CHARACTERISTIC OF THE VERTICAL SEISMIC WAVES ASSOCIATED WITH THE 1995 HYOGO-KEN NANBU (KOBE), JAPAN EARTHQUAKE ESTIMATED FROM THE FAILURE OF THE DAIKAI UNDERGROUND STATION

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SUMMARY

The dynamic behavior of underground structures built by cut-and-cover methods is discussed. A simple model analysis shows that a column supporting the overburden at midspan (central column) can resonate upon incidence of an elastic wave of a specific frequency. The analytical results indicate that not only the size and material properties of the column, but also the static load acting on the column (overburden) is a decisive factor that influences the resonant frequency. Based on the results obtained by the analysis, the mechanism of the failure at the Daikai Underground Station in Kobe caused by the 1995 Hyogo-ken Nanbu, Japan, Earthquake is investigated. It is shown that the wave-induced damage to underground structures can concentrate on the sections with specific overburden, and from the induced damage, it is possible to estimate the frequency characteristics of the associated seismic waves.

KEY WORDS: Dynamic failure; central column; resonance of structures; Hyogo-Ken Nanbu Earthquake; Daikai Station; characteristics of seismic waves

1. INTRODUCTION

Earthquakes rarely induce failure of underground structures such as mines and tunnels. However, severe damage to this type of structures, although small in number, was caused in Kobe, Japan by the disastrous 1995 Hyogo-ken Nanbu (Kobe) Earthquake[1-11]. The earthquake occurred on 17 January 1995 at 5:46 a.m. local time and struck the densely populated, industrially developed region of Kobe and Osaka (Hanshin region) in west-central Japan. The moment magnitude was 6.9 and strong ground motion lasted for some 20 seconds and caused considerable damage within a radius of 100km from the epicenter[1].

The worst damage to the large-scale underground facilities was the collapse of the Daikai Underground Station in Kobe (Figure 1). The underground railway (Kobe Rapid Transit Railway), built by cut-and-cover methods, opened in 1968[1-4]. A two-track line runs under the central part of Kobe that is located about 20km from the epicenter of the earthquake. At the Daikai Station, the reinforced concrete columns supporting the roof at midspan (central columns) failed catastrophically, and the roof slab dropped almost onto the tracks [Figure 1(a), (c)]. The collapse of over 20 central columns [Figure 1, 2(a)] induced subsidence of maximum 2.5m of the street above, with substantial settlement over an area of 100m by 20m [Figure 2(b)][1-7]. Aside from this collapse-induced movement, no distinct evidence of permanent ground deformation by other causes such as liquefaction was found at the site[4]. This failure is the first case of severe earthquake-induced damage to a modern underground facility due to the reasons other than fault displacement or instability near the portal[4].

It is interesting to note that the damage was concentrated onto the central columns at the specific sections (②-②, ③-③ and ④-④ in Figure 1). The columns between the stations (e.g. at the section ①-①) were hardly damaged[2]. In the city of Kobe, only little damage was found in the underground facilities with small overburden, e.g. at the section ⑤-⑤ of the Daikai Station [Figure 1(f)] and in the Sannomiya underground shopping center[2]. Hence, the overburden, i.e. the static load acting on the columns, might have an influence on the failure of the columns.

As the possible reasons of the collapse of the columns at the Daikai Station, several models have been proposed: failure in shear and/or bending due to the horizontal vibrations; and buckling due to the vertical impact[1-11]. However, it is difficult to explain the damage generation using the shear/bending model: Large shearing deformation of structures such as observed on the surface is not expected in the underground where the structural movement is restricted by the surrounding media[2]. Moreover, the columns at the Daikai Station were designed not to induce bending moments at their ends, and in Kobe, considerable vertical oscillations were experienced and failures of structures that can be explained more easily with a vertical oscillation model have been reported[8,9]. Therefore, the failure was possibly induced by vertical oscillations[2,8,9].

In this study, a simple model is employed to investigate the mechanism of damage concentration onto the columns at the specific sections. Especially, the effect of the vertical oscillations and the overburden is addressed, but this does not necessarily mean that the horizontal vibrations had no effect at the Daikai Station.

