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ON THE DYNAMIC INTERACTION BETWEEN GROUND AND A GROUP OF STRUCTURES SUBJECTED TO HORIZONTAL VIBRATIONS

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The mechanical behavior of a structure subjected to seismic/blast waves is usually analyzed individually, but if we consider the collective behavior of a group of structures, previously unrecognized results may be obtained. It may also be possible to evaluate the physical characteristics of incident waves inversely from the damage patterns induced to structures by the waves. In this study, through the structural damage observed in the Doge area of Wajima City on the occasion of the 2007 Noto Peninsula, Japan, earthquake, we consider the dynamic interaction between ground and a group of structures, and suggest that the structures may actually show the dynamic coupled behavior called the "town effect" or "city effect."

Key Words : *collective behavior, earthquake hazard, city effect, town effect, dynamic rock/soil-structure interaction*

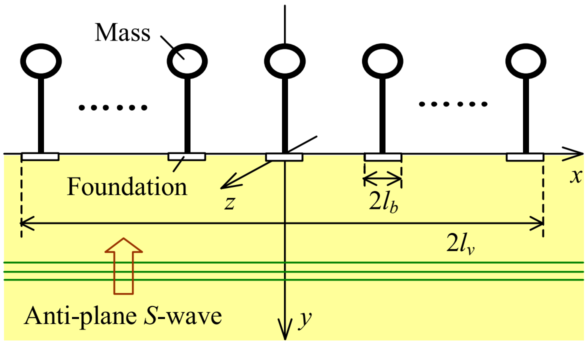
1. Introduction

A conventional seismic analysis usually considers a single structure on/in a rigid/deformable body that is subjected to dynamic vibrations. In these analyses, the dynamic coupling effect between structures themselves is not taken into account. However, if many structures are built densely in a developed area, the dynamic interaction between each structure may not become negligible. The interest in multiple interactions between the ground and structures in an urban environment appeared after the 1985 Michoacan earthquake that generated sever damage to Mexico City. The difficulties of classical computational methods in matching the seismic records have given the idea[1)] that part of the seismic energy transmitted to the buildings may be redistributed in their neighborhood through multiple interactions between structures and the ground. This phenomenon is called "site-city interaction," and recent simulations[2-4)] based on different models representing a city (or town) and various numerical techniques (Green functions, finite elements, etc.) seem to support this idea[5)].

The first purpose of this contribution is to briefly summarize the results of the recent theoretical study on the fully-coupled problem of multiple-interaction between the ground and buildings in a town[5)]. We shall see that the buildings significantly interact with each other through the ground and the resonant (eigen) frequencies of the collective system (buildings) become lower than that of a single building. This phenomenon may be called the "city effect" or "town effect." Then, secondly, by considering the actual damage patterns caused to the surface structures in the Doge area of Monzen district of the city of Wajima by the 2007 Noto Peninsula, Japan, earthquake, we shall show that the generation of severe damage in the area may better be explained by the "town effect," rather than by investigating the seismic performance of each building individually.

2. Theoretical Basis

Consider a two-dimensional anti-plane problem of a homogeneous, linear elastic half-space, representing rock mass or soil near the free surface. We suppose that N



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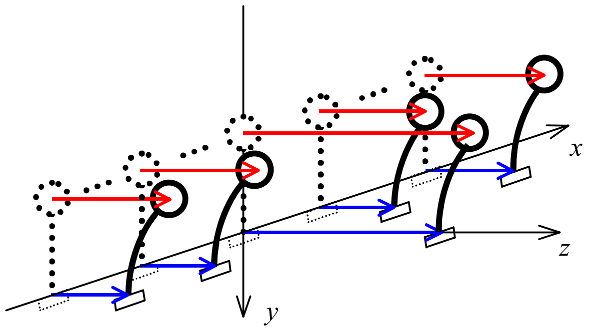


(b)

