EFFECTS OF HIDDEN VALLEY ON GROUND RESPONSE AND DAMAGE DISTRIBUTION IN THE 1993 KUSHIRO-OKI EARTHQUAKE

Kohji TOKIMATSU[1], Toru SEKIGUCHI[2] And Akio ABE[3]

SUMMARY

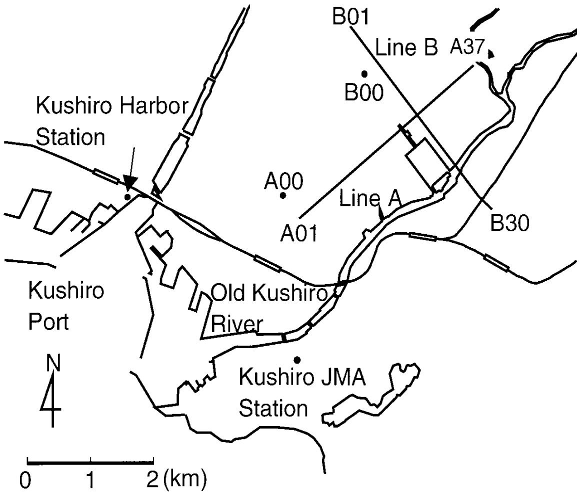
Effects of a hidden valley on the ground response and damage distribution are studied based on a case history during the 1993 Kushiro-oki earthquake at which liquefaction-induced uplifts of manholes of sewer lines were concentrated in specific areas in Kushiro-cho. Microtremor measurements are conducted along two lines passing through the damaged areas, and the horizontal to vertical amplitude ratios (H/V) of microtremors are determined. The two-dimensional shear structures across the damaged areas are then estimated based on a inverse analysis of microtremor H/V data, assuming that they reflect those of surface waves. It is shown that: (1) hidden valleys exist below the sedimentary deposits, and (2) the manhole damage tends to have concentrated on the ground above the top of the slope of the hidden valleys. Two-dimensional dynamic analyses are conducted using the inverted shear wave velocity profiles including a hidden valley. It is found that not only the computed peak ground surface accelerations but also the maximum shear strains in the sedimentary deposit above the top of the slope of the hidden valley are significantly larger than those in other areas, and that this difference might have caused the concentration of the manhole damage.

INTRODUCTION

The Kushiro-oki earthquake (M=7.8) that occurred on January 15, 1993, damaged various structures and lifelines including sewer lines in Kushiro city and its vicinity [Japanese Geotechnical Society, 1994; Public Works Research Institute, 1994]. Of particularly noticeable was the uplifts of manholes of sewer lines that concentrated in specific areas in Kushiro-cho. Possible causes of the damage were considered to be liquefaction of backfill around the manholes and/or near-surface soils. Available boring logs to a depth of 20 m, however, do not vary considerably between the damaged and undamaged areas, suggesting possible effects of deeper soil conditions including irregular basin structures on the ground response characteristics in the region [Japanese Geotechnical Society, 1994]. It is, however, difficult to estimate two-dimensional shear wave velocity (Vs) structures using conventional geophysical methods with boreholes.

Despite its unclear theoretical background, the microtremor H/V spectrum method originally proposed by Nakamura and Ueno (1986) is appealing for two-dimensional soil profiling as it can be performed on the ground surface without any borehole. This method has recently been backed up theoretically [Tokimatsu and Miyadera, 1992; and Lachet and Bard, 1994] and becomes applicable to Vs profiling [Tokimatsu et al., 1998]. Based on the improved technique, microtremor measurements are conducted in Kushiro-cho and two-dimensional Vs structures across the damage zones are estimated. Two-dimensional dynamic analyses are then conducted using the estimated shear wave velocity profiles including a detected hidden valley.

