NONLINEAR ANALYSIS OF SURFACE GROUND MOTION BY DIGITAL CONTROL ON-LINE EXPERIMENTAL METHOD

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SUMMARY

This paper describes new hybrid system to compute the nonlinear response and to analyze the nonlinear restoring force characteristics of a surface ground during a strong earthquake. This experimental method was first developed by the author. The experimental apparatus consists of an digital calculator connected to a dynamic tri-axial soil testing machine. By means of this hybrid computing system, the author has got the nonlinear restoring force characteristics of a saturated sandy ground against a sine input wave.

INTRODUCTION

Generally it is necessary to grasp the relation of stress vursus strain regarding a structure, in order to analyze the nonlinear response of the structures against the dynamic external force. For that purpose, the behavior of the structure is numerically analyzed by using usually a stress-strain relation standardized into a specific model by mathematical equations. The procedure will be likewise followed with regard to the nonlinear vibration analysis of surface ground when an earthquake happens.

Two major problematic points arise in connection with the above analytical method. One is a dynamic testing method by which a stress-strain relation can be obtained. Another is the standardization of the thus obtained stress-strain relation into a specific model. Usually, nonlinear restoring force characteristics of the soil are analyzed by the dynamic test based upon a stress controling method. In case of the saturated sand we can not continue to hold the aimed value of the hydraulic controlling system until the perfectly liquefied state is attained even with reference to stress controlling.

As a mode to dissolve such difficulty, a method of nonlinear vibration analysis by an on-line real time experimental method was brought forward by Hakuno(1969), one of the authors, for the first time in the world, and the efficiency has now been proved. By use of this analytical method, the authors analyzed the nonlinear response and restoring force characteristics of saturated sandy ground to which a random wave was given (1982).

In this paper, we analyze the nonlinear restoring force characteristics of saturated sandy ground against sine input wave (3 Hz).

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ON-LINE EXPERIMENT METHOD

Outline of the method

In order to numerically analyze the nonlinear vibration of the structures against the seismic external force, a relational equation representing a relationship of 'restoring force vs. displacement' is required.

But in on-line experiment method the standardization of the restoring force characteristics into a specific model is not made and response calculation is carried out upon real time basis by being provided with the real restoring force from the dynamic test.

Since the soil exhibits very complicated nonlinear restoring force characteristics, it is a considerable degree of difficult thing to assume the characteristics with great accuracy. It can be therefore said that the on-line experimental method with which no standardization of the restoring force characteristics into a specific model is proceeded is adequate enough to analyze the nonlinear vibration characteristics of the ground.

With the on-line testing apparatus for the soil which is newly developed for this study, a tri-axial soil testing apparatus is used as the dynamic tester and digital calculator is used as the calculating device. Illustrated in Fig.1 is a block chart for the on-line real time experimental method for soil.

As seen in Fig.1, this on-line real time experimental system is equivalent to surface ground motion system during the earthquake. Therefore, by use of this experimental method, we can clarify the nonlinear restoring force characteristics that correspond to various input forces.

Maximum response value on the surface ground

In this study, the displacement of the surface ground is calculated from the strain of specimen by assuming the surface ground be an elastic body. The following are the calculations employed in this study: If we take into account of the boundary condition that the value of the shearing stress is zero on the surface ground, the horizontal displacement u at the depth x under the surface ground which is in shearing vibration is given as below.

$$u(t,x)=F(t-\frac{x}{Vs})+F(t+\frac{x}{Vs}) \quad \text{---------(1)}$$

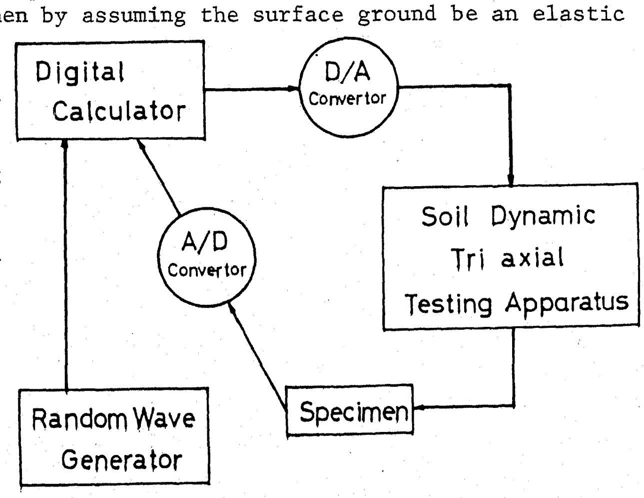

Fig. 1 Block-chart of on-line experiment

If we assume that a sine

wave having the first natural circular frequency ω_1 predominates to the extremest extent, the function F is represented as

$$F(t \pm \frac{x}{Vs}) = A \sin \omega_1 (t \pm \frac{x}{Vs}) \quad \text{---------------}(2)$$