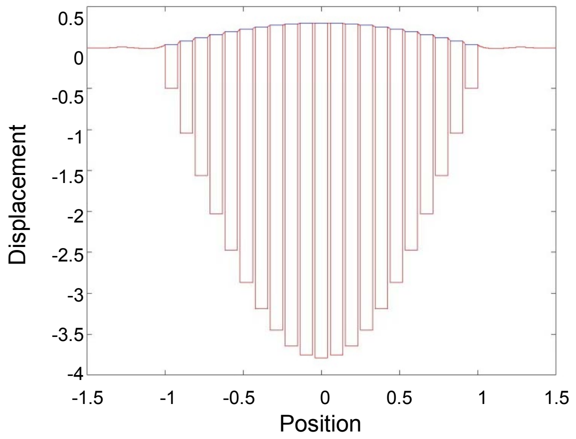
Fig.1 The "town model" employed in the analysis: (a) Buildings are uniformly distributed on a straight line (x-axis) of a linear elastic half-space. Each building is represented by a rigid foundation, a mass at the top of the building and a linear elastic spring that connects the mass and foundation; and (b) Due to dynamic interaction between waves, buildings and ground, each building may have different mechanical behavior even for a simple SH-wave incidence.

buildings are uniformly distributed in the town located on the free surface along the x-axis at $-l_v \le x \le l_v$, with $2l_b$ being the width of the rigid foundation of each building [Fig.1(a)]. We further assume that all buildings have the same mechanical characteristics, represented by the foundation (mass m_0), the mass m_1 at the top of the building and the elastic spring (elastic modulus k) connecting the two concentrated masses, the foundation and the mass. The elastic spring produces resistant force that is proportional to the elastic modulus k and the relative horizontal displacement of the top of the building m_1 with respect to the foundation m_0, with $k = 2G_b l_b/h$ and $m_1 = 2l_b h\rho_b$. Here, G_b, ρ_b and h are the shear modulus, mass density and height of the building. The system is subjected to anti-plane (SH) waves, with frequency f, impinging upon and interacting with the buildings. Due to this dynamic interaction, each building may have different movement even for this simple shear wave incidence [Fig.1(b)].

A rigorous eigenvalue analysis[5] shows collective behavior of the system, with the associated eigenfunctions drawn in Fig.2 for a town consisting of 21 buildings having the same characteristics [m_1/m_0 = 1.5, l_b/h = 0.5, l_b/l_v = 0.04, shear wave speed ratio (building)/(elastic half-space) = 1.5, ρ_b/(mass density of elastic half-space) = 0.1]. Figures 2(a), (b) and (c) correspond to the smallest (fundamental mode), second smallest (second mode) and largest (21st mode) eigenvalues, with $\xi \equiv 2\pi f\, l_b/\beta$ = 0.779288, 0.79844 and 1.1012, respectively. Here, f is eigenfrequency and β is the shear wave speed of the elastic half-space. Note that the eigenvalue of a single building is given as 1.185959, which is larger than any eigenvalue ξ associated with the collective behavior of the buildings, suggesting the existence of the "town effect." Figures 2 shows along the horizontal x-axis the displacement of the foundation in blue and that of the top of the building in red. In this harmonic analysis, displacement distributions are equivalent to those of velocities and accelerations, and if we can assume that the level of dynamic damage caused to each building is proportional to the (absolute values of) velocities or accelerations experienced, we can see that for the fundamental mode [Fig.2(a)], the building in the middle of the group (located at position x = 0) is subjected to the severest vibration while for the second mode [Fig.2(b)] the same building experiences no dynamic impact. Thus, slight change in eigenvalues (i.e., wave frequencies) can induce this totally different dynamic behavior, which may not be explained through conventional analyses. Figure 2(c) indicates that the highest mode gives rather large and complicated movement of the buildings: Consecutive buildings vibrate to the opposite directions that may cause serious damage to the whole town including the rock/soil ground.

3. The 2007 Noto Peninsula, Japan, Earthquake

Here, based on the analytical results summarized above, we shall study the generation of seismic damage patterns in the Doge area. The earthquake occurred on March 25, 2007, around 09:05 a.m. (local time) at a depth of 5 km, and the moment magnitude M_w was 6.7 (USGS). The epicenter of the quake is located offshore from the Noto



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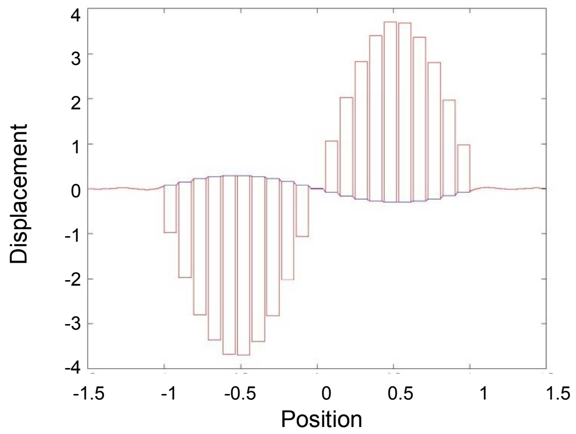

