EFFECT OF NON-LINEAR DYNAMIC INTERACTION ON SECTIONAL FORCE OF BRIDGE PIERS SUBJECTED TO PULSE-LIKE GROUND MOTIONS

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ABSTRACT: In this study, we discuss the effects of uplift in spread foundation and yielding of underlying soils on the sectional force of bridge piers subjected to pulse-like ground motions. The effects could lead to reducing bridge damage caused by pulse-like ground motions. We simulated the pulse-like ground motions with sinusoidal pulse. We found that the sectional force of bridge piers subjected to the pulse-like ground motions was reduced by the uplift in spread foundation and the yielding of underlying soils. We also found that, regardless of the pulse acceleration amplitude, the sectional force was minimized, while the ratio Tp/Te of pulse period Tp to natural period Te was between 1 and 1.2, where the natural period Te was the primary natural period of the model that expressed the soil as an elastic body without considering the foundation uplift.

KEYWORDS: *Highway Bridge, Spread Foundation, Non-Linear Dynamic Interaction, Pulse-Like Ground Motions*

1.0 INTRODUCTION

The evaluation of the seismic performance of a bridge structure is an important concern in establishing reasonable anti-seismic measures. The effect of non-linear dynamic interaction on the sectional force of bridge piers was evaluated by Kawashima and Hosoiri [1], who studied a typical highway bridge having a spread foundation designed using the seismic coefficient method. To model the effect of the soil, they defined a spring that resisted a rocking motion and investigated the foundation uplift by neglecting the reaction force from the tensile side of the ground at the base of the footing. They showed that the spread foundation was uplifted when it was subjected to strong ground motion like the one experienced during 1995 Hyogoken-Nanbu Earthquake; in turn, the foundation uplift functioned as a type of seismic isolation effect against the response of the bridge. Cremer et al. [2] also showed the seismic isolation effect due to non-linear dynamic interaction. In addition, Inoue and Mikami [3] investigated the reduction in the sectional force of structures from the energetics viewpoint; this was caused by the uplift in spread foundation and the yielding of underlying soils. They used the macro-element model [4], which considers the spread foundation uplift and the yielding of underlying soils at the same time. They showed that a remarkable reduction of section force due to the uplift in spread foundation and the yielding of underlying soils, depending on characteristics of input motions and the input energy imparted to the structure by an earthquake tended to be reduced due to the effect of foundation uplift.

On the contrary, in recent years, in response to the recognition that the pulse waveform of strong ground motion (i.e., the pulse-like ground motions) plays an important role in evaluating the seismic response and seismic performance of structures, a variety of studies [5-6] have been conducted using the simulated pulse-like ground motions as the input motions. These studies focused attention on the characteristics of the pulse-like ground motions. The pulse-like ground motions has been prominently observed in inland earthquakes, such as 1995 Hyogoken-Nanbu Earthquake and 2004 Niigataken-Chuetsu Earthquake. However, the reduction in the sectional force of the bridge piers, which is caused by the uplift in spread foundation and the yielding of underlying soils, has not been investigated using the simulated pulse-like ground motions. It is not sufficiently clear how this effect appears against pulse-like ground motions. With these studies as a background, our study investigated the effect of uplift in spread foundation and yielding of underlying soils on the sectional force of bridge piers subjected to the pulse-like ground motions by focusing attention on the characteristics of the pulse-like ground motions. In this study, the simulated pulse-like ground motions were applied to typical highway bridges having a spread foundation.

2.0 MACRO-ELEMENT OF SPREAD FOUNDATION

In this study, we used the macro-element model developed by Nakatani et al. [4] The model can consider the effect of uplift in spread foundation and yielding of underlying soils. The model also allows efficient analysis because both the degree of freedom and computational complexity are negligent. Refer to Nakatani et al. [4] for the details. In the macro-element model, the foundation-soil system subjected to the combined loads is deemed to be one element, assuming that the foundation is a rigid. The displacements and loads at the center of the foundation are defined in Figure 1.

