I - B 113 Coupled Nonlinear Response of Reclaimed Soils to Strong Earthquakes[1]

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INTRODUCTION

The vertical array records obtained at Port Island during the 1995 Kobe earthquake are of particular interest in earthquake geotechnical engineering, this is due to that the site consisted of a thick reclaimed surface layer which was fully liquefied during shaking events. The records have been used by a number of researchers to study various issues of interest. For example, the characteristic of vertical amplification was discussed by Yang and Sato (1998). In this paper, the nonlinear response of the reclaimed site is analyzed by a fully coupled finite element method. The purpose of the present study is to simulate the acceleration time histories, pore water pressure responses and stress-strain histories of soils using a state-of-the-art constitutive soil model, and further to discuss the relation of these responses to the observed characteristics of ground motions.

NONLINEAR AMPLIFICATION

The acceleration records in both E-W and N-S directions clearly indicate that nonlinear amplification occurred during the shaking events. Fig. 1 shows the variation of peak accelerations along the depth. It can be seen that a significant reduction of the amplitudes of horizontal motions occurred when seismic waves travelling from the bottom to the surface. A spectral analysis has indicated a typical feature that the predominant period of surface motion was elongated during shaking history, as shown in Fig. 2, in which the Fourier spectra at three time phases are included. Obviously, in the second phase which corresponds to strongest shaking, long period waves were dominant. All these features are expected to be attributed to the nonlinear behavior of surface reclaimed soils, especially the effects of pore water pressure build-up in soils.

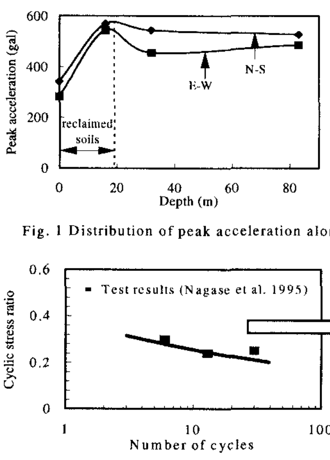

Fig. 1 Distribution of peak acceleration along depth

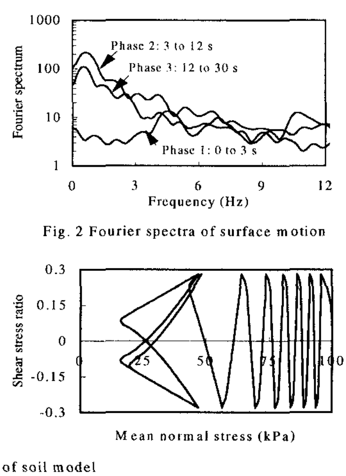

Fig. 2 Fourier spectra of surface motion

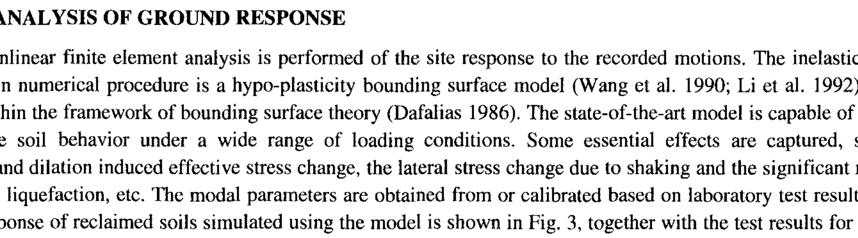

Fig. 3 Cyclic response of soil model

COUPLED ANALYSIS OF GROUND RESPONSE

A coupled nonlinear finite element analysis is performed of the site response to the recorded motions. The inelastic soil model incorporated in numerical procedure is a hypo-plasticity bounding surface model (Wang et al. 1990; Li et al. 1992) which was developed within the framework of bounding surface theory (Dafalias 1986). The state-of-the-art model is capable of realistically simulating the soil behavior under a wide range of loading conditions. Some essential effects are captured, such as the compression and dilation induced effective stress change, the lateral stress change due to shaking and the significant reduction of stiffness upon liquefaction, etc. The modal parameters are obtained from or calibrated based on laboratory test results. A typical undrained response of reclaimed soils simulated using the model is shown in Fig. 3, together with the test results for the samples obtained in laboratory. Due to the limited space, in the following only the calculated results for N-S direction are presented. The results for E-W direction in general show a similar feature. Fig. 4 shows the calculated and recorded acceleration time histories at

