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BASIC CHARACTERISTICS OF DYNAMIC INTERACTION BETWEEN A RAILWAY VIADUCT AND ADJACENT BUILDINGS ON THE BASIS OF FEM ANALYSIS AND MICROTREMOR OBSERVATION

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ABSTRACT

Dynamic interaction between a railway viaduct and adjacent buildings based on FEM analysis and microtremor measurements is investigated. Results indicate that the effective input motion to the viaduct is reduced considerably due to the presence of rigid foundations of adjacent buildings. However, when the rocking mode of the adjacent building(s) dominates, the effective input motion tend to increase. Furthermore, the influence of inertial interaction is found to be significant.

Keywords: Kinematic interaction; Inertial interaction; Railway viaduct; Adjacent buildings

1. INTRODUCTION

In large metropolitan areas, there are many cases where large buildings are built adjacent to a railway viaduct. These buildings are quite massive compared to the size and weight of a railway viaduct. In an event of an earthquake, response of such buildings can have an adverse effect on the railway viaducts; considerations for such are too serious to be ignored.

Influence of dynamic response of buildings on the adjacent structures has been studied based on the combination of thin-layer method, volume method, and finite element method (Wen and Fukuwa 2006a, Wen and Fukuwa 2006b). Field-based studies on this issue are also available (Kawamoto et al. 2008), wherein the seismic observation, forced oscillation experiment, microtremor measurement, etc. were conducted.

Though these researches focus on the dynamic soil-structure interaction between buildings and foundations of adjacent structures, influence of buildings on the adjacent civil engineering structures such as railway viaducts is missing from the literature. With foregoing discussions that the influence of adjacent buildings on a railway viaduct can be too serious to be ignored and that there is an insufficient understanding to explain the mechanism of change in the response of a railway viaduct (due to the motion of an adjacent building), the current work focuses on the dynamic interaction between a railway viaduct and building(s) in the vicinity of the viaduct.

A three-dimensional Finite Element Method (FEM) analysis was carried out on a building-soil-railway viaduct model. Results from the FEM model are further validated against the microtremor measurements. Parametric frequency response analyses were carried out in analyzing the effective input motion to the railway viaduct from the view point of both the kinematic and inertial interactions (i.e., components of soil-structure interaction effects). Microtremor measurements were recorded on a bridge (similar to a railway viaduct) and on adjacent buildings connected by the bridge.

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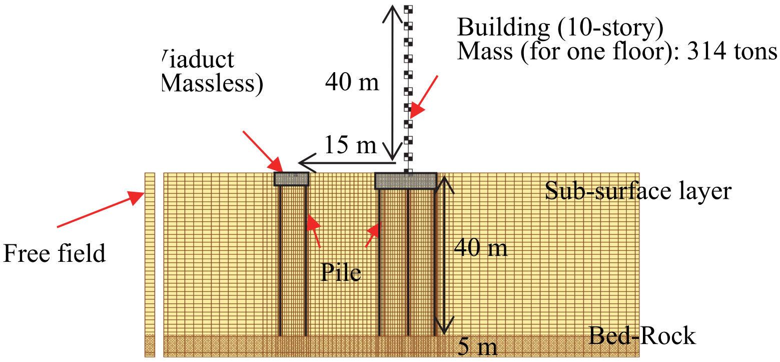


Figure. 1 Overview of the analysis model

Table 1 List of specifications for the structures

(a) Railway viaduct

	Sectional area (m^2)	Sectional secondary moment (m^4)
Column	5.90	1.49
Pile	0.785	0.049

(b) Building

	Sectional area (m^2)	Sectional secondary moment (m^4)
Column	0.020	2.37×10^5
Pile	1.77	0.249

Table 2 Analyzed cases

Case	α_m	α_k	V_s(m/s)	Memo
Case0	0	0	100	No building
Case1	0	1	100	
Case2	1	1	100	Basic case
Case3	10	1	100	
Case4	10	10	100	
Case5	10	10	50	
Case6	10	10	200	

2. OVERVIEW OF THE FEM ANALYSIS

Figure 1 shows the overview of a three-dimensional FEM model. Table 1 shows the specifications of the railway viaduct and the building employed in the model. Specifications of the building and the viaduct are based on literatures Architectural Institute of Japan (2015) and Railway Technical Research Institute (2001), respectively. Distance between footing centers of the 10-story building and the railway viaduct is 15 m. Foundations for both the building and the viaduct are pile foundations. Thickness of the single-layered sub-surface layer is 40 m with the elastic shear wave velocity (Vs) of 100 m/s. Thickness of the bed-rock layer, on the other hand, was modelled to be 5 m with the elastic shear wave velocity 400 m/s. Structures were modelled as beam elements while the soil was modelled as solid elements. Mass of the viaduct was ignored and it's over ground component was not modeled in order to evaluate the effective input motion. To be noted is that as this work focuses on understanding the fundamental behaviors, all elements were modelled to behave linearly (i.e., linear elastic model). Soil and structures are connected with rigid beam elements; possible separation of piles from the soil is ignored.

