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Non-linear transient behavior during soil liquefaction based on re-evaluation of seismic records

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ABSTRACT

Focusing on soil liquefaction, the seismic records during the Niigata-ken earthquake in 1964, the southern Hyogo prefecture earthquake in 1995 and the 2011 off the Pacific coast of Tohoku earthquake are analyzed by the non-stationary Fourier spectra. The shift of dominant frequency in the seismic record of Kawagishi-cho during the Niigata-ken earthquake is evaluated based on the time-variant property of dominant frequencies. The reduction ratio of the soil stiffness is evaluated from the shift ratio of dominant frequency. It is detected that the pulse wave in the transient process during the progressing liquefaction is composed of the primary mode and the secondary modes. Using the seismic records at the underground of Port Island during the southern Hyogo prefecture earthquake in 1995, the amplification of liquefaction is evaluated by comparing the maximum amplitude spectra of seismic records at GL 0 m and GL-83 m. The average shear strain of underground is calculated from the numerically integrated displacement profiles and the deterioration ratio of stiffness is evaluated from the G-γ relation. The amplification of liquefaction at Chiba bay area is evaluated by using the ratio of the maximum amplitude spectra of CHB024 and CHBH10 (Borehole) from the mainshock and the aftershock of the 2011 off the Pacific coast of Tohoku earthquake.

1. Introduction

Earthquake engineering has piled up the countermeasures to mitigate the seismic hazard based on the investigation on the hazard aspects and the analysis of seismic records. The 2011 off the Pacific coast of Tohoku earthquake (Mw 9.0) and the following tsunami caused severe hazards in wide areas of Japan. Many field investigations and analytical researches have been conducted by the public institutions and researchers [1–4].

In Japan three seismic hazards occurred every two years from 2007 and many seismic records with large acceleration were measured at the nuclear power plants close to the epicenter. Peculiar pulse waves were observed in the seismic records during the Niigata-ken Chuetsu-oki earthquake in 2007 and the Suruga-bay earthquake in 2009. These pulse waves were measured at the local points. The present authors have adopted the non-stationary Fourier spectra [5] and have detected the occurring mechanism of pulse waves, such as the non-linear interaction between a building and surrounding soil [6–8] and the local deformation at the underground [9]. The numerically integrated displacement profiles were evaluated in the deformation process of the underground and calculated the shear strain using the relative displacement at underground. The deterioration ratio of soil stiffness was certified by fitting it to the G-γrelation [10].

In this paper, the seismic records including soil liquefaction are analyzed using the above analytical method. The historical hazard due to soil liquefaction in Japan occurred fifty years ago during the Niigata-ken earthquake (M_{JMA} 7.5) in 1964 [11,12]. The typical hazards due to soil liquefaction, such as the uneven settlement and the upset of reinforced concrete buildings, were observed (see Fig. 1). The shift of dominant frequency was detected in the non-stationary Fourier spectra of the seismic records and the softening ratio of underground soil was estimated.

Severe soil liquefaction hazard occurred 20 years ago at Port Island during the southern Hyogo prefecture earthquake in 1995 (M_{JMA}7.3). The shear strain in the underground was calculated from the numerically integrated displacement profiles and the softening ratio of soil stiffness was evaluated by fitting it to the G-γrelation.

The 2011 off the Pacific coast of Tohoku earthquake caused the soil liquefaction hazard at Chiba bay area which is 350 km far from the epicenter. The pulse wave including cyclic mobility is analyzed by the non-stationary Fourier spectra and an secondary mode is detected as a result of occurring mechanisms of the pulse wave using the seismic records of CHB024 (K-NET) [13].

The novelties of this paper are (i) to apply the approach of the non-stationary Fourier spectra to soil liquefaction problems and make clear that the shift of dominant frequency is closely related

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to the transient process during soil liquefaction, (ii) to demonstrate that the shear strain in the underground calculated from the numerically integrated displacement profiles enables the computation of the softening ratio of soil stiffness during soil liquefaction and (iii) to show that the pulse wave including cyclic mobility consists of the primary and secondary modes.

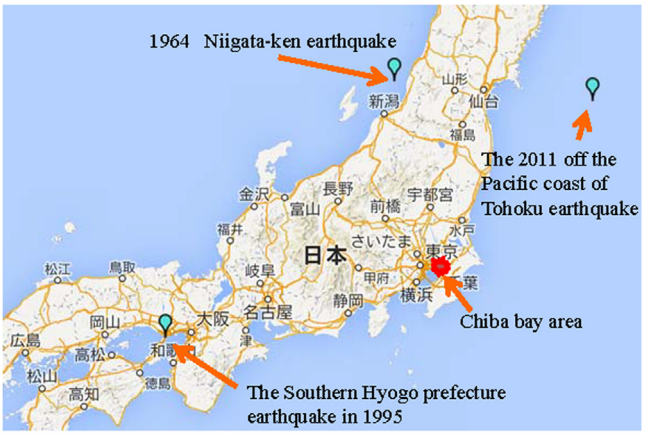

Fig. 1. Site map of earthquake events (http://www5.ocn.ne.jp/~botan/map_g.html).

