STUDY ON FILTERING EFFECT OF FOUNDATION SLAB
BASED ON OBSERVATIONAL RECORDS

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ABSTRACT

Recent studies on earthquake records have shown that the earthquake response of a large rigid foundation has less intensity than that of the adjacent free field. This phenomenon is called "filtering effect" of foundation slab and is considered to arise from restriction of wave motion by the rigid foundation and from disturbance of wave propagation, especially in high-frequency components. The present study tries to provide an explanation of the filtering effect of a foundation slab using the observed earthquake records of the Hollywood Storage Building Basement and the adjacent P.E. Lot during the San Fernando Earthquake in 1971. The effective input motions to the building foundation were computed from the free field motions by passing through the numerical lowpass filter representing filtering effect of foundation slab. The structural model in which both the filtering effect and soil-structure interaction effect were taken into consideration was represented and the dynamic response of this model to the effective input motion was calculated. It was found that the response of this model gives a similar tendency to observed record.

INTRODUCTION

In seismic analyses of structures, earthquake motions which are imagined at some ground surface or underground are applied as input motions to structural models as shown in Fig. 1-a. This is founded on the assumption that a seismic wave arrives at a structure with the same amplitude and phase over the entire foundation area. However, when accelerograms obtained at two observation points located twenty or thirty meters apart are examined in detail, a difference in amplitude and phase delay are recognized in high-frequency components. It is expected that input motion effective for structural response is partially offset by the phenomenon of phase delay restricted by the rigid foundation (Fig. 1-b).

In 1970, one of the authers, Yamahara, first pointed out this phenomenon and attempted to explain its effect by numerical filter using earthquake records taken at a school building of Hachinohe Technical College during aftershocks of the Tokachioki Earthquake in 1968.[1] Yamahara named this phenomenon "filtering effect" and proposed the ratio η of amplitude of foundation slab to that of ground motion as follows:

$$\eta = \frac{\xi}{\pi} \mathrm{SIN} \frac{\pi}{\xi} \qquad (1)$$

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where ξ means the ratio of wave-length to the length of the building. The relationship between η and ξ described by Eq. (1) is graphically shown in Fig. 2. Yamahara supposed that the effective input to a building is evaluated by eliminating higher frequency components from the original ground motion, and is approximated by numerical lowpass filter. Let X_k be a digitalized time history of ground motion and Y_k an effective input motion. The filter which describes an effective input is defined

$$Y_k = \frac{1}{n} \{ X_{k-(n-1)/2} + \cdots + X_{k-1} + X_k + X_{k+1} + \cdots + X_{k+(n-1)/2} \} \quad (2)$$

where k is a positive integer, while n is a positive odd number and is given by

$$n = L/(\Delta t \cdot V) \quad (3)$$

where Δt is sampling interval of time history, L is length of foundation and V is wave velocity on ground surface. The frequency response function of this filter $H(\omega)$ is given by

$$H(\omega) = \frac{1}{n} \{ 1 + 2 \cos(\omega\Delta t) + 2 \cos(2\omega\Delta t) + \cdots + 2 \cos(\tfrac{n-1}{2} \omega\Delta t) \} \quad (4)$$

and $H(\omega)$ is shown in Fig. 3. For convenience sake, a filtering parameter τ which represents the characteristics of this filter is defined.

$$\tau = n \cdot \Delta t = L/V \quad (5)$$

in which τ represents an averaging time interval of Y_k.