Table 2 shows the analyzed cases. Coefficients α_m and α_k show magnifications of the mass of the building and the rigidity of the over ground component of the viaduct against the set values for a basic case (Case 2). Additionally, Case 0 (where no adjacent building exists), is considered for comparison purposes. As for the analysis, frequency response analysis was carried out with respect to the base input condition; vibration frequencies were set at an interval of 0.05 Hz and the frequency response function of each position with respect to the base position was calculated. Damping for each element was considered to be 5%.

3. DYNAMIC INTERACTIONS BASED ON FEM

3.1 Influence of kinematic interaction

Fig. 2 shows the response ratios of the viaduct footing with respect to the free-field ground for Cases 0 and 1. In Case 0, where no building is present, only the input loss effect appears for the viaduct

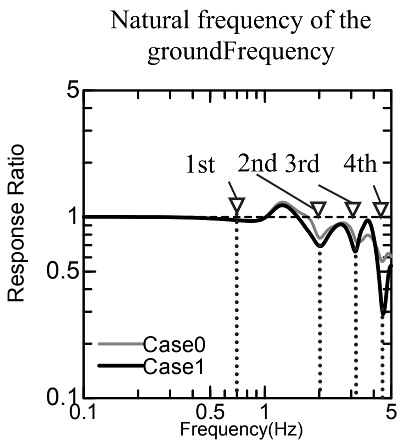


Fig. 2 Difference in effective input motion to the viaduct due to rigidity of the foundations of the building

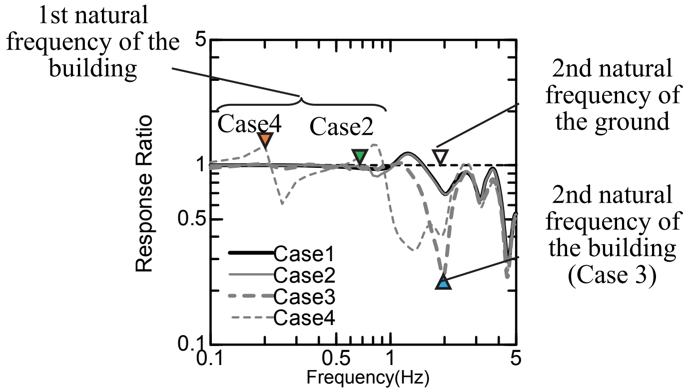
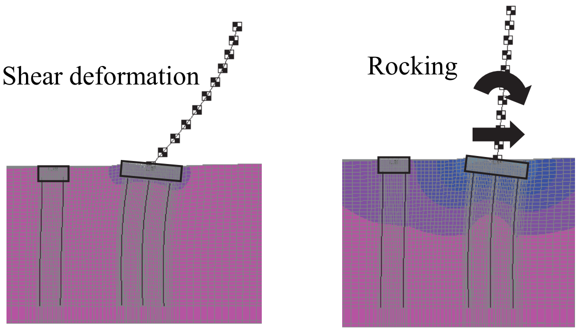


Fig. 3 Difference in effective input motion to the viaduct due to the mass of the building



