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Experimental Study on Dynamic Soil-Structure Interaction

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Abstract

This paper describes the dynamic characteristics of embedded foundation on the soft ground, especially the effects of backfill sand obtained from the forced vibration tests and the earthquake observations of block-modeled foundation.

From the results of the forced vibration tests, it was recognized that the displacement amplitude of the full-backfilled foundations in time of resonance remarkably decreases compared with the case of non-backfill. In case of full-backfill, a clear resonance did not appear at its natural frequency. These phenomena can be verified from earthquake observations. We recognized a good agreement comparing the calculated values from velocity response of the foundation by Sway-Rocking model with the spring coefficients obtained from measurement values of earth pressure cells.

1. Introduction

Many studies have been made on dynamic characteristics of soil-structure interaction to evaluate the behaviour of structures during earthquake. However, in regard to the behaviour of an embedded foundation on the soft ground, studies have not been performed sufficiently.

We have carried out a series of the forced vibration tests and the earthquake observations on three different-sized block-modeled foundations and a large-sized foundation, with the purpose of evaluating the dynamic characteristics of embedded foundations on the soft ground, the restraint effects of backfill sand and scale effects of foundations, taking a opportunity of construction of a shaking table.

This paper describes the dynamic characteristics, mainly the restraint effects of backfill sand obtained from the result of the forced vibration tests and the earthquake observations. We would like to report the scale effects at the next opportunity.

2. Outline of Field Tests

2-1 Outline of Field Tests

The forced vibration tests and the earthquake observations have been carried out on the three different-sized block-modeled foundations in cases of non-backfill, half-backfill and full-backfill respectively, as shown in Fig. 1, 2.

2-2 Measurement Items

The measurement points were arranged as shown in Fig.1 in order to record the followings.

1) Velocity response of the block-modeled foundations and the surrounding ground
2) Dynamic earth pressure at the bottom and side face of "block A" during the vibration

2-3 Test Site

The geology and the soil property of the test site are shown in Fig. 3. The block-modeled foundations A, B and C were set up at loam.

3. Result of Forced Vibration Tests

3-1 Characteristics of Response

We report only on the results of "block A" within a series of vibration tests. Fig.4 (a), (b) show resonance curves and phase curves at the top of the foundation in three kinds of backfill conditions. In Fig. 4(a), several peaks of resonance curves are recognized. The curve of non-backfill has two peaks at 5.8Hz and 13.0Hz, and that of half-backfill at 7.2Hz and 12.0Hz. On the other hand, in case of full-backfill, a peak appears only at 4.2Hz which is a predominant frequency of surrounding ground, and the displacement response has a tendency to decrease slightly as frequency increases over 4.2Hz. Comparing the displacement responses of the foundation, those at the time of resonance in cases of half-backfill and full-backfill drop to about 1/5, 1/30 of that in non-backfill case respectively. From phase curves shown in Fig. 4(b), a natural frequency of each case when the phase lag indicates 90° is 5.8Hz in non-backfill case, 8.0Hz in half-backfill and 14.0Hz in full-backfill. Although a peak does not appear at 14.0Hz in case of backfill as above mentioned, natural frequency is found to be 14.0Hz from the phase curve.

3-2 Consideration of Backfill Effects

In this section, we will consider effects of backfill sand comparing complex stiffness, which is calculated from the velocity response of foundation using Sway-Rocking model, with spring coefficient which is obtained from measurement values of earth pressure.

Fig. 5 describes the S-R model used in case of backfill. This model consists of two kinds of complex stiffness. One stiffness, which expresses the effects of interaction at the bottom, is calculated from non-backfill case tests and is given to this model as a known value with the assumption that this value is not changed in both non- and full-backfill cases.

The other is the stiffness, ($\mathbf{K}_{HS}$, $\mathbf{K}_{RS}$), which expresses the effects of backfill sand and is evaluated in this model.

