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# EXPERIMENTS STUDY ON SOIL-PILE DYNAMICS USING ELECTROMAGNETIC INDUCTION TYPE SHOCK WAVE SOURCE

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In order to clarify soil-pile dynamics, a new experimental method using an electromagnetic induction type shock wave source was developed. In the experiment, a ground model was made of water-cured urethane polymer, and a pile of urethane was buried in this gel-like ground. An impulse with duration time of 0.5 ms was given to the pile head by the shock wave source. This device consists of an aluminium circular plate and a flat solenoid coil close to this plate. A capacitor discharge through the solenoid serves as the energy source. Using this device makes it possible not only to estimate exact response characteristis of soil-pile systems pretty well but also to follow sharp wave fronts by photoelastic experiments.

## 1. INTRODUCTION

The interaction between a pile and the surrounding soil can be theoretically studied on the basis of either continuous or discretized models. Continuous models such as those proposed by Tajimi[1], Novak[2)~5)] and the other reserchers can be used to estimate the wave dissipation effect qualitatively, while discretized models have the advantage of being able to incorporate nonlinearity and nonhomogeneity of soil-pile systems.

In recent years, the so-called substructure method has developed so as to combine the merits of these two methods[6]. Using the substructure method, it becomes possible to bring the nonreflecting boundary effect into analyses by discretized models. However, it should be noted that defects of both discretized models and continuous ones are also involved in the analyses. When the substructure method is used, special considerations are necessary for frequency range, boundary conditions and so on.

An experimental method can be used not only for examination of these new-developed numerical methods but also for estimation of dynamic properties of complicated soil-pile systems. Here, it is necessary to devise a way of reducing the effect of waves reflected from unavoidably settled model boundaries. It might be achieved by using a shock wave source and by leaving the needless reflected waves out of consideration. It is usually the case that a powder explosion or a mechanical blow such as that by a drop hammer is used as the shock wave source. But, it is difficult to make perfectly the same wave form repeatedly by these methods. Furthermore, when we use a mechanical shock wave source, we must remember that the duration time of a blow depends on the mechanical impedance of the model, and that it is difficult to shorten the duration time if the impedance of the object is small.

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The authors have an opinion that it would be better to substitute an electromagnetic induction type shock wave source[7] for the explosive or the mechanical one. The device consists of an aluminium circular plate on a driving surface on the model and a flat solenoid coil close to the plate. A capacitor discharge through the solenoid serves as the impulsive energy source.

In this paper, the detail of the experimental method using the device is described, and the applicability of the method is examined through percussion tests of model piles driven into two types of gel-like model ground.

## 2. EXPERIMENTAL METHOD

### ( 1 ) Experimental Materials

In order to get the clear observation of wave propagation in the model ground, it is convenient to make the model ground of soft rubber-like material with low shear wave velocity, Gelatine and polyacrylamide may be the most typical materials serving the purpose. Shear wave velocity in the gelatine gel or in the polyacryl-amide gel can be easily controlled within the range 2 to 6 m/s by changing the mixing ratio of substances dissolving in each solvent. Forthermore, it is worthy of special mention that photoelastic sensitivity of gelatine is so high that we can observe not only the effect of dead weight but also the sharp wave fronts propagating slowly with large amplitude by the photoelastic method.

For all these good features, some difficulties arise in conducting experiments. When gelatine is used, it requires careful treatment not to induce thermal stress in the model in the curing process of the hot solution. If the experiments extends over a long time, we have to devise a way of preventing the gelatine gel from becoming stale. These problems can be solved by substituting polyacrylamide for gelatine. We, however, must remember that polyacrylamide is deadly poisonous.

The authors adopted water-cured urethane as a suitable substitute for above materials. The excellent characteristics of the adopted polymer are as follows :

① Since the urethane is formed by mixing water and water-curable urethane prepolymer sol under regular thermal condition, there is no need to prepare a boiling apparatus. Thus a satisfactory ground model without thermal stress can be obtained.

② The polymer is innoxious and antiseptic.

③ Mass density and Poisson's ratio are about 1.1 and 0.5 respectively. These values are common to most gel-like materials. Stress-strain relation of the polymer can be easily controlled so that it coincides with that of the gelatine gel or the polyacrylamide gel.