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the surface and the depth of 16 m. It can be seen that the calculated acceleration histories are very similar to the field records. The simulated stress-strain histories at depths of 7.7 m and 51.3 m during the shaking are shown in Fig. 5. Here, the shear stress is normalized to the initial effective vertical stress. Obviously, the soils at the shallow depth (7.7 m) showed a dramatic reduction of soil stiffness. Especially, it is noted that the shear modulus of soils was almost reduced to zero while the shear strain remained at a large level at the final stage of strong shaking, this indicates that the soils fully liquefied. The soils at deeper layer (51.3 m), on the other hand, responded generally in a linear manner, with no appreciable reduction of stiffness and with a low level of strain. Fig. 6 depicts the excess pore water pressure responses at the depths of 7.7 m and 51.3 m during the shaking. The pore pressure is normalized with the corresponding initial effective vertical stress. It is seen that an abrupt rise in excess pore water pressure took place during the phase of strongest excitation (Phase 2, 5 s to 8 s). For the soils at the depth of 7.7 m, the excess pore pressure reached the value of initial effective vertical stress around at 8 s, which resulted in a full soil liquefaction.

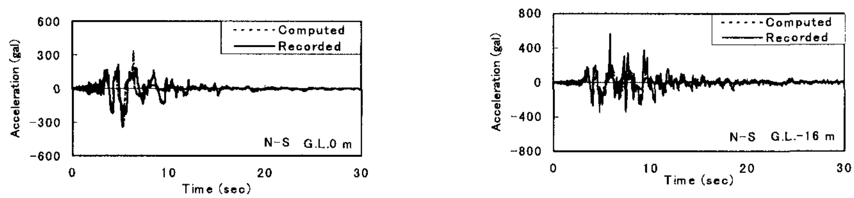
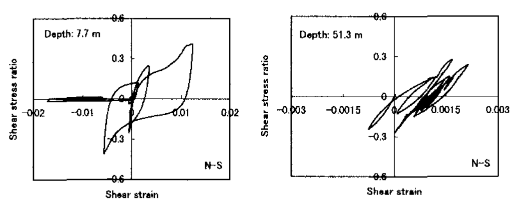


Fig. 4 Simulated acceleration time history



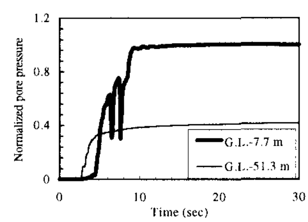


Fig. 5 Calculated stress-strain history

Fig. 6 Pore water pressure response

To clearly show the relation of ground motion and the soil behavior during shaking events, in Fig. 7 the stress-strain histories of soils at the depth of 7.7 m at different time stages are given. It is observed that, at the first time stage which corresponds to weak shaking (peak acceleration less than 0.1 g at all depths), the soil responded linearly with the strain level at the order of 0.01%, which is the typical threshold strain for sand, meanwhile the generated excess pore water pressure at this stage was very small, as shown in Fig. 6. Corresponding to this stage, the spectra of the surface motion were dominated by high frequency components (with peak frequencies of 4.5 Hz and 10.8 Hz). During the second stage which corresponds to strong shaking, the soil exhibited an obvious nonlinearity with the peak strain of the order of 1%. The generated excess pore pressure reached the value of 75% of initial effective vertical stress at 6 s. During the period from 6 s to 12 s, the abrupt loss of soil stiffness upon liquefaction was clearly observed. The amplitude of shear strain approximately reached the value of 2%. Correspondingly, the long-period waves were dominant in surface motion (with peak frequency of 0.6 Hz).

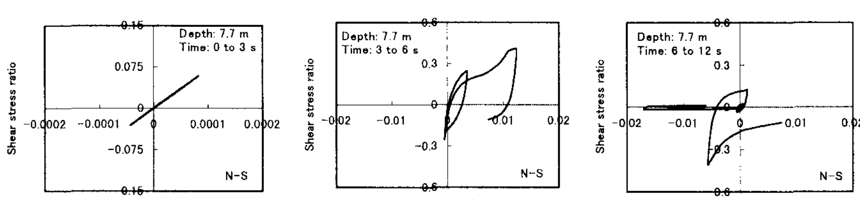


Fig. 7 Stress-strain behavior at three stages

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