[1] *Dept of Architecture and Building Engineering, Tokyo Institute of Technology, Tokyo, Japan Email:kohji@o.cc.titech.ac.jp*
[2] *Dept of Architecture and Building Engineering, Tokyo Institute of Technology, JapanEmail:hsekiguc@post.arch.titech.ac.jp*
[3] *Tokyo Soil Research Co. Ltd., Tsukuba, Japan Email: abe@tokyosoil.co.jp*



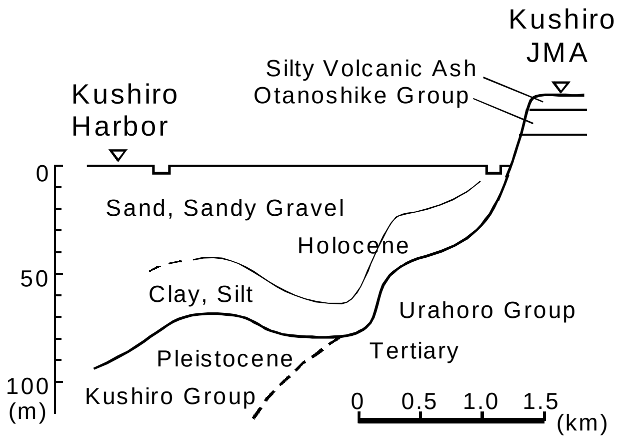


Figure 1: Map of Kushiro city and its vicinity

Figure 2: Geological cross section

The objects of this study are to demonstrate the use of microtremor H/V spectra for two-dimensional shear wave velocity profiling and to examine possible effects of irregular basin structures on the concentration of manhole damage.

GEOLOGICAL CONDITIONS AND EARTHQUAKE-INDUCED MANHOLE DAMAGE

Figure 1 shows a map of Kushiro city and its vicinity and Fig. 2 shows a geological cross section across the city from northwest to southeast [Tokimatsu et al., 1998]. Located on the southeast of the Old-Kushiro River is a plateau covered by a thin layer of silty volcanic ash that overlies a Tertiary rock, called Urahoro Group. Developed on the northwest of the river is a flat alluvial deposit of Holocene soils that overlies the Urahoro Group or a Pleistocene layer called Kushiro Group. The depth to the Urahoro and Kushiro Groups generally increases westward from about 20 m to more than 80 m.

Figure 3 shows the shear wave velocity profiles at Site A00 [Kataoka and Sasatani, 1995] and at the Japan Meteorological Agency at Kushiro (Kushiro JMA) [Tokimatsu et al., 1998], the locations of which are shown in Fig. 1. Figure 3 indicates that the shear wave velocities are 120-150 m/s for the near-surface soils, 200-300 m/s for the underlying Holocene sand and sandy gravel, 650-800 m/s for the Pleistocene Kushiro Group and the Tertiary Urahoro Group, and about 1600 m/s for the Cretaceous rock that occurs at a depth of approximately equal to or greater than 100 m. Strong motion accelerograms were registered at two sites in Kushiro city during the 1993 Kushiro-oki earthquake. These include the Kushiro JMA station on the plateau and the downhole

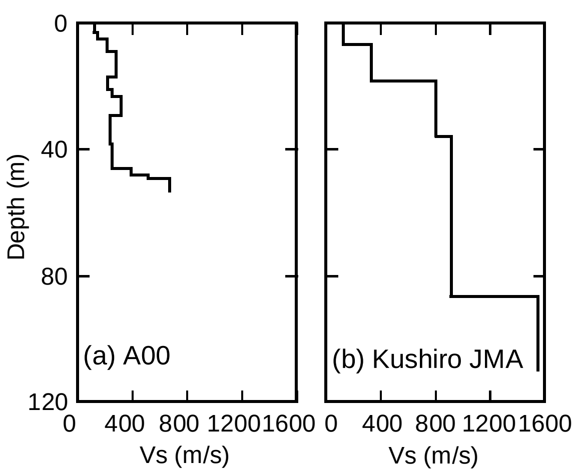


Figure 3: Shear wave profiles at two sites

Figure 4: Uplifted manhole in Kushiro-cho (Courtesy of Mr. Y. Suzuki)

