HORIZONTAL IMPACT AND THE DYNAMIC BEHAVIOR OF A GROUP OF STRUCTURES

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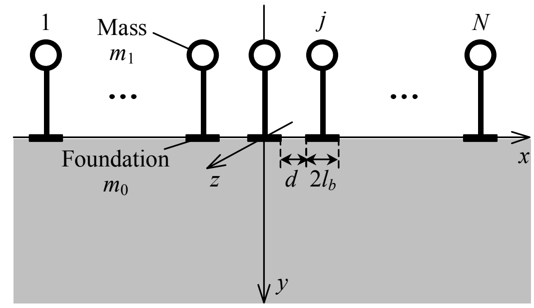
Recent study has indicated "unexpected" mechanical behavior of a group of structures subjected to dynamic loading such as seismic or blast waves and impacts: The "unexpected" behavior may be recognized if the behavior of the structural group is analyzed collectively and each structure is not handled individually. In this contribution, by treating the real examples of structural damage caused by the 1976 Friuli, Italy, earthquake and the 2001 World Trade Center disaster (horizontal aircraft impact) in New York City, we consider the dynamic interaction between a group of structures through the anti-plane waves in the ground, and based on the elastodynamic theory, we show that such structures may actually behave "unexpectedly": The phenomenon may be called the "town effect" or "city effect."

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

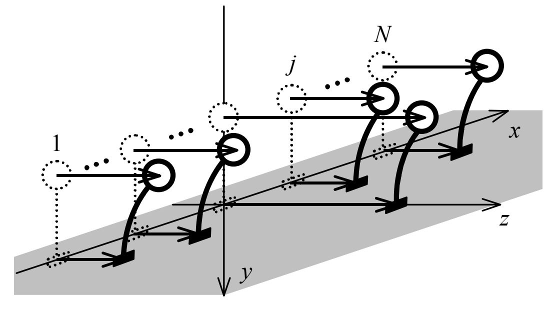
1. Introduction

As indicated by our previous study[1)], in conventional analyses in engineering seismology a structure is usually considered to consist of complex, realistic components and the vibration characteristics are analyzed in great detail but the interaction between structural vibrations and the waves in the ground (rock mass, soil) is most often ignored. It may be difficult, however, to conclude that the dynamic interaction between multiple structures and waves is practically unimportant, because structures do exist next to each other, either on or in the ground, in a developed environment, i.e., in a town or a city.

Indeed, a fully-coupled elastodynamic analysis utilizing a simplified model of a town (Fig.1)[1)-2)] clearly shows that, due to the dynamic interaction through (the waves in) the ground, the eigenfrequencies of the collective multiple-building system become lower than the resonant frequency of a single building. This shift of eigen-frequencies may be called the "town effect" (or "city effect"). In this study, we shall briefly summarize some quantitative information about this effect and also investigate (1) the generation mechanism of the alternate structural damage levels caused by the 1976 Friuli, Italy, earthquake (Fig.2) and (2) the structural collapse due to



(a)



(b)

Fig.1 The "town model" used in the analysis (modified after Ghergu and Ionescu[2)]): (a) N buildings are spatially uniformly located on the horizontal surface of a linear elastic half-space; and (b) Dynamic interaction between the buildings and anti-plane elastic waves in the ground gives each building mechanically different behavior even for a single vibration frequency of the town.

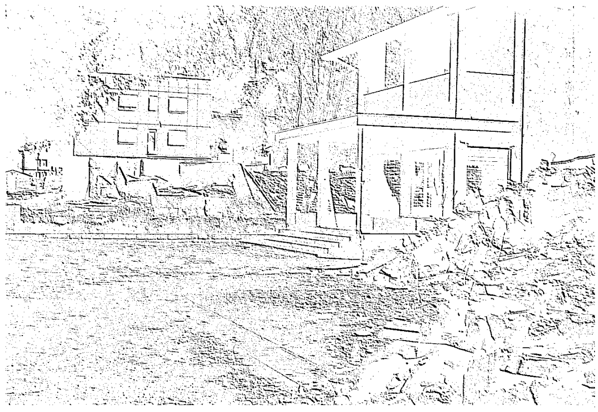


Fig.2 Structural damage in the Friuli region in Italy found just after the 1976 earthquake (This sketch is based on one of the original photographs taken by Prof. H.P. Rossmanith in Vienna).

the horizontal aircraft impact during the 2001 World Trade Center disaster in New York City. The practical importance of the "town effect" will be shown.