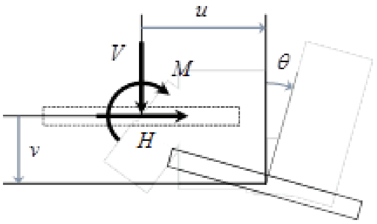


Figure 1: Definition of displacements and loads for the macro-element

The arrow in Figure 1 indicates the positive direction of the displacements. These are expressed by the following equations:

$$x = (v \quad u \quad \theta)^T \tag{1}$$

$$F = (V \quad H \quad M)^T \tag{2}$$

The relation between an increment of displacement (dx) and that of the load (dF) is shown with the next equation:

$$dF = \left(D^{el} + D^{up} + D^{pl}\right)^{-1} dx \tag{3}$$

where D^{el} is an elastic compliance, D^{up} is an uplift compliance, and D^{pl} is a plastic compliance. The increment of displacement (dx) is the sum of three components, as shown in the following equation:

$$dx = dx^{el} + dx^{up} + dx^{pl} \tag{4}$$

where dx^{el}, dx^{up}, and dx^{pl} are the elastic, uplift, and plastic components of the displacement, respectively.

3.0 STUDY USING SIMULATED PULSE-LIKE GROUND MOTIONS

3.1 Definition of Simulated Pulse-Like Ground Motions

In this study, the pulse-like ground motions were simulated by the sinusoidal pulses. The time history of acceleration ($a(t)$) of the sinusoidal pulse used in the study is defined by the following equation:

$$a(t) = \begin{cases} A_p \sin \dfrac{2\pi t}{T_p} & \left(0 \le t < T_P\right) \\ 0 & \left(T_P \le t\right) \end{cases} \tag{5}$$

where A_p is an amplitude of pulse acceleration, and T_p is the pulse period.

3.2 Approach Used in the Study

In our study, we reviewed how the effect of foundation uplift and yielding of underlying soils on the sectional force of bridge piers changed with changes in the pulse period (T_p) and natural period (T_e), which characterize the pulse-like ground motion and target system.

3.3 Examination Object

The highway bridge [7] shown in Figure 2 was reviewed in this study. This bridge was designed (for trial) in accordance with the specifications for highway bridges (in 1996). Two soil conditions used in the study are (1) sandy soil with an N-value around 50 and (2) sandy soil with an N-value around 25 (i.e., Soil (2) was softer than Soil (1)). The *Vs* of the soil with an N-value of about 50 was 295 m/s (*Vs* = 295 m/s), and the one with an N-value of about 25 was 230 m/s (*Vs* = 230 m/s). Two foundations of different sizes were used; the smaller one (1) measured 6.5 m × 7 m and the larger one (2) measured 10 m × 10 m. To simplify the analysis, the substructure and superstructure supported by the substructure were combined as one unit. We assumed that these two substructures were rigidly supported despite the fact that they were connected with a rubber bearing, because the stiffness of the rubber bearing was sufficiently rigid.

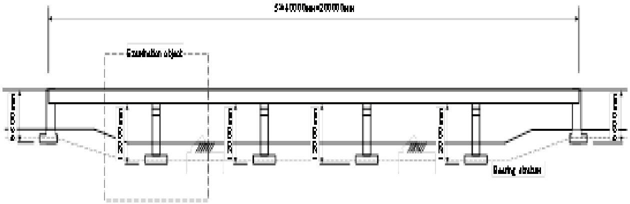


Figure 2: Examination object [7]

The target of analysis is the response in the bridge axis, which plays a critical role in the seismic design. In the real world, it is expected that the response of bridge piers is non-linear. However, considering the non-linearity in the foundation-ground system makes the phenomena more complex and makes the discussion to complete the purpose of this study difficult. Therefore, we assumed that the bridge piers were linear elastic bodies and evaluated the base shear, which causes damages on the structure in response to the pulse-like ground motion. A schematic diagram of the structure-foundation-soil systems is illustrated in Figure 3.

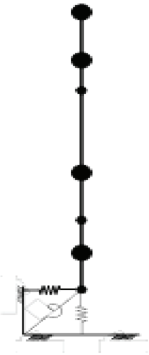


Figure 3: Schematic diagram of structure-foundation-soil system

Factors that characterize the non-linear characteristics of soil-foundation system, such as the bearing capacity surface, plastic potential, hardening rule parameters, and soil density were those proposed in the experiment conducted by Nova and Montrasio [8] and Nakatani et al [4]. The internal friction angle ϕ and soil density ρ were set as shown below with the sandy soil having $V_s = 295$ m/s; they were used to determine the parameter R_0 of the hardening rule, the ultimate bearing capacity (V_m) of the ground at the base of the foundation when the load was applied vertically at the center, and the yield surface parameter μ. The parameter R0 of the hardening rule is decided by the next equation as similarly used by Shirato et al.

$$R_0 = 100 \times V_m / B \tag{6}$$

where, R_0, V_m, and B are expressed in kN/m kN, and m, respectively. The ultimate bearing capacity (V_m) of the ground at the base of the foundation when the load is vertically applied at the center is set in accordance with the formula stipulated in the specifications for highway bridges [10]. The internal friction angle ϕ and soil density ρ are also set in accordance with the specifications for highway bridges [10]. However, it is important to note that the effect of the earth covering is neglected.