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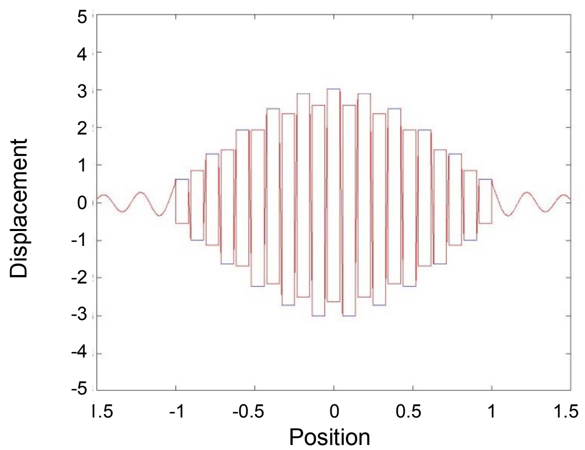
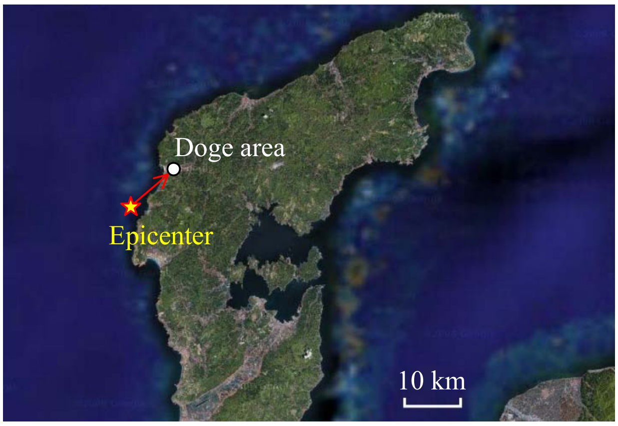


(c)

Fig.2 Vibration modes of the 21-building-system on a linear elastic half-space[5)]: (a) Fundamental mode corresponding to the smallest eigenvalue of the problem; (b) Second mode; and (c) 21st mode. The positions and displacements of the buildings are normalized, and the displacements of the foundations are drawn in blue and those of building tops are shown in red.

Peninsula in the Sea of Japan. The closest populated area, Doge of the Monzen district of the city of Wajima, is only some 10 km from the epicenter [Fig.3(a)]. There, many of the houses had traditional wood-frame structures with post, beam and mud walls, and those wood buildings showed various seismic performances[6-8)]. Figure 3(b) shows a typical distribution of damage levels of 21 buildings along the main street of the Doge area. The damage level was defined as follows: Level 4: Collapsed (shown in red); 3: tilt greater than or equal to 1/50 but not collapsed (yellow); 2: tilt between 1/200 and 1/50 (green); and 1: tilt smaller than or equal to 1/200 (blue). For graphical clarity, the same damage distribution is shown in a diagram in Fig.3(c) where we recognize that the distribution has roughly four peaks. That is, if we can again assume that the damage level is proportional to the acceleration or velocity experienced at each building, the town was collectively under the fourth vibration mode during the earthquake. The strong motion seismograph at the nearby Monzen Branch Office of Wajima City showed the peak ground acceleration (PGA) of 1303.8 cm/s^2 and the peak ground velocity (PGV) of 80 cm/s. These values, together with a simple relation $2\pi f$ = PGA/PGV, suggest that the dominant frequency f at that site may be about 2.6 Hz.

If we set the parameters, shear wave speed of the ground (elastic half-space) β = 140 m/s and the half-length of each building l_b = 7 m, then the original eigenfrequency of a single building is 3.78 Hz. This resonant frequency, typical of traditional wooden Japanese houses, may be too high compared with the estimated dominant frequency of 2.6 Hz. However, if we treat the buildings in the town collectively and use the eigenvalues shown in the previous chapter, the eigenfrequency becomes 2.48 Hz (fundamental mode), 2.54 Hz (second mode) and 3.51 Hz (highest 21st mode). Those resonant frequencies, causing serious damage to the town, are lower than the original eigenfrequency of a single building, and the dominant frequency f evaluated from seismological observations (2.6 Hz) lies in this range of frequencies, probably being responsible for the fourth mode vibrations in Fig.3(c). The roughly corresponding damage distributions for the three vibration modes (1, 2 and 21) are shown in Fig.4. We notice that slight difference in dominant wave frequency gives totally dissimilar damage patterns, especially in the middle section of the town.



