Study on Inertial and Kinematic Interaction in Pile Bent Structures

Atsuhiro USAMI
Soil Dynamics and Earthquake Engineering Laboratory,
Center for Railway Earthquake Engineering Research (Former)

Yoshitaka MURONO
Center for Railway Earthquake Engineering Research

Hiroki MOTOYAMA
Structural Dynamics and Response Control Laboratory, Center for Railway Earthquake Engineering Research

Pile bent structures have no underground beam, so the distribution of bending moments between the pile and pier is continuous. It is therefore considered that the dynamic response characteristics of the pile bent are complexly affected by the displacement of the ground and inertial forces, but this inertial and kinematic interaction is unclear. In this paper, the inertial and kinematic interaction acting on the pile bent structures is studied by nonlinear time-history dynamic analysis. As a result, it is revealed that the moment due to the inertial force is dominant on the pier and the pile which is located at a small depth, and the displacement of the ground has an influence not only on the moment at the pier but also that at the pile.

Keywords: pile bent, soil-structure interaction, inertial interaction, kinematic interaction

1. Introduction

General viaducts usually have underground beams along and across the railroad track direction. Underground beams are expected to perform two functions: one is to level the resistance in each foundation, the other is to distribute the horizontal forces acting on the piles. However, because constructing underground beams increases the amount of soil to be excavated and decreases the workability for arranging reinforcement at the top of piles, there are problems with respect to cost and construction time. Recently, pile bent structures or viaducts without underground beams have often been used for the construction of grade separation.

Numerical analyses [1, 2, 3] and experiments [4] show that structures with piles constructed on soft ground are affected by ground displacement as well as inertial force. Seismic deformation methods need to be used to design railway viaducts, where ground displacement acts on structures through a spring element expressing soil-structure interaction [5]. This analysis showed that ground displacement in normal viaducts with underground beams mainly affects the foundations. On pile bent structures, however, it is necessary to consider the possibility that the ground displacement effect extends to the upper structures because bending moments are not divided between the piles and columns by underground beams. Therefore, a complex influence of both of the ground displacement and inertial force is exerted on the structure, but the properties of such dynamic interactions are not yet clear. As such studies were carried out to examine the dynamic response of pile bent structures using numerical analysis considering nonlinearity, as well as the influence of the ground displacement and inertial force.

2. Target structure and numerical model

The target structure was a pile bent structure as shown in Fig. 1. A numerical model was constructed integrating a free field and structure system. This model is suitable for considering dynamic soil-structure interaction. Beam elements were applied in this construction to structural members and spring elements to the interaction between the soil and the piles. The model is shown in Fig. 2. Level 2 earthquake motion (Spectrum II) shown in Fig. 3 was applied as input motion [5]. Nonlinearity of the soil was considered by applying the modified Ramberg-Osgood model [6] to G-γ relation calculated from the parameters used in the standard seismic design [7] and γ0.5 estimated by the equation proposed by Yasuda and Yamaguchi [8].

In this study, only the direction perpendicular to the track was studied and the equivalent natural period at yielding point in this direction is 1.03 sec.

The subsurface ground has a thick layer whose N-value is almost zero as shown in Fig. 4. By eigenvalue analysis,
the natural period of this ground is calculated at 1.36 sec and categorized as soft ground by railway seismic design in Japan.

3. Analysis case

The purpose of this study is to clarify the effect of the ground displacement and inertial force to the pile bent viaducts. Therefore, two cases were analyzed: the first was a normal analysis considering both the ground displacement and the inertial force, the other was an analysis considering only the ground displacement by removing the mass of the model. These two cases were entitled “total-system case” (or case 1) and “ground-system case” (or case 2) respectively. The effect of the inertial force was examined by investigating the difference between them both.

4. Analysis results

4.1 Comparison of the target cases

Figure 5 shows the waveforms of the acceleration, velocity, and displacement at the top of the viaduct from 5 sec to 30 sec. The response waveforms of the ground-system case (case 2) are smaller than that of the total-system case.
(case 1) because of the absence of the inertial force. Moreover, between the two cases, the time when the maximum amplitude occurs is different.

Figure 6 shows the distribution of the maximum displacement and bending moment. At the deeper level than $1/\beta$ ($\beta$: characteristic value of a pile), two distributions of the displacement are almost equal. On the other hand, at the shallower level than $1/\beta$, that of the total-system case (case 1) is larger than that of the ground-system case (case 2). In the former area, the effect of the ground displacement is dominant, and in the latter area, the effect of the inertial force is involved.