2. MODEL ANALYSIS

Consider a column of a cross-sectional area A, height h, mass density ρ and elastic modulus E that always supports the overburden M (Figure 3). Assume that the bottom of the column (x=0) is subjected to a harmonic (displacement) disturbance $u = u_0 e^{2\pi i c_b t/\lambda}$. Here, t is time and u_0, λ are the displacement amplitude and the wavelength of the incident wave, respectively. In this contribution, the behavior of the whole system, not the movement of a local part, is discussed as the first-order analysis of the problem.

The velocity of the elastic wave propagating in the column c_b is given by:

$$c_b = \sqrt{E/\rho}\,, \tag{1}$$

and the equation of motion is expressed as:

$$\partial^2 u/\partial t^2 = c_b^2\, \partial^2 u/\partial x^2. \tag{2}$$

The solution that satisfies Equation (2) is generally written as:

$$u = ae^{2\pi i(c_b t + x)/\lambda} + be^{2\pi i(c_b t - x)/\lambda}, \tag{3}$$

where a and b are constants that are determined from the boundary conditions:

$$u = u_0 e^{2\pi i c_b t/\lambda} \qquad \text{at } x = 0; \text{ and}$$

$$M\,\partial^2 u/\partial t^2 + \sigma A = 0 \qquad \text{at } x = h. \tag{4}$$

Here, stresses are positive if they are tensile. Using the relation between the stress σ and the strain $\partial u/\partial x$:

$$\sigma = E\,\partial u/\partial x, \tag{5}$$

one can rewrite the boundary conditions (4) as:

$$u = u_0 e^{2\pi i c_b t/\lambda} \qquad \text{at } x = 0; \text{ and}$$

$$M\,\partial^2 u/\partial t^2 + AE\,\partial u/\partial x = 0 \qquad \text{at } x = h. \tag{6}$$

Substituting Equation (3) into (6) and considering that the boundary conditions hold for arbitrary time t, one obtains the following simultaneous equations:

$$\begin{bmatrix} 1 & 1 \\ (-M\omega^2 + 2\pi i AE/\lambda)e^{2\pi i h/\lambda} & -(M\omega^2 + 2\pi i AE/\lambda)e^{-2\pi i h/\lambda} \end{bmatrix} \cdot \begin{Bmatrix} a \\ b \end{Bmatrix} = \begin{Bmatrix} u_0 \\ 0 \end{Bmatrix}. \tag{7}$$

Here ω (= $2\pi c_b/\lambda$) is the angular frequency of the harmonic wave. The constants a and b can be determined by solving the simultaneous equations (7):

$$\begin{Bmatrix} a \\ b \end{Bmatrix} = \frac{u_0}{\Delta} \begin{Bmatrix} (M\omega^2 + 2\pi i AE/\lambda)e^{-2\pi i h/\lambda} \\ (-M\omega^2 + 2\pi i AE/\lambda)e^{2\pi i h/\lambda} \end{Bmatrix}, \tag{8}$$

where

$$\Delta = \left(\frac{4\pi AE}{\lambda} \cos\frac{2\pi h}{\lambda} - 2M\omega^2 \sin\frac{2\pi h}{\lambda} \right) i. \tag{9}$$

From Equations (3), (5) and (8), the displacement and stress fields are obtained:

$$u = \frac{u_0}{\Delta} \left\{ (M\omega^2 + 2\pi i AE/\lambda)e^{2\pi i(c_b t + x - h)/\lambda} - (M\omega^2 - 2\pi i AE/\lambda)e^{2\pi i(c_b t - x + h)/\lambda} \right\}, \tag{10}$$

$$\sigma = \frac{2\pi i E u_0}{\Delta\lambda} \left\{ (M\omega^2 + 2\pi i AE/\lambda)e^{2\pi i(c_b t + x - h)/\lambda} + (M\omega^2 - 2\pi i AE/\lambda)e^{2\pi i(c_b t - x + h)/\lambda} \right\}. \tag{11}$$

Stresses and displacement at the bottom (x = 0) and top (x = h) of the column are given as follows:

- *Stress at the bottom (x = 0) of the column*

$$\sigma = \frac{2\pi i E u_0}{\Delta\lambda}\left\{(M\omega^2 + 2\pi i AE/\lambda)e^{2\pi i(c_b t - h)/\lambda} + (M\omega^2 - 2\pi i AE/\lambda)e^{2\pi i(c_b t + h)/\lambda}\right\}, \tag{12}$$