Eq.(1) is converted to

$$u(t,x) = A \sin \omega_1 (t - \frac{x}{Vs}) + A \sin \omega_1 (t + \frac{x}{Vs}) \quad \text{--------}(3)$$

At that time, the shearing strain γ of the surface ground is provided by following equation.

$$\gamma = \frac{\partial u}{\partial x} = \frac{\omega_1}{Vs} A \{ -\cos \omega_1 (t - \frac{x}{Vs}) + \cos \omega_1 (t + \frac{x}{Vs}) \} \quad \text{----------}(4)$$

If we also assume that the specimen of the tri-axial soil testing apparatus is placed at the depth H, the shearing strain γ_H of the ground at the depth H is obtained by putting x=H in Equation (4). Thus, we acquire

$$\gamma_H = \frac{\omega_1}{Vs} A \{ -\cos \omega_1 (t - \frac{H}{Vs}) + \cos \omega_1 (t + \frac{H}{Vs}) \} \quad \text{--------------}(5)$$

Here, it should be assumed that the maximum shearing strain γ_{max} of the specimen obtained by the tri-axial soil test equals the maximum shearing strain γ_{Hmax} created at the depth H of the surface ground. From the Equation (5),

$$\gamma_H = \frac{\omega_1}{Vs} A \{2 \sin \omega_1 t \cdot \sin \frac{\omega_1}{Vs} H\} \quad \text{--------------------}(6)$$

If it is furthermore assumed that since $\omega_1 = 2\pi f_1$ the depth H suffices an equation representing the primary natural frequency $f_1 = Vs/4H$, $\sin \omega_1/Vs\ H = 1$ in the Equation (6), and the maximum values of it is given as below.

$$\gamma_{Hmax} = 2 \frac{\omega_1}{Vs} A \quad \text{------------------------------------}(7)$$

Therefore, $\gamma_{max} = \gamma_{Hmax}$

$$A = \frac{Vs}{2\omega_1} \gamma_{max} \quad \text{--}(8)$$

Since the value of γ_{max} is known from the tri-axial soil test, the value of A can be determined from the Equation (8). The horizontal displacement u_s is the value when x=0 in the Equation (3),

$$u_s = 2 A \sin \omega_1 t \quad \text{------------------------------------}(9)$$

From the Equation (9), the response velocity v_s and the reponse acceleration a_s on the surface ground are obtained, respectively. Furthermore , we can determine their absolute maximum value v_{smax} and a_{smax}. By use of these equations, response values of ground can be concretely obtained.

PHYSICAL PROPERTIES OF SAND, SPECIMEN AND MODEL GROUND

Values of physical properties of sand and the model ground used in the analysis are shown in Figure 2 and Table 1. For the tri-axial vibration soil test, specimen composed of Toyoura standard sand and normal sand (river sand). Dimensions of the specimen are 5 cm diameter and 10 cm height.

