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Dynamic effects of backfill and piles on foundation impedance

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ABSTRACT: The paper presents effects of backfill and piles on foundation responses and impedance functions through a series of oscillation tests of pile and mat foundations. Several factors are considered in the experiment such as foundation type, number of piles, distance among piles, backfill and soil nonlinearity and each effect is investigated through comparison of the impedance functions. It is pointed out that pile existence and backfill are effective in increasing both real and imaginary parts of the impedance functions.

1 INTRODUCTION

Soil structure interaction has not explicitly been included into the earthquake resistant design code in Japan. Main reasons for this situation are; 1)a great variaty of soil and foundations, and 2)that experimental data are not well arranged as data for the design. It implies that dynamic impedance of foundations will be approximately taken into the design when the impedance will be evaluated with acceptable accuracy. The objectives are to clarify dynamic soil structure interaction of pile foundations, and to evaluate effects of piles, backfill and soil nonlinearity on impedance functions for design purposes, through a series of experimental studies.

The study is aimed at evaluating the effects of piles and backfill separately, through comparison among experimental results of four typical foundation types illustrated in Fig. 1. Specimens of pile foundations and a mat foundation were constructed and extended during five years at a site for minimizing effects of soil condition on experimental results.

Oscillator tests, ambient vibration tests were repeated at several construction stages of the foundations. A lot of instruments were installed to measure displacements of pilecaps, strains of piles, earth pressures of pilecaps, etc. Measured data were processed into resonant curves and impedance functions.

Several factors which have an influence on the response are considered. In the effects of piles, the effects of pile existence, number of piles and distance among piles are examined. To investigate the effects of backfill, the impedance of foundations with backfilled pilecap is compared with that with trenches around pilecap. In addition, the effects of soil nonlinearity is discussed through the experimental results of a pile foundation with small diameter pipes.

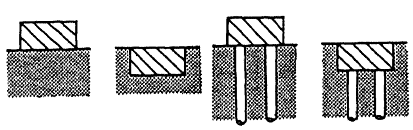

Fig. 1 Four types of foundations

2 SPECIMENS AND SETUP

2.1 Specimens

a)Single Pile: Two kinds of piles were used. One is a steel pipe pile(40cm in diameter, 9mm in thickness and 6m in length) and the other is a prestressed high-strength concrete (PHC) pile (35cm, 6cm, 6m). All of piles were driven by a diesel hammer.

b)Two-pile Foundation: Pile foundations with steel or PHC piles and a mat foundation were constructed. Pilecaps were made of the reinforced concrete(RC) and those dimensions were 1m x 2m x 1m. The mat foundation had the same size as the pilecaps and was excit-

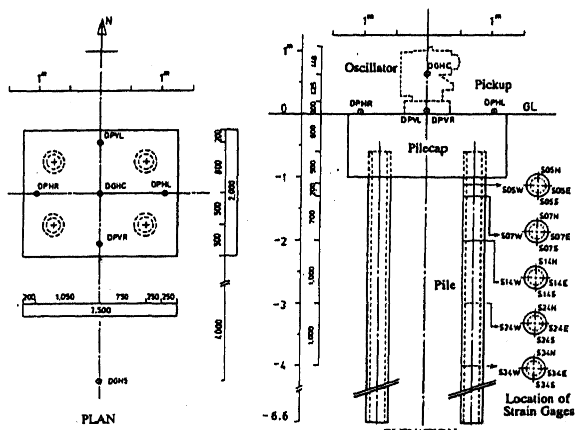

Fig. 2 Specimen of pile foundation and instrumentation

ed in comparison with the pile foundations.

c)Four-pile Foundation: There were pile foundations with the same materials and a mat foundation. The dimensions of the pilecaps were 2m x 2.5m x 1m. As an example of the pile foundations, plan and elevation are illustrated in Fig. 2.

d)Additional Four-pile Foundation: A pile foundation consisted of small diameter steel pipes (101.6mm, 3.2mm, 6m) and a pilecap(RC, 1.2m x 1.2m x 0.6m). The foundation was laterally pushed and pulled to 1.5 times displacement as the pile diameter by a static hydraulic jack after dynamic testing.