In the latter 1970s, studies on this filtering effect came to be actively made, particularly in the field of development of a practical aseismic design for nuclear power plants. Newmark, Hall and Morgan (1977) proposed a numerical technique to explain this effect by averaging acceleration records of a free field.[2] Scanlan (1976) represented a soil-basement model by using continuously distributed springs and a rigid foundation. And he showed that the travelling wave can be replaced by the averaged time history.[3] In SMIRT (1977), Ray, Bernreuter and Whitley et al. reported similar results.[4,5,6]

EXAMINATION OF FILTERING EFFECT

The earthquake records of the Hollywood Storage Building Basement and the P.E. Lot during the San Fernando Earthquake in 1971 are typical examples of records which were simultaneously observed at a basement of a structure and an adjacent free field.[7] The Hollywood Storage Building is a 14-story reinforced concrete frame structure, constructed in 1925 and founded on concrete piles. As shown in Fig. 4, accelerographs are located in a corner of the basement and at the free field 34 m from the structure. Therefore, it can be considered that the P.E. Lot record represents behavior of ground motion which is not influenced by a structure and the Basement record represents behavior of a foundation slab.

To demonstrate that the filtering effect can be approximated by simple lowpass filter given by Eq. (2), observed records and analytical results were compared as described below (Fig. 5). First, the P.E. Lot records were filtered by Eq. (2) and the results obtained compared with the Basement records. Fig. 6 shows the results examined about NS components of the P.E. Lot and Basement records. The P.E. Lot record (Fig. 6-a) contains high-frequency components and the maximum acceleration is 167 gal. In the Basement record (Fig. 6-b), high-frequency components are attenuated and the maximum value is 104 gal. The maximum value of the latter is 60% of the former and a similarity is not recognized between these records. Fig. 6-c shows the calculated effective input motion obtained from the P.E. Lot record using Eq. (2). In this case, it was found that a filtering parameter $\tau = 0.1$ sec gives the best similarity with the Basement record.

In the same manner, EW components were examined and the results are shown in Fig. 7. Fig. 7-c is a calculated result for $\tau = 0.1$ sec in Eq. (2) and the result agrees well with the Basement record (Fig. 7-b). Fig. 8 gives the results of examination of up-down components. In this case, however, the calculated result is different from the Basement record in the top half.

In a stable linear system, the dynamic characteristics of the system can be described by a frequency response function H(f), which is defined as follows:

$$H(f) = G_{xy}(f)/G_x(f) \tag{6}$$

where $G_{xy}(f)$ is a cross-spectral density function of input and output, $G_x(f)$ is an input power spectral density function. Eq. (6) contains amplification and phase factors.

The amplification factors between the P.E. Lot records and the Basement records were calculated by Eq. (6) and the results are shown in Fig. 9 by the solid line. And the amplification factor presented in Eq. (4) for $\tau = 0.1$ sec is shown in Fig. 9 by the dotted line. According to these results, there is a general tendency of observed and calculated results agreeing with each other, although, strictly, they are different.

A PRACTICAL APPROACH

As described previously, it was proved that the filtering effect of a foundation slab is approximated by a numerical lowpass filter. It is well known that the earthquake response of a structure is more or less influenced by a soil-structure interaction effect in general. In this chapter, the authers show a practical approach which considers both a filtering effect and a soil-structure interaction effect using the mathematical model of the Hollywood Storage Building in the EW direction. Duke et al. (1970) studied about this building and showed a structural dynamic model of it.[8] The structural model used here is quoted from the study of Duke et al., and the stiffness which represents a soil-structure interaction effect is given on the assumption that the stress distribution under the rigid body is uniform.

An eigenvalue analysis for this structural model is carried out and eigenfrequencies f_n, participation factors β_n and eigenvectors V_n for each mode are obtained. From these parameters and modal damping factors h_n, a frequency response function H(f) between input motion and the response of the i-th story is given as follows:

$$H_i(f) = \sum_{n=1}^{N} \beta_n V_{ni} \left[\frac{1 + 4h_n^2(f/f_n)^2}{\{1-(f/f_n)^2\}^2 + 4h_n^2(f/f_n)^2} \right]^{\frac{1}{2}} \exp(-i\varepsilon_n) \qquad (7)$$

where

$$\varepsilon_n = \tan^{-1} \frac{2h_n(f/f_n)^3}{1-(1-4h_n^2)(f/f_n)^2} \qquad (8)$$

