THE DEVELOPMENT OF A SUBSTRUCTURE ON-LINE TESTING SYSTEM FOR SEISMIC RESPONSE ANALYSIS OF A GEOTECHNICAL SYSTEM

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ABSTRACT

A substructure on-line testing (SOT) system was developed for the purpose of conducting a quantitative simulation of the behavior of horizontal subsurface layers subjected to earthquake motions (SH wave) under undrained conditions. In this method, a computer analysis of the seismic response and a pseudo-dynamic loading test which estimates the restoration force of the materials were combined with a computer on-line data processing system. With the SOT system, which was devised to analyze the overall seismic response behavior of subsoils, an on-line test was adopted only for layers demonstrating complicated hysteretic behavior with respect to a restoration force, while a numerical model was applied to the remaining layers. The following tests were conducted in order to verify this system: 1) The reliability of a series of 6 hollow torsional shear apparatus installed in the SOT system was verified by comparing the test results with the results of cyclic undrained simple shear tests conducted by Tatsuoka et al. (1989); 2) A test on a quasi-elastic specimen was conducted based on the SOT system using a test algorithm developed for this study, and an elastic analysis was carried out using the modulus of elasticity obtained from this test. Based on a comparison between the respective results of the test and the analysis, the reliability of the test algorithm was verified; 3) Using the system thus verified, a seismic response liquefaction test on a saturated sandy subsoils was conducted, which showed that the SOT system developed in this study was capable of accurately simulating the seismic response of a level subsoils.

Key words: computer application, earthquake, laboratory test, liquefaction, pseudo-dynamic test, subsurface layers, torsional simple shear apparatus (IGC: D7/E8)

INTRODUCTION

In the on-line test method, a computer-run earthquake response analysis and a pseudo-dynamic loading test to estimate the restoration force of materials are combined by a computer on-line data processing system. This is a numerical simulation method in which the results of the experiment are used directly.

Since 1969, when this method was first proposed by Hakuno et al. (1969), research has been progressing mainly in the construction field in Japan and the United States (Iemura, 1984; Hanson and McClamroch, 1984; Mahin and Shing, 1985; Takanashi and Nakashima, 1987). As a result, this method has been confirmed as being capable of accurately reproducing earthquake response behavior, though it is admittedly still in a transitional period between the phases of development and practical use. On the other hand, a substructure on-line testing method has been developed combining an on-line test, which is conducted only for members of a structural system with complicated hysteretic behavior of restoration force, and a computer numerical analysis applied to the remaining members (Nakashima et al., 1985; Dermitzakis and Mahin, 1985; Nakashima et al., 1990).

One of the early studies on the on-line method applied to the subsoils was that conducted by Katada et al. (1984) with a cyclic triaxial testing apparatus. There are however two prerequisites for the on-line system to be applied to a geotechnical problem: 1) a laboratory soil shear test to obtain the restoration force must adequately reproduce the characteristics of the natural ground; 2) the influences of the important factors which govern the subsurface behavior (effective stress, anisotropy, rotation of principal stress axis, non-coaxiality, etc.) must be reflected directly in the restoration force used for the response analysis.

When the analysis is limited to the most fundamental one-dimensional problem of an undrained saturated...
sand, the following technical problems must be solved in order to obtain highly reliable data from a response analysis: 1) discretization for a lumped mass model close to an actual horizontally-layered subsoils and reproduction of the initial stress conditions (multiple-degree-of-freedom system; application to the substructure method and reproduction of in-situ anisotropic stress conditions); 2) laboratory soil test simulation of the deformation behavior of a horizontally-layered subsoils during earthquakes attributable to an SH-wave (reproduction of the cyclic undrained simple shear mode); 3) adoption of hardware which can accurately control the deformation of a soil specimen identical with the results obtained from an earthquake response analysis and development of software which compensates for any experimental inaccuracy due to the limitation of control accuracy.

Kusakabe et al. (1990) developed an on-line testing system of 2-degrees-of-freedom (2DOF) using a twin-type hollow torsional simple shear apparatus, and conducted a simulation of the liquefaction behavior of saturated sand. This paper discusses the basic concept of an on-line test, describes the newly developed substructure on-line testing system, and verifies its reliability. In addition, the results of a liquefaction test conducted on loose sand deposits using the verified system were examined.

