Dynamic soil properties estimated from downhole array data recorded at the Kashiwazaki-Kariwa nuclear facility in the 2007 Niigata-ken Chuetsu-oki earthquakes

Propriétés dynamiques estimatives du sol d'après une série d'enregistrement verticale obtenue au Centrale Nucléaire de Kashiwazaki-Kariwa pendant les Séismes de Niigata-ken Chuetsu-oki de 2007

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ABSTRACT

Dynamic properties of soil deposits at two sites (one near Unit 5 and the other near the Service Hall) at the Kashiwazaki-Kariwa nuclear power plant were back calculated using strong motion recordings obtained during the 2007 Niigata-ken Chuetsu-oki earthquakes. The method used to figure this inversion was genetic algorithm, coupled with a one-dimensional equivalent linear response analysis, in which damping ratios will vary with the Fourier shear strain amplitude in the frequency domain. Our back-analysis has demonstrated that the surface layer at the Service Hall consisting of Holocene and Pleistocene dune sands showed strong nonlinear behavior during the main shock, with the underlying Pliocene Nishiyama Formation remaining elastic. The Pleistocene Yasuda Formation occurring near the ground surface at Unit 5, as well as the underlying Nishiyama and Shiiya Formations, also remained nearly elastic, but exhibited higher damping ratios. It is believed that the different dynamic soil behavior between the two sites may have led to the strikingly different site amplification between the two sites during the main shock.

RÉSUMÉ

Les propriétés dynamiques de couches de sol a proximité du Batiment #5 et de L'Unité de Service au Centrale Nucléaire de Kashiwazaki-Kariwa ont été calculées à l'inverse, d'après une série d'enregistrement verticale de déplacements forts notés a ces deux sites pendants les séismes de Niigata-ken Chuestsu-oki en 2007. La technique du calcul appliquée était un algorithme génétique, lié d'une analyse de réponse linéaire à une dimension, dans laquelle les coefficients d'amortissement varieront selon l'amplitude Fourier de la déformation au cisaillement dans le domaine de fréquence. Notre analyse a posteriori a démontré que le gisement de surface auprès de l'Unité de Service, se composant d'ensablements des époques holocène et pléistocène, a montré une forte comportement linéaire pendant le séisme principal, en même temps que la sous-couche de Nishiyama Formation pliocène est restée élastique. La Yasuda Formation pléistocène se trouvant plus près à la surface du sol autour du Batiment #5, si bien que la Nishiyama et Shiiya Formations étant à la base, sont restés à peu près élastique, tout en présentant des coefficients d'amortissement plus élevés. Les divers comportements dynamiques du sol observés dans les deux sites auraient pu conduire à des amplifications du site en contraste frappant obtenues pendant le séisme principal.

Keywords : back-analysis, dynamic response analysis, damping ratio, earthquake, nonlinear soil properties, shear modulus

1 INTRODUCTION

The Niigata-ken Chuetsu-oki earthquake (M_j=6.8) that occurred on July 16, 2007, with an epicenter off the Niigata Prefecture, affected not only the coastal areas of the southwestern Niigata prefecture but also the Kashiwazaki-Kariwa nuclear power plant of Tokyo Electric Power Company (TEPCO). The operation of the plant has been halted for more than one and a half years, presumably due to very strong ground shaking at the site and the resulting settlements of backfills around the critical buildings.

A total of 97 accelerometers of old and new systems were installed at the site (TEPCO 2007a). The strong motions at 33 locations including one downhole array at the Service Hall were recorded for the main shock, but unfortunately, the recordings obtained at the other 63 locations including three free-field downhole arrays close to the reactor buildings were lost, with the exception of the peak values as well as some pen-writing recordings (TEPCO 2007a, 2007b; Tanaka et al. 2008). Recently, the pen-writing recordings including NS components at Unit 5 have been digitized (Tanaka et al. 2008).