(a) Case 2 (b) Case 4

Fig. 4 Shape of vibration mode of the building at the first natural frequency

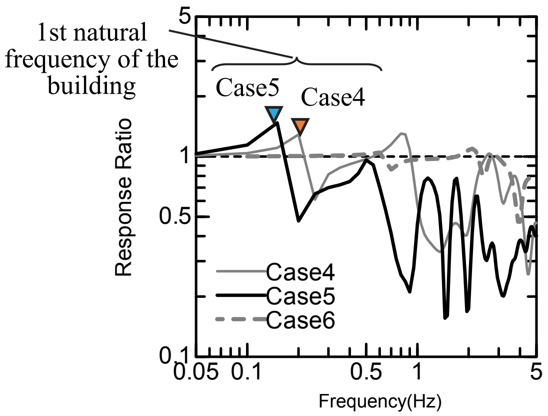
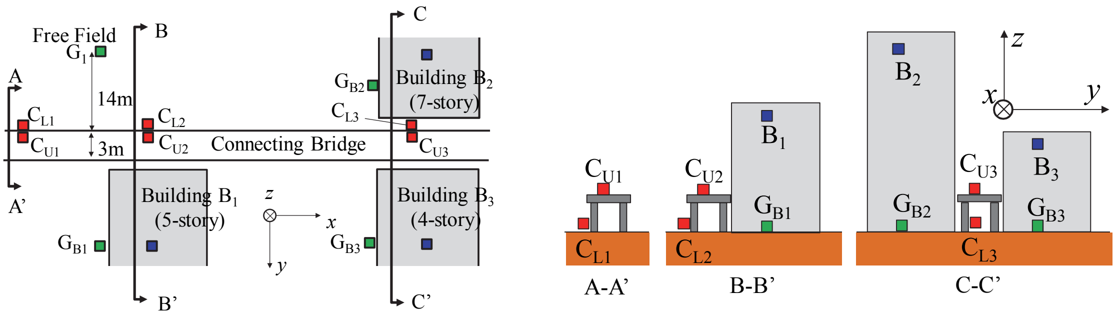


Fig. 5 Difference in effective input motion to the viaduct due to soil stiffness

foundation after the second and subsequent modes of the free field. On the other hand, Case 1, where a massless building is present, shows that in the second to fourth modes of the free field with frequencies of 2 to 5 Hz, response of the viaduct footing is significantly reduced compared to that of the Case 0. This indicates that the building's rigid foundation resulted in having some impact in restricting the soil deformation, reducing the effective input motion to the viaduct.

3.2 Influence of inertial interaction

Fig. 3 shows the response ratios of the viaduct footing with respect to the free field ground for Cases 1 through 4. In Case 2, the response ratio is almost the same as that in the Case 1 where the building is massless in every mode including the first mode (frequency of about 0.5 Hz). On the other hand, in Case 3 where only the mass of the building is significant, response of the soil (frequency of about 2 Hz) in the second mode decreased. Also, in the Case 4 where the mass and rigidity of the building are significant, response of the ground decreases in the second mode. Additionally, response of the building increases in the first mode (frequency of about 0.18 Hz). Fig. 4 shows the mode shape of the building at the first natural frequency for Cases 2 and 4. In Case 2, the shear deformation mode of the building becomes dominant (Fig. 4 (a)) that results in restricting the propagation of vibrations to the surrounding soil, thereby lowering the influence on the viaduct. In Case 4, on the other hand, the rocking mode of the building becomes dominant (Fig. 4 (b)), allowing the propagation of vibrations to the surrounding soil and thereby leading to an additional input motion to the viaduct; the response of the viaduct increases. Moreover, the decreasing trend of the response of the ground at the second mode in Cases 3 and 4, as discussed under sub-section 3.1, is attributable to the influence from the restraint effect on soil deformation due to the rigidity of the building foundations. However, in Case 3, as an



(a) Plan view (b) Sectional view of measurement

Fig. 6 Installation positions of micrometer machines

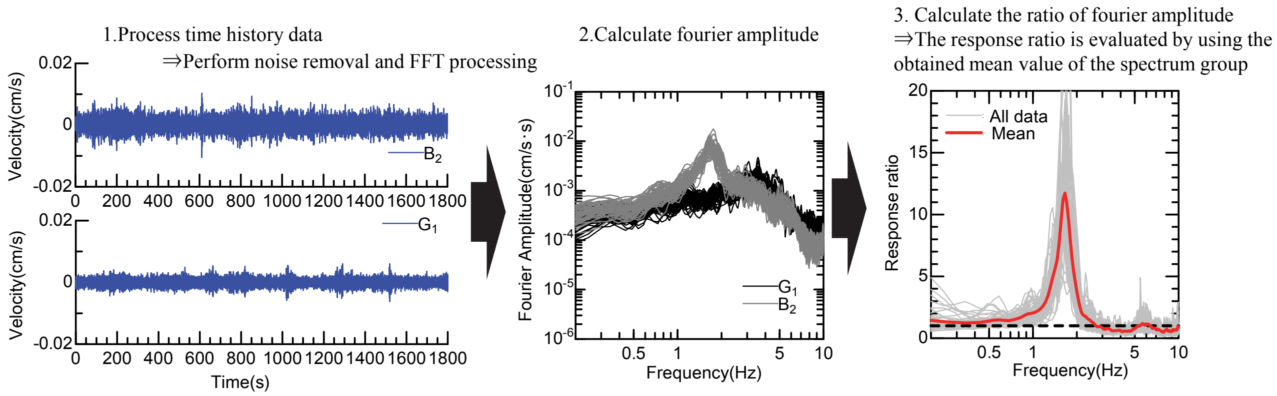


Fig.7 Orgnaization method from microtremor measurement

analogous trend develops in the building at the second mode within a similar frequency band, it is probable that the building acts as a mass damper in reducing the response against the vibration of the surrounding soil.