2. The Model

Assume, for simplicity, that N buildings are uniformly distributed in a town located along the x-axis on the surface ($y = 0$) of a two-dimensional, homogeneous, isotropic linear elastic half-space. Here, $2l_b$ is the width of the rigid foundation of each building and d is the equal separation distance ($1 \le j \le N$; Fig.1(a)). There exists only anti-plane horizontal displacement in the z-direction. Further, assume that each building has the same mechanical characteristics and consists of a foundation (no height but mass per unit length m_0), a mass m_1 (= $2\rho_b l_b h$; per unit length) at the top and the elastic spring connecting m_0 and m_1 (spring constant $2\mu_b l_b/h$), with ρ_b, μ_b and h being the mass density, shear modulus and height of the building. Due to the dynamic interaction, the displacement amplitude of every foundation (or mass at the top) may become different from each other even for a single vibration frequency of the town (Fig. 1(b)). At this moment, it may be convenient to introduce the normalized frequency ξ for the following discussion

$$\xi = 2\pi f l_b / c_S, \tag{1}$$

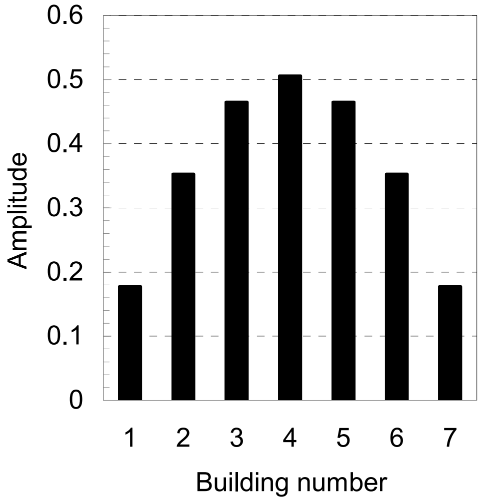
where f is the frequency of vibration and c_S is the shear wave speed of the linear elastic ground.

Figure 3 illustrates the distribution of the normalized, maximum absolute displacement amplitudes of the foundations for the k-th vibration mode of a town with seven buildings having the identical mechanical characteristics ($N = 7$, $1 \le k \le 4$). In (semi-)analytically generating this figure (and also Fig. 4 below), it is assumed that $d/l_b = 0.4$, $h/l_b = 2$, $m_1/m_0 = 1.5$, $\rho_b/\rho = 0.1$ and $(c_S)_b/c_S = 1.5$, as suggested for European towns[1)-2)], where ρ and $(c_S)_b$ are the mass density of the ground and the shear wave speed in the buildings, respectively. Figure 3(a) pertains to the first vibration mode ($k = 1$) where the building in the middle of the town, number 4, may be subjected to the severest vibration and therefore more damage may be expected to this building than to the others. This distribution is very similar to that for the highest seventh mode ($k = 7$), but the vibration is more "out-of-phase" for $k = 7$. In the second mode ($k = 2$, Fig.3(b)) the same building 4 in the middle experiences no dynamic impact, and like in the sixth mode ($k = 6$), specific buildings (2 and 6) are subjected to stronger vibrations. The third mode ($k = 3$, Fig.3(c)) shows again the displacement of the building 4 is the largest one and also in the similar fifth mode ($k = 5$) every third building may have a larger displacement. Figure 3(d) indicates that every second building (1, 3, 5 and 7) is under much stronger vibration in the fourth mode ($k = 4$).