All of specimens were installed in the ground in Building Research Institute whose shear velocities are shown in Fig. 3. Soil beneath the surface is called the Kwanto loam.

2.2 Oscillator

Oscillator tests and ambient vibration tests were carried out. An oscillator(maximum force is 3 tons) was installed on the foundations, and steady-state and sweep oscillation with constant eccentric moment were conducted. The eccentric moment should be set up on condition that displacements of each foundation were almost equal. Frequencies of the oscillation were 2 to 25Hz for the horizontal direction(NS and EW) and 2 to 40Hz for the vertical one.

Depth (m)	Soil Type	S-Wave Velocity(m/s)
0 – 0.9	Embankment	100
0.9 – 2.5	Loam	
2.5 – 5.6	Fine Sand	200
5.6 – 7.6	Clay with Sand	260
7.6 – 11.0	Clay	190
11.0 – 13.8	Clay	160
13.8 – 20.6	Fine Sand	330
20.6 –	Alternation of clay and sand	230

Fig. 3 Shear wave velocity at test site

Table 1 Experiment series and eccentric moment (unit of moment;kg.cm)

Foundation Type	Pile Material	Backfill of pilecap	Number of Piles		
			Single Pile	Two Piles	Four Piles
Pile	Steel φ400 t9 L6000	No	NS : 10.08 EW : 10.08 UD : 10.08	NS : 20.14 EW : 15.11 UD : 20.14	NS : 60.02 EW : 60.02 UD : 40.18
		With		NS : 30.18 EW : 25.16 UD : 20.14	NS : 79.58 EW : 79.58 UD : 40.18
	PHC A-type φ350 t60 L6000	No	NS : 10.08 EW : 10.08 UD : 10.08	NS : 22.65 EW : 20.14 UD : 20.14	NS : 60.02 EW : 60.02 UD : 40.18
		With		NS : 30.18 EW : 25.16 UD : 20.14	NS : 79.58 EW : 79.58 UD : 40.18
Mat		No		NS : 15.11 EW : 10.08 UD : 10.08	NS : 20.14 EW : 20.14 UD : 20.14
		With		NS : 20.14 EW : 20.14 UD : 15.11	NS : 40.18 EW : 50.13 UD : 40.18
			Foundation with 4 Small Diameter Piles		
Pile	Steel φ102 t3.2 L5900	No	NS : 10.08 40.18 79.58	EW : 10.08 40.18 60.02 79.58	UD : 10.08 20.14 40.18 79.58 152.99 250.00
		*Separated between bottom of pilecap and ground surface			

Note;NS, EW and UD mean excited directions.

2.3 Instrumentation and data analysis

Measured items are as follows.

a)Displacements of pilecaps were measured by using electromagnetic transducers(natural period is 1 sec. and damping ratio is 0.7) and servo-type transducers.

b)Strain gages were attached on the surface of steel piles and on that of prestressed steel bars in PHC piles.

c)Earth pressures on pilecaps were measured to evaluate effects of backfill on the foundation response.

d)Shear forces at bottom of pilecaps were measured by the hand-made equipment.

Data of the oscillator tests were processed into response curves, and impedance functions. Real and imaginary parts of the impedance correspond to stiffness and radiation damping, respectively. The impedance functions are derived from the displacements and the rotational angles of pilecaps. In the horizontal oscillation, the pilecaps are assumed to be a rigid body with sway and rocking spring. In the vertical oscillation, those are assumed to be a single degree of freedom system with the vertical spring.

2.4 Experimental series

Experimental parameters are summarized as follows.

a)Foundation type(pile and mat)

b)Pile material(steel and prestressed concrete)

c)Number of piles(single, two and four piles)

d)Distance among piles(ratios of distance to diameter are 2.5 and 3.75 in NS and EW directions in steel pile foundations) or aspect ratio for mat foundations

e)Backfill of pilecaps

f)Eccentric moment(especially for the additional pile foundation)

Table 1 summarizes the experimental series and eccentric moment for steady state vibrations.