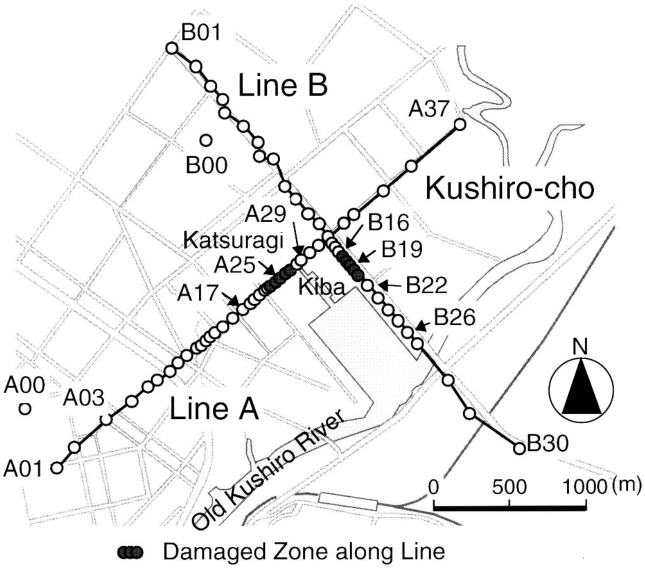


Figure 5: Map showing zones of manhole along damage Lines A and B

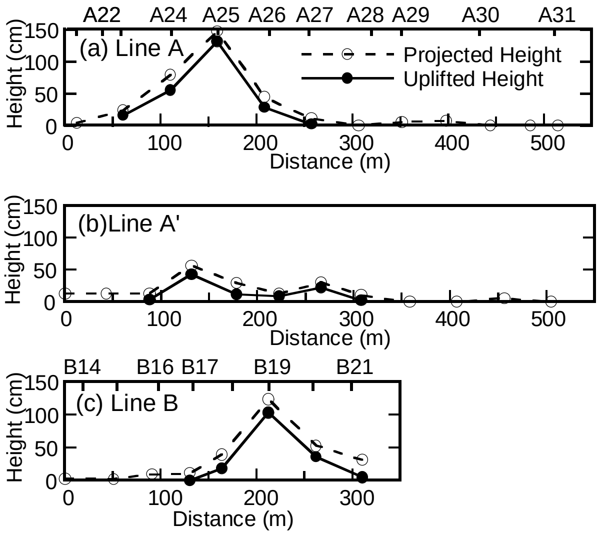


Figure 6: Distribution of uplift height of manholes (after Public Works Research Institute)

array station in the Kushiro Harbor district on deep alluvium. The peak ground acceleration at the Kushiro JMA station was 7.11 m/s [Kashima et al., 1994], while those on the ground surface and at a depth of 77 m at the Kushiro Harbor station were 4.69 and 2.62 m/s [Matsunaga et al., 1994], respectively.

In Kushiro city and its vicinity, sewer pipes and manholes were extensively damaged. A large number of manholes were uplifted and protruded from the ground by up to 1.5 m, as shown in Fig. 4. Of particularly noted was the concentration of manhole uplifts in specific areas of Kiba and Katsuragi, Kushiro-cho [Japanese Geotechnical Society, 1994; Public Works Research Institute, 1994]. Figure 5 shows a map indicating the zones of manhole damage along the two lines indicated as Lines A and B. Figure 6 shows the distribution of uplift height of manholes along the two lines [Public Works Research Institute, 1994]. Uplift occurred over a length of 200 m from A22 to A27 along Line A with a maximum value of 1.5 m at A25, and over a length of 150 m from B17 to B21 along Line B with a maximum value of 1.0 m at B19. The uplifted manholes had a diameter of about 1 m and a height of 2.18-5.17 m.

The near-surface soil conditions are very similar between damaged and undamaged zones. The area was formerly wetland comprising of peat with a thickness varying from 0.5-2 m, which has been filled with sandy soils with the development of the city. Peat was underlain by a loose layer of Holocene sands with N-values generally less than 10. This layer is further underlain by a dense layer of Holocene sands with N-values greater than 30 at depths of 8-13 m. The watertable was located at a depth of about 2 m. Sand volcanoes sporadically observed on the ground surface near the uplifted manholes suggest that soil liquefaction of the backfill around the manholes and/or of the underlain Holocene sands was the major cause of the uplift.