The downhole array records at the Service Hall as well as Unit 5 seem to be particularly important not only to determine the input rock outcrop motions for analytically reviewing dynamic behavior of the critical buildings but also to estimate nonlinear dynamic soil properties at the site that are definitely required for the analysis. The objective of this paper is to estimate dynamic soil properties based on an inverse analysis of the downhole array records using genetic algorithms combined with a one-dimensional equivalent linear response analysis.

2 SITE CONDITIONS AND OBSERVED RECORDS

The Kashiwazaki-Kariwa nuclear power plant is located along the coast on the north of Kashiwazaki city, about 16 km from the epicenter. Figure 1 shows a map of the site together with the locations of the downhole arrays near Service Hall and Unit 5 reactor building. Figure 2 shows the geological and

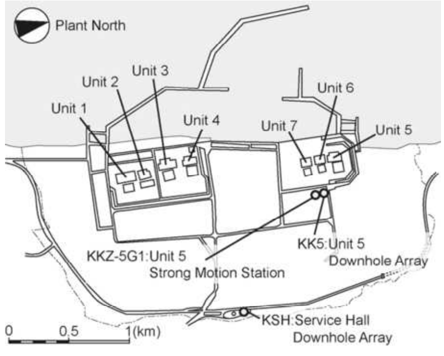

Figure 1. Map showing locations of downhole arrays

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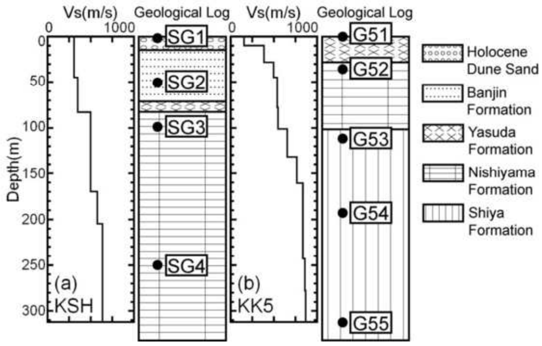

Figure 2. Geological and geophysical logs

geophysical logs along with the locations of the downhole accelerometers. The elevation of the Service Hall is 67.5 m, which is 55.2 m higher than that of Unit 5 (12.3 m). The Holocene and Pleistocene sand dune deposits at Service Hall overlie the Pleistocene Yasuda Formation that in turn overlies the Pliocene Nishiyama Formation, while the Pleistocene Yasuda Formation outcrops at Unit 5, overlying the Pliocene Nishiyama and Shiiya Formations. The shear wave velocities, V_{so} of the Holocene sand dune (New sand dune), Pleistocene sand dune (Banjin Formation), Yasuda, Nishiyama, Shiiya Formations vary from 300- 850 m/s.

The Service Hall downhole array includes three-component accelerometers installed at four depths, while the Unit 5 array at five depths, as shown in Figure 2. The NS and EW directions of the accelerometers were set to the two principal axes of the plant buildings and thus were rotated clockwise 18.9 degrees from the true ones.

The downhole array recordings for the main shock as well as two aftershocks that occurred at 15:37 hrs and 17:42 hrs on the same day, herein called aftershocks L and S, are used for this study (TEPCO 2007a-2007c). Figure 3 shows the NS acceleration time histories observed at the Service Hall during the main shock and Table 1 summarizes peak accelerations observed with the arrays during the three events. The peak ground acceleration at the Service Hall during the main shock