- *Stress and displacement at the top (x = h) of the column*

$$u = \frac{4\pi i AE u_0}{\Delta\lambda} e^{2\pi i c_b t/\lambda}, \tag{13}$$

$$\sigma = \frac{4\pi i EM\omega^2 u_0}{\Delta\lambda} e^{2\pi i c_b t/\lambda}. \tag{14}$$

In the case the determinant of the matrix in Equation (7) is zero (i.e. $\Delta = 0$), or:

$$2\pi M \sin\frac{2\pi h}{\lambda} - A\rho\lambda\cos\frac{2\pi h}{\lambda} = 0, \tag{15}$$

no solution can be obtained. Physically, Equation (15) is the condition for the resonance of the column and indicates that the parameters related to the resonance of the column are: the overburden M; cross-sectional area A; height h; mass density ρ of the column; and the incident wavelength λ. In the following text, the condition (15) will be applied to explain the damage distribution at the Daikai Underground Station and estimate the frequency characteristics of the seismic waves associated with the 1995 Hyogo-ken Nanbu (Kobe) Earthquake. It will be shown that an underground structure can function as a sensor that detects a certain frequency component of seismic waves.

3. RESULTS AND DISCUSSION

The relation between the normalized resonant wavelength λ/h (the ratio of the wavelength to the column height) and the normalized overburden $M/(Ah\rho)$ (the ratio of the overburden to the column mass) can be obtained from Equation (15). The relation is shown in Figure 4 for the range $0.5 \le \lambda/h \le 20$. Figure 4 suggests that the waves satisfying the condition $2 < \lambda/h < 4$ never induce resonance of a column. In reality, the wavelength of a seismic wave is much larger than the height of a structure ($\lambda/h >> 1$). Therefore, actual seismic waves will not satisfy this condition ($2 < \lambda/h < 4$) and will be able to induce resonance of a column.

Referring to the real dimensions of the Daikai Station, the relation between the resonant frequency of the incident wave and the load M acting on the column is calculated. The results are shown in Figure 5. In the calculations, the following material properties are used.

Cross-sectional area A:	$0.4\times1.0\text{m}^2$ (at the station)
	$0.4\times0.6\text{m}^2$ (between the stations)
Height of the column h:	5.5m
Mass density ρ:	2200kg/m^3
Wave velocity c_b:	4100m/s

From Figure 5, the dominant frequency of the seismic waves that impinged upon the Daikai Station can be estimated: Assuming that the density of the surrounding medium is 1800kg/m^3, the interval of the columns is either 3.5m (at the Daikai Station) or 2.5m (between the stations) and regarding the tunnel as a frame structure, one can calculate the load M acting on the column at each section of the box structure (sections ①-① to ⑤-⑤ in Figure 1). The load at each section in Figure 1 is listed in Table 1. Figure 5, together with Table 1, indicates that in the case the dominant frequency of the incident wave is about 17Hz, the overburden M that induces resonance is some 235ton (at the Daikai Station) or 140ton (between the stations) and only the columns at the sections ②-②, ③-③ and ④-④ [Figure 1(c)-(e)] resonate (or vibrate strongly) and can fail. In this case the columns at the sections ①-① and ⑤-⑤ [Figure 1(b), (f)] do not resonate. As the epicenter of the Hyogo-ken Nanbu Earthquake is located very close to the Daikai Station, it is possible that these high frequency seismic waves interacted with the station before attenuation. This example shows that underground structures can detect waves of a specific frequency, and the wave-induced damage to underground structures can concentrate on the sections with specific overburden.

4. CONCLUSIONS

By analyzing a model of elastic wave propagation, we have shown that a wave of a specific frequency can induce resonance of a column supporting the overburden at midspan. It has been indicated that the overburden plays an important role in the resonance of the column. From the damage of the Daikai Underground Station in Kobe caused by the 1995 Hyogo-ken Nanbu earthquake, the dominant frequency of the seismic waves that impinged upon the station has been estimated. It is possible that high frequency seismic waves struck the Daikai Station before attenuation, because the epicenter is located only some 20km from the station.

The model employed in the analysis can be applied to investigate the dynamic behavior and stability of the columns used for surface facilities. It is known that the wave-induced failure of the columns and piers supporting elevated expressways and railroads is similar to that of underground columns. Further study including the analysis of the dynamic failure of such elevated structures is needed. For a more precise analysis, the impact and transient response of columns should be also taken into account.