④ Under the same experimental conditions, water-cured urethane is the strongest among the gel-like materials mentioned above with the same solution concentration.

⑤ The polymer is transparent, and the photoelastic sensitivity is extremely low.

Special attention should be paid to the last item 5). Since the photoelastic sensitivity of the water-cured urethane is so small such as one or two-tenths of that of gelatine, we can follow the waves travelling in a three-dimensional model of urethane as dynamic distortion of photoelastic fringes by inserting a gelatine plate of the same mechanical properties in the model ground[8),9)].

The most serious trouble in using urethane is due to carbon dioxidide bubbles which appear in the curing process. These small bubbles come up gradually to the surface of the urethane solution. The bubbles which do not reach to the surface within the solidification time remain permanently in the cured polymer. The denser and the warmer the urethane solution is, the larger is the amount of entrapped bubbles. These bubbles have serious effects on Poisson's ratio and transparency of the model. Hence, special precautions should be taken to prevent the bubbles from being trapped inside the model.

In order to examine the bubbling properties, two kinds of water-curable urethane prepolymer sol were prepared as the solute in water. One is bifunctional prepolymer sol called MYH-T 3. If the concentration of the solution does not exceed 20 %, almost all bubbles in the solution come up to the surface in the first one hour or two of the curing process. However, if the concentration does not reach to 10 %, each bubble does not become large enough to get sufficient buoyancy in the viscous solution. This leads to white wax-like turbidity of the gelled model. Hence, we must controll the concentration within the range 10 to 20 %. The other prepolymer sol called MYH-T 6 is the mixture of bifunctional prepolymer sol and trifunctional one. The mixing ratio of the former to the latter is 1 : 0.3. Consequently, the intermolecular cross linking of the urethane polymer becomes more complicated, and the water-cured polymer is stiffer than that made from MYH-T 3. It is desirable to keep the concentration, just as the concentration of the MYH-T 3 solution being controlled, within the range 10 to 20 %. Fig. 1 shows shear wave velocity-concentration relations for the three kinds of solution. In spite of the restiction of concentration, we can widely control the shear wave velocity in the urethane model by blending these kinds of prepolymer sol.

We adopted a stiff urethane bar (diameter ; 10 mm, length ; 233 mm) as a model of PC pile. Longitudinal wave velocity in this bar is about 200 m/s. When the bar is regarded as an equivalent model of a PC pile with a diameter of 30 cm and a length of 7 m (JIS A 5335), water-cured urethane having shear wave velocity of 3 m/s corresponds to the saturated soft ground with shear wave velocity of 60 m/s.

(2) Manufacturing Process of Model

In order to observe the wave fronts radiated from a model pile as the moving photoelastic fringes, we made a sandwich-like ground model of urethane in which a gelatine plate was inserted. It is desirable to reduce thermal stress in the gelatine plate. Hence, the gelatine plate, on which acceleration transducers and the model pile had been previously placed, was dug out from a double mold (Fig. 2, Fig. 3(a) and Fig. 3 (b)). At this stage, all sides of the gelatine plate were still restrained by acrylic frames. This plate was carefully inserted in the tank filled with the urethane solution along the guide (Fig. 3(c)). After the urethane solution had been cured, the upper frame exposed on the surface of the sandwich-like ground model was removed (Fig. 3(d)). Adopting the process, the gelatine plate, whose Poisson's ratio is about 0.5, is fixed in the urethane gel under the static liquid pressure. Accordingly, principal stress difference

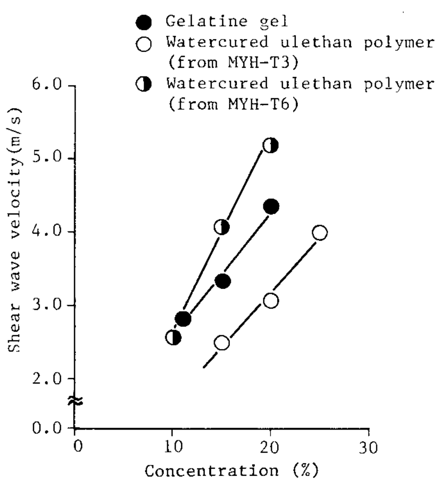



Fig. 1 Variation of shear wave velocity of gel with solution concentration.