Regarding the bending moment, its distribution shows the same characteristics as that of the displacement. However, there is a remarkable property in the ground-system case (case 2) such that the bending moment occurs in the upper structure. From this result, it can be concluded that in pile bent viaducts the ground displacement affected the cross-section force in the upper structure unlike the normal viaducts.

4.2 Analysis of the effect of the ground displacement and the inertial force

The effects of the ground displacement and inertial force were analyzed by focusing on the bending moment. In this analysis, the bending moment of the inertial-force-system case ($M_a$) was calculated at the difference between that of the total-system case ($M_t$) and that of ground-system case ($M_g$) using the following equation.

$$M_a = M_t - M_g$$

(1)

Figure 7 shows the results of three points; the top point of the viaduct, the middle point between the ground level and $1/\beta$ and the middle point between $1/\beta$ and the pile toe.

Fig. 6 Distribution of the maximum response value

Fig. 7 Waveforms of bending moment
level and $1/\beta$ and the middle point between $1/\beta$ and the pile toe. Figure 8 shows the distribution of the maximum bending moment of the total-system case, the inertial-force-system case and the ground-system case.

From Fig. 8, it is apparent that the following equation is not true at the top of the viaduct.

$$M_{\text{max}} \neq M_{g\text{max}} + M_{a\text{max}} \quad (2)$$

This equation means that the bending moment of the ground-system case and that of the inertial-force-system case aren’t maximized at the same time. Because these two bending moment are out-of-phase, it seems that the bending moment of the ground-system case does not contribute to that of the total-system case.

Checking the waveform of the acceleration on the top of the viaduct and that of the ground displacement, also confirms the difference of the phase between the bending moment of the top of the viaduct caused by the ground displacement and that by the inertial force. Figure 9 shows these two waveforms in the total-system case. At the time the bending moment maximized (at 13.79 sec), the acceleration also is maximized. On the other hand, the amplitude of the ground displacement is just half of the maximum value.

The focus was then placed directly on the phase difference between the ground displacement and the acceleration on the top of the viaduct and plot an orbit made by these two responses normalized by the maximum amplitude as shown in Fig. 10. Black and white triangles were placed at the maximum value of the ground displacement and the acceleration of the top of the viaduct respectively in Fig. 10. If both values are in-phase, the coordinates indicated by the two triangles should be close. Now that these two points are distant, these two responses, the ground displacement and the acceleration of the top of the viaduct, tend to show an out-of-phase relationship especially in the relatively large amplitude area.

At the middle point between the ground level and $1/\beta$, the bending moment of the total-system case is smaller than that of the inertial-force-system case. Due to the out-of phase relationship between the ground displacement and the inertial force, the bending moment caused by the ground displacement and that caused by the inertial force cancelled each other.

According to past studies making mention of this, if employing a method in which the bending moment caused by the ground displacement and that of the inertial force are estimated separately like in the seismic deformation method, it is necessary to consider the phase difference of the ground displacement and inertial force in calculating the total bending moment [9, 10]. However, such studies are mainly on the piles of a viaduct with underground beams. This study shows that regarding pile bent viaducts, it is necessary to consider the phase difference in the responses of the upper structure. Studies on the specific method or the applicability of the seismic deformation
method should be subjects for future research.

5. Conclusions

A study was conducted into the effect of ground displacement and inertial force on pile bent structures by using dynamic analysis. The following characteristics concerning pile bent structures were found:

1) The ground displacement affects the bending moment of the upper structure.
2) Observations revealed that there is a phase difference between ground displacement and inertial force.

Future research would need to consider a method for calculating the total cross-section force of the members of structures including the upper structure.

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Authors

Atsuhiro USAMI
Researcher, Soil Dynamics and Earthquake Engineering Laboratory, Center for Railway Earthquake Engineering Research (Former)
Research Areas: Earthquake Engineering

Yoshitaka MURONO, Dr. Eng.
Director, Center for Railway Earthquake Engineering Research
Research Areas: Earthquake Engineering, Seismic Design, Soil-Structure Interaction

Hiroki MOTOYAMA
Laboratory Head, Structural Dynamics and Response Control Laboratory, Center for Railway Earthquake Engineering Research
Research Areas: Earthquake Engineering