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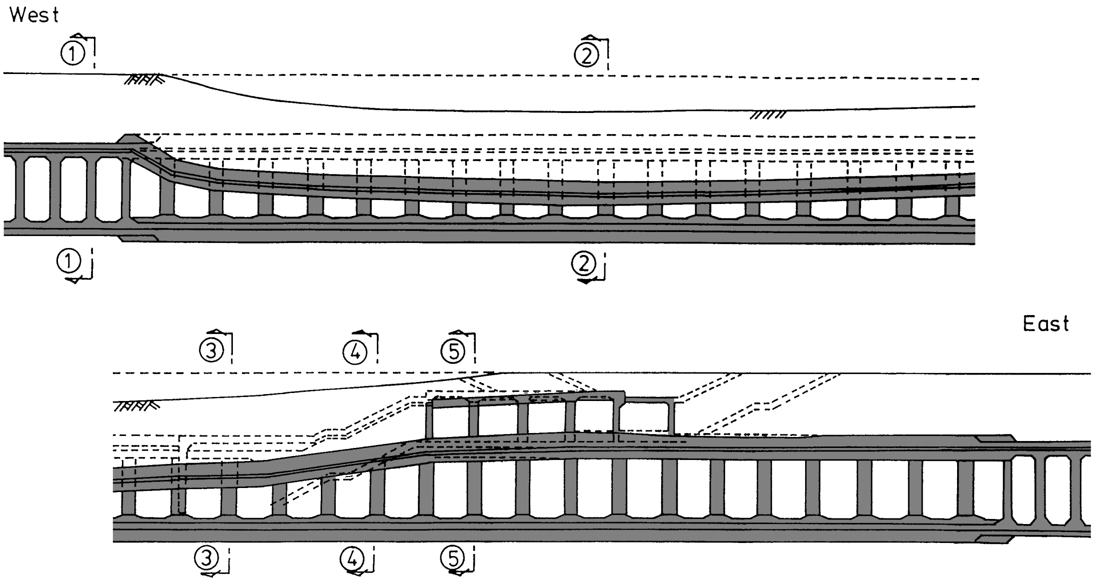
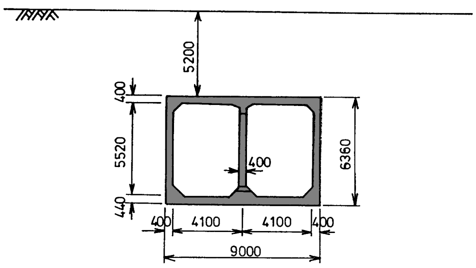
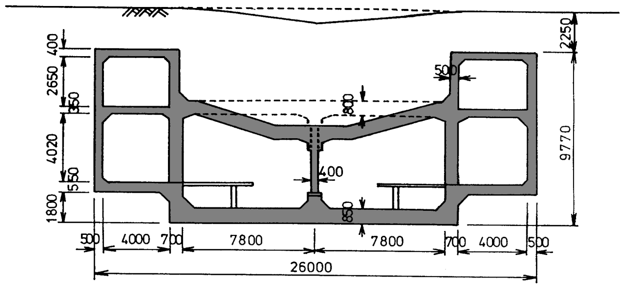