CONCEPT OF THE ON-LINE TEST

In this study, an N-layer subsoil is modelled into a lumped mass model of N-degrees of freedom (NDOF) as shown in Fig. 1(a), and an earthquake motion was input from its base. The test procedure is outlined below:

(1) The equation of motion of the lumped mass model was solved at the stage of seismic response calculation as shown in the left half of Fig. 1(b). In the figure, Accg denotes the input acceleration; M, the mass matrix; C, the viscous damping matrix; F, the restoration force vector; L, the unit vector; K, the initial rigidity matrix; Ẋ, the relative acceleration vector; Ẋ, the relative velocity vector and α and β, the Rayleigh damping constants.

In this study, the condition of α = β = 0 was adopted, and only hysteresis damping was taken into consideration. As for the numerical integration, the linear acceleration method was used initially, while the central difference method was then used as a second step. (2) As shown in the right half of Fig. 1(b), the shear strain, γi-γN, of each layer, which is calculated from the displacement of the seismic response, X1-γN, obtained by a response calculation, was input for each corresponding layer of the N-layer model by means of a strain control method. (3) When γi-γN was obtained in each soil specimen within a pre-determined allowable limit, each corresponding shear stress, τi-γN, was automatically measured. (4) These values were then transmitted to the computer by means of an on-line system which performed the response calculation in the succeeding steps. The seismic ground response was simulated by repeating this procedure within the time duration of an earthquake motion.

In this test, evaluation of the interaction among specimens was done only in the equation of motion, since each specimen was independently controlled under an undrained condition. In addition, should the viscous damping be negligible, the shear strain did not have to be imposed at the actual rate, since the predominant damping in sand is hysteresis.

SUBSTRUCTURE ON-LINE TESTING (SOT) METHOD

In order to obtain highly reliable response data from the on-line test, one must discretize the soil layers to approximate the actual profile of the subsurface soils, as well as reproduce the state of their initial stress. In addition, due to the frequency characteristics of the input subsoil motion, no layer could be too thick. Should the on-line test be conducted for the entire multi-layered subsurface profile, a costly system would be required as well as a complicated test procedure. The SOT system shown in Fig. 2 was therefore developed. In this method, the restoration force of layers subject to liquefaction or large-
scale deformation was obtained using a 6 series hollow torsional shear apparatus, while that of the remaining layers was obtained based on a numerical model. The behavior of the entire subsoil system was then analyzed. The test apparatus for the 6DOF system, verification tests, the test algorithm used for the SOT method, and verification of its practicability and reliability are discussed below.

TESTING SYSTEM AND VERIFICATION

Hollow Torsional Shear Apparatus

Photograph 1 shows an overview of the 6DOF system. In a single-degree-of-freedom system, the effect of displacement control error on the experiment at response results is not so large, since only the first mode of vibration can be treated in the system. It is well known indeed that the response results are largely influenced by the displacement control error in a multiple-degree-of-freedom system (Mahin and Shin, 1985). For such a case, the larger influence of the experimental error is obtained for the response of a higher vibration mode (Nakashima and Kato, 1989). Accordingly, a harmonic-gear AC servomotor which provided high precision for the displacement control was employed. The resolution of the motor at its outer rotation axis was 0.0036 degrees per computer output digit. For specimens with an outer diameter of 100 mm, an inner diameter of 60 mm, and a height of 100 mm, the resolution of the shear strain, \( \gamma \), was equivalent to \( \Delta \gamma \approx 5 \times 10^{-6} \). The shear strain, \( \gamma \), was measured using a non-contact-type displacement transducer, while the total axial stress, \( \sigma_z \), and the shear stress, \( \tau \), of the specimen were measured using a two-directional load cell. These sensors were installed in the triaxial cell. The effective horizontal confining pressure of the specimen was measured using a differential pressure transducer. A 14 bit A/D converter was also used for data acquisition.

Cyclic Undrained Torsional Simple Shear Test (CTSS) Method

The cyclic undrained simple shear deformation of the soil elements within a horizontally layered subsoils during earthquake was reproduced following the method proposed by Tatsuoka et al. (1989) as described below. After applying anisotropic consolidation, the saturated specimen was placed under undrained conditions. This was done by enclosing de-aired water inside the hollow cylindrical specimen, and keeping the height of the specimen constant during shear. For these strain conditions, an accurate simple shear deformation mode was obtained, providing the volumetric strain of the specimen = 0, axial strain = 0, and outer and inner radius strain = 0.