2. First seismic record of soil liquefaction (Kawagishi-cho)

The first historical seismic records of soil liquefaction in Japan were measured during the Niigata-ken earthquake in 1964, in which an impressive seismic hazard occurred in a reinforced concrete building, such as the upset and the uneven settlement. The hazard seems to be caused by the sedimentary sand layer of the alluvium plain. This drastic seismic hazard in buildings and bridges were propagated in the world through the photographs and the seismic records, from which the researches were focused on the dynamical cyclic process of the liquefaction phenomenon [14–16]. In the 50 years after this seismic event, several seismic hazards due to soil liquefaction occurred and new findings were accumulated by many researchers [17–19].

2.1. Analysis by non-stationary Fourier spectra

Nonlinear interaction between a building and the surrounding soil has been focused in the previous research [5]. The pulse wave

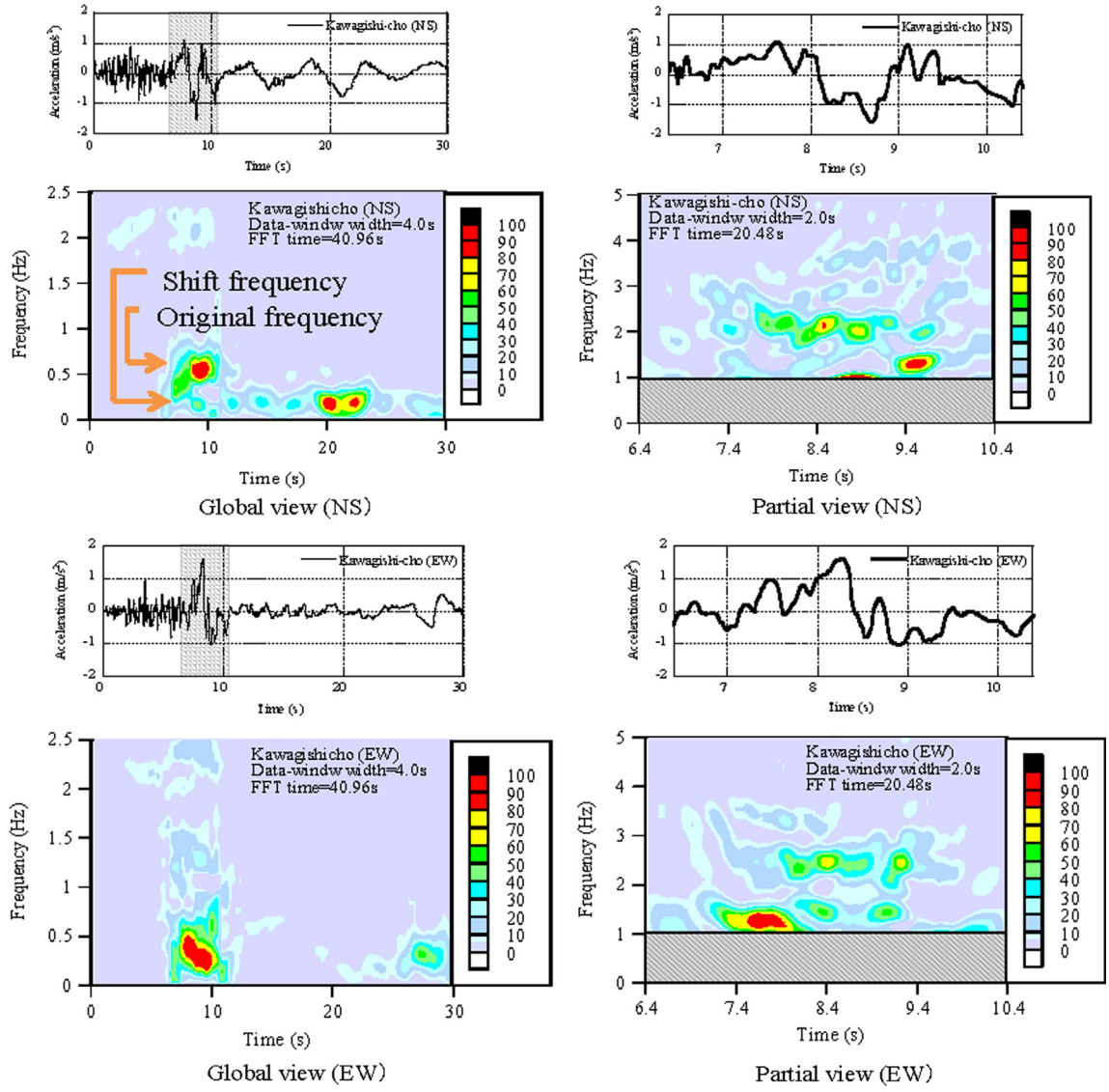

Fig. 2. Non-stationary Fourier spectra of primary mode of ground motion at Kawagishi-cho.