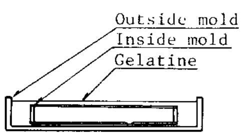



Fig. 2 Double mold for a gelatine plate.

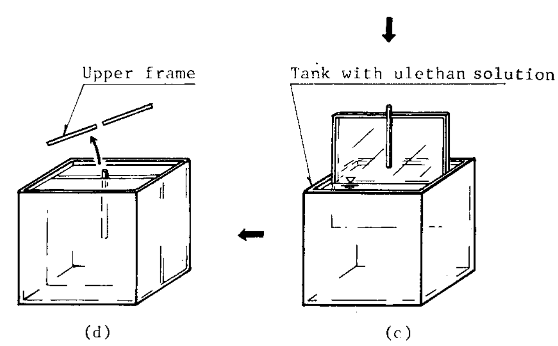



Fig. 3 Process of making model ground.

at any point in the gelatine plate is frozen to be zero, and then, no static photoelastic fringe appears. This makes it easy to observe the sharp wave fronts by the photoelastic method.

This process is also applicable to the manufacture of the sandwitch-like ground model composed of several layers. However, in this case, it may be difficult to wipe out static photoelastic fringes because of the more complicated manufacturing process as follows :

① The gelatine plate composed of several strips is set in the vacant acrylic tank.

② The placing-curing process of the urethane solution is repeated so as to form a stratified model.

Two types of sandwitch-like model were prepared. One is a homogeneous isotropic ground model with shear wave velocity of 3 m/s. The other is two-layered ground model. The shear wave velocity in the surface layer (17 cm in thickness) and that in the base are 2.6 m/s and 4.3 m/s respectively.

(3) Electromagnetic Induction Type Shock Wave Source

Fig. 4 shows the schematic view of the electromagnetic induction type shock wave source used in the experiment. This device, as previously stated, consists of an aluminium disk (radius ; 10 mm) on the pile head and a flat solenoid close to the disk. A capacitor discharge through the solenoid serves as the impulsive energy source. Under the condition that the gap between the solenoid and the aluminium disk is perfectly fixed, the repulsive force $F$ induced between the solenoid and the disk can be given as follows :

$$F=F_0 \exp(2h\omega_0 t)\sin^2 \omega_0' t \cdots\cdots (1)$$

where

$$F_0=N\frac{\pi\mu_0 n^2}{L},\quad N=\frac{CV^2}{2},\quad \omega_0'=\omega_0\sqrt{1-h^2},$$

$C$ : electrostatic capacity (F),

$V$ : charging voltage (V),

$h$ : damping constant of the series resonance circuit,

$n$ : number of turns of the solenid,

$L$ : total inductance (H),

$\mu_0$ : space permeability ($1.26\times10^{-6}$ Vs/Am),

$\omega_0$ : natural circular frequency of the series resonance circuit.

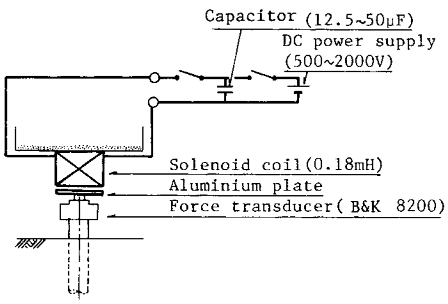



Fig. 4 Electromagnetic induction type shock wave source.

Eq. (1) represents a series of impulses proportional to the square of the alternating current induced in the circuit. It may be necessary to insert a suitable resistance which is large enough for the trailing impulses to disappear. However, even if no resistance is inserted in the circuit, the amplitude of the current is reduced in alternating process by the so-called skin effect, and in practice, no sooner discharges the capacitor than the trailing impulses diminish to be negligibly small, because the gap between the solenoid and the aluminimn disk on the pile head is suddenly enlarged by the repulsive force. This leads to the phenomenon that only a succession of a few repulsive forces is impressed on the pile head. There may be no serious problem regarding the succession of two or three repulsive forces as a simple repulsion with the same amount of impulse. Accordingly, it did not need to use a variable resistance for modifying the repulsion wave form.

It should be noted that the repulsion wave form is strongly affected by the mechanical impedance of the model. Hence. it is necessary to control the suitable wave form empirically. For this purpose, 20 oil-impregnated capacitors (10 μF, 1 000 V max.) were prepared and arranged to be a suitable capacitor.

