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ANALYSIS OF THE ENERGY RESPONSE OF SOIL TO EARTHQUAKE

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SUMMARY

The strength of soil decreases and finally soil might be destroied during the strong ground motion. Therefore, it is necessary to understand the destroy process of soil by its absorbed hysteresis energy. As the above purpose, in this study, the absorbing conditions of hysteresis energy of saturated sand were analysed. The following conclusions are obtained in this analysis:1.Absorbing conditions depend on the kind of soil, even though input earthquake wave is same. 2.The final absorbed energy changes between 0.6 and 5.5 joule under the analytical conditions in this study.

INTRODUCTION

When strong seismic motion is applied to structures, both equipment and machinery and the structural members are damaged. We therefore must determine what degree of seismic force causes structures to collapse and the extent of damage caused by such a force in order to provide earthquake resistance and safety to structures, and economical designs for such structures. Past earthquake records show that a fairly high seismic amplitude of the input acceleration wave and fairly long duration of an earthquake are required to destroy most structures. That is a considerable amount of earthquake energy must be transferred to a structure for it to be destroyed.

When an external seismic force is applied to structures, they vibrate with gradual deformation. This deformation created by vibration varies from moment to moment, structures collapsing because of the accumulation of repeatedly generated plastic strain. The effects of the work done by such external forces appear as forms of mechanical energy change in a structure.

Other types of destruction, such as subsidence of ground, cracks in ground and liquefaction of saturated sandy ground, also affect the ground that supports structures. Moreover, destruction takes place when there are soil-structures, e.g. embankments. Therefore, we must investigate the safety of the supporting ground and any nearby soil-structures as well as the safety of the structures themselves. We also need to throughly analyze rigidity changes in soil that are caused by strain energy.

We therefore here report on the process of the accumulation of the strain energy related to the liquefaction of saturated sandy ground and its relation to the progress of liquefaction.

ENERGY RESPONSE OF SINGLE DEGREE OF FREEDOM

The equation used to calculate the strain energy of S.D.F. is

$$\int_{t_1}^{t_2} m\ddot{x}(t)\dot{x}(t)dt+\int_{t_1}^{t_2} c\dot{x}(t)\dot{x}(t)dt \; +\int_{t_1}^{t_2} R(t,x)\dot{x}(t)dt=-\int_{t_1}^{t_2} m\ddot{y}(t)\dot{x}(t)dt \tag{1}$$

This equation (1) is an energy equilibrium equation of S.D.F. system. The first term on the left denotes the kinetic energy of a vibration system, the second term the damping energy, and the third term the strain energy. The right side gives the seismic input energy. The amount of strain energy is a major factor in whether destruction takes place. The equation giving the strain energy between t1 and t2 is obtained from equation (2);

$$\int_{t_1}^{t_2} R(t,x)\dot{x}(t)dt=\frac{1}{2}\{R(t_2,x_2)\dot{x}(t_2) \; +R(t_1,x_1)\dot{x}(t_1)\}(t_2-t_1) \tag{2}$$

By use of equation (2) at individual time steps, the strain energy present during each step can be calculated.

INADEQUACY OF THE METHOD FOR CALCULATING ENERGY

Response analyses usually are made with a nonlinear restoring force model, and the amount energy of in the vibration system is calculated from the response values obtained. Moreover trials by which to calculate the strain energy directly often are made by conducting a dynamic test of the test materials by the steady displacement control or steady load control method. The amount of energy that must be absorbed to produced destruction can be not, however, be determined by this methods. Consequently, we have used the experimental results of an on-line earthquake-response loading test to calculate the strain energy. Because factors with strong nonlinearity, like that for saturated sandy ground, are dealt with in our study, the conventional method could not be used to calculate the actual amount of energy. We therefore, calculated the amount of energy using an on-line earthquake-response loading test.

THETHEORY AND FEATURES OF THE ON-LINE EARTHQUAKE-RESPONSE LOADINGTEST OF SOIL

Main Points of the Analytical Method

Materials present various nonlinearities because of the amplitude and frequency characteristics of the dynamic force and the natural frequency of the surface of the underlying soil. If we can test materials dynamically, taking into account these points, the problem of nonlinearity is solved. Hakuno(1969) developed an on-line experimental unit which consists of a computer that analyzes numerically the dynamic behavior of a vibration system and a dynamic testing machine that determines the actual restoring forces of materials that make up the vibration system. He called his analytical technique the on-line experimental method. This method also can be called a pseudo dynamic test method or a hybrid experimental method.