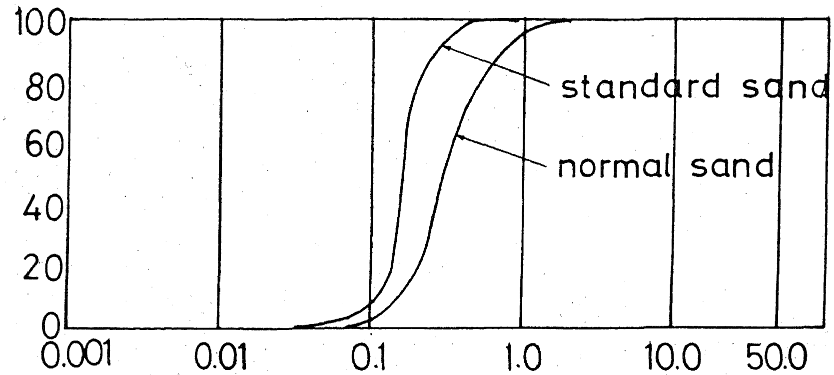

Fig.2 Grain Size Accumulation Curve of Sand used in Analysis

Table 1 Characteristics of Surface Ground Model

FIRST NATURAL FREQUENCY	f	1.2	Hz
SHEARING WAVE PROPAGATION VELOCITY	Vs	150	m/sec
DAMPING FACTOR	β	0.02	

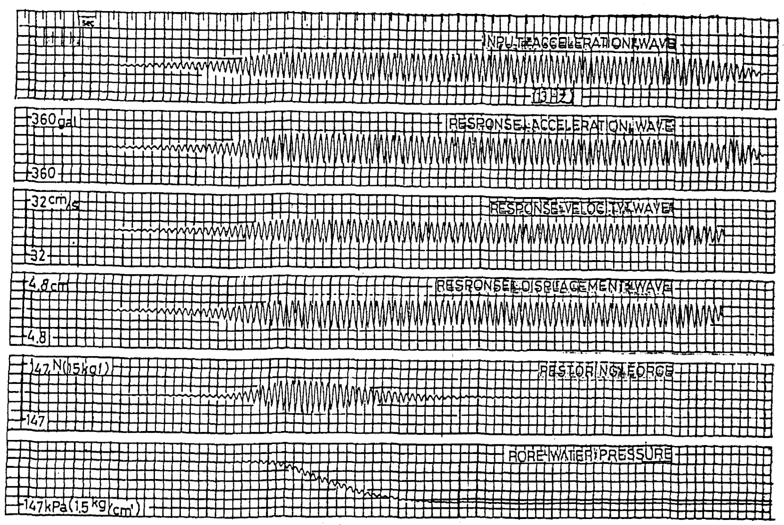

Fig.3 Experimental Results-Part 1 (Saturated Standard Sand, Dr=26.1%)

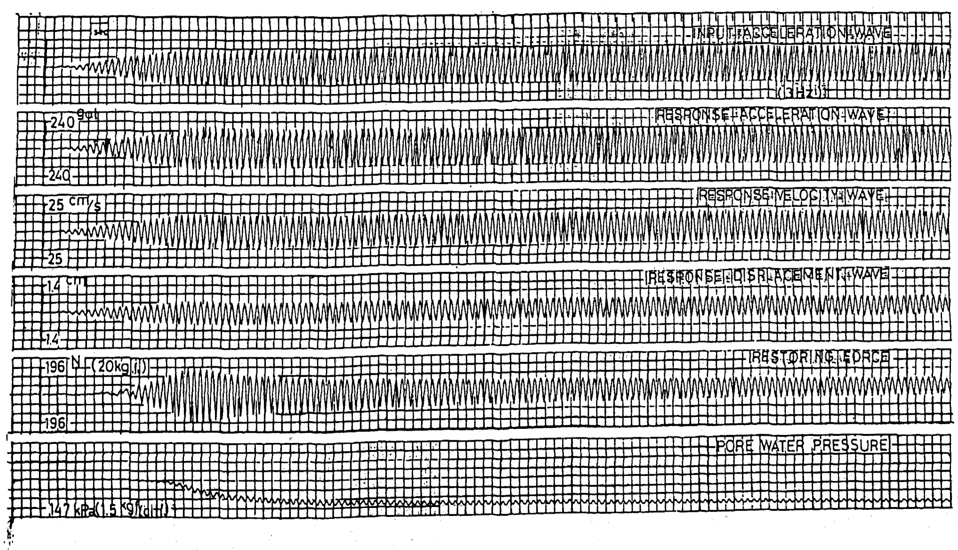

Fig.4 Experimental Results-Part 2 (Saturated Normal Sand, Dr=27.9%)

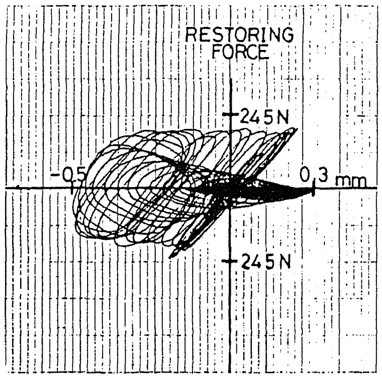

Fig.5 Hysteresis Loop (Standard Sand)

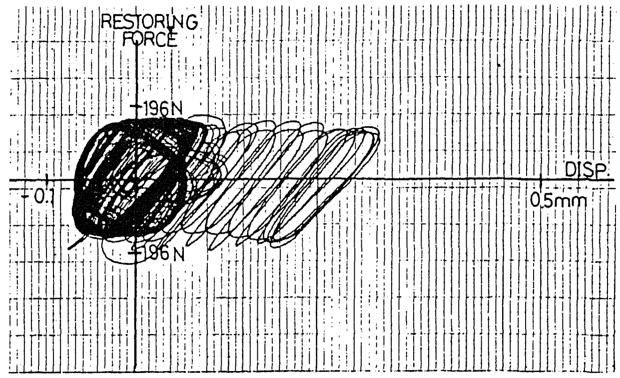

Fig.6 Hysteresis Loop (Normal Sand)