First, the frequency response function between input and a basement response considering only the soil-structure interaction effect was computed by Eq. (7). In this case, damping factors were given by the direct evaluation method[9] for 10% first-order modal damping. The result obtained is shown in Fig. 10 by the dot-dash line. The solid line in Fig. 10 indicates a frequency response function between the P.E. Lot record and the Basement record in the EW direction. The two do not resemble each other. Fig. 11 shows the time histories of the computed response of a basement and observed records. On comparing them, the computed result is excessively amplified and the maximum value is 40% larger than the Basement record. According to these examinations, it was found that a simple soil-structure interaction model as assumed here can not explain a real phenomenon. Therefore, it is considered that earthquake ground motion is attenuated by the filtering effect of a foundation slab and the structure responds to this effective input motion with a soil-structure interaction effect.

Hence, it would be satisfactory if the procedure represented as follows is suitable for the practical dynamic response analysis of structures.

1) Computation of an effective input motion from a time history observed at a ground surface using a numerical lowpass filter.
2) Computation of the response of a structure considering the soil-structure interaction effect.

According to this procedure, an effective input motion was obtained from the P.E. Lot record for a filtering parameter of τ = 0.15 sec and a response of a basement was calculated. A frequency response function between the P.E. Lot record and the basement response obtained was computed. The dotted line in Fig. 10 shows the result and Fig. 11-d the time history of computed result. This analytically obtained result agrees well with the Basement record both in frequency domain and in time domain. Namely, the trend of decline in the high-frequency region and that of peaks are identical to the observed result of frequency response function. The time history of the computed basement response agrees well with the Basement record and the maximum values are approximately equal to each other.

CONCLUDING REMARKS

The existence of a filtering effect of foundation slab was estimated from examinations of observed records of the Hollywood Storage Building Basement and the P.E. Lot. And it was proved that this effect is represented by a numerical lowpass filter and that a simple structural model in which both the filtering effect and the soil-structure interaction effect are considered gives the best approximation of this phenomenon. In order to substantiate this effect for application to design, it is looked forward to that additional research to clarify the general characteristics of this effect will be promoted based on a variety of earthquake observations.

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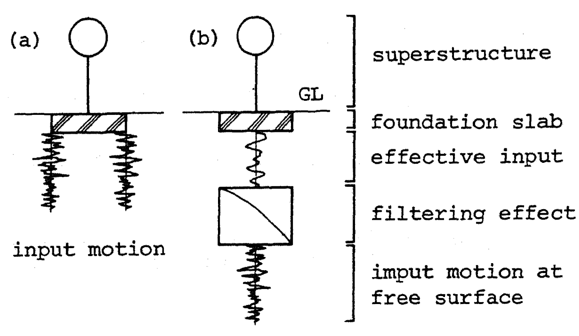