Equation of motion is as follows:

$$\begin{bmatrix} M & O \\ O & I_G \end{bmatrix}\begin{pmatrix} \ddot{u} \\ \ddot{\theta} \end{pmatrix} + \begin{bmatrix} \mathbf{K}_{HB}+\mathbf{K}_{HS} & -\mathbf{K}_{HB}\cdot S-\mathbf{K}_{HS}(S-\frac{L}{2}) \\ -\mathbf{K}_{HB}\cdot S-\mathbf{K}_{HS}(S-\frac{L}{2}) & \mathbf{K}_{RB}+\mathbf{K}_{RS}+\mathbf{K}_{HB}\cdot S^2+\mathbf{K}_{HS}(\frac{L^2}{3}-LS+S^2) \end{bmatrix}\begin{pmatrix} u \\ \theta \end{pmatrix} = mrw^2\begin{pmatrix} 1 \\ \ell \end{pmatrix}e^{iwt} \quad \ldots(1)$$

where $\mathbf{K}_{HB} = K_{HB} + iC_{HB}$, $\mathbf{K}_{HS} = K_{HS} + iC_{HS}$

$\mathbf{K}_{RB} = K_{RB} + iC_{RB}$, $\mathbf{K}_{RS} = K_{RS} + iC_{RS}$

u : horizontal displacement

θ : rotational angle around center of gravity

M : mass of foundation

I_G : moment of inertia around center of gravity mr : eccentric moment of exciter

w : circular frequency

L, S, ℓ : shown in Fig. 5

Fig. 6(a), (b) show the complex stiffness K_{HS}, K_{RS}. They show that K_{HS}, C_{HS} and C_{RS} have a tendency to increase with an increase of frequency collectively. It is interesting that K_{HS} increase in spite that K_{HB} at the bottom is constant or decrease slightly.

In regard to the measurement values of earth pressure, it is difficult to evaluate them quantitatively because we arranged only a few cells in this test and the credibility of absolute values is not so sufficient. So, we will study qualitative consideration on these phenomena. Fig. 7 shows a coefficient of vertical subgrade reaction k_V' calculated with the measurement values of earth pressure cells at the bottom in non- and full-backfill cases. Both two kinds of k_V' have an approximate agreement and its value is not so influenced by backfill. So, it seems to be possible to substitute the complex stiffness at the bottom in non-backfill case for full-backfill case.

Fig. 8 shows the comparison of the real part of transtational complex stiffness K_{HS} at the side with the transtational spring coefficient k_{HS} evaluated to the value of whole side from the measurement values of an earth pressure cell installed at the upper part of side face. It is recognized that both K_{HS} and k_{HS} have a similar tendency. They increase to around 15Hz and are almost constant over that point.

Fig. 9 shows the comparison of the real part of rotational complex stiffness ($K_R = K_{RB} + K_{RS}$) in case of full-backfill with the rotational spring k_R obtained from the values of earth pressure cells at the bottom and the side. Here k_R is obtained from a coefficient of vertical subgrade k_V' at the bottom and a coefficient k_H' at the side with the assumption of triangular distribution of earth contact pressure, as following:

$$k_R = k_V' \cdot (b_B^2/3) \cdot A_B + 2 \cdot k_H' \cdot (b_S^2/3) \cdot A_S \quad \text{.................} \quad (2)$$

where A_B : area of bottom

A_S : area of side in parallel with rotational axis

$2b_B$: width of foundation at a right angle with rotational axis

$2b_S$: depth of backfill sand

Another two kinds of values are added in Fig. 9 to consider the phenomena easily, former term k_{RB} (bottom) and latter term k_{RS} (side) of eq. (2). K_R and k_R have a good qualitative agreement mainly because k_{RS} at the side is similar to K_R. It is interesting that K_R tends to increase under the influence of backfill sand. A qualitative difference seems to be caused by uncertainty of earth contact pressure distribution, evaluation of share spring at the side, etc.

As mentioned above, the real parts of both transtational and rotational complex stiffness are qualitatively verified by the value of earth pressure.

On the other hand, it is difficult to verify the imaginary part (damping) by the value of earth pressure, because vibration mode is complicated and measurement points are not so many. Accordingly, further investigation should be performed.

4. Results of Earthquake Observations

The earthquake observations were carried out with the vibration tests.