Specimen and Test Method

The sand used for the test was Toyoura sand with about 90% quartz content (the density of soil particles, \( \rho_s = 2.645 \text{ g/cm}^3 \), the ratio of fines content = 0, \( D_0 = 0.175 \text{ mm} \), \( D_{10} = 0.129 \text{ mm} \), \( U_c = 1.52 \), \( e_{min} = 0.975 \), and \( e_{min} = 0.607 \)). The specimen was produced using the air pluviation method (height, 200 mm, outer diameter, 100 mm, and inner diameter, 60 mm). The values indicated hereafter, including the stress and the shear modulus, have been normalized by 98 kPa, and expressed along with a suffix "m", for example, \( \sigma_{m} = \sigma_{m}/98 \text{ kPa} \). Regarding the anisotropic consolidation, after applying the final effective horizontal stress ratio, \( \sigma_{in} = 0.67 \) isotropically, the deviatoric axial stress ratio, \( \Delta \sigma_{in} = 1.00 \) was added axially, which determined a final effective axial stress ratio of \( \sigma_{in} = 1.67 \). The void ratio, \( e \), of the 6 specimens ranged from 0.781 to 0.792. A CTSS test with constant shear stress amplitude was conducted based on the shear-strain controlled mode.

Test Results

Figure 3 shows the relationship between the cyclic shear stress ratio and the number of cycles required to cause 3% shear strain for double amplitude. The figures expressed in Fig. 3 are the void ratio, \( e \), after the anisotropic consolidation; those with open circles are the values obtained by Tatsuoka et al. (1989) under roughly
the same conditions, while those with solid circles are those obtained using 6 sets of the 6DOF system in this study. In consideration of the difference in void ratio, \( e \), between these two studies, the figure illustrates that the 6DOF system used in this study was capable of precisely conducting a CTSS test.

**TEST ALGORITHM FOR THE SOT METHOD AND VERIFICATION TEST**

**Numerical Integration**

The initial concept of a substructure on-line testing (SOT) method was proposed by the inventors and developers of the on-line testing method (Hakuno et al., 1969). This method however has not been applied for practically except for a few extremely simple cases. One of the major reasons hindering the application of this method is the difficulty in numerical integration. With the central difference method (CDM), which is considered adequate for on-line tests, the restoration force is used but rigidity evaluation is not required. In addition, one of the advantages of the CDM is that it does not require iterative corrections (convergence calculations) under loading for an inelastic specimen which is greatly dependent on strain-history. One of its disadvantages is that the stability of its solution is conditional (i.e., integration time intervals must be sufficiently small in comparison with the natural period of the structure to be analyzed). When the SOT method is used for a system with a large degree of freedom (number of mass points) or a structural system with high rigidity, the operator-splitting method (Hughes et al., 1979) has been proven effective for obtaining stable, precise solutions (Nakashima et al., 1990).

In a subsoil system with soft subsurface layers, both the rigidity and the degree of freedom are relatively small. Thus, a new method to utilize the conventional CDM was developed in this study as described below. Initially, the linear acceleration method was used in the same manner as the conventional method. Starting with the second step, however, the integration time interval, \( \Delta t \), was made sufficiently small, and the renewal of the restoration force (displacement control to apply shear strain, \( \gamma \) and measurement of stress, \( \tau \) in the experiment) was conducted every few steps. This efficient method maintains the stability of a solution, avoiding the loading operation which results in experimental errors in the displacement control, which are smaller than the measurement limit, thus reducing the time required for a test.

**Suppressing the Adverse Effects of Test Errors**

When an on-line test is conducted, the displacement is controlled based on the shear strain, \( \gamma_{fs} \), as a target value, which corresponds to the response displacement obtained by the response calculation in the \( i \)-th step, and then the shear stress, \( \tau_{s} \), is measured. At this point, an allowable error bound, \( \pm \Delta \gamma_{e} \), is established in order to determine the convergence for the target value. For the displacement control between step \( i-1 \) and step \( i \), the absolute value, \( |\gamma_{m}-\gamma_{m-1}| \), of the measured strain increment, being smaller than the calculated absolute value, \( |\gamma_{e}-\gamma_{e-1}| \), of the strain increment, is called undershooting, while the opposite case is called overshooting. Nakashima et al. (1989) proved that undershooting errors were a major factor which distorted the response by promoting the response of the highest mode vibration of a system. A similar phenomenon was observed in an online-test for a subsurface profile based on the 2-degree-of-freedom system (Kusakabe et al., 1990); therefore, a test algorithm for the system, by which the adverse effect of experimental errors could be suppressed, was proposed. The test algorithm to cope with such problems is discussed below.