Fig. 1 Earthquake Input to Structure

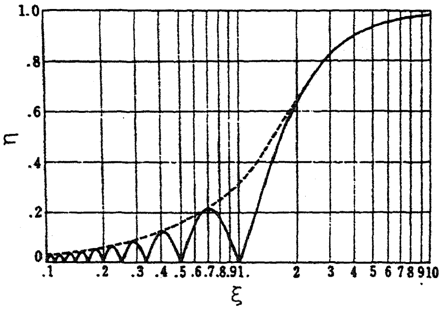

Fig. 2 Amplification Factor of the Filtering Effect

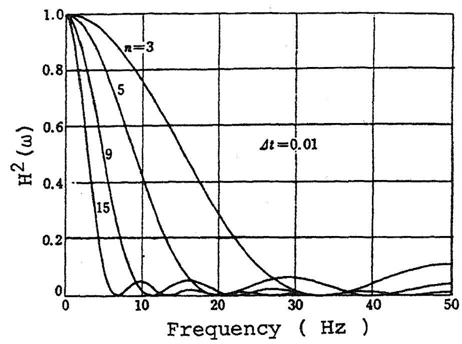

Fig. 3 Filter Characteristic of the Function $H^2(\omega)$

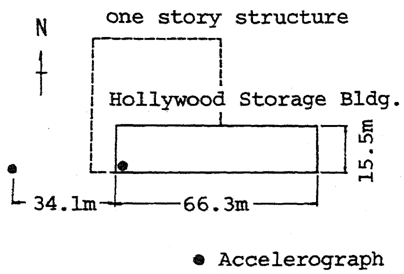

Fig. 4 Building Plan and Location of Seismographs

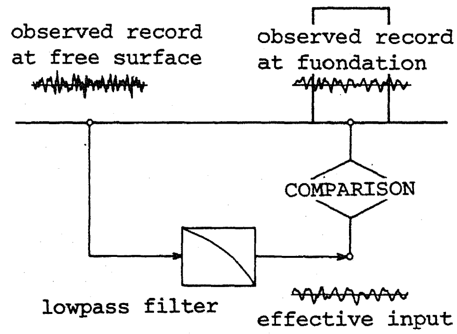

Fig. 5 Comparison of Calculation and Observation

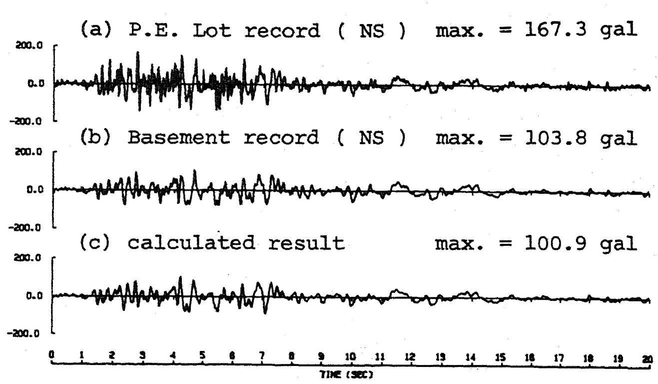

Fig. 6 Comparison of Observed Record and Calculated Result Only the Filtering Effect is Considered (NS Component)

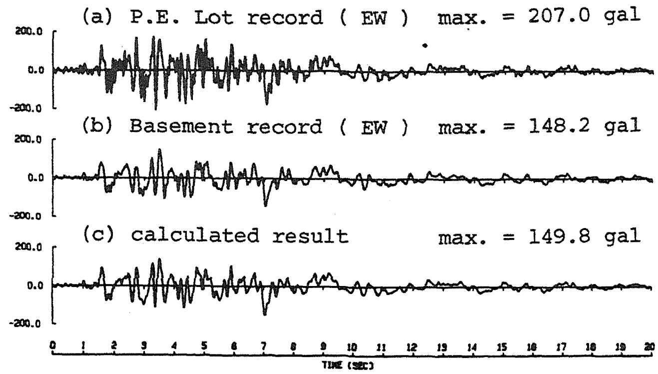

Fig. 7 Comparison of Observed Record and Calculated Result
Only the Filtering Effect is Considered (EW Component)

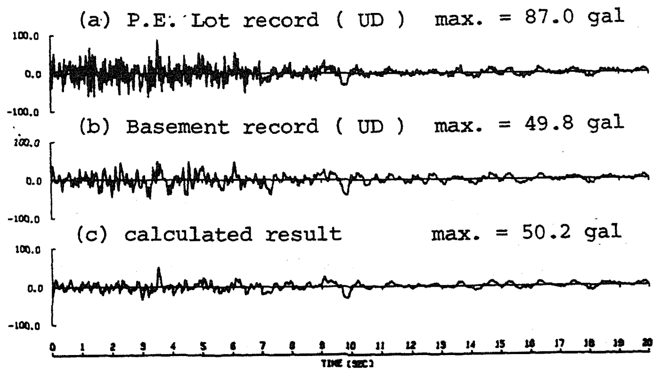

Fig. 8 Comparison of Observed Record and Calculated Result
Only the Filtering Effect is Considered (UD Component)