Fig. 10(a),(b) show the comparison of power spectrum of the horizontal response on the top of the foundation and the ground as for the typical seismic wave observed at "block A" in the condition of both non- and full-backfill.

In case of non-backfill, peaks appear at 4.2Hz and 6.5Hz of the foundation. Whereas it appears at only 4.2Hz on the ground. This peak at 4.2Hz is the predominant frequency of the surrounding ground, and the other at 6.5Hz is close to the natural frequency obtained by the vibration tests.

On the other hand, in case of full-backfill, the peak of spectrum of the foundation appears only at 4.2Hz. However, the peak at 14.0Hz, which is the natural frequency of the soil-structure interaction, does not appear. This agrees with the results obtained from the resonance curve of vibration tests. Moreover, it is recognized that the full-backfilled foundation does not exceed the surrounding ground in amplitude.

5. Conclusion

As the conclusion, the following facts can be pointed out in regard to the dynamic characteristics of embedded foundation on the soft ground, and especially the backfill effects obtained from the forced vibration tests and the earthquake observations.

1) The displacement amplitude of the full-backfill foundation in time of resonance remarkably decreases and the natural frequency becomes higher compared with the case of non-backfill. Furthermore in case of full-backfill foundation, resonance peak does not appear at the natural frequency.

2) We recognized a good agreement comparing the calculated values from velocity response of the foundation by S-R model with the spring coefficients obtained from measurement values of earth pressure cells. As the results, it was found that both spring and damping increase with an increase of frequency because of backfill sand. Moreover, the frequency characteristics of the spring can be verified by the coefficients of vertical and horizontal subgrade reaction obtained from the dynamic earth pressure.

3) The conclusion as mentioned 1) was also assured from the earthquake observations.

We have been analyzing the forced vibration tests and the earthquake observations of the large-sized foundation (width 16m, breadth 16m, height 7.2m) in order to investigate the application from this conclusion to the large scale foundation. As we have a lot of data from many earth pressure cells which are installed at the bottom and the side face of the foundation, we will perform more detail investigations on this study.

Reference

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/ 2 / Hirata, K., Ueshima, T., Shiomi, S. "Vibration Test of Foundation on Bedrock" 8th. WCEE, vol. III, 1984.

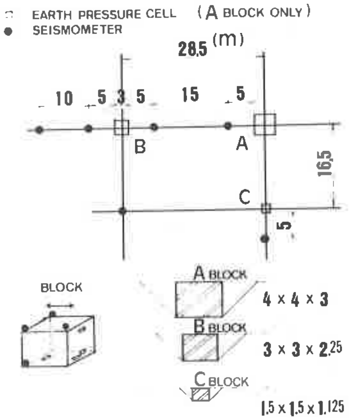


Fig. 1 Block Size and Arrangement of Instruments

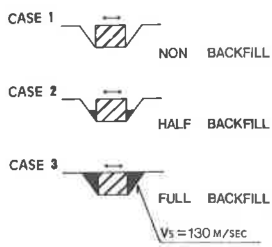


Fig. 2 Backfill Condition

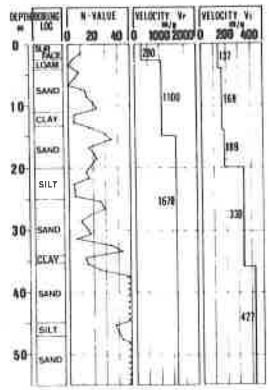
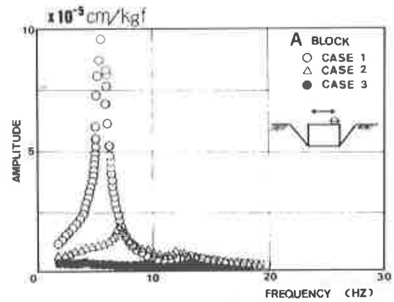
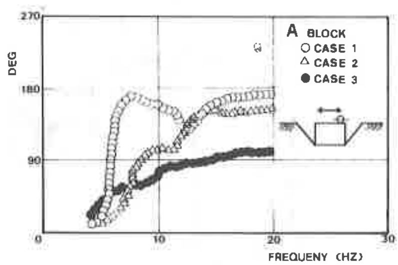