When the maximum value, \( \gamma_{\text{max}} \), of a target shear strain was smaller than the order of \( 10^{-3} \), an elastic calculation was conducted for layers to which the on-line testing method was applied, using the initial shear modulus, \( G_{0} \), measured in advance. Only when the \( \gamma \) obtained from this calculation was greater than the resolution of displacement control was this strain applied to the specimen. Layers where \( \gamma_{\text{max}} \) exceeded the order of \( 10^{-3} \) were transferred successively to the on-line test. The error force, \( \Delta \tau \), which originated from the difference between the target value, \( \gamma_{c} \), and the measured value, \( \gamma_{m} \), was not corrected. The resolution of displacement control for the shear strain was double that of the 2-degree-of-freedom system (\( \gamma = 5 \times 10^{-5} \)), and the allowable error bound, \( \pm \Delta \gamma_{e} \), was reduced by 1/20 to \( \pm 5 \times 10^{-7} \). This resulted in an extremely minute overshooting becoming predominant in the convergence condition. In addition, for the displacement used to solve the equation of motion, the computed displacements which provided stable response data were used instead of the measured ones, referring to the study made by Shing et al. (1983).
Analytical Model for the Verification Test

In order to verify both the hardware and software developed for the SOT system, a substructure on-line test and numerical analysis were conducted in the following manner. A response test using a quasi-elastic rubber specimen, and an elastic analysis using the secant modulus measured in the test were conducted. The respective results were then compared. The test model is shown in Table 1. M1 and M2 are layers analyzed by a numerical model (linear elastic), while S1 to S6 are layers treated by the on-line test. Figure 4 shows the time history of input accelerogram (max = 100 × 10^{-2} m/s) applied to the base (bottom surface of S6). This input accelerogram was established by the Academic Committee of JSSMFE for the Seismic Behavior of Ground and Earth Structures (1989).

Results of the Verification Test

The time histories of the relative displacement of each layer obtained by the SOT test and the elastic analysis are shown in Figs. 5 and 6, respectively. The rubber specimen exhibited a hysteretic damping of several percent when γe approached 5 × 10^{-3}. Thus, a comparison was made during the time when the specimen behaved as a linear elastic body, which was from 0 to 8 seconds. During this period, the number of time steps for numerical integration carried out in response calculations was almost 1350 (Δt = 0.005925 seconds). The displacement control and measurement of restoration force were conducted repeatedly during the test, extending the real time axis. The number of these steps was 675 (Δt = 0.01185 seconds), which amounted to half of the former value. The results of the SOT test agreed well with those obtained from elastic analysis. It was therefore concluded that the response behavior could be simulated accurately based on the test results.

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Layer</th>
<th>ρ (t/m³)</th>
<th>G₀</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(1)M1</td>
<td>1.8</td>
<td>218</td>
</tr>
<tr>
<td>2</td>
<td>(2)M2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>(3)S1</td>
<td>1.9</td>
<td>47</td>
</tr>
<tr>
<td>4</td>
<td>(4)S2</td>
<td></td>
<td>36</td>
</tr>
<tr>
<td>5</td>
<td>(5)S3</td>
<td>1.9</td>
<td>34</td>
</tr>
<tr>
<td>6</td>
<td>(6)S4</td>
<td></td>
<td>38</td>
</tr>
<tr>
<td>7</td>
<td>(7)S5</td>
<td>1.9</td>
<td>116</td>
</tr>
<tr>
<td>8</td>
<td>(8)S6</td>
<td></td>
<td>98</td>
</tr>
</tbody>
</table>

\[ G₀ = G/98 \text{ kPa} \]

Liquefaction Test on Sandy Ground Using the SOT System

Test Conditions

Using the SOT system thus verified, a seismic response liquefaction test which was conducted following the Kawagishi-cho model established by the Committee (1989) of the 1964 Niigata earthquake. The sand used was Toyoura Sand as mentioned before. Although this sand was different in many respects from that of Kawagishi-cho, the relative density, initial effective
Table 2. Test conditions for SOT

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Layer</th>
<th>( \rho ) (t/m³)</th>
<th>Initial stress condition</th>
<th>Void ratio after consolidation: ( e )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(1)M1 (2)M2</td>
<td>1.8</td>
<td>( \sigma'<em>c/\sigma'</em>{in} ) Max</td>
<td>Case1 0.785 0.795 0.794</td>
</tr>
<tr>
<td>2</td>
<td>(3)S1</td>
<td>1.9</td>
<td>0.450 0.225 0.785</td>
<td>Case2 0.791 0.789</td>
</tr>
<tr>
<td>3</td>
<td>(4)S2</td>
<td>1.9</td>
<td>0.630 0.315 0.769</td>
<td>Case3 0.789</td>
</tr>
<tr>
<td>4</td>
<td>(5)S3</td>
<td>1.9</td>
<td>0.855 0.428 0.787</td>
<td>Max 0.802 0.801</td>
</tr>
<tr>
<td>5</td>
<td>(6)S4</td>
<td>1.9</td>
<td>1.125 0.563 0.793</td>
<td>Case1 0.796 0.795</td>
</tr>
<tr>
<td>6</td>
<td>(7)S5</td>
<td>1.9</td>
<td>1.395 0.698 0.779</td>
<td>Case2 0.784 0.773</td>
</tr>
<tr>
<td>7</td>
<td>(8)S6</td>
<td>1.9</td>
<td>1.665 0.833 0.770</td>
<td>Case3 0.791 0.790</td>
</tr>
</tbody>
</table>

confining pressure and initial shear modulus for the test were similar to those of the Kawagishi-cho model.