(4) Measuring System

Fig. 5 shows the location of acceleration transducers and measuring directions. It is desired for each transducer to have a wide frequency range and light weight because it encounters relatively high frequency tremor in the gel-like ground model where the use of heavier transducers would alter the wave form. Hence, we adopted a piezoelectric acceleration traasducer (Rion PV 90 A) whose frequency range covers from near DC to 25 kHz. The transducer is 6 mm in diameter, 10 mm in height and 1.2 g in weight.

The measuring system is shown schematically in **Fig. 6**. After output signals from the accelerometers and the force transducer (B & K 8 200) on the pile head are conditioned by charge amplifiers (EMIC 505 CA), they are transmitted to the magnetic tape recorder (TEAC R-81). It should be noted that some output signals such as those from the transducers near the shock wave source contain high frequency components which can not be recorded by the FM type data recorder. Consequently, these data were converted into serieses of digital values at the time interval of 1 $\mu$s by AD converters built in the wave memory, and were saved on floppy disks through the personal computer (SHARP MZ 2 000).

A common approach to record the moving photoelastic fringes produced by an impact is to use a continuous light source and a high speed framing camera (or streak photography). We, however, adopted the simpler method using an ordinary camera and a xenon lamp, because it is possible to reproduce perfectly the same repulsion wave form by using the electromagnetic induction type shock wave source. The shock wave signal from the acceleration transducer at the pile head is transmitted to the microcomputer (NEC TK-85) so as to act as the trigger of operation of controling the illumination instant. The high-intensity, short-duration flash of xenon lamp is diffused by the frosted glass, and passes through the polariscope arrangement, between which the transparent ground model is mounted. Consequently, we can easily take a transient picture of moving fringes by an open-shutter camera. If we use an instant camera, it becomes possible to rearrange the experimental condition by consulting the immediately developed and printed photographs.

It is desirable to photograph moving fringes in the monochromatic light. For this purpose, a glass filter having a band center wave length of 5461 Å is attached to the camera lens to filter out all of emission except the monochromatic component. This leads to the noticeable reduction of the light thrown upon the film. However, using the electromagnetic induction type shock wave source, it becomes possible to stack perfectly the same fringe images on a film, and finally, a clear photograph can be obtained.

## 3. EXPERIMENTAL RESULTS AND DISCUSSIONS

### (1) Repulsive Force

The driving voltage measured between the both terminals of the solenoid coil is shown in **Fig. 7**. As shown in the figure, the damping constant and the natural circular frequency of the series resonance circuit are 0.114 and 14 400 rad/s, respectively. The observed natural circular frequency is almost the same as the calculated one (14 900 rad/s) under the assumption that the inductance of the whole circuit is much the same as that of the solenoid coil (0.18 mH). Plugging these observed constants into Eq. (1), the repusive

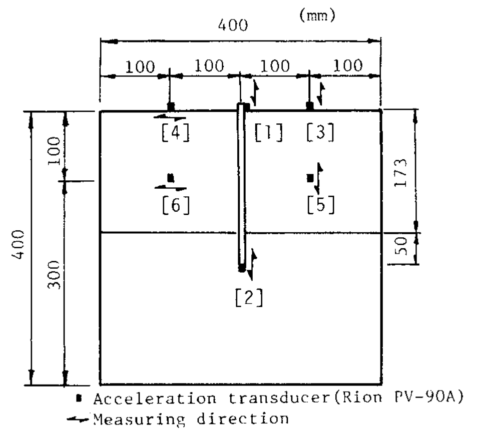



**Fig. 5** Location of acceleration transducers.

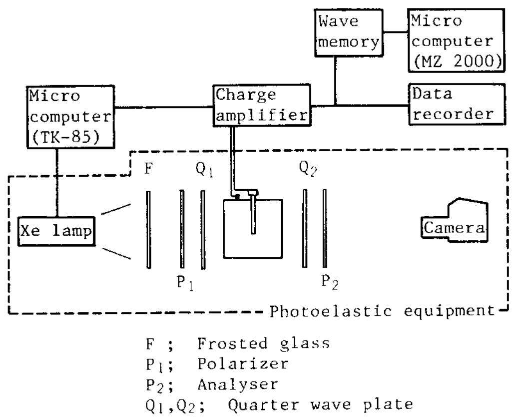



**Fig. 6** Measuring system.

force $F$ induced in the restrained gap between the solenoid and the aluminium disk can be obtained as follows (Eq. (2) and **Fig. 8**) :

