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GROUND MOTION OF SUBSURFACE IRREGULAR SOIL EXCITED BY VIBRATOR

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SUMMARY

This paper deals with detailed measurements of surface ground motion generated by forced vibration of a reinforced concrete model footing placed on a topographic irregular ground. Observations indicate that the variations of measured velocity amplitudes are highly frequency dependent and do not always decay monotonously with increasing the source-receiver distance. They also indicate that it is the measurement points of a filling ground in the vicinity of an interface between a cutting ground and a filling ground that the surface ground motions are significantly amplified.

INTRODUCTION

It has been recognized that the dynamic behavior of a structure during an earthquake is considerably affected by the geologic formation and the dynamic property of the soil medium. In particular, the topographic irregularities in the soil medium seem to have a tremendous effect on the characteristics of the earthquake ground motion, together with the associated structural damage of the building. There have been many theoretical studies1)-5) about the elastic wave propagation in or around such geologic and topographic irregularities of the soil medium, but only a few experimental studies6)-8) about the effects of the amplification and focussing properties of elastic wave motions resulting from the local geologic and subsurface soil conditions on the surface ground motion of topographic irregular site.

In the present study, we examine experimentally the dynamic characteristics of a topographic irregular ground, especially focussing on the effects of patterns and frequencies of propagating waves generated by forced vibration of footings on the velocity amplitude variations of a experiment site which was turned out to a flat surface ground from a hill composed of a steep ridge and canyon feature. The variations of measured velocity amplitudes have been modelled by a two-dimensional model of an arbitrarily-shaped soil deposit excited by forced vibration of a footing and it is analyzed by the indirect boundary integral method.

OUTLINE OF THE EXPERIMENT

Fig. 1 shows the plan of measurement site and setting of model footings which were used for forced vibration. Four kinds of lines were selected as detailed measurements of surface ground motions taking into account the wave velocity profiles derived by refraction surveys of the site before carrying out the experiments of forced vibration of a footing. Four cylindrical footings made of reinforced concrete, which were the same size , 3.5 m in diameter and 1 m high, were placed at four different points, that is, three of them(indicated by A, B and C) were placed at the cutting ground and the one (indicated by D) at the filling ground.

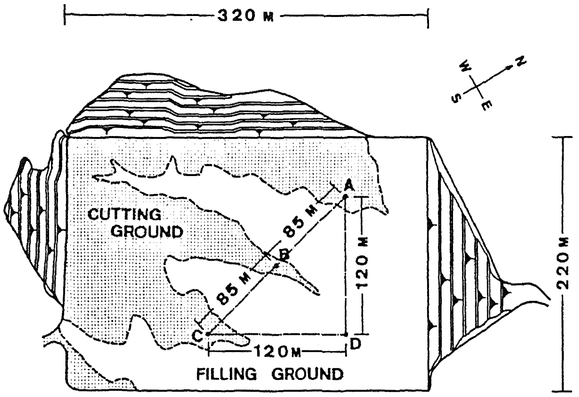

Fig. 1. The experiment site and the locations of excited footings.

In order to examine the effect of wave patterns generated by forced vibration on the dynamic characteristics of surface ground motions along ABC line, each of A, B and C footings was excited in three kinds of directions: a vertical direction and two different horizontal directions(i.e. parallel and perpendicular to ABC line). Since ABC line runs roughly in NS direction, each parallel or perpendicular direction to ABC line will be hereafter denoted as NS or EW direction, respectively. Each footing was excited by a servohydraulic-type vibrator which generated a linear sweep excitation over the frequency band 5 - 30 Hz for a period of time, 9 or 300 sec.

We measured three components(EW, NS and vertical) of velocities of a excited footing (A, B and C) as well as of measurement points at intervals of 5 m along ABC line, but when spectral contents of adjoining measurement points were found to be significantly different from each other, measurement points were taken at intervals of 2 m.

EXPERIMENTAL RESULTS

As described before, each footing was excited in a linear sweep excitation over the frequency band 5 - 30 Hz for a period of time, 9 or 300 sec. Some preliminary computations were carried out for evaluating the velocity amplitudes for excited footing as well as measurements points subjected to the excitation for a period of time, 9 or 300 sec. Since the results of them revealed that the duration of excitation did not have any influence on those responses for the present experiment, all subsequent responses were analyzed for the excitation during 9 sec for the purpose of saving computational time. The velocity amplitudes for the measurement points were normalized by the velocity amplitude in the excited direction of the footing and they are referred as the relative amplitudes in the following results.