Table 2 Resonant frequencies (foundations without backfill)

Foundation Type	Pile Material	Backfill of pilecap	Number of Piles		
			Single Pile	Two Piles	Four Piles
Pile	Steel φ400 t9	No	NS : 11.00 12.82 EW : 10.61 12.87 UD : ----	NS : 14.10 EW : 10.57 UD : ----	NS : 12.82 EW : 13.75 UD : ----
	PHC A-type φ350 t60	No	NS : 11.12 13.38 EW : 10.70 13.44 UD : ----	NS : 15.23 EW : 11.01 UD : ----	NS : 14.05 EW : 14.25 UD : ----
Mat		No		NS : 8.24 EW : 6.17 UD : 15.27	NS : 8.52 EW : 8.76 UD : 15.50
			Foundation with 4 Small Diameter Piles		
Pile	Steel φ102 t3.2	No	NS : 13.00(10.08) 11.65(40.18) 9.72(79.58) UD : ----	EW : 11.79(10.08) 10.12(40.18) 9.54(60.02) 9.14(79.58)	

Note;Value in parentheses means eccentric moment.

3 EXPERIMENTAL RESULTS

Table 2 presents the resonant frequencies of the foundations without backfill. As an example of results, the foundation response(4 steel piles, NS direction, no backfill) is shown. The displacement response(amplitude and phase lag) of the pilecap is presented in Fig. 4. The amplitude is normalized by the generated force and the phase lag means the angle of the response to the force. The resonance occurs at 12.8Hz in frequency. The strain response of piles through depth is shown in Fig. 5. The strain gages were attached on the surface of piles symmetrically with respect to the axis. The data in the figure are opposite strains(northern and southern sides)in the oscillated direction. The strains of the northern side are larger at the pile head through the depth. On the other hand, the strains of the southern side are larger with depth. It results from combination of axial and bending strains. Distribution of axial force and bending moment at the resonant frequency is illustrated in Fig. 6. The bending moment at the pile head is opposite to that at 2m in depth and the amplitude of the latter is larger than that of the former. The axial force through the depth is almost constant. It is pointed out that skin friction between pile and soil is negligibly small near the ground surface.

4 DYNAMIC EFFECTS OF PILES

4.1 Existence of piles

The first point in the effects of the piles is the effect of pile existence on the response. Through the comparison of response between pile and mat foundations with no backfill, the effects of piles are investigated.

Figure 7 shows the horizontal displacement response of the pilecaps. The resonant frequency of the pile foundation is about 1.5 times that of the mat foundation. The horizontal displacement and the rotational angle of the pile foundation tends to be smaller than those of the mat foundation at the frequencies.

The horizontal and rotational impedance functions are indicated in Figs. 8 and 9, respectively. Real parts of the impedance tend to be constant or gradually decrease with frequencies. Imaginary parts increase with frequencies. In both horizontal and rotational impedance, the effect of piles is observed. The horizontal and rotational stiffness of the pile foundation in low frequencies is about 2 and 5 times that of the mat

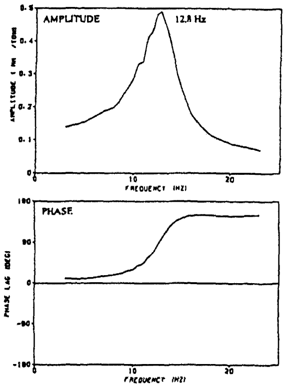

Fig. 4 Horizontal displacement of pilecap (4 steel piles, NS, no backfill)

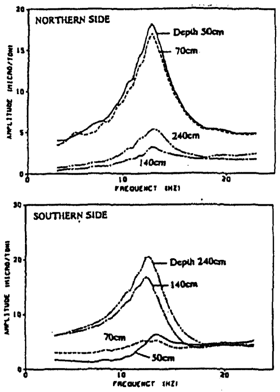

Fig. 5 Strains of pile with depth (4 steel piles, NS, no backfill)