The nonlinear vibration equation for a S.D.F. system is

$$m\ddot{x}(t)+c\dot{x}(t)+R(t,x)=-m\ddot{y}(t) \tag{3}$$

in which R(t,x) is the nonlinear restoring-force function. For nonlinear calculations, R(t,x) is required. When displacement enters the plastic range, the 'restoring force vs. the displacement relation' obviously can not be expressed as linear. It will be represented by a complicated hysteresis loop. In our calculations, we used the restoring force characteristics obtained from the specimen in the tri-axial testing apparatus as the restoring force of the soil(See Fig.1). Because no standardization of the stress-strain relation in a specific model is used in this method, the characteristics of the restoring force are adequate for the analysis of complicated nonlinear vibration of surface ground.

This analytical technique is used widely in the field of architecture. This on-line experimental procedure has been used to obtain analytical data on various types of structural members. For saturated sand, value of the hydraulic controlling system can not be obtained until the perfectly liquefied state is reached. This difficulty can be overcome if we use the on-line real time experimental method. With this dynamic test method, the dynamic behavior of ground composed of soil can be expressed as a S.D.F.S. system, the natural frequency of this system being first natural frequency of the surface ground. The vibration equation of this system can be solved and loaded to the soil specimen simultaneously. Katada and Hakuno have developed an on-line earthquake-response loading test apparatus which consists of an analogue computer with which to calculate ground motion and a dynamic tri-axial soil-testing machine that is used to obtain the actual restoring force of liquefying sand(3). They also have analyzed the saturated sand of surface ground and obtained the stress-strain curve up to the perfectly liquefied state.

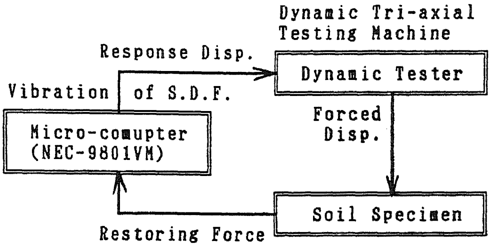

Fig.1 Block Diagram of the On-line Earthquake-response Loading Test used to analyze the dynamic properties of soil

Experimental Apparatus and Control Program The experimental apparatus used consisted of the dynamic tri-axial soil-testing apparatus and a micro-computer(NEC-PC9801VM). The dynamic tri-axial soil-testing machine is equipped with gauges for various purposes: in the specimen for detecting pore-water pressure and displacement, in a loaded piston for displacement, and in the tip of the oil-pressure actuator for the vertical load. The micro-computer was connected electrically to the dynamic tester by A/D and D/A converters. We used the linear acceleration method. With this program, computation was faster and better analytical accuracy could be obtained by performing the BASIC compiler on MS-DOS. Operation also was simpler, one calculation step, dt, being about 0.02 seconds with this experimental apparatus and program. We could calculate the response values with the same rapidity as the actual phenomenon.

STRAIN ENERGY CALCULATED FROM THE RESULTS OF THE ON-LINE EXPERIMENTAL-LOADING TEST

Calculation of Strain Energy Calculation of the strain energy from equation (2) suggests a problem as to how the response values $\ddot{x}(t)$, $\dot{x}(t)$, and $x(t)$ of S.D.F. and the restoring force $R(t)$ are to be obtained. Usually, these values can be found from a numerical analysis that uses a nonlinear restoring-force function model of the soil. By contrast, in our study, an on-line earthquake-response loading test was conducted on saturated sand, and a response value opposing the input acceleration was obtained. By using the response-loading results and the input acceleration, $\ddot{y}(t)$, we obtained the mass ,m, and the damping coefficient,c, for individual energy.The amount of strain energy accumulated could be obtained from

$$W_h(t)=\sum_{i=1}^{N}E_s(t_i) \tag{4}$$

Analytical Results of the On-line Earthquake-response Loading Test

1)Dynamic properties of the S.D.F. and characteristics of the specimen

In ascertaining the nonlinear restoring force with the on-line earthquake-response loading test, we determined the restrictive pressure,p, of a soil specimen to be 1.5kgf/cm2. As the specimen sand, we used Toyoura standard sand (see Table 1) that was perfectly saturated sand. For the relative densities, a loosely packed (Dr= about 30%) and a densely packed (Dr= about 70%) state were chosen. On the basic of the natural frequency of the S.D.F. being f=1.5Hz and the damping coefficient h= 0.10, we could analyze the nonlinear restoring force characteristics (see Table 2).