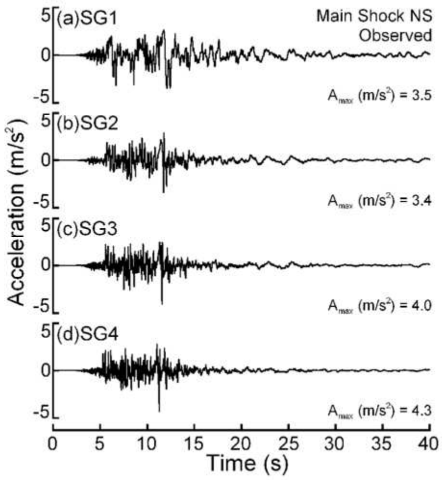

Figure 3. Acceleration time histories at Service Hall

Table 1. Peak accelerations during three earthquakes

Sensor ID	Peak acceleration (m/s^2)			Sensor ID	Peak acceleration (m/s^2)		
	S	L	Main		S	L	Main
SG1	0.35	1.6	3.5	G51	0.39	2.2	9.6
SG2	0.15	1.3	3.4	G52	0.31	1.4	4.2
SG3	0.17	1.4	4.0	G53	0.22	1.1	3.9
SG4	0.18	1.4	4.3	G54	0.16	1.3	4.2
				G55	0.16	1.2	4.1

was de-amplified from 4.3 m/s^2 at a depth of 250 m to 3.5 m/s^2 near the ground surface, losing their short period component. This contrasts well with the other data sets in which the peak ground accelerations at Unit 5 in all the three events as well as those at Service Hall during the two aftershocks were amplified. This suggests that the difference in dynamic soil properties between the sites might have played an important role in the site response observed during the earthquakes.

3 INVERSE ANALYSIS USING GENETIC ALGORITHMS

Dynamic soil properties are back-calculated for the deposits of the two sites at the Kashiwazaki-Kariwa nuclear power plant based on the strong motion downhole array records during the 2007 Niigata-ken Chuetsu-oki earthquakes. The goal of this inversion is to find a soil layer model that minimizes the misfit between observed and computed Fourier amplitudes and phase angles between any of the two depths in an array defined as:

$$S = \sum_{i=1}^{K-1}\sum_{j=i+1}^{K}\int_{f1}^{f2} w^2\left\{\log_{10}(A_{oij}(f)) - \log_{10}(A_{cij}(f))\right\}^2 df + \alpha\sum_{i=1}^{K-1}\sum_{j=i+1}^{K}\int_{f1}^{f2} w^2\left\{\log_{10}(P_{oij}(f)) - \log_{10}(P_{cij}(f))\right\}^2 df \quad (1)$$

in which A_m, A_c, P_m and P_c are the observed and computed Fourier amplitudes and phase angles between the i-th and j-th accelerometers in the array, K is the number of accelerometers, f_1 and f_2 are the minimum and maximum frequencies to be considered, and w is a weighting factor defined as 1/f.

It is assumed that A_c in the above equation be determined with a one-dimensional equivalent-linear response analysis of a deposit in which damping ratios are dependent on the Fourier amplitude of shear strain in the frequency domain (e.g., Sugito et al, 1994), which is an extended version of SHAKE (Schnabel et al, 1972) to improve its deficit in over-damping in the short period range during strong shaking. It is also assumed that the target soil deposit consists of N sub-layers including the bottom half space, each characterized by the mass density, thickness, equivalent shear wave velocity, and damping ratio in the frequency domain defined as:

$$h(f)=h_{min}+(h_{max}-h_{min})(\gamma_{eff}(f)/\gamma_{ref})/(1+\gamma_{eff}(f)/\gamma_{ref}) \quad (2)$$

$$\gamma_{eff}(f) = 0.8\,\gamma_{max}\cdot\Gamma(f)/\Gamma_{max}(f) \quad (3)$$

in which h_{min} and h_{max} are the minimum and maximum damping ratios; γ_{ref}, γ_{max}, $\gamma_{eff}(f)$, $\Gamma(f)$ and $\Gamma_{max}(f)$ are the reference shear strain, maximum shear strain in the time domain, effective shear strain for a given frequency *f*, Fourier amplitude of shear strain at a given *f*, and the maximum Fourier amplitude of shear strain in the frequency domain, respectively. Thus, once knowing all the soil properties in the deposit, A_c and P_c in Eq. (1) can be determined by iterative procedure until h(*f*) becomes compatible with Fourier amplitude of shear strain.