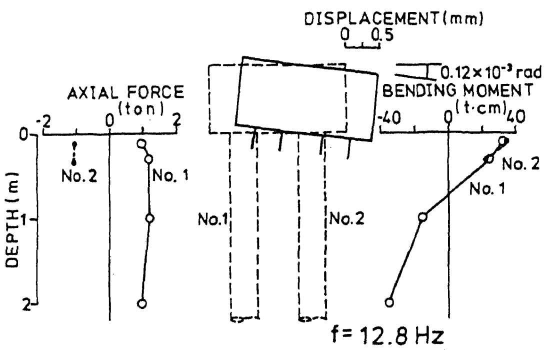

Fig. 6 Displacement of pilecap and internal force of pile at resonant frequency (4 steel piles, NS, no backfill)

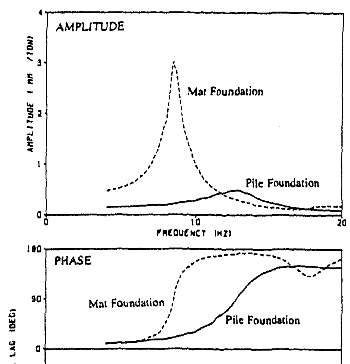

Fig. 7 Horizontal displacement of pilecap with foundation type (4 steel piles, NS)

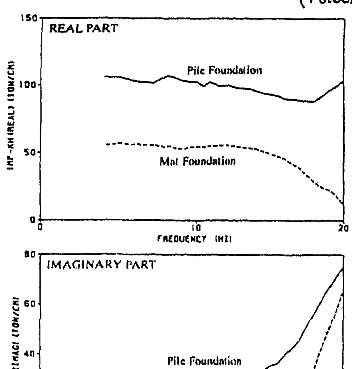

Fig. 8 Horizontal impedance with foundation type (4 steel piles, NS)

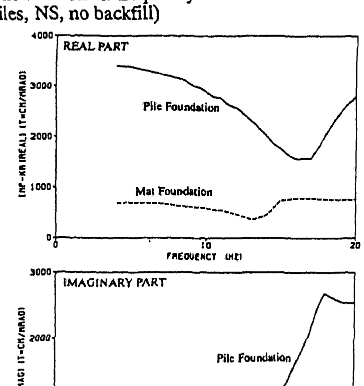

Fig. 9 Rotational impedance with foundation type (4 steel piles, NS)

foundation, respectively. Especially the effect of piles in the rotational mode is remarkable. On the vertical impedance shown in Fig. 10, the pile existence is considerably effective in increasing axial stiffness and radiation damping.

4.2 Distance among piles

The four piles were located at four corners of rectangular pilecaps. Data of different distances among piles were gained by changing excited directions. The ratios of the distance to pile diameter in the steel pile foundation are 2.5 and 3.75 in NS and EW directions, respectively.

The impedance functions in horizontal and rotational modes are presented in Figs. 11 and 12, respectively. Real and imaginary parts of impedance functions increase with distance among piles. This tendency is most remarkable in the real part of rotational impedance function. In order to compare between foundation types, the horizontal impedance functions of the mat foundation are shown in Fig. 13. While the configuration of the foundation is a rectangle(2.5m x 2.0m), the difference of the impedance between the excited directions is not distinguished.

4.3 Number of piles

Figure 14 shows horizontal impedance functions of the two pile and four pile foundations. As number of piles increases, the real part of impedance functions (per one pile) becomes smaller due to dynamic group pile effects. The phenomenon is very similar to static group pile effects. On the other hand, the imaginary part tends to be large with number of piles. The number of piles has very little influence on the imaginary part. Group pile effects in radiation damping seem to be comparatively small. The vertical impedance functions with number of piles are indicated in Fig. 15. The vertical impedance has almost the same characteristics as the horizontal impedance. The effect of number of piles on vertical impedance is a little larger than that on horizontal one.

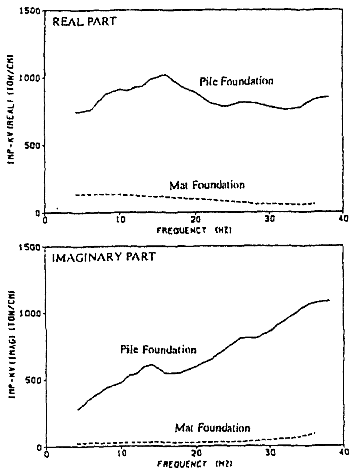

Fig. 10 Vertical impedance with foundation type (4 steel piles)