A code was established to identify each test. The code consisted of four different abbreviations describing a name of excited footing, a direction of excitation, a measurement line and a measured component of surface ground motion.

The code is read as follows:

↙Name of excited footing
↙Measurement line
B(UD)BA-UD
↑ ↖Measured component
Direction of excitation

And another code was established to identify the measurement point. For example, as shown in Fig. 2, BC40 stands for the measurement point which was located at a distance of 40 m from B footing along BC line.

Fig. 2 shows the relative amplitudes of UD component of surface ground motion versus the source-receiver distance for the different values of frequency of excitation. Though the relative amplitudes along BA line(Fig. 2a) except the result for 10 Hz decay monotonously with increasing the source-receiver distance, those along BC line(Fig. 2b) are amplified appreciably in the vicinity of BC60 and they decay significantly after BC60. This difference between them could be ascribed to the scattering properties of wave propagation resulting from the different subsurface irregularities. It can be seen from Fig. 2b that the relative amplitude for 7 Hz decays monotonously with increasing the source-receiver distance, but that for 10 Hz is amplified approximately 4.5 times as much as that for 7 Hz in the vicinity of BC60.

Fig. 3 shows the relative amplitudes of transverse component of surface ground motion versus the source-receiver distance for the different values of frequency of excitation. The relative amplitudes at a distance of about 64 m from C footing are more amplified for the lower frequency band ranged from 7 Hz to 9 Hz than for the higher frequency band ranged from 10 Hz to 14 Hz. In addition, the peak amplitudes occur at the measurement points more distant from the source than those such as shown in Fig. 3b. It is the relative amplitude for 14 Hz that is most amplified at CB65 among those and it is amplified about 7 times as much as that at CB50 which is deamplified.

Fig. 4 shows the relative amplitudes of transverse component of surface ground motion versus the source-receiver distance for the different values of frequency of excitation. The relative amplitudes are most amplified for the lower frequency band ranged from 8 Hz to 10 Hz at a distance of about 64 m from the source(B footing) and they are amplified about 7 times as much as those in the vicinity of BC58 which are deamplified. And it is also observed that the relative amplitudes for 15 Hz and 16 Hz increase significantly in the vicinity of BC66. The relative amplitudes for the higher frequency band oscillate significantly repeating not only local amplification but also deamplification as far as they reach maximum at some points of the filling ground just before the cutting ground in the vicinity of C footing. These oscillations in the amplitude variations depending upon the measurement points could be ascribed to an interference phenomenon between propagating waves and reflecting waves from the cutting ground. Since some part of energy radiated from excited B footing which propagates toward C footing through irregular subsurface ground is scattered at the interface between the filling soil and the relative stiff soil and it is reflected toward the surface, the phenomenon of wave interference will occur focussing its energy on some points of the ground depending upon the wavelengths of propagating waves.

THEORETICAL RESULTS

As described before, it was observed that the velocity amplitude variations along BC line were highly frequency dependent and that they were significantly amplified at some measurement points in the vicinity of the interface between the cutting ground and the filling ground. The variations of measured velocity amplitudes have been modelled by a two-dimensional model of an arbitrarily-shaped soil deposit excited by forced vibration of a footing.

Geometry of the problem is shown by Fig. 5. A subsurface irregularity along BC line underlain by a soft soil deposit is assumed to be a two-dimensional model of an arbitrarily-shaped soil deposit (denoted by soil medium I) , which is characterized by mass density, ρ_I, and shear wave velocity, β_I. Soil medium I is surrounded by a half-space soil medium (denoted by soil medium II), which is