$$F=F_0 \exp(-3\,280\,t)\sin^2(14\,300\,t) \cdots\cdots (2)$$

where

$$F_0=3.32\times10^3\ \mathrm{N}$$

The observed repulsion wave form at the pile head is shown in **Fig. 9**. The first peak value is 95 N, which is about one-24th of the calculated value because the mechanical impedance at the pile head is extremely low. It can also be recognized on the wave form that the repulsive force turns negative momentarily, primarily because of the inertia of the mass of the aluminium disk attached to the force transducer on the pile head (See **Fig. 4**). The trailing wave amplitude after the third peak is negligibly small. Consequently, one equivalent impulse may be substituted for the succession of three repulsions with the total duration time of about 0.5 ms.

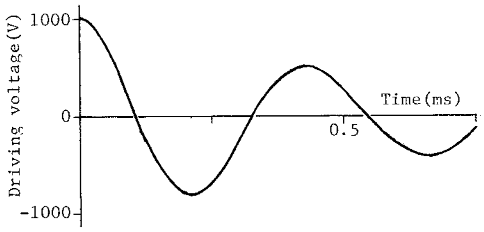



Fig. 7 Measured driving voltage.

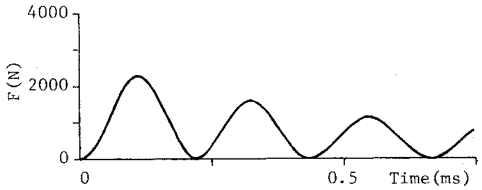



Fig. 8 Computed force applied to the pile head.

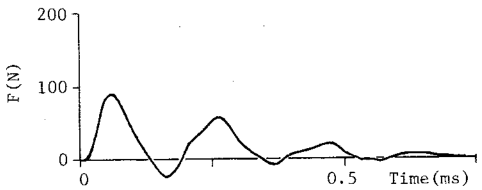
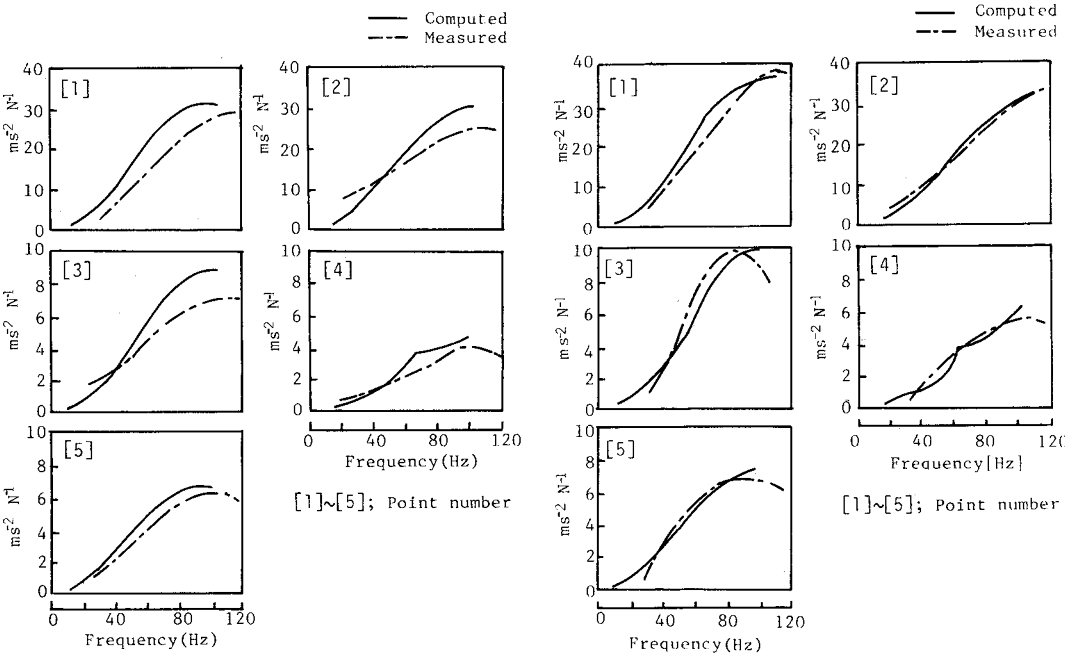



Fig. 9 Measured force applied to the pile head.