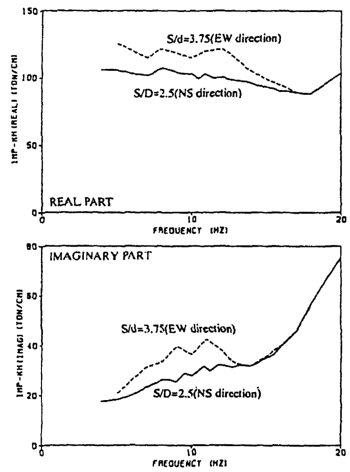

Fig. 11 Horizontal impedance with distance among piles (4 steel piles)

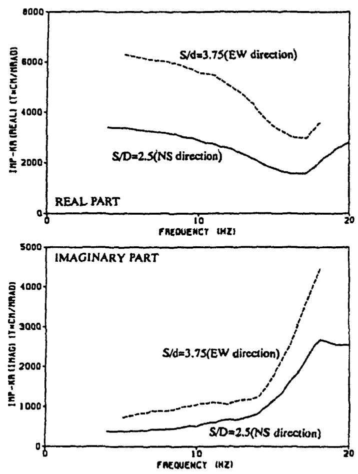

Fig. 12 Rotational impedance with distance among piles (4 steel piles)

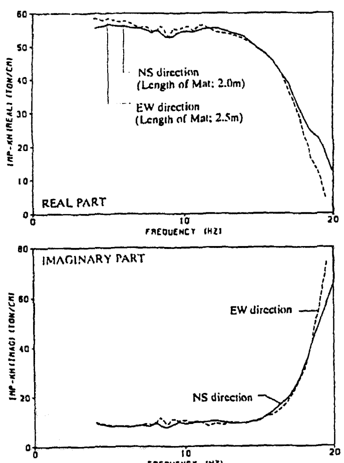

Fig. 13 Horizontal impedance with excited direction (mat foundation)

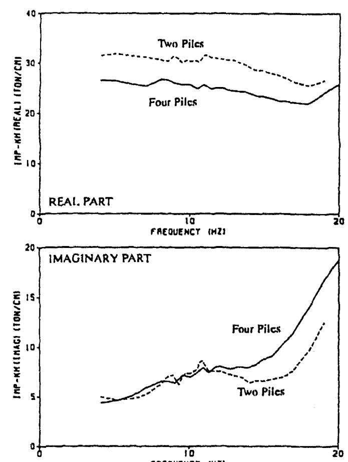

Fig. 14 Horizontal impedance with number of piles (steel pile, NS)

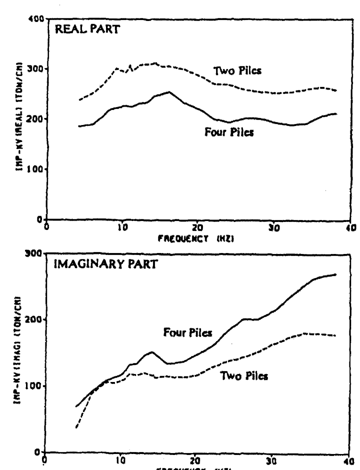

Fig. 15 Vertical impedance with number of piles (steel pile)

5 DYNAMIC EFFECTS OF BACKFILL

In the previous section, the responses of foundations whose pilecaps are not backfilled are discussed. These foundations had trenches(80cm in width and 100cm in depth)around pilecaps. The trenches were backfilled by sand and the sand with a little water was rammed down by man-power. The backfilled soil is not so dense because of limitation of the man-power. In this section, the effects of backfill are investigated through making a comparison of responses between backfilled foundations and no-backfilled ones.

In the response of pilecaps indicated in Fig. 16, the amplitude of displacement response becomes small by the backfill and the resonant frequency is not found out in the amplitude. The amplitude curve is not smooth compared with that of no-backfilled foundation. As dynamic behavior of the backfill itself changes with frequencies, the influence of backfill on foundation responses seems to be complicated. There seems the reason that the backfilled soil was not well compacted.