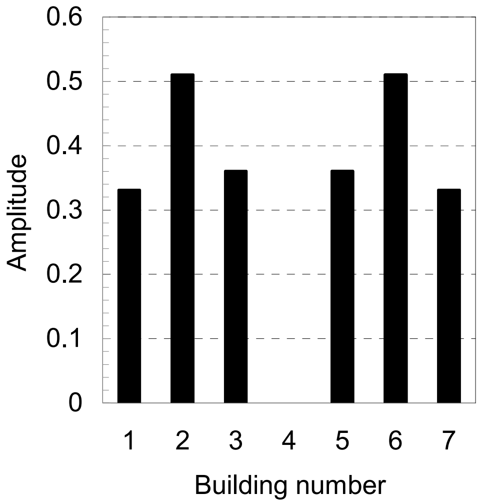
In Fig.4, the normalized eigenfrequencies of all vibration modes are shown for the identical town ($N = 7$). As seen in this figure, the eigenfrequency ξ_k of each vibration mode [$1 \le k \le N$ (= 7)] is smaller than that of a single building with the same foundation ξ_0 (= 1.186; for a single mass m_1-spring-foundation m_0 system) but larger than ξ_∞ [= 0.75; for a single (or an N-) mass m_1-spring system on a rigid half-space]. Thus, Fig.4, together with Fig.3, clearly demonstrates the theoretical existence of the "town effect" and indicates that slight change in vibration frequencies can induce totally different dynamic behavior of the town, which may not be systematically, or in a unified way, explained through conventional analyses handling each individual building separately.

3. The 1976 Friuli, Italy, Earthquake

One of the historically largest earthquakes in Italy has struck the Friuli region in 1976, and a surprisingly "regular" (periodic) damage distribution was found in the epicentral area (Fig.2) where each adjacent building has experienced completely different mechanical behavior: One building totally collapsed while the next one was almost undamaged, and this alternate "collapsed-



(a)



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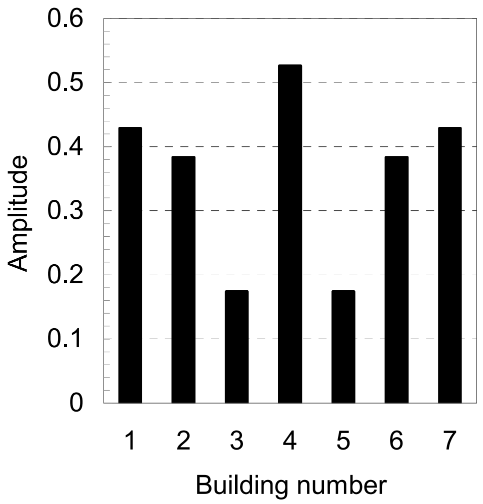

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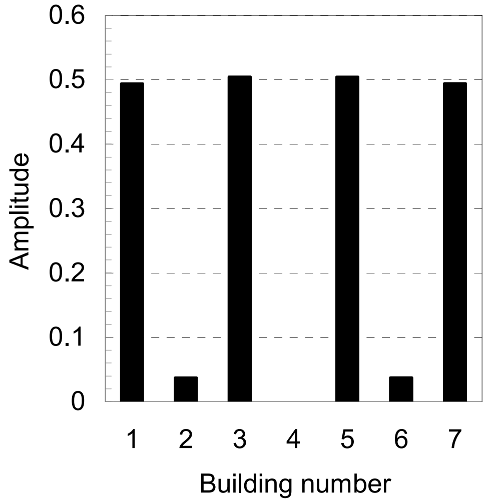

(d)

Fig.3 Vibration modes of the 7-building-system on a linear elastic half-space: (a) Fundamental; (b) Second; (c) Third; and (d) Fourth mode [$d/l_b = 0.4$, $h/l_b = 2$, $m_1/m_0 = 1.5$, $\rho_b/\rho = 0.1$ and $(c_S)_b/c_S = 1.5$].