### (2) Dynamic Response of the Soil-Pile System

The sequence of 1 024 values of each wave form sampled every 200 $\mu$s was transformed into a Fourier spectrum. Here, the needless wave signal from unavoidably settled model boundaries was substituted by the sequence of zeros. Each spectrum was divided by the impulse applied to the pile head to be a frequency response function of acceleration. In order to estimate the obtained frequency respose functions, we compared these values with the calculated ones by the substructure method proposed by Konagai[10]. In the method, a pile consists of discrete rigid disks whose radius is equal to that of the pile. They are connected in series by linear linkages. The ground stiffness supporting each disk is expressed as a complex function of frequency. This means that noticeable amount of energy in a pile dissipates through wave propagation into the continuous half space. Since it is difficult to obtain the exact ground stiffness supporting a rigid disk, the assumption that the dynamic contact pressure distibution is much the same as the static one is adopted. Accordingly, the precise solutions by the method should be limited within the range of $A(=\omega R_0/V_S)$ being 0 to $\pi/3$, where $\omega$, $R_0$ and $V_S$ are the circular frequency, the radius of the disk and the shear wave velocity in the ground, respectively. By the method, the motion of the pile and that of the ground can be obtained separately. After the interface forces between disks and the groung are obtained, we can calculate the ground tremor by applying the dynamic reciprocal theorem to the Lamb's solution[11] which represents wave propagation in a semi-infinite elastic solid caused by one point sinusoidal source on the surface of the solid. As the result of the approximation, the effects of reflected waves from the boundary of strata and dispersion of the Rayleigh wave are left out of consideration, and yet, they are not so serious if the observing point is located near the pile. Another additional assumption was made to calculate the underground tremor. It is that the amplitude of the cylindrical shear wave radiated from the pile is dominant and is reduced in inverse proportion to the square root of the distance between the pile axis and the wave front.

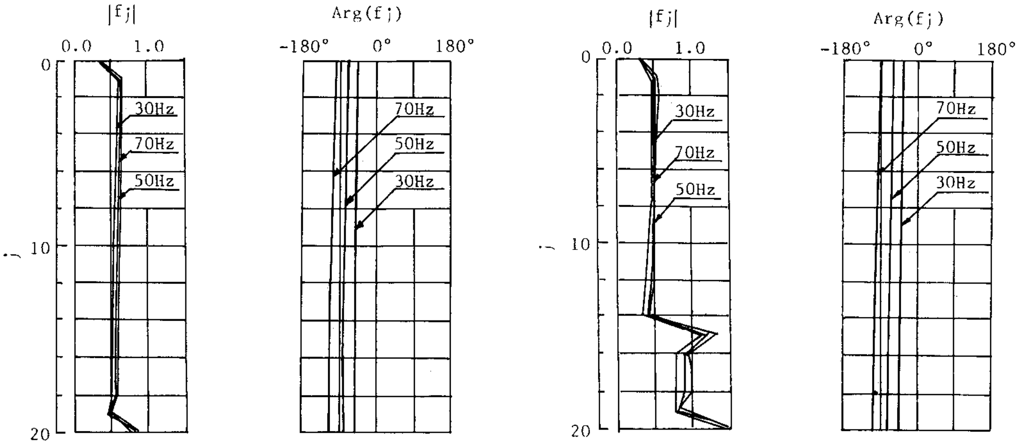
We arranged the experimental results of frequency response together with the corresponding computed values point by point, and showed them in **Fig. 10** (a) (model ground without a surface layer) and **Fig. 10** (b)




(a) Model ground without a surface layer

(b) Model ground with a surface layer

**Fig. 10** Frequency response of acceleration.




(a) Model ground without a surface layer

(b) Model ground with a surface layer

**Fig. 11** Interface forces between disks and model ground.

(two-layered model ground). Computation of response curves is limited within the range of frequency being 0 to 100 Hz, which satisfies the previously mentioned condition that the value of $A(=\omega R_0/V_s)$ does not exceed $\pi/3$. The model soil-pile system seems to have the first natural frequency of 100 Hz. However, each response curve does not feature an apparent peak because of large radiation damping. In this frequency range, the measured values almost agree with calcu-