Adopted in the optimization using Eq. (1) is genetic algorithm (GA; Goldberg, 1989, Kobayashi et al., 1999) in which four parameters including the equivalent shear wave velocity, minimum and maximum damping ratios and reference shear strain of each sub-layer are sought with other parameters such as the thickness and mass density being predetermined and with N=15 or 14, I=4 or 5, T=81.92 s, f_{max}=25 or 5 Hz, and f_{min}=0.2 Hz.

In the GA space, an 8-bit Gray coded integer is used for each of the unknown parameters. This leads to a 4x8xN480-bit integer (chromosome) for an individual soil layer model consisting of N sub-layers with four unknown parameters each. An initial population of 200 soil layer models is generated randomly, covering the range of possible solutions, and the succeeding generation of the same population is reproduced until the 500th generation. The parameter search ranges are 0-5% for h_{min}, 15-40% for h_{max}, 10^{-4}-10^{-2} for γ_{ref} and (0.05-0.5)V_{so}-(0.7-1.2)V_{so} for V_s. A roulette wheel-selection is used

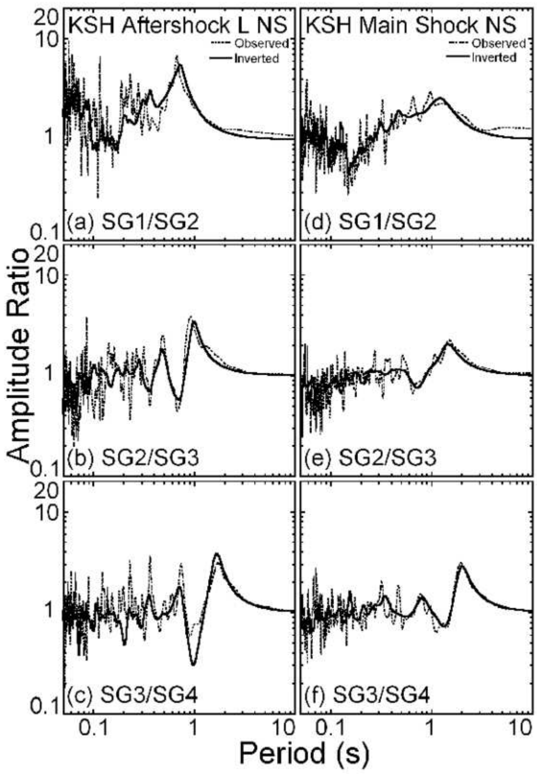

Figure 4. Observed and computed amplitude ratios at at Service Hall array

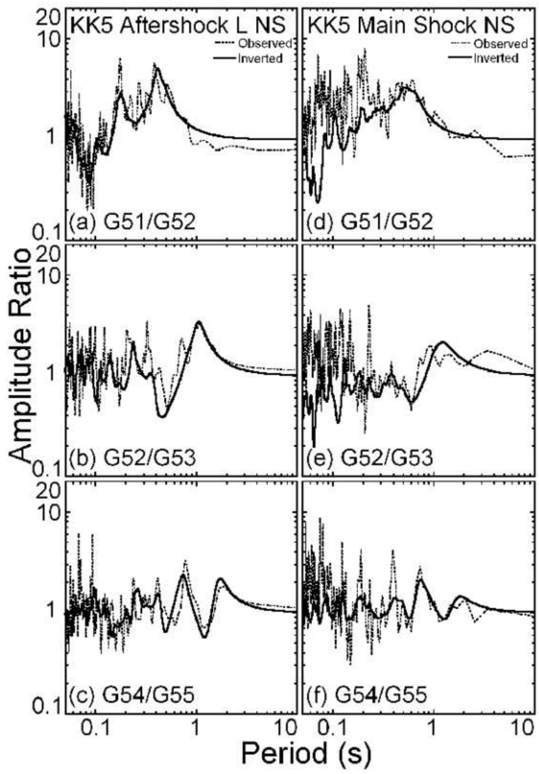

Figure 5. Observed and computed amplitude ratios at Unit 5 array

to choose and mate a pair for the new generation based on the fitness of each individual soil layer model defined by 1/F, with a crossover rate of 0.7 and a mutation rate of 0.02. The soil layer model having the best fitness in the final generation is assumed to be the solution for one trial. A total of ten trials are made for each set of the array data observed during the main shock and the two aftershocks L and S.