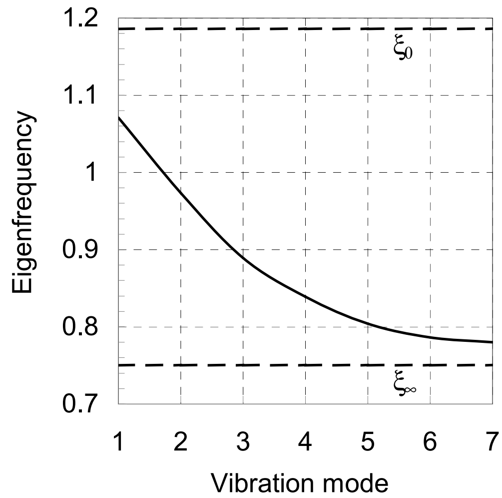

Fig.4 Normalized eigenfrequncy ξ_k ($\equiv 2\pi f_k\ l_b/c_S$) associated with the vibration mode k [$1 \le k \le N$ (= 7)] of a town that consists of seven identical buildings [$d/l_b = 0.4$, $h/l_b = 2$, $m_1/m_0 = 1.5$, $\rho_b/\rho = 0.1$ and $(c_S)_b/c_S = 1.5$].

undamaged" pattern was repeated further. It might be easier to explain that the "dissimilar but regular" damage distribution is attributed to, say, the strength or construction year of each building. However, if the buildings with short separation distances are subjected to almost the same (frequency components of) seismic waves under very similar geological situations, the structural damage may be, to some extent, also comparable. Figure 2 suggests, even when we accept the importance of the causes like the fragility of each individual structural component, it is not simple to explain, systematically and comprehensively from these "plausible" causes, the generation of the clearly alternate damage levels in such a short distance. Here, based on the analytical model and results summarized above, we try to briefly explain the generation mechanism of this seismic damage pattern[1].

The main shock (Richter magnitude M_L = 6.5) occurred on 6 May 1976, with the epicenter located about 25 km north of the city of Udine and the focal depth being some 10 km. The main shock was preceded by an M_L = 4.5 foreshock, and followed by a large number of aftershocks, with the largest ones on 15 September 1976 (M_L = 6.1 and 5.8)[3)-4)]. The spectral response estimated from the main shock and aftershocks of this Friuli 1976-1977 earthquake sequence for the TLM1 (Tolmezzo-Ambiesta dam) accelerograph site at the top of a calcareous hill shows the dominant (peak) frequencies f_d of observed seismic waves near the epicenter to be about 2, 3.8, and 6-8 Hz[5)]. Figure 2 suggests, if we can assume the number of buildings in the affected "town" was seven and, again, if all buildings there had (approximately) the same mechanical properties and the damage level is proportional to the maximum acceleration (equivalent to velocity or displacement in this harmonic analysis) of each building, the town might have been collectively under the fourth vibration mode during the earthquake (compare Fig.2 with 3(d): Every second building may totally collapse under much stronger vibrations). If the observed values, the shear wave speed of the ground c_S = 225 m/s[5)] and the length of each building $2l_b$ = 16 m (height h = 8 m), as well as the same geometrical and mechanical properties as in the last chapter, are employed, then, based on the analytical results, the original eigenfrequency of a single building with a rigid foundation may be evaluated approximately as $f_0 = \xi_0 c_S/(2\pi l_b)$ = 5.3 Hz. This resonant frequency, in the typical natural frequency range of short reinforced concrete buildings, may be too high compared with the seismologically estimated dominant frequencies f_d = 2 and 3.8 Hz (and lower than the other f_d = 6-8 Hz), and it does not seem straightforward to explain the generation of damage pattern in Fig.2 using this "conventional" resonant frequency for a single building. However, if the buildings in the town are treated collectively and the normalized eigenfrequencies ξ_k associate with the "town effect" are used, the dimensional eigenfrequencies $f_k = \xi_k c_S/(2\pi l_b)$ become approximately 4.8 Hz (first mode, k = 1), 3.8 Hz (fourth mode, k = 4), or 3.5 Hz (seventh mode, k = 7), respectively. One of the dominant frequencies f_d evaluated from the observations (3.8 Hz) lies in this range of "collective" eigenfrequencies f_k, and it is well comparable to that of the fourth vibration mode f_4, as expected from Figs. 2 and 3(d). The other dominant frequencies (2 and 6-8 Hz) are either too low or too high for the resonance of the town or a single building. As stated earlier, slight difference in dominant wave frequency component gives totally dissimilar damage patterns, especially in the middle section of the town, and there are still many unknown or unconsidered factors in the model, but the present study may have shown one possible real example of the "town effect."