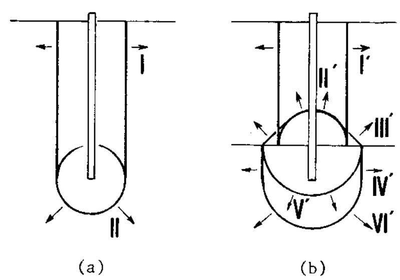
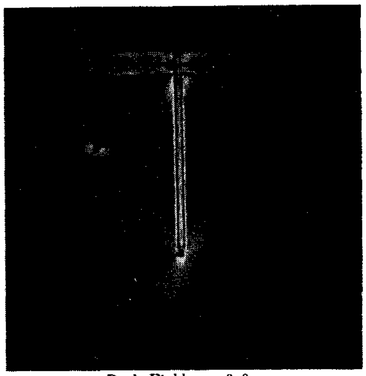
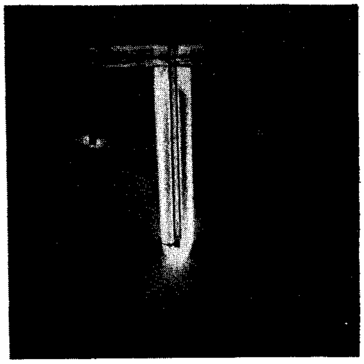


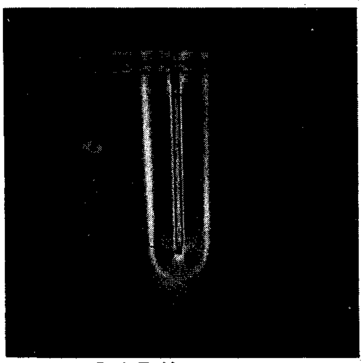

**Fig. 12** Observed wave fronts.



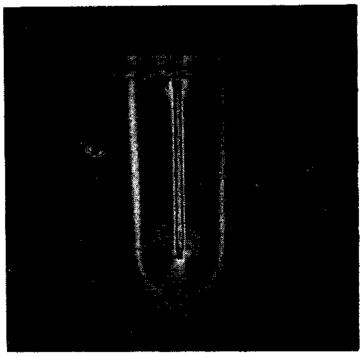
Dark Field 0.0 ms



Dark Field 4.8 ms

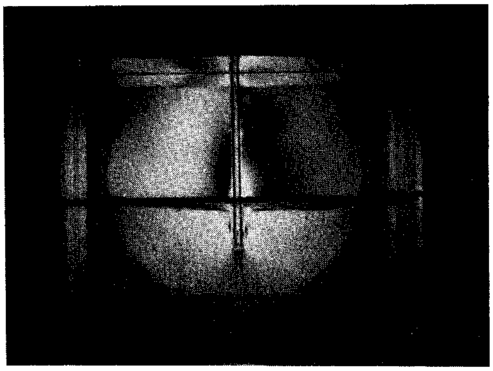


Dark Field 9.5 ms

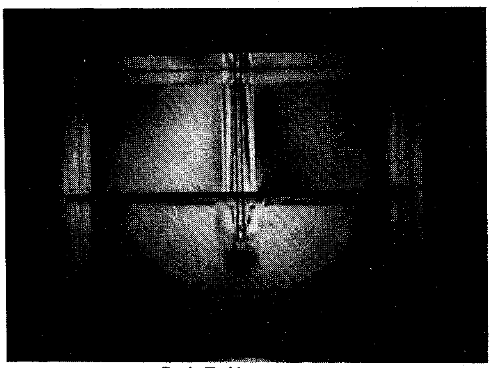


Dark Field 14.0 ms

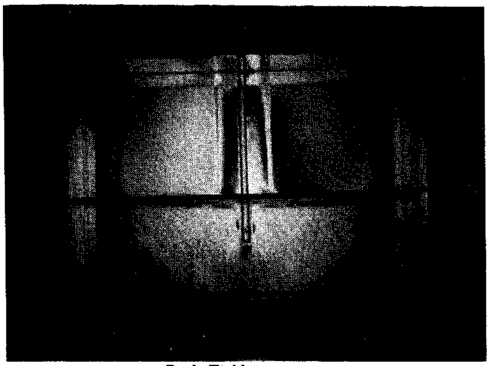
(a) Model ground without a surface layer