Fig. 3 Site Geology and Soil Property



a) Resonance Curve



b) Phase Curve

Fig. 4 Resonance and Phase Curves of Three Kinds of Backfill Conditions

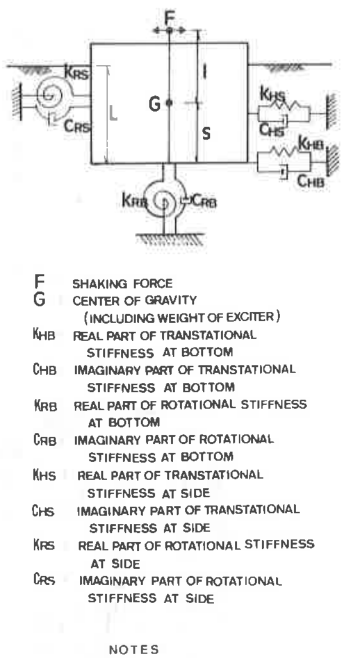


Fig. 5 Sway-Rocking Model

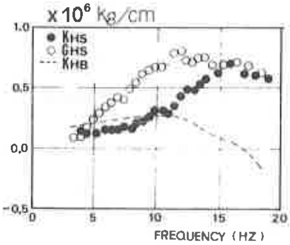
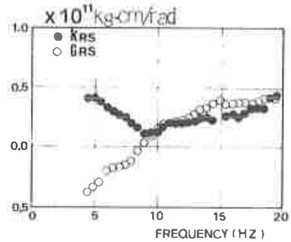


Fig. 6 a) Transtational Complex Stiffness



b) Rotational Complex Stiffness

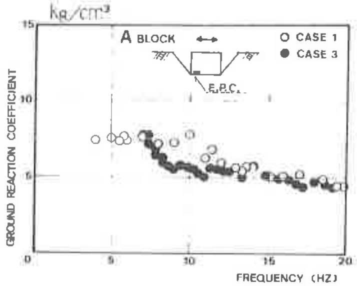


Fig. 7 Comparison of k_v' in case of Non- and Full-Backfill

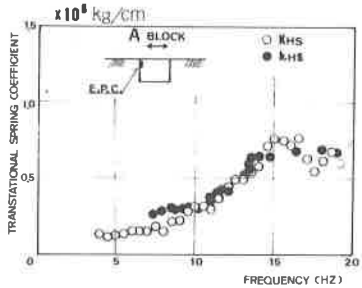


Fig. 8 Comparison of K_{HS} and k_{HS}in case of Full-Backfill

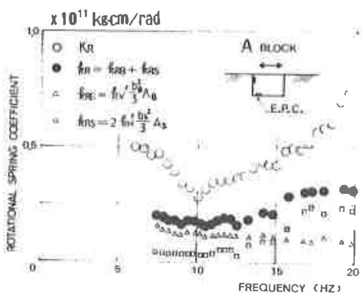
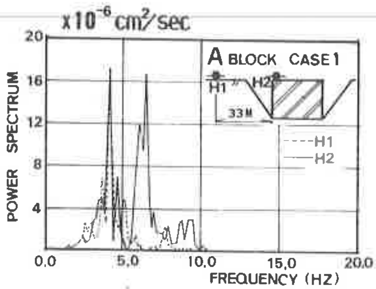
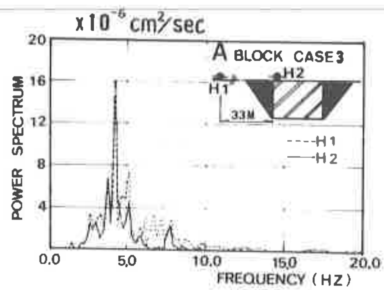


Fig. 9 Comparison of K_R and k_R in case of Full-Backfill



a) Non-Backfill



b) Full-Backfill

Fig. 10 Comparison of Power Spectrum Non- and Full-Backfill