Equivalent linear method with complex frequency for site response analyses to near-fault fling-step displacements

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The equivalent linear method is commonly used for site response analyses in engineering practice. However, it cannot evaluate the displacement response of the ground subject to fling-step displacements because the fling-step displacements are characterized by non-zero final values, making the application of ordinary Fourier transform with real frequency inappropriate. On the other hand, in seismology, the use of complex frequency is a well-established technique. It was proposed by Phinney [1] and has since been widely and successfully adopted in computational seismology for the calculation of ground motions including near-fault fling-step displacements with the discrete wavenumber (DWN) method [2, 3]. As pointed by Wu et al. [4], the use of complex frequency is essential in avoiding the inconsistency between the theoretical and discrete Fourier transforms when the DWN method is applied to a displacement waveform with a nonzero final value. Therefore, in this study, the complex frequency was introduced to the equivalent linear method for the seismic ground response analyses subjected to near-source fling-step displacements.

The newly developed method was applied for analyzing the recordings at the KiK-net KMMH16 vertical array during the mainshock of the 2016 Kumamoto earthquake sequence. The vertical array contains two acceleration sensors on the ground surface and in the borehole at a depth of 252 m (NIED Strong-motion Seismograph Networks). We adopted the soil profile including the PS logging data at KMMH16 provided by NIED. We also used the density profile re-evaluated by Goto (Personal communication). Moreover, we also adopted the nonlinear soil properties at KMMH16, i.e., the stiffness-strain and damping-strain relations, which were again estimated by Goto (Personal communication) based on Ramberg-Osgood model. In the following we will show the results for the EW-components. Based on Boore [5], the accelerograms were integrated in time domain after a baseline correction and the resultant velocity waveforms were corrected by subtracting linear functions. Then the corrected velocity waveforms were integrated again in time domain to obtain displacement time histories at GL-252m and GL-0m. The former was used as the input ground motion for the equivalent-linear analyses.

Fig. 1 showed the results. **Fig. 1 (a ~ c)** shows good agreement between the synthetic and observed time histories for acceleration, velocity and displacement, respectively. In particular, the agreement is excellent for the displacement waveforms including the fling-step as well as the initial vibratory components. The maximum acceleration was underestimated but the phases were reproduced very well. **Fig. 1(d)** shows that the agreement between the observed and synthetic spectral ratio is excellent especially for the fundamental mode. **Fig. 1 (e ~ g)** show the peak acceleration, velocity and strain as a function of depth. The tendencies in the peak strain in **Fig. 1(g)** is similar to the results by Suetomi et al. [6] in a sense that the maximum strain occurred near GL-8m ~ 9m, even though different soil models were used in the analyses. The maximum strain is approximately 0.6%, which is less than 1%. These results well demonstrated that, the equivalent linear method with complex frequency is applicable to seismic ground response analyses subject to fling-step displacements.

Acknowledgment

Strong motion data and the soil profile at KMMH16 were provided by the National Research Institute for

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Earth Science and Disaster Resilience. The authors also express their appreciations to Hiroyuki Goto, Associate Professor of Kyoto University, for sharing his knowledge on the soil profile and dynamic soil properties at KMMH16, and suggestions regarding the application of the parameters.

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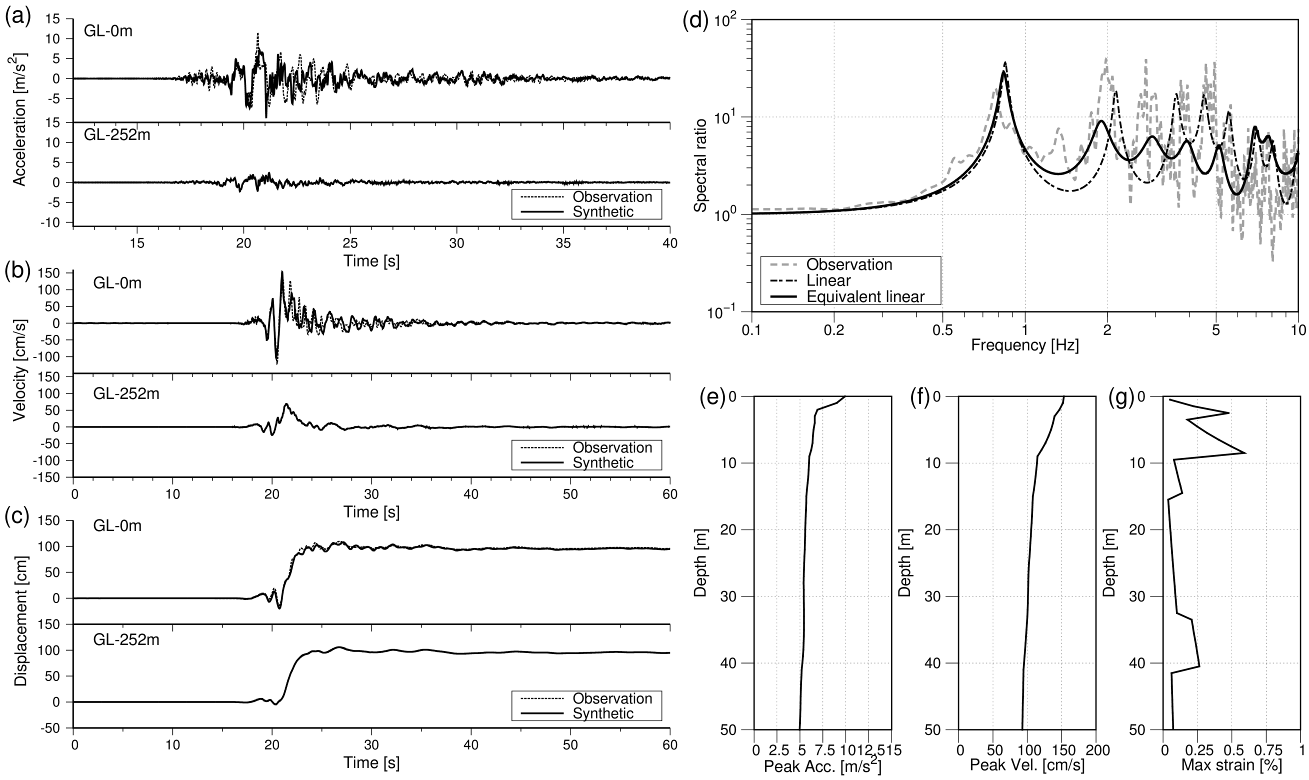

Fig. 1 Observed and synthetic time histories for (a) acceleration, (b) velocity, and (c) displacement. Also plotted are the (d) spectral ratios and the peak responses along the depth for (e) acceleration, (f) velocity and (g) strain.

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