Dark Field 0.0 ms



Dark Field 4.8 ms



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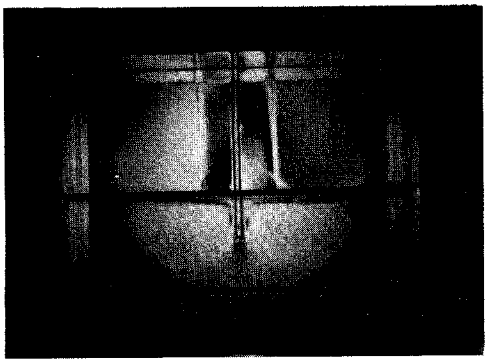

Dark Field 14.0 ms

(b) Model ground with a surface layer

Fig. 13 Radiation of wave fronts.

lated ones.

Fig. 11 shows typical examples of the computed soil-disk interface force distribution along the pile axis. As is evident in the figure, the interface force distribution is almost uniform along the axis without some special points such as the pile end ($j=20$) and the point of intersection of the pile and the strata boundary ($j=15$). This shows that it is appropriate to assume that the cylindrical shear wave is dominant around the pile foundation.

(3) Motion of Photoelastic Fringes

We photographed the shear wave propagation from the pile into the half space of gel-like ground every 4.7~4.8 ms by the proposed photoelatic method, and showed the prints in Fig. 13(a). They were photographed in the white light of xenon lamp, because, as far as moving fringes of low order are concerned, there is little difference of informations whether in monochromatic light or in white light. Moving fringes are sharply recorded on each print as bright lines in the dark field. As sketched in Fig. 12 (a), two kinds of wave front are observed. One (Ⅰ) is the cylindrical shear wave front and the other (Ⅱ) is the spherical wave front radiated from the pile end. The brightness of the spherical moving fringe near the pile axis diminishes more rapidly than the others because of the well-known directivity of shear wave amplitude due to a one-directioal point source.

Fig. 13(b) shows the shear wave propagation in the two layered ground model. As sketched in Fig. 12 (b), we can observe not only the cylindrical wave front (Ⅰ′) but also the circular conical wave front (Ⅲ′) together with the inscribed sphere (Ⅱ′). The circular intersection of the cone and the strata boundary must coincide with the cut end of the cylindrical wave front (Ⅳ′) traveling in the second stratum. However, it is difficult to detect the shear wave fronts travelling in the second stratum as the moving photoelastic fringes, probably because the principal stress difference in the second stratum was noticeably reduced by spherical (Ⅵ′) or conical (Ⅲ′) wave radiation.

## 4. CONCLUSIONS

The purpose of this paper is to discuss the applicability of the experimental method for soil-pile dynamics using an electromagnetic induction type shock wave source. The sharp impulse induced by the device is all that can be desired not only in estimating the precise response characterstics of soil-pile models but also in performing photoelastic observation of elastic wave fronts. We prepared sandwitch-like (urethane-gelatine-urethane) ground models in order to observe the moving photoelastic fringes in the gelatine plate, and conducted percussion tests of the model pile.

The conclusions obtained through the study are as follows:

(1) The gelatine plate, on which the model pile and acceleration transducers were placed, was sunk into the urethane solution in the transparent acrylic tank. No static photoelastic fringe appears because the gelatine plate is fixed in the urethane polymer under the static liquid pressure.

(2) The problem in using the water-cured polymer is that carbon dioxidide bubbles appear in curing process. Bubbles which remain in the cured polymer have serious effects on Poisson's ratio and transparency of the model. In order to expel as much bubbles as possible, it is desirable to control the concentration of the urethane solution within the range 10 to 20%.

(3) Frequency response functions calculated from observed wave form trailing zeros as the substitute for the needless waves reflected from the model boundary, agree well with those calculated by the substructure method in which the ground is replaced by a semi-infinite half space.

(4) The repulsion induced by the electomagnetic induction type shock wave source is so strong and transient that we can photograph sharp wave fronts as the bright photoelastic fringes in the short-duration flash of xenon lamp.

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