4. The 2001 World Trade Center Disaster in New York City

On September 11, 2001, each of two commercial airliners was flown into one of the two 110-story towers of the World Trade Center (WTC) Complex in New York City. The structural damage caused to each tower by the horizontal impact, combined with the ensuing fires, resulted in the total collapse of each building. As the towers collapsed, massive debris clouds consisting of crushed and broken building components fell onto and blew into surrounding structures, causing extensive collateral damage. In total, 10 major buildings experienced partial or total collapse and approximately 30 million square feet (2.8 km^2) of commercial office space was removed from the service, of which 12 million (1.1 km^2) belonged to the WTC Complex[6)]. Numerous seismic signals from two plane impacts and building collapses from the two WTC towers were recorded, and collapses of the twin towers generated large seismic waves, observed up to 428 km away. The North Tower collapse was the largest seismic source and had local magnitude M_L = 2.3[7)]. Thus, the idea that structural vibrations do radiate waves into the ground may be supported, and it is worthwhile to try to consider this disaster, especially the collapse of the twin towers by aircraft impact, with possible dynamic multiple-structure-wave interaction taken into account.

If the two high-rise buildings are regarded as a "town" and our model is applied to the problem with the parameters d/l_b = 4/3, h/l_b = 14, m_1/m_0 = 1.5, ρ_b/ρ = 0.1 and $(c_S)_b/c_S$ = 1.5, then the normalized eigenfrequencies for the first (k = 1) and second (k = 2) vibration modes of the collective behavior of the towers are (semi-) analytically found to be $\xi_k \equiv 2\pi f_k\, l_b/c_S$ = 0.111 and 0.108, respectively (Fig.5). In this two-building-system, the distribution of the maximum absolute displacement amplitudes of the foundations is the same for both first and second vibration modes, and in Fig.5, again, the "town effect" may be observed: The eigenfrequency ξ_k of each vibration mode is smaller than that of a single building with the same foundation ξ_0 (= 0.169), and in this case ξ_k is rather close to ξ_∞ (= 0.107) obtained for an m_1-spring system on a rigid plane; The resonant frequency of the twin towers is only about 65 % of that for a single tower which stands "independently" or does not dynamically interact with another building. The twin towers may have "unexpectedly" collapsed due to this coupling effect.

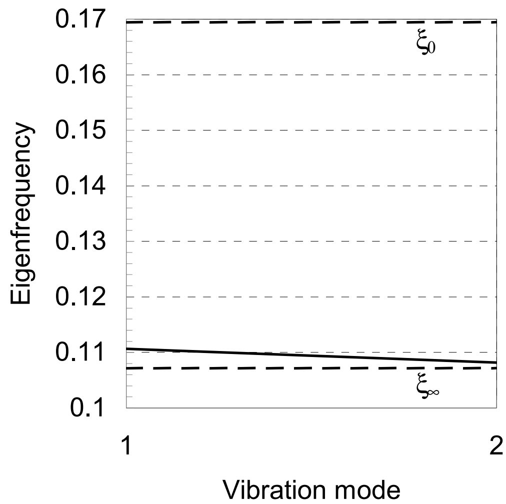

Fig.5 Normalized eigenfrequncy ξ_k related to the k-th vibration mode [$1 \le k \le N$ (= 2)] of the two-(high-rise-)building-system [d/l_b = 4/3, h/l_b = 14, m_1/m_0 = 1.5, ρ_b/ρ = 0.1 and $(c_S)_b/c_S$ = 1.5].

5. Conclusions

It has been shown that the collective mechanical behavior of a group of structures subjected to anti-plane horizontal vibrations may be different from the ones expected through conventional seismic analyses. Two example cases has been investigated: the generation mechanism of the unique structural damage distribution in the Friuli region observed in 1976; and the vibration of the twin-tower-system found in the World Trade Center Complex in the city of New York. It has been indicated that the structures may in fact have shown the dynamic collective behavior called the "town effect." The analytical model employed in this investigation is certainly simple, but even so, it may possess the essential nature that will play an important part in comprehending the dynamic performance of a group of structures in developed regions around the world.

Acknowledgments: This study has been financially supported by the Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT) through the "KAKENHI: Grant-in-Aid for Young Scientists (A)" program (No. 22686044).

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