The horizontal and rotational impedance functions in pile foundation are shown in Figs. 17 and 18, respectively. On the horizontal impedance, the backfill is effective at low frequencies in the real part. The effect of backfill is remarkable at all frequencies in the imaginary part. Figures 19 and 20 indicate the impedance functions of the mat foundation. In the case of mat foundation, the backfill effect is more remarkable than that in the pile foundation. Values of horizontal impedance in the mat foundation are almost the same as those in the pile foundation except at high frequencies in the real part.

6 DYNAMIC EFFECTS OF SOIL NONLINEARITY

To investigate the effects of soil nonlinearity on the response of pile foundations, a pile foundation with small diameter pipes was designed. It was intended that the excited force would be relatively increased by considering the specimen with low stiffness.

The displacement response of the pilecap are shown

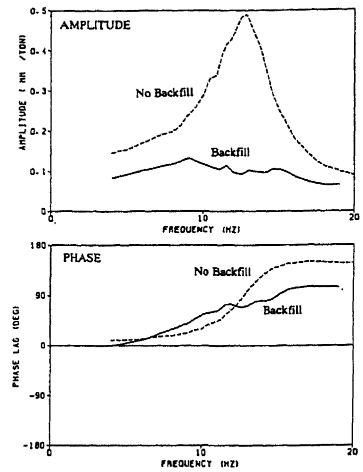

Fig. 16 Horizontal displacement of pilecap with backfill (4 steel piles, NS)

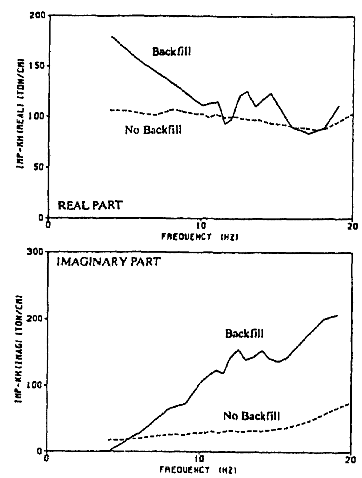

Fig. 17 Horizontal impedance with backfill (4 steel pile, NS)

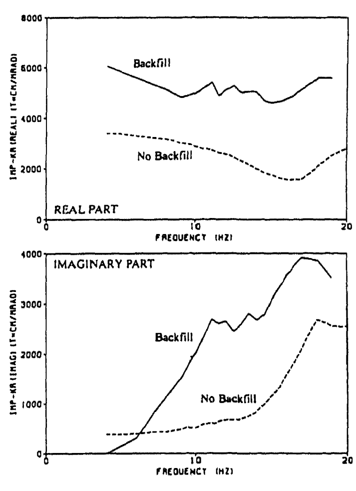

Fig. 18 Rotational impedance with backfill (4 steel pile, NS)

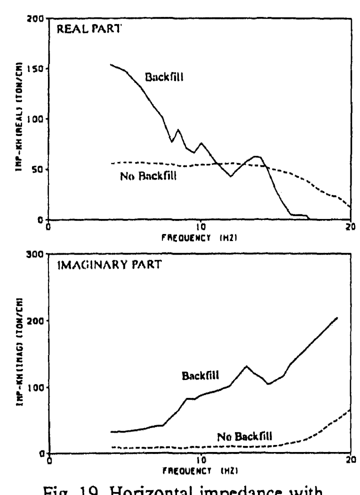

Fig. 19 Horizontal impedance with backfill (mat foundation, NS)

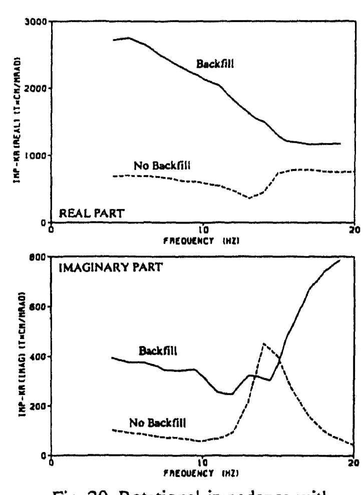

Fig. 20 Rotational impedance with backfill (mat foundation, NS)

in Fig. 21 with eccentric moments of the oscillator. With increasing the excited force which is proportional to the eccentric moment, resonant frequencies of the foundation are gradually low and corresponding amplitudes are large. It results from decrease of subgrade reactions to piles as increasing displacement of piles.