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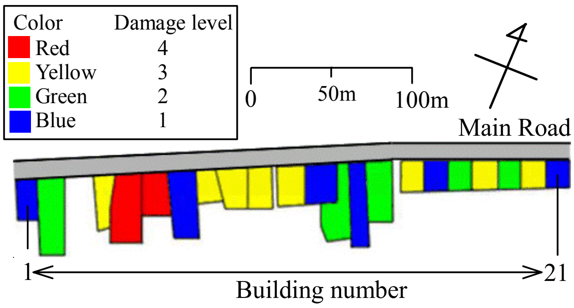

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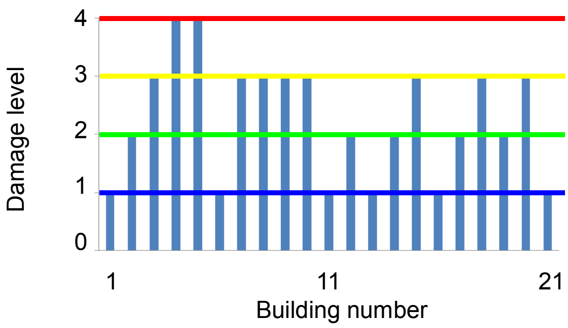
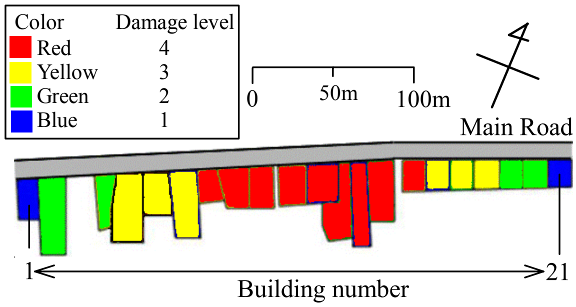


(c)

Fig.3 The 2007 Noto Peninsula, Japan, earthquake and its damage to surface structures in the Doge area of Wajima City. (a) The considered area is located only some 10 km away from the epicenter of the quake; (b) A typical distribution of damage levels of 21 buildings along the main street (modified after [6]); and (c) The diagram showing the damage level of each building. If we can assume that all 21 buildings have (more or less) same mechanical properties and the induced damage level is proportional to the acceleration or velocity experienced at each building, this kind of diagram can be directly compared with the ones showing the vibration modes of the system (Fig.2).



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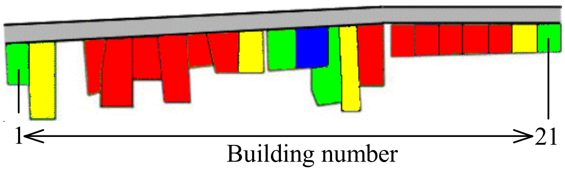

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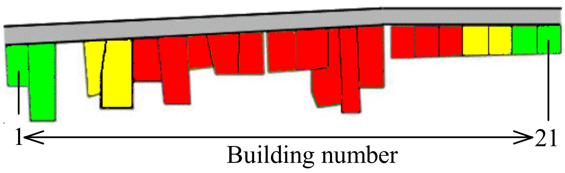

(c)

Fig.4 The distributions of damage levels of the 21 buildings in the Doge area, estimated from the vibration modes shown in Fig.2: (a) Fundamental mode (2.48 Hz); (b) Second mode (2.54 Hz); and (c) Highest 21st mode (3.51 Hz). We notice that slight difference in incident wave frequency renders totally dissimilar damage patterns of the buildings in the town.

4. Conclusions

It has been shown that the collective mechanical behavior of a group of structures subjected to horizontal waves may be different from the ones expected through conventional seismic analyses that treat each individual building separately. As an example, the structural damage patterns caused in the Doge area by the 2007 Noto Peninsula, Japan, earthquake have been studied, and it has been suggested that the structures may actually show the dynamic collective coupled behavior called the "town effect" or "city effect" that cannot be explained by conventional analyses. Although the model employed in this study is quite simplified, it still holds the basic characteristics that might play a crucial role in understanding the seismic performance of a group of surface/underground structures in urban areas.

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