Table 1 Physical Properties of Toyoura Standard Sand

Specific Gravity	2.63
Uniformity Coefficient	1.59
D10(mm)	0.18

Table 2 Analytical Conditions

Restricted Pressure	1.5 kgf/cm2
Natural Frequency	1.5 Hz
Damping Factor	0.1

2)Input wave

A seismic acceleration wave recorded in Akita Port during Nihonkai Chubu Earthquake (May 26,1983,M=7.7) was used as the input wave(5). In waveform, the NS component wave was impulsive; whereas, the EW component wave tended to be continuous. In the analysis, the maximum values of the waves were used by rectifying them as 200gal.

3)Experimental results of the on-line earthquake-response loading test

Using the input wave and the test specimen described, we conducted a loading test. The experimental results for the Akita Port records and for the loosely packed sand are shown in Fig.2(1)and (2). For pore water pressure, there is no excessive increase for the EW component wave during liquefaction in comparison with that for the NS component wave. This may be because of the characteristics of the input wave. Fig.3(1) and (2) shows the restoring force vs. the displacement relation for saturated and loosely packed sand during liquefaction.

4)Accumulation of strain energy

By substituting the analytical results reported in the previous section in equation (2), we could calculate the strain energy. The approximately 60% strain energy accumulated in 4-5 seconds during the excessive state with the NS wave reflects the rapid increase in pore water pressure shown in Fig.2(1). With the EW wave, the increase was less approximately 75% of the strain energy was accumulated.

CONSIDERATION OF THE ABSORBING PROCESS OF STRAIN ENERGY

A comparison was made of the relation of strain energy accumulation in saturated sand and a time series of pore water pressure increases. The amount of strain energy accumulated,Wh(t), was divided by its maximum value,Whmax, then normalized; the result was called the normalized accumulated strain energy. The pore water pressure,PWP(t), divided by its maximum value ,PWPmax, was called the normalized pore water pressure.

The waveform for this comparison that was made in a time series for the calculated, normalized accumulated strain energy and the normalized pore water pressure increases are given in Fig.4(1),(2). In both cases, comparisons of the factors up to the state of perfect liquefaction were made. When the normalized accumulated strain energy process was compared with the normalized pore water pressure increases, they were in good correspondence.

The strain energy required for saturated sand to be perfectly liquefied was obtained. For the maximum input acceleration of 200gal, the strain energies required for loosely packed saturated sand to become perfectly liquefied state were

EW component wave at Akita Port . . . approximately 3.0 (joule)
NS component wave at Akita Port . . . approximately 2.0 (joule)

The strain energies required for densely packed sand, to become perfectly liquefied were

EW component wave at Akita Port . . . approximately 4.0 (joule)
NS component wave at Akita Port . . . approximately 5.0 (joule)

By dividing these values by the depth of the specimen, we obtained the strain energy per unit volume.

CONCLUSIONS

Observations of the accumulation of strain energy were made during liquefaction of saturated sandy ground. The strain energy accumulated by saturated sand during an earthquake was obtained from response analysis results used in the on-line earthquake-response loading test method. Our conclusions, given below, are based on the accumulation of strain energy during the liquefaction of saturated sand.

(1)The process by which strain energy is accumulated corresponds well to the process by which pore water pressure is increased. This is evidence that the strain energy accumulated during liquefaction is due to the nonlinearity produced by the degradation of the rigidity of the sand because of pore water pressure.

(2)The strain energy required for perfect liquefacion depends on the relative density of the sand. Densely packed sand is hard to liquefy, two to three times the strain energy being required in comparison to the loosely packed sand.

(3)For an input acceleration of 200gal, saturated sand in a tightly packed state becomes perfectly liquefied between 2 to 5 joules.