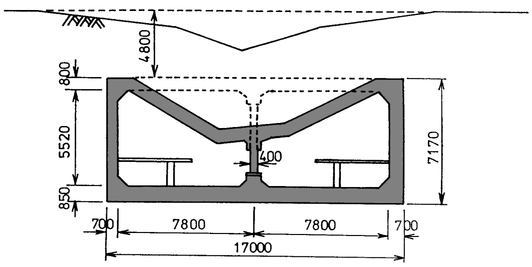
(a) Longitudinal section



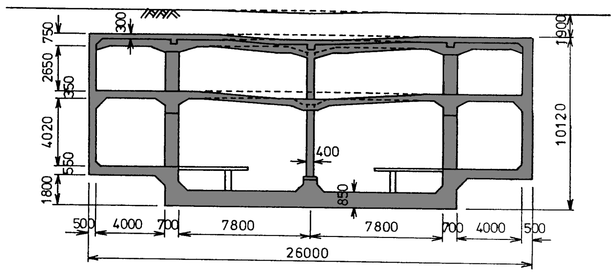
(b) Section ①-①



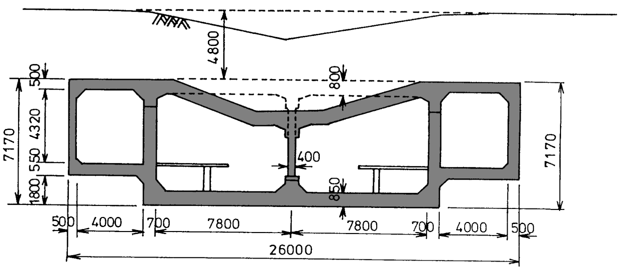
(e) Section ④-④



(c) Section ②-②



(f) Section ⑤-⑤



(d) Section ③-③

Figure 1. (a) Longitudinal and (b)-(f) cross sections of the Daikai Underground Station after the 1995 Hyogo-ken Nanbu Earthquake (all units in mm) (modified from the figures in [2]).

(a) 

(b) 

Figure 2. Dynamic failure of the Daikai Underground Station, Kobe. (a) Failure of columns supporting the roof at midspan (central columns) resulted in the collapse of the roof [Near the cross-section ④-④ in Figure 1(e)]; and (b) substantial settlement of the roadway caused by the collapse of the Daikai Station underneath.

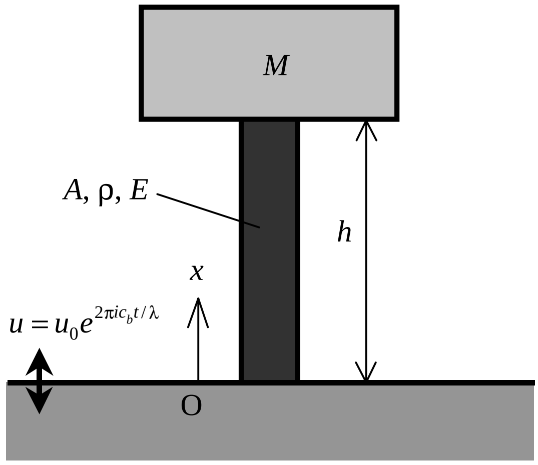


Figure 3. A column with overburden *M* subjected to vertical oscillations.

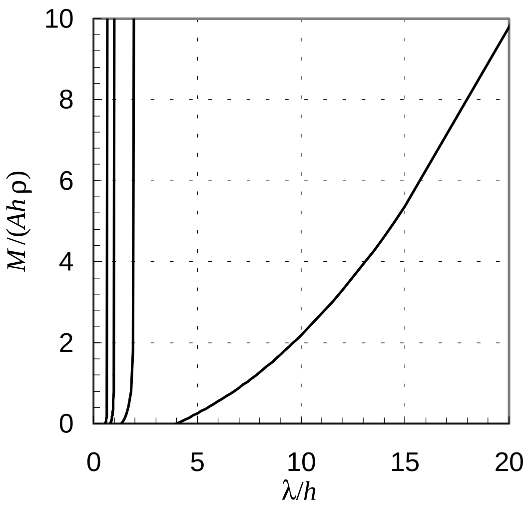


Figure 4. The relation between the normalized resonant wavelength (λ/h) and the normalized overburden ($M/Ah\rho$).

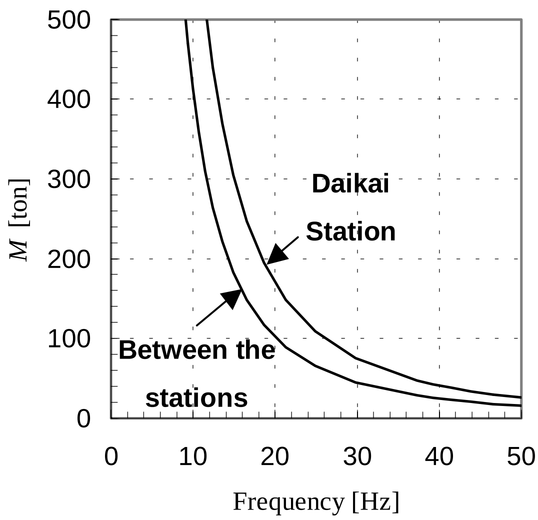


Figure 5. The relation between the resonant frequency of the incident wave and the overburden M in and near the Daikai Station.

Table 1. The overburden supported by the central column at each section in Figure 1.

Cross-section	Overburden M [ton]
①-①	90
②-②	225
③-③, ④-④	240
⑤-⑤	95