3.3 Influence of soil stiffness

In order to see the influence on the effective input motion to the viaduct due to the soil stiffness, Fig. 5 shows the response ratios of the viaduct footing with respect to the free field ground for Cases 4 through 6. As a result, in the softer ground condition (Vs = 50 m / s, 100 m / s), kinematic interaction and inertial interaction due to the existence of the building described in 3.1, 3.2 remarkably appears. On the other hand, it does not appear clearly in the hard ground condition (Vs = 200 m / s). From this, it can be seen that the smaller the soil stiffness is, the more likely the effective input motion to the viaduct is affected by the presence of the building.

4. OVERVIEW OF MICROTREMOR MEASUREMENT

In order to confirm the effects of dynamic interactions between the viaduct and adjacent buildings, field-based microtremor measurements were carried out on the campus of Saitama University. A bridge connecting buildings at the second floor level was used as an observation object. Installation positions of the micrometer machines are shown in Fig. 6. Three scenarios were considered to evaluate responses: (a) no any adjacent building is present (section A-A'), (b) adjacent building is present on only one side (section B-B'), and (c) adjacent buildings are present on both sides (section C-C'). Micrometers were installed at the top of the connecting bridge (C_{u1}–C_{u3}) and at the bottom end of the columns (C_{L1}–C_{L3}). Moreover, micrometers were installed on the top floors of the buildings (B_1–B_3) and on the ground (G_{B1}–G_{B3}) in the close proximity to the buildings. Additionally, micrometers were installed on the free field (G_1) at a position far enough away from each sensor.
The observation and organization method is shown in Fig. 7.Measurement was conducted for 30 minutes with a sampling frequency of 200 Hz. Time history data of the measurement was divided into data units for every 20.48 seconds (resulting 4096 units), followed by calculation of Fourier amplitude spectrum for each unit. In addition, various response ratios discussed in detail under section 5 were

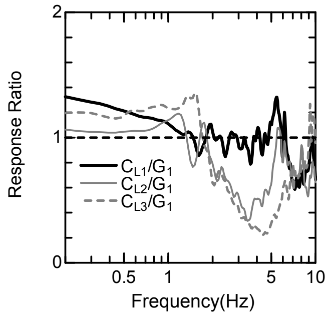


Fig. 8 Horizontal response ratio at the bottom of the connecting bridge with respect to the free field

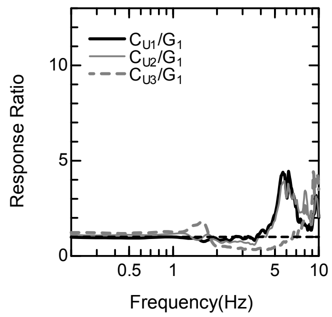


Fig. 9 Horizontal response ratio at the top of the connecting bridge with respect to the free fieldFig.

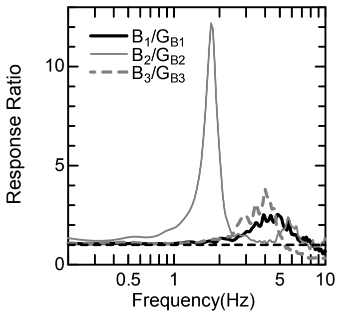


Fig. 10 Horizontal response ratio on the top floor of the building with respect to the ground close to the building

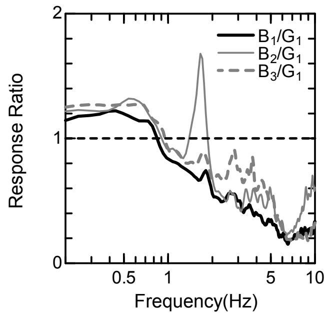


Fig. 11 Vertical response ratio on the top floor of the building with respect to the free field

evaluated by using the obtained mean value of the spectrum group.