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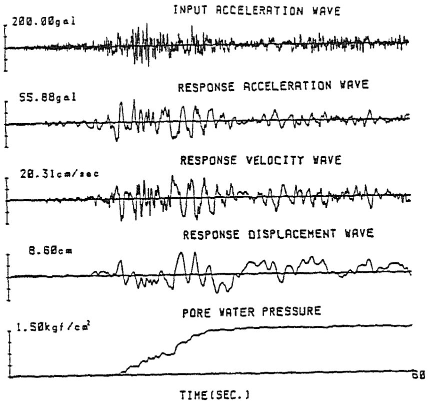

Fig.4(1) On-line Earthquake Response Test (Saturated and Loosely Packed sand : Dr=31.3%, AKITA EW Component)

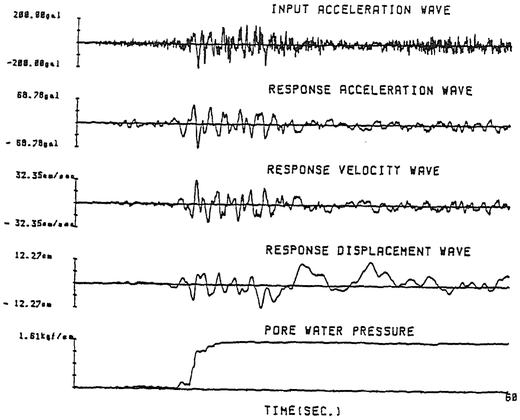

Fig.4(2) On-line Earthquake Response Test (Saturated and Loosely Packed sand : Dr=21.2%, AKITA NS Component)

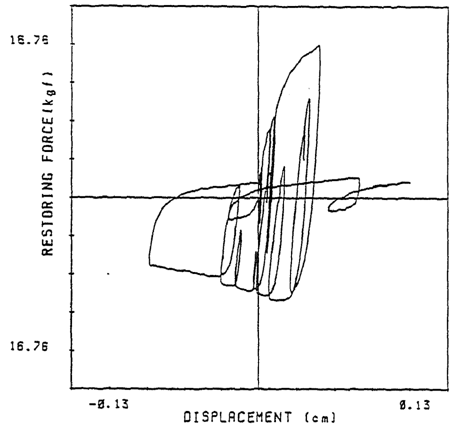

Fig.5(1) Restoring Force vs. Displacement (Illustration from Fig.4(1))

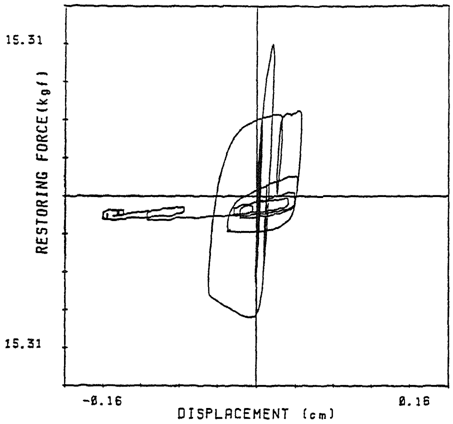

Fig.5(2) Restoring Force vs. Displacement (Illustration from Fig.4(2))

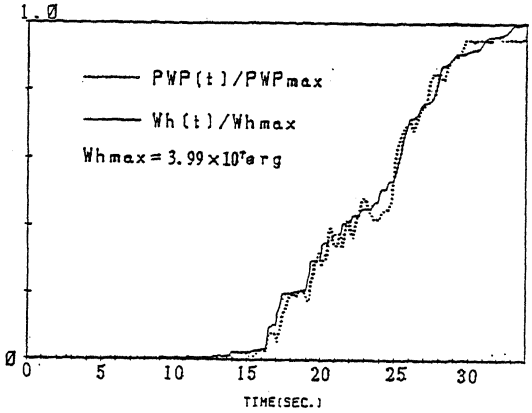

Fig.6(1) Comparison of Normalized Strain Energy and Normalized Pore-water Pressure (Illustration form Fig.4(1))

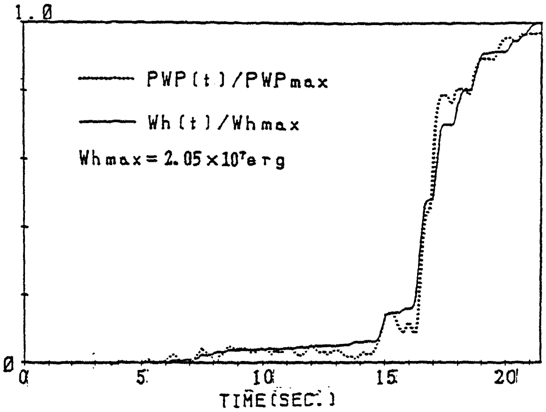

Fig.6(2) Comparison of Normalized Strain Energy and Normalized Pore-water Pressure (Illustration form Fig.4(2))