4 DYNAMIC SOIL PROPERTIES FROM INVERSION

Figures 4 and 5 compare the Fourier amplitude ratios computed for the back-calculated soil layer models having the best fitness with those of the observed records for the aftershock L and the main shock. A good agreement exists between the observed and computed amplitude ratios, indicating that the back-calculated soil profiles are reasonably reliable.

Figure 6 shows the distribution of back-calculated equivalent shear wave velocity with depth for the three events compared with an available V_s profile determined by PS logging. The estimated shear wave velocities at depths smaller than about 70 m at Service Hall are significantly smaller in the main shock than in either of the two aftershocks. In contrast, those at deeper depths at Service Hall as well most of the layers at Unit 5 during the three events are almost identical. The back-calculated shear wave velocities are generally consistent with the available shear wave velocity profile, except for the shallow depths where even V_s back-calculated for the aftershock S are significantly smaller than the available V_s values. This poses a question about the accuracy of the available V_s profile at the shallow depths.

Figure 7 shows the back-calculated strain-dependent shear modulus and damping ratios of the two sites during the three earthquakes. The shear modulus has been normalized with respect to the elastic shear modulus estimated using $G_o = \rho V_s^2$ in which V_s is the average of the back-calculated values for the aftershock S. The shear modulus ratios of the sand dune deposits at Service Hall as well as the Yasuda Formation at Unit 5 decrease to 0.05-0.5 and their damping ratios increase to about 20-35% with shear strains up to 2×10^{-3} - 3×10^{-2} during the main shock. Also shown in the figures are the laboratory test data for sand tested under confining pressures (Kokusho, 1980) similar to those of the dune sands. The back-calculated strain-dependent shear modulus ratios are consistent with those of the previous study but the back-calculated damping ratios are slightly higher than those of the previous study. The shear modulus of the Pliocene Nishiyama and Shiiya Formations are about 1.0 and do not show any significant nonlinear behavior irrespective of the level of ground shaking but the back-calculated damping ratios of those formations at Unit 5 vary depending on shear strain.

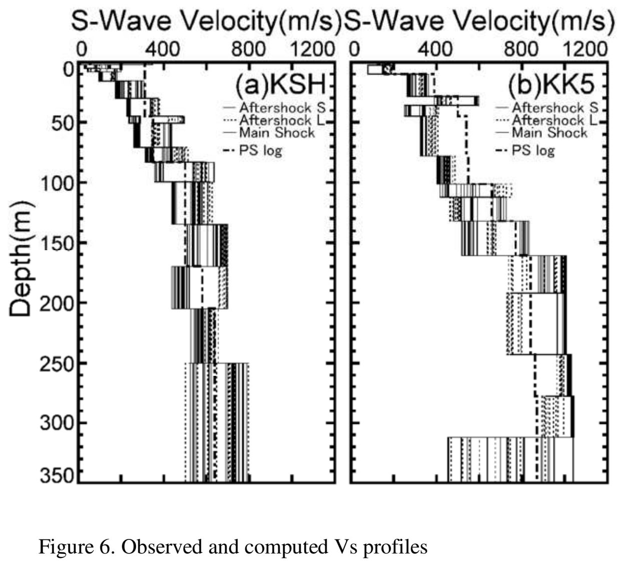

Figure 6. Observed and computed Vs profiles

5 CONCLUSIONS

Dynamic soil properties are back-calculated using the strong motion downhole array recordings at the Kashiwazaki-Kariwa nuclear power plant during the 2007 Niigata-ken Chuetsu-oki earthquakes. The back-analysis has shown the following conclusions:

(1) The surface layer at the Service Hall consisting of Holocene and Pleistocene dune sands showed strong nonlinear behavior during the main shock, with the underlying Pliocene Nishiyama Formation remaining elastic.