Except for the height of the hollow specimen, which was 100 mm (200 mm in the above subsection), details such as the method of specimen production, the CTSS test method and the test algorithm for the SOT method were the same as stated before. The test conditions are listed in Table 2. Linear elastic calculation was conducted for layers (1) and (2) (M1 and M2), both of which were above the ground-water table, while the on-line test was conducted for layers (3) to (8) (S1 to S6). Cases 1 and 2 were tested for the same conditions in order to study reproducibility. The Case 3 test was carried out after the Case 2 test was completed, using the same specimens. In Case 3, the excess pore water pressure of each specimen which built up during the Case 2 test was dissipated, and the specimens were reconsolidated at the initial effective confining pressure in order to cause liquefaction under the same input conditions.

Test Results

The test results for the three cases are discussed below. Figure 7 shows the time histories of the excess pore water pressure ratio, \( u/\sigma'_{in} \), normalized by the initial axial effective stress, \( \sigma'_{in} \). The time histories of the shear stress ratio, \( \tau/\tau_n \) (restoration force), the shear strain, \( \gamma \), are shown in Figs. 8 and 9, respectively. Figures 10 and 11 show the relationship between \( \tau/\tau_n \) and \( \gamma \) as well as the effective stress path expressed by \( \gamma \) and \( \sigma''_{in}/\sigma'_{in} \) of S5 (the 7th layer) which liquefied in Cases 1 and 2 but not in Case 3.

Reproducibility (Comparison between Cases 1 and 2)

The general behavior of \( u/\sigma'_{in} \) (Fig. 7), \( \tau/\tau_n \) (Fig. 8) and \( \gamma \) (Fig. 9) for each layer (S1 through S6) is similar in both Case 1 and Case 2. In particular, as shown in Fig. 7, liquefaction was observed in the same layer (the 7th layer, or S5), and the time when the liquefaction occurred was almost identical. In addition, the relationship between the stress and strain (Fig. 10) and the effective stress path (Fig. 11) coincide for a test of this type. These test results prove that the system developed for this study is capable of providing a seismic response analysis with highly reproducible results.

Example of Liquefaction (Comparison between Cases 2 and 3)

The void ratio, \( e \), in the process of anisotropic consoli-
Fig. 8. Time history of $\tau/\tau_a$

Fig. 9. Time history of $\gamma$

dation after earthquake in Case 2 is almost invariable (see Table 2). S5 nevertheless was liquefied in Case 2 as shown in Fig. 7, while in the reliquefaction test in Case 3, S2 (the 4th layer) was liquefied earlier (around 8 seconds after the commencement of the earthquake). It appears that the seismic response behavior varies, reacting quite sensitively to the differences in the values of $e$ and the

history of shear strain. This is also clearly reflected in the relationship between $\tau/\tau_a$ and $\gamma$, and that between $\tau/\tau_a$ and $\sigma_v/\sigma_{v0}$ of S5 as shown in Figs. 10 and 11. In addition, as shown in Fig. 9, the closer the layer is located to the surface (i.e., as the initial effective confining pressure decreases), the more residual strain is accumulated in the process of liquefaction.
CONCLUSIONS

For the purpose of conducting a quantitative simulation of the response behavior of horizontally layered subsoil profile subjected to an earthquake motion (SH-wave) under undrained conditions, a substructure on-line testing (SOT) system was developed and verified. As a result, the following conclusions were obtained:

1) By reproducing the cyclic undrained torsional simple shear test conducted by Tatsuoka et al. (1989), the reliability of the hollow torsional shear apparatus used for the SOT system was verified.

2) A test based on the SOT system was conducted for a quasi-elastic subsoil profile using the test algorithm developed for the SOT system. A comparison of the results obtained respectively by the test and an elastic analysis proved that the test algorithm was reliable.

3) This system as developed proved to be capable of ac-
accurately simulating the seismic response of the subsoils, based on a seismic response liquefaction test conducted on a saturated sand using the SOT system.

REFERENCES