Two types of foundation-soil systems were investigated and the response from one system was compared with that from another system: (1) a linear model (wherein the ground is assumed to be elastic) and (2) a non-linear model (wherein the ground is assumed to be elasto-plastic and the foundation is uplifted). Only the elastic compliance in Equation 3 in Section 2 is considered in the linear model, and all the compliances (i.e., the elastic compliance, uplift compliance, and plastic compliance) in Equation 3 are considered in the non-linear model. The primary periods of the linear models are T_e.

3.4 ExaminationStudy Using the Simulated Pulse-Like Ground Motions

Four cases were studied wherein the ratios T_p/T_e were 0.8, 1.0, 1.2, and 1.4. Two levels of the pulse acceleration amplitude, which is one of the values characterizing the pulse-like ground motions, were used: 200 and 800 gal.

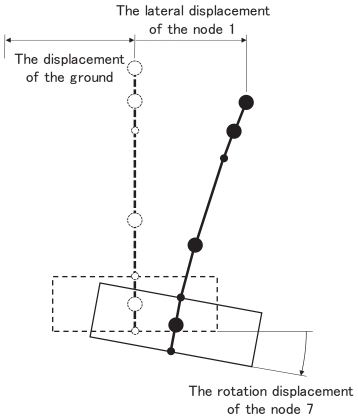
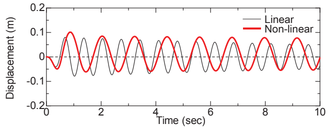
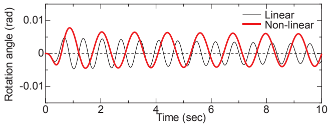


Figure 4: Definition of response displacement

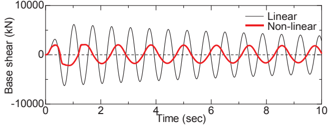
The time step used in the non-linear seismic response analysis using the macro-element model was 0.000005 seconds. The average acceleration method was used as the time-integration method. The response displacement of the bridge evaluated in this study was defined as shown in Figure 4.



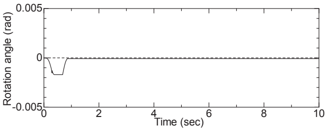
(a) Horizontal displacement of node1



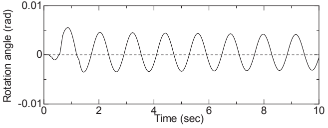
(b) Rotational displacement of node7



(c) Base shear



(d) Plastic component of rotational displacement



(e) Uplift component of rotational displacement

Figure 5: Seismic response

The following samples of the evaluations of structures (soil with V_s = 230 m/s, foundation size = 6.5 m × 7 m, $T_p/T_e = 1.0$, and pulse acceleration amplitude = 200 gal) are shown in Figure 5: (a) Horizontal displacement at node 1, upon which the inertial force of the super structure acted, (b) rotational displacement at node 7, located at the base of the foundation, and (c) the plastic and uplift components of rotational displacement in the non-linear model. A comparison among Figures 5(a), 5(b), and 5(c) reveals that the difference in response among the models becomes prominent right after the start of vibration and that the response starts showing a longer period as the foundation uplift and the yielding of underlying soils keep progressing. Also observed in Figure 5 (c) is that the sectional force is significantly reduced. The relation between the reduction in the sectional force and the pulse period is shown in Figures 6 and 7. In these figures, the vertical axis is the ratio T_p/T_e, and the horizontal axis is the ratio of base shear to the maximum base shear in the linear model, which indicates the measure of sectional force reduction on the bridge piers due to the foundation uplift and the yielding of underlying soils.

