s, and because the modified wave changes at 0.05s intervals, the acceleration increments don't change the interval.

When comparing the restoring force and the velocity wave in Figure 11(a), the acceleration increment of JMA Kobe becomes about 10 cm/s^2 at 4.65 s and restoring force reach yield strength. After time slightly passes, the velocity wave is influenced, whose velocity has been increasing decrease. Now it starts to decrease, and the velocity of each case forks, and the ductility factors worn by the response have almost the same occurrence difference. This result suggests, that the JMA Kobe peaks at 4.65 s are one of the causes of the differences of the displacement responses of each case. The velocity response changes from positive to negative in the order of cases 1,2, and 3 between 4.85 s and 4.98 s, The restoring force of each case returns from the plasticity to the elasticity zone, and the difference of the ductility factor becomes greater.

Now we look at the acceleration increments of the modified wave and the time history response of the restoring force and the velocity (Figure 11(b)). In 4.65 s the acceleration increment of the modified wave peaks, and the slope of the velocity wave of R-3DOF changes from positive to negative, and form R-3DOF to the R-SDOF branch. This slope is steeper than R-SDOF, and the velocity quickly changes from positive to negative at about 0.1 s, restoring force return elasticity zone. R-SDOF increases the displacement to restore the R-SDOF force in the plasticity zone.

The cause of the different responses is probably the influence of the spread foundation and the ground and the increment peak of the modified wave at 4.65 s.



(a) Period 0.712 s (S-3DOF, JMA Kobe) (b) Period 0.965 s (case7, modified wave)

Figure 11. Time history response of input earthquake motion and superstructures

4. CONCLUSION

We analyzed the elasto-plastic earthquake response of the highway bridges of 48 cases supported by the spread foundation. We considered the period and the height of the superstructure effect on the asymmetric coefficient and the ductility factor, and the relation among the asymmetric coefficient, the ductility factor, and the residual displacement. Furthermore, we compared the displacement waves of each period, and examined the asymmetric response. Our results are summarized as follows.

1) When we input the modified wave to SDOF and 3DOF, the ratio of the asymmetric coefficient and ductility factor frequently increased. We conclude that modified wave is effective when the asymmetric response is considered.
2) Because the asymmetric coefficient and the residual displacement where R-SDOF and R-3DOF considered the influence of P-Δ effects become greater than S-SDOF and S-3DOF, we must investigate the influence of the P-Δ effects to study the asymmetric response.

Based on this study, we can disperse the asymmetric response caused by input earthquake motion and the elasto-plastic restoring force characteristics of superstructures. Moreover, to clarify the mechanism of the asymmetric response, we will study the restoring force characteristics of superstructures with a rigid-plastic model. To combine a rigid-plastic model and modified waves, we not only can easily clarify the cause of the asymmetric response by input earthquake motion, but also the different responses of each object models.

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