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Simultaneous identification of time and space variant dynamic soil properties during the 1995 Hyogoken-Nanbu earthquake

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Abstract

Time and space variant soil properties at a liquefied site were simultaneously identified in the time domain by using borehole array strong motion records. During soil liquefaction at a site, soils usually show a wide variety of non-linear behavior along the depth as well as non-stationary behavior. Strong ground motion records were obtained at Port Island borehole array observatory, Kobe, during the 1995 Hyogoken-Nanbu earthquake. In this study, the instrumented soil was modeled by the equivalent linear MDOF system, and an extended Kalman filter with local iteration was employed for the identification of the soils. The identification process was successfully conducted, and the stress–strain relationships of the soils at the liquefied site were obtained from different depths all at once.

Keywords: Simultaneous identification; Kalman filter; Non-stationary; Non-linear; Hyogoken-nanbu earthquake; Liquefaction; Borehole array

1. Introduction

Strong motion records were obtained at Port Island borehole array observation station during the 1995 Hyogoken-Nanbu earthquake. Liquefaction took place widely throughout the island, devastating embedded lifeline structures and port facilities. Hence, the observed strong motion records are expected to include remarkable liquefaction effects. Dynamic behavior of soils at large strain amplitudes has yet to be sufficiently understood since experiments for it are difficult. It is therefore quite significant to analyze inversely the dynamic behavior of soils by using the observed strong motion records.

Various investigations to evaluate the dynamic properties of liquefied soils by using the strong motion records have been carried out. Zeghal et al. [1,2] identified Wildlife site seismic behavior employing the accelerations and pore-water pressures recorded during 1987 Elmore Ranch and subsequent Superposition Hills earthquakes. In view of the fact that acceleration records are available only at the surface and downhole stations, a simple technique, which assumes linear interpolation, was utilized to evaluate shear stress and strain histories. Several investigations have also been conducted on the dynamic behavior of soils by using the records observed at Port Island. Zeghal et al. [2], Elgamal et al. [3], Kazama et al. [4] obtained seismic shear stress–strain relationships of soils by applying Koga and Matsuo's simple method [5] to the strong motion records. This method, originally developed for the analysis of shake table tests, employs linear approximations to the distribution of accelerations between seismometers and obtains stress–strain relationships of soils based on the difference method. Kamiyama et al. [6] computed the stress–strain relationships based on the difference procedure, then applied complex envelop method to show the non-stationary variations of shear stiffness ratios and damping ratios. Yoshida et al. [7] used an extended Kalman filter technique for the inverse analysis of soil dynamics, assuming soil non-linearity to be a multi-linear model. Among these procedures, the Kalman filter technique for the analysis of observed records is quite effective because it extracts and avoids modeling errors.

From that point of view, Mikami and Sawada [8] employed a Kalman filter to obtain shear stress–strain relationships of the soil between the two seismometers

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closest to the surface at Port Island site. They modeled the soil by a SDOF system and applied an extended Kalman filter with weighted local iteration. In this study, the identification process is further developed by modeling the site by a MDOF system. This enables us to compute the stress–strain relationships of soils from different depths at the site simultaneously, even though the soils show a variety of non-linear behavior along the depth. Since there are four seismometers in the vertical borehole, the soil is modeled by a three-degree-of-freedom equivalent linear system and the aforementioned Kalman filter algorithm is applied to it to obtain stress–strain relationships of the soil. Moreover, some methods of soil mass modeling at the liquefied site are examined.

2. Process of identification

2.1. Equivalent linear modeling of the ground

The instrumented soil is modeled here on the assumption that the seismometers are installed at $n+1$ different depths. For the application of the Kalman filter, the number of degrees of freedom is determined by the number of seismometers because each degree of freedom needs observation information. The level of the most deeply installed seismometer is assumed to be the base of the soil model. Thus the strong motion records observed at this depth are used as inputs to the system and the records at higher levels are treated as outputs from the system. Therefore, the soil in which $n+1$ seismometers are instrumented is modeled by n-DOF system. In this study, the stiffness and the damping parameters of the soils are to be identified, whereas the mass parameters are assumed to be known. The equivalent linear governing equation is given as below.

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = -[M]\{\ddot{x}_g\} \quad (1)$$

where $\{x\}$ = displacement vector relative to the base, $\{x_g\}$ = absolute displacement vector at the base, $[M]$ = mass matrix, $[C]$ = damping matrix, $[K]$ = stiffness matrix.

On the other hand, the governing equation with non-linear restoring force is given as follows

$$[M]\{\ddot{x}\} + \{Q(x,\dot{x})\} = -[M]\{\ddot{x}_g\} \quad (2)$$

By equating Eqs. (1) and (2), the non-linear restoring force is given by Eq. (3).

$$\{Q(x,\dot{x})\} = [C]\{\dot{x}\} + [K]\{x\} \quad (3)$$

Stress–strain relationships are identified on the basis of this equation.

Attention should also be directed to the modeling of soil mass. Because of the fact that the vertical distance between seismometers varies widely and the seismometers are not always installed densely enough along the depth for the purpose of inverse analysis, using lumped mass modeling may lead to significant errors due to unbalanced and inappropriate modeling. Lumped mass modeling in this case assumes that the distribution of horizontal acceleration is constant within a wide range from the seismometer to the halfway point from the other seismometers when soil mass is uniformly distributed. This may lead to fatal errors if a part of the soil liquefies and the acceleration distribution fluctuates along the depth. Thus, the consistent mass is used in this study assuming linear distribution of ground acceleration between seismometers, as Zeghal et al. [1,2] and Kazama et al. [4] assumed. The consistent mass matrix is expressed as follows.

$$m_{ij}^k = \int_0^{H_k} \rho_k(z) N_i(z) N_j(z) \mathrm{d}z \quad (4)$$

here, $\rho_k(z)$ = soil density distribution of segment k, H_k = thickness of soil, $N_i(z)$, $N_j(z)$ = interpolation functions expressed below.

$$N_i(z) = 1 - \frac{z}{H_k} \quad (5)$$

$$N_j(z) = \frac{z}{H_k} \quad (6)$$

2.2. State space expressions

To solve Eq. (1), the linear acceleration method is employed as follows.

$$\{\ddot{x}(t+1)\} = [A]^{-1}[-[M]\{\ddot{x}_g(t+1)\} - [C]\{\mathrm{a}(t)\} - [K]\{b(t)\}] \quad (7)$$

$$[A] = [M] + \frac{1}{2}\Delta t[C] + \frac{1}{6}\Delta t^2[K] \quad (8)$$

$$\{\mathrm{a}(t)\} = \{\dot{x}(t)\} + \frac{1}{2}\Delta t\{\ddot{x}(t)\} \quad (9)$$

$$\{b(t)\} = \{x(t)\} + \Delta t\{\dot{x}(t)\} + \frac{1}{3}\Delta t^2\{\ddot{x}(t)\} \quad (10)$$

Here, Δt = time step.

This equation advances the solution from time t to $t+1$. The input term in Eq. (1) includes noise because the observed records are used as input. The input noise is extracted by using the Sawada's method [9] which incorporates the acceleration difference as below

$$w(t) = \ddot{x}_g(t+1) - \ddot{x}_g(t) \quad (11)$$

This function $w(t)$ becomes the acceleration difference when the input acceleration does not include any noise. However, the input usually includes noise, so that the function consists of the acceleration difference and the noise. Using this function, the transition of the input acceleration, velocity and displacement are expressed as follows

$$\ddot{x}_g(t+1) = \ddot{x}_g(t) + w(t) \quad (12)$$