5. DYNAMIC INTERACTIONS BASED ON MICROTREMOR OBSERVATION RESULTS

5.1 Influence of kinematic interaction

Fig. 8 shows the response ratios in the horizontal direction (*y* direction as in Fig. 6 (a)) at the bottom of the connecting bridge with respect to the free field G_1. The figure shows that the approximate value of response ratio at point C_{L1}, which has no adjacent building(s), is 1. This suggests that the input loss effect due to the connecting bridge itself is small. On the other hand, at point C_{L2} (adjacent to building B_1), the response ratio decreases to a frequency of about 2 to 5 Hz. At point C_{L3} (adjacent to buildings B_2 and B_3), the response ratio decreases to a frequency of about 2 Hz to 7 Hz. This can be attributed to the influence of the restraining effect on the soil deformation due to the presence of adjacent buildings. The response ratio of C_{L3}/G_1, on the other hand, decreases significantly than that of C_{L2}/G_1. It can be inferred that as the number of adjacent buildings increases, the influence from the restraint effect on soil deformation becomes pronounced; this seems to have an impact on the decrease in response ratio.

5.2 Influence of kinematic interaction

Fig. 9 shows response ratio in the horizontal direction (*y* direction as in Fig. 6 (a)) at the top of the connecting bridge with respect to the free field G_1. At point C_{U1}, which has no adjacent buildings, and at point C_{U2}, which is adjacent to building B_1, almost the same behavior was observed. At point C_{U2}, even though the input loss effect due to building B_1 is observed, the influence on the response of the top of the connecting bridge is limited. At both points, the predominant frequency is approximately 6 Hz and is considered to be the first natural frequency in the direction perpendicular to the bridge axis. In contrast, the figure indicates that point C_{U3}, which lies adjacent to buildings B_2 and B_3 shows a different trend. Specifically, (1) a peak is not detected with a frequency of around 6 Hz as in the case of the points C_{U1} and C_{U2}, and (2) the response ratio increases with a frequency of around 1.7 Hz. As in Fig. 8, considering that the input loss effect at point C_{L3} is particularly significant for frequency close to 4 Hz through 6 Hz, (1) is considered to be due to small input motion at the predominant frequency (6 Hz) of the connecting bridge. Although the input loss effect is confirmed at the point C_{L2}

(Fig. 8), since the response ratio is almost 1 at the predominant frequency of the connecting bridge (6 Hz), the peak of the connecting bridge is clearly identified at point C_{U2}.
Consequently, in order to analyze the trend (2), the response ratios in the horizontal direction (*y* direction as in Fig. 6 (a)) of each building (B_1 to B_3) with respect to the ground in close proximity to each building (G_{B1} to G_{B3}) are shown in Fig. 10. The figure shows the first natural frequency of the building B_2 to be about 1.7 Hz. The response ratios of each building (B_1 to B_3) in the vertical direction with respect to the free field G_1 (*z* direction as in Fig. 6 (a)) are shown in Fig. 11. It is noteworthy that frequency of about 1.7 Hz for building B_2 is also included in the vertical component. On the other hand, the component of natural frequency in the horizontal direction of the buildings B_1 and B_3 (approximately 4 to 5 Hz) is not found in the vertical component. Results suggest that the rocking mode of vibration of the building B_2 has an influence on the vibration of the connecting bridge. Such behavior is analogous to the finding based on FEM analysis for the rocking behavior of the building on the railway viaduct as detailed under section 3.

6. CONCLUSION

In the current work, relation between the difference in building specifications and the difference in the scale of the effective input motion on the railway viaduct was analyzed based on frequency response analysis in order to understand the influence of adjacent buildings on a railway viaduct. Moreover, microtremor measurements were carried out on a connecting bridge, which is similar to a railway viaduct, and the buildings connected by the bridge. Following conclusions can be inferred based on the obtained results:
1) when buildings exist, due to the rigidity of their foundations, effective input motion to the viaduct is reduced. This effect was confirmed by both the FEM analysis and the microtremor measurements; input motion to the connecting bridge was found to further reduce.
2) when the rigidity and mass of the buildings are significant (i.e., rocking mode of the buildings becomes dominant and the influence of inertial interaction becomes pronounced), the effective input motion to the viaduct increases within the natural frequency band. This effect was confirmed not only by the FEM analysis but also by the microtremor measurement. Additional vibration was provided as an input to the connecting bridge via the surrounding soil, leading to an increase in the response.
3) when the rigidity and mass of the buildings are small, but the rigidity of the soil is large (i.e., shear deformation mode of the buildings becomes dominant and the influence of inertial interaction becomes smaller), influence on the effective input motion to the viaduct is limited.
This study provided an understanding on the basic characteristics of the influence that adjacent buildings have on a railway viaduct. In the future, further efforts will be made with the aim of developing a method to evaluate the change in the response of a railway viaduct due to differences in building specifications and soil conditions.

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