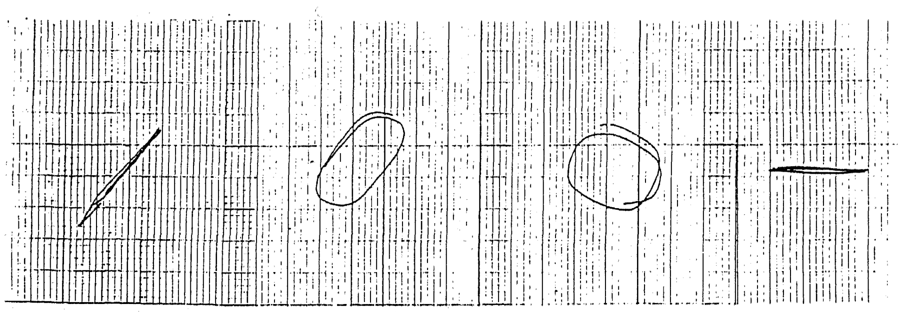

Fig.7 Variation of Hysteresis Loop (Standard Sand)

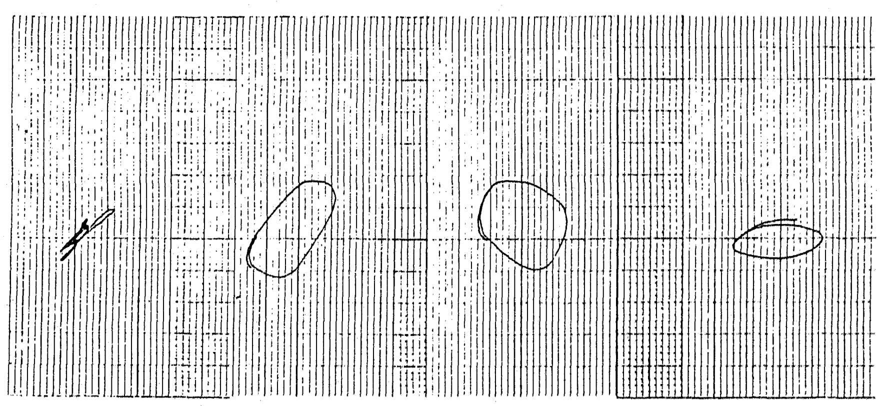

Fig.8 Variation of Hysteresis Loop (Normal Sand)

EXPERIMENT RESULTS AND THEIR CONSIDERATIONS

Results of saturated sand specimen to which vibration is given are shown in Fig. 3 (standard sand) and Fig. 4 (normal sand). As explained from the Figure, the reaction force decreases in proportion to the rise of of pore-water pressure caused by giving vibration and liquefaction of the specimen. When pore-water pressure exceeds approximately 1/2 of the lateral pressure (1.5 kgf/cm^2), the reaction force decreases and absolute response acceleration gradually tends to zero.

A reaction force-displacement curve obtained by giving vibration to the specimen and by taking the sine wave (3 Hz) as an input acceleration wave to vibration system that is equivalent to surface ground is shown in Fig.5 and 6. As the specimen is softened and liquefied by giving vibration, a hysteresis loop changes as shown in Fig.7 and 8. The curve has at first almost linear response because the specimen vibrates with a definite rigidity. As time lapses, the hysteresis loop becomes swollen and almost like an elliptic curve. When vibration is developed and liquefaction is expedited, the restoring force is almost diminished (especially in case of standard sand).

CONCLUSIONS

A nonlinear vibration analytic mode using on-line real time experimental method where a tri-axial vibration soil testing apparatus and digital calculator are built in is proposed. Availing ourselves of this analytical way, we tried the analysis of the nonlinear restoring force characteristics of saturated sandy ground during sine wave (3 Hz) is being given.

As the result of attempting the nonlinear vibration analysis by the on-line real time experimental method the following facts have been ascertained. With regard to a reaction force-displacement curve, the following facts are ascertained. The reaction force-displacement curve is toughly classified as the three stages as shown below, in accordance with the degree of liquefaction. This is :

(1) a stage of a line in the linear vibration immediately after vibration is given,

(2) a stage of the area of the hysteresis becomes drastically greater,

and (3) a stage of rigidity being lost and a hysteresis loop with almost only displacement.

In case the specimen is saturated sand, the reaction force is diminished and nears almost zero in proportion to the state of liquefaction.

ACKNOWLEDGEMENT

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