The decrease of the subgrade reactions has effects on impedance functions illustrated in Figs. 22 and 23. The effect of soil nonlinearity on impedance functions are distinguished in both horizontal and rotational ones. On the horizontal impedance, both real and imaginary parts decrease with excited forces. In the real parts of rotational impedance, though the same characteristics are observed, the effect of excited forces is less than that in the horizontal impedance. Compared between horizontal and vertical displacements at pile heads in the horizontal oscillation, the horizontal displacements are larger than the vertical ones. As the displacements of piles are small in the vertical oscillation, the effect on soil nonlinearity is not found in the vertical impedance indicated in Fig. 24.

7 CONCLUSIONS

Concluding remarks on dynamic effects of piles and backfill on impedance functions are summarized as follows.

1)The effect of pile existence are remarkable in rotational and vertical impedance because of stiffness increase due to axial resistance of the piles.

2)Due to group pile effects, stiffness of the pile foundations (per pile) becomes small with the number of piles, while damping is not much affected by the number of piles in low frequencies. Group pile effects in damping are comparatively small.

3)Backfill effects on stiffness and damping are remarkable at almost all frequencies. Backfill increases both stiffness and damping.

4)The effect of soil nonlinearity tends to decrease both real and imaginary parts of impedance functions.

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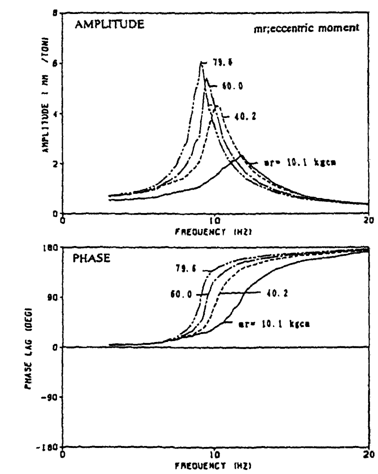

Fig. 21 Horizontal displacement of pilecap with eccentric moment(small diameter pile,EW)

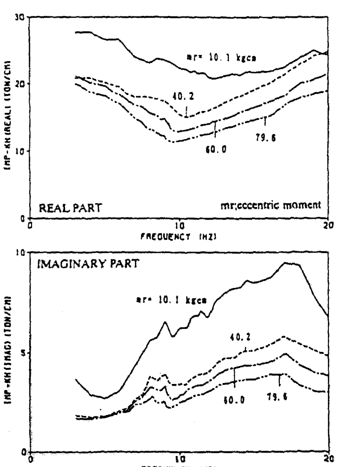

Fig. 22 Horizontal impedance with eccentric moment (small diameter pile, EW)

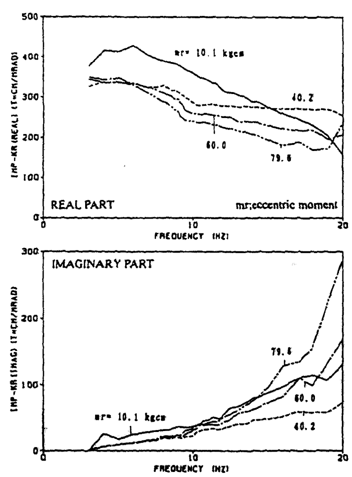

Fig. 23 Rotational impedance with eccentric moment (small diameter pile, EW)

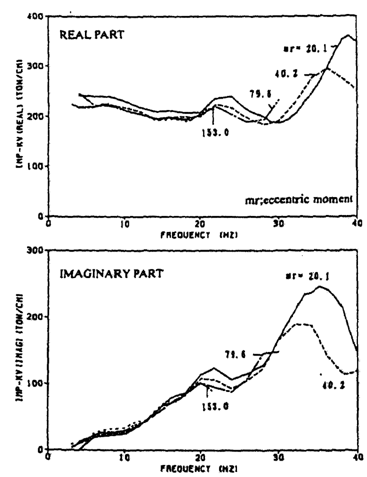

Fig. 24 Vertical impedance with eccentric moment (small diameter pile, EW)