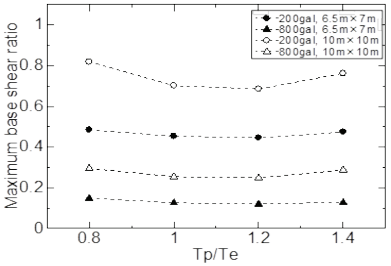


Figure 6: Relation between stress reduction effects and pulse period (soil with V_s = 295m/s)

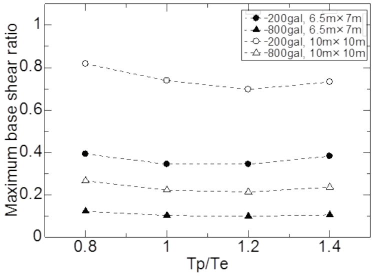


Figure 7: Relation between stress reduction effects and pulse period (soil with V_s = 230m/s)

As it can be seen in Figure 6 and Figure 7, the effect of sectional force reduction caused by foundation uplift and yielding of underlying soils became the largest when the ratio Tp/Te was between 1 and 1.2, and the effect slowly became less prominent as the ratio started departing from this range of 1 to 1.2,showing its dependency on the pulse period. This is due to the fact that, despite the response of the linear model, which tended to hit its maximum value in the range where the ratio Tp/Te was between 1 and 1.2, the period of the model became longer as the foundation uplift and the yielding of underlying soils increased, and thus, the zone of the pulse period in which the response became largest was shifted, causing the response to be suppressed.

The figures also show that the larger the pulse acceleration amplitude and narrower the foundation width, the more sectional force was reduced. This is because the foundation tended to be more uplifted and the yielding of underlying soils tended to be more non-linearized as the pulse acceleration amplitude became large and as the foundation width narrowed, regardless of the ground stiffness. the larger the pulse acceleration amplitude and narrower the foundation width, the more sectional force was reduced. This is because the foundation tended to be more uplifted and the yielding of underlying soils tended to be more non-linearized as the pulse acceleration amplitude became large and as the foundation width narrowed, regardless of the ground stiffness. Figure 8 shows the maximum base shear-pulse period relation for the case: soil with V_s = 295 m/s, foundation size = 10 m × 10 m, peak acceleration of pulse-like ground motions is 200 gal. We can see that the linear model's response is the largest in the case that the range of T_p/T_e is from 1 to 1.2 and the non-linear model's response is the largest when T_p/T_e is 1.6.

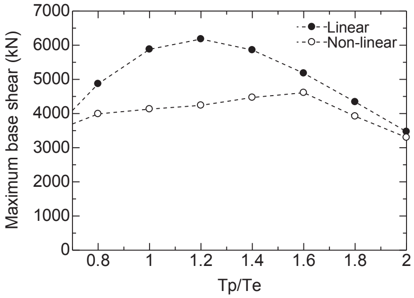


Figure 8: Relation between maximum base shear and pulse period

4.0 CONCLUSIONS

The effect of the foundation uplift and the yielding of underlying soils on the sectional force of bridge piers subjected to pulse-like ground motions was investigated by focusing attention on the characteristics of the pulse-like ground motions. In our study, we used a sinusoidal pulse to simulate the pulse-like ground motions, and we used four types of analytical models (i.e., a combination of two foundation widths and two types of soil conditions) to simulate a road bridge with a spread foundation.

We found that, regardless of the pulse acceleration amplitude due to foundation uplift and yielding of underlying soils, the sectional force of the bridge piers was reduced to its maximum (in other words, was minimized) when the ratio T_p/T_e was between 1 and 1.2, where T_e is the pulse period and T_e is the primary natural period of the model, which expresses the foundation as an elastic body without considering the foundation uplift. This reduction occurred despite the response of the model expressing the foundation as an elastic body, without considering that as the foundation uplift increased, the sectional force tended to reach its lowest value in the range where the ratio T_p/T_e was between 1 and 1.2; the period of the model became longer as the foundation uplift and the yielding of underlying soils increased. Thus, the zone of the pulse period in which the response became the largest shifted, causing the response to be suppressed. The reduction in the sectional force increased as the pulse acceleration magnitude became larger and as the foundation width became narrower. This occurred because the foundation tended to be uplifted and the foundation tended to be more non-linearized, regardless of the ground stiffness. We expect that these findings are a useful and effective way to more precisely understand the aseismic performance of bridge structures having a spread foundation and to establish reasonable anti-seismic measures. We will continue to study many other models.

We might find that when we consider the effects of the earth covering and the suction at the bottom of the foundation, which were not included in the present study, the foundation uplift can be suppressed, resulting in a smaller reduction in sectional force. In addition to these studies, in the near future, it will be necessary to include the non- linearity of bridge piers.

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