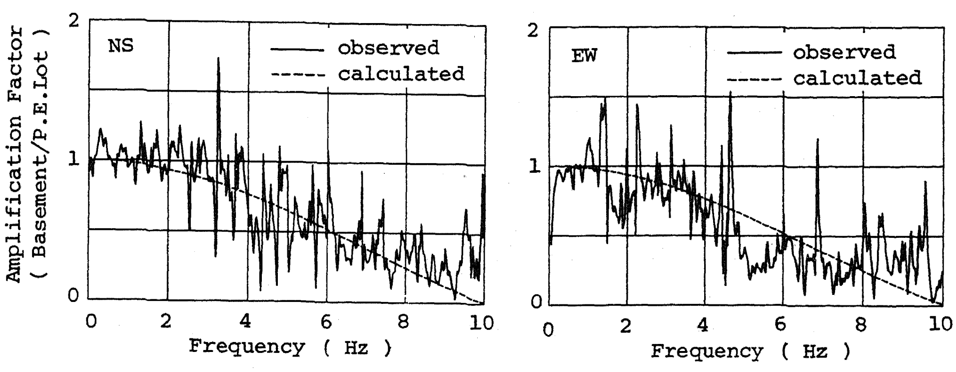

Fig. 9 Comparison of Observation and Calculation by the Frequency
Response Function, Only the Filtering Effect is Considered

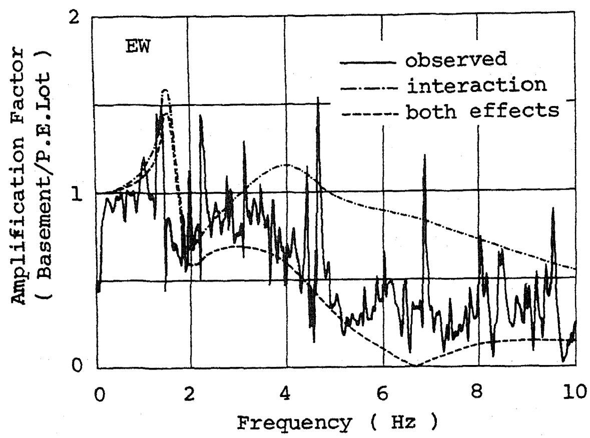

Fig. 10 Comparison of Observation and Calculation by the Frequency Response Function

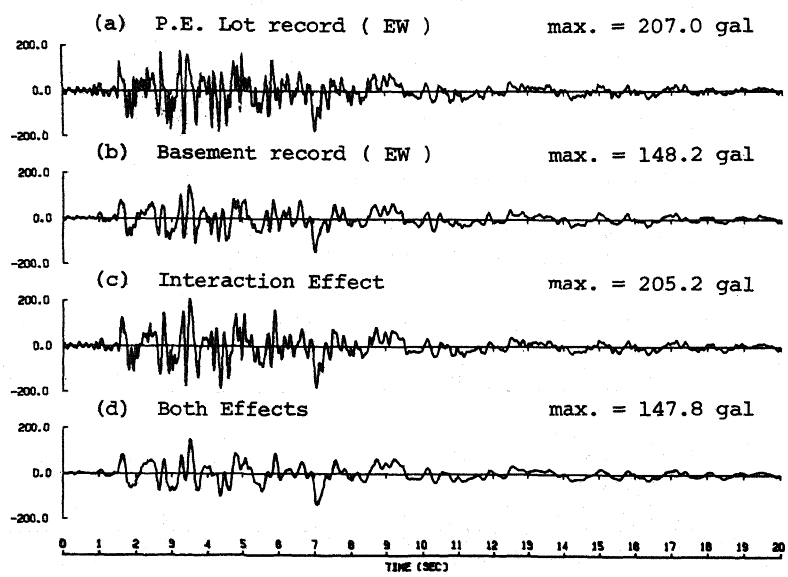

Fig. 11 Comparison of Observed Record and Calculated Result