(2) The Pliocene Yasuda Formation that occurs near the ground surface at the Unit 5 as well as the underlying Nishiyama and Shiiya Formations also remained almost elastic, but had higher damping ratios.

(3) The different dynamic soil behavior between the two sites could have led to completely different site amplification between the two arrays during the main shock.

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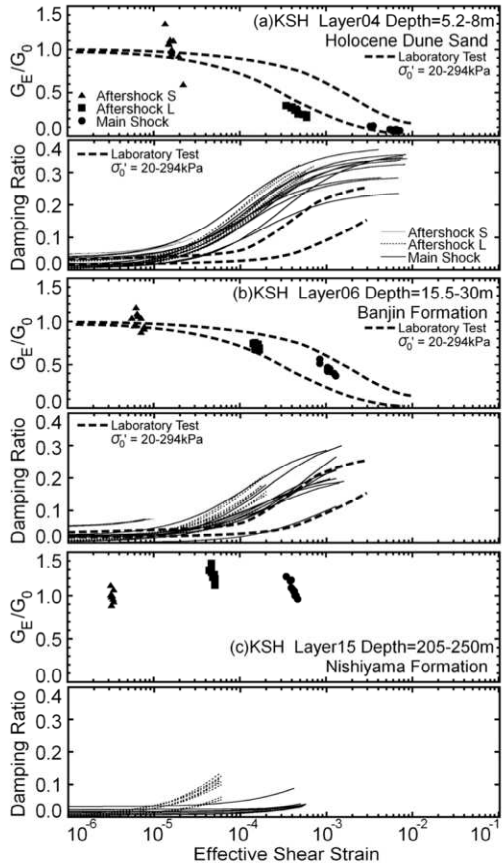

Figure 7. Computed dynamic soil properties at Service Hall

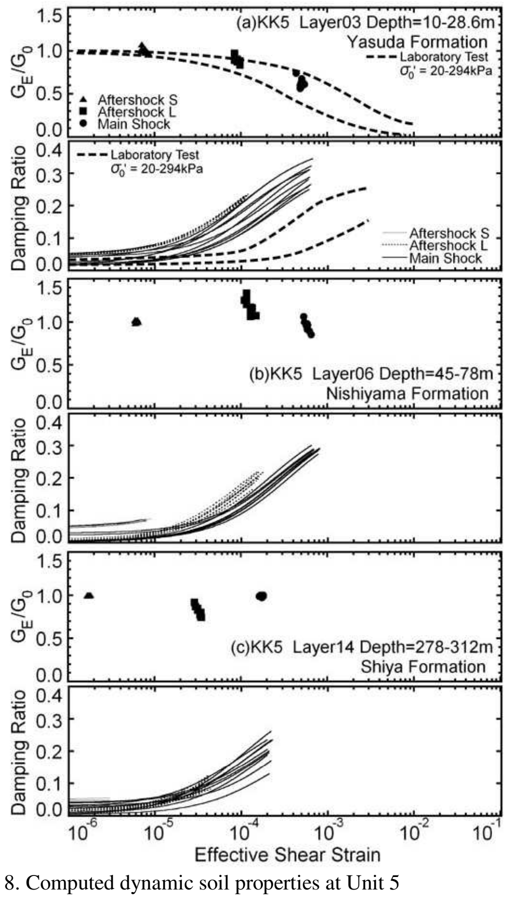

Figure 8. Computed dynamic soil properties at Unit 5