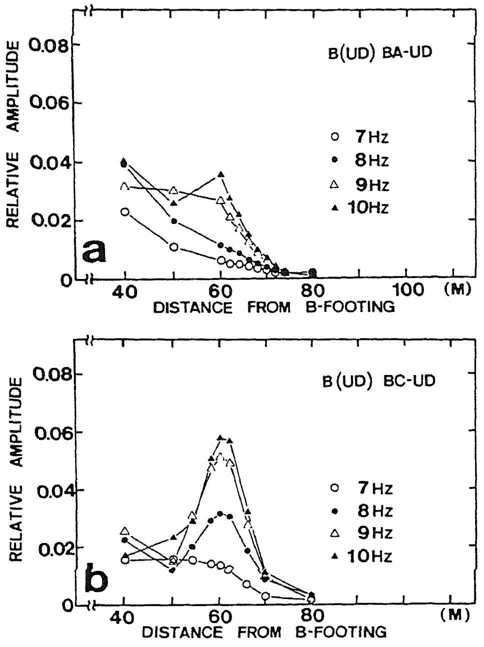

Fig. 2. Relative amplitudes of UD component of surface ground motion excited by B footing in the vertical direction.

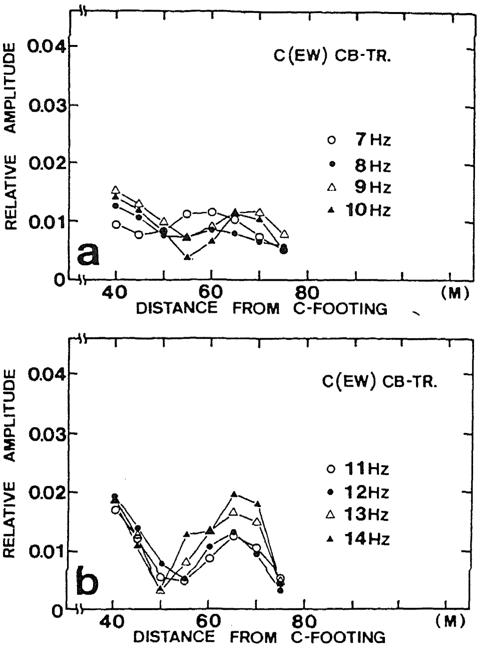

Fig. 3. Relative amplitudes of TR. component of surface ground motion along CB line excited by C footing in EW direction.

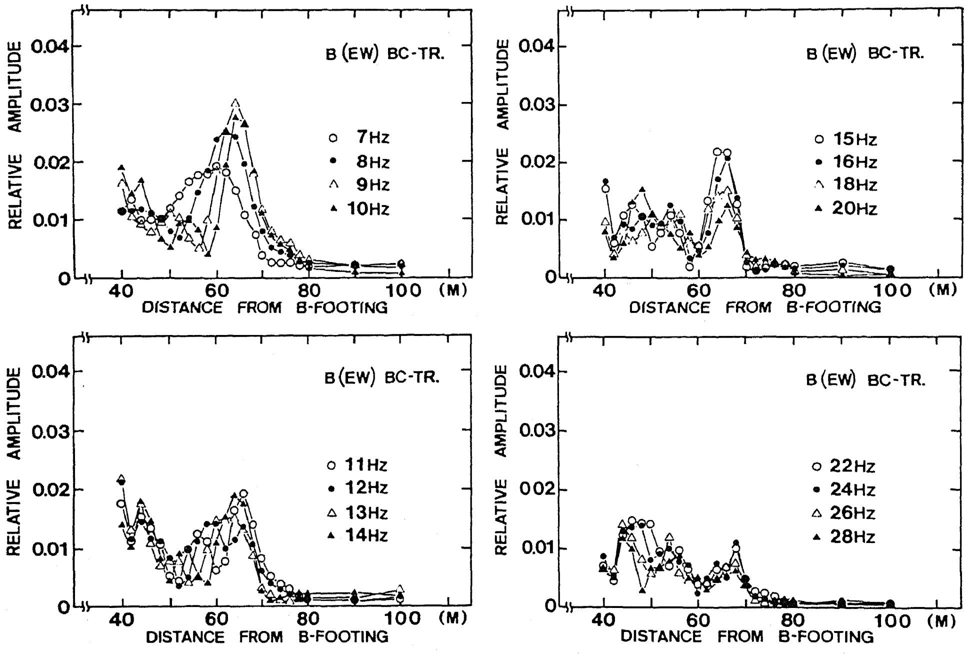

Fig. 4. Relative amplitudes of TR. component of surface ground motion along BC line excited by B footing in EW direction.

characterized by mass density, ρ_2, and shear wave velocity, β_2. An interface between the soil media I and II is denoted by L_1 and perfect bonding along the interface is understood. The material of them is assumed to be linearly elastic, homogeneous and isotropic. B footing which was used for forced vibration is assumed to be located at a distance of D from the center of the soil deposit and to have a rigid embedded semi-elliptical cross-section. The problem model is of the antiplane-strain type, i.e., both the soil media I and II and the footing extend to infinity perpendicular to the plane of the drawing and the motion of them takes place along z axis only. Three different curves are defined inside and outside the soil deposit and inside the embedded footing along which single layer potentials are assumed for the analysis by the indirect boundary integral method. The detail of the analysis is not herein described due to the limitation of space.

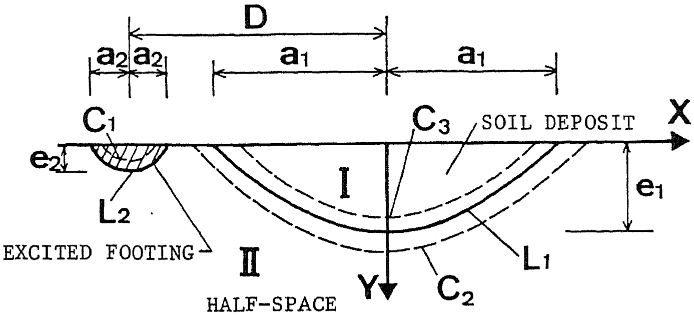

Fig. 5. Model of excited footing, soil deposit and surrounding half-space.

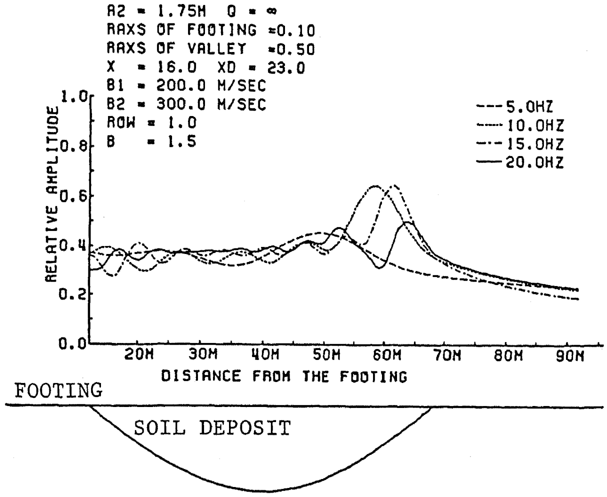

Fig. 6. Computed surface relative amplitudes in subsurface irregular media.

Fig. 6 shows an example of some numerical results on the surface relative velocity amplitude variations throughout the soil deposit and the half-space soil media for four different values of frequency of excitation, i.e., 5 Hz, 10 Hz, 15 Hz and 20 Hz. The interface between the soil deposit and the half-space soil is assumed to be a shape of cosine function whose width and depth are 56 m and 14 m, respectively, and the width and embedded depth of the excited footing are assumed to be 3.5 m and 0.175 m, respectively. Shear wave velocities in the soil deposit and the half-space soil medium are assumed to be 200 m/sec and 300 m/sec, respectively, while mass densities of them to be the same. The responses for 10 Hz and 15 Hz are more amplified at a distance of about 60 m from the excited footing than those for 5 Hz and 20 Hz. These computed results appear to coincide qualitatively with the observed results shown in Fig. 4.

CONCLUDING REMARKS

Scattering of harmonic waves by topographic irregular ground is studied experimentally with the detailed measurements of a surface ground motion generated by forced vibration of a reinforced concrete model footing placed on the subsurface irregular ground which was turned out to the flat surface ground from a hill composed of a steep ridge and canyon feature. Each of three different footings was excited in three kinds of directions to generate different patterns of wave propagation.

Observations indicate that the variations of measured velocity amplitude are most influenced by SH wave motion among various types of propagating waves and that they are highly frequency dependent. They also indicate that the measured velocity amplitudes do not always decay monotonously with increasing the source-receiver distance and that it is the measurement points of the filling ground in the vicinity of the interface between the cutting ground and the filling ground that the surface ground motions are significantly amplified. The variations of measured velocity amplitudes have been modelled by a two-dimensional model of an arbitrarily-shaped soil deposit excited by forced vibration of a footing and it is analyzed by the indirect boundary integral method. It is shown that the computed amplitude variations coincide qualitatively with the observed ones.

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