MICROTREMOR H/V SPECTRA FOR SHEAR STRUCTURE PROFILING

Since the near-surface soil conditions are similar between damaged and undamaged zones, other factors such as irregular basin structures formed below the area [Okazaki et al., 1966] have been suggested as a possible cause of the concentration of manhole damage [Okazaki, 1993; and Japanese Geotechnical Society, 1994]. However, not only reliable basin configuration but also the shear wave velocity profile below the area is unavailable. Thus, microtremor measurements were conducted at about 70 locations along Lines A and B as shown in Fig. 5, to provide data for determining the shear wave structures along the lines. The working principle of the mocrotremor measurements is based on the following:

(1) Microtremor horizontal to vertical (H/V) spectral ratios observed at a site correspond to those of surface waves [e.g., Tokimatsu and Miyadera, 1992; Tokimatsu, 1995];
(2) If the impedance ratio between the surface layer and the underlying stiff layer of a site is high, the microtremor H/V ratios of the site has a distinct peak, and the peak period could be equal to the natural site period [Tokimatsu, 1995];

(3) The H/V spectral ratios of surface waves can be determined theoretically for a given shear wave profile [Tokimatsu and Arai, 1998, and Arai and Tokimatsu, 1998]; and
(4) A shear wave velocity profile below a site can be estimated based on an inverse analysis of microtremor H/V data, provided that they correspond to those of surface waves [Arai and Tokimatsu, 1998].

The equipment used consists of amplifiers, low-pass filters, 16-bit A/D converter, and a notebook computer, all built-in a portable case; and a three-component velocity sensor with a natural period of 5 s. At each location, microtremor ground motions were observed for about 15 minutes and digitized at equal intervals of 0.01s. Sixteen sets of data consisting 4096 points each were made from the recorded motions and used for the H/V spectral analysis. The distance between adjacent two stations ranged from 20 - 300 m, depending on the variation of microtremor H/V spectra between two stations. The microtremor H/V spectral ratio used in this paper, $(H/V)_M$, is defined as [Tokimatsu and Arai, 1998; and Arai and Tokimatsu, 1998]:

$$(H/V)_M = \sqrt{{S_{NS}}^2 + {S_{EW}}^2} / S_{UD} \tag{1}$$

in which S_{UD} is the Fourier amplitude of microtremor vertical motion, and S_{NS} and S_{EW} are those of the two orthogonal horizontal motions.

The solid lines in Figs. 7 and 8 show selected H/V spectra at several sites along the two lines. Figure 9 shows spatial variations of H/V spectra along the two lines using the gradations shown in the legend. At each site, the H/V spectrum has a prominent peak, indicating that the impedance ratio of the site is relatively high. Besides, the peak period of H/V spectrum varies from 0.5-1.3 s, depending on the location. Namely, on Line A, the H/V peak period is almost constant at 0.5 s between A01 and A09 and between A29 and A37. But it drastically increases from 0.5s to 1.3 s and then back again to 0.5 s between A09 and A29, with a maximum value near A17. On Line B, in contrast, it is almost constant at 0.5 s between B10-B16 and increases to 1.3 s towards both ends of the line. The variation in H/V peak period suggests that the shear wave structure varies considerably along the lines, even though no topographical variation exists.

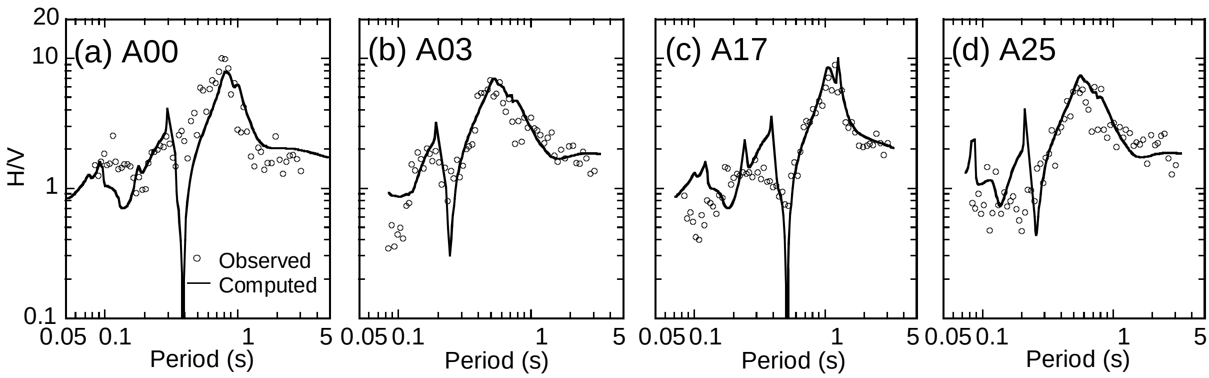


Figure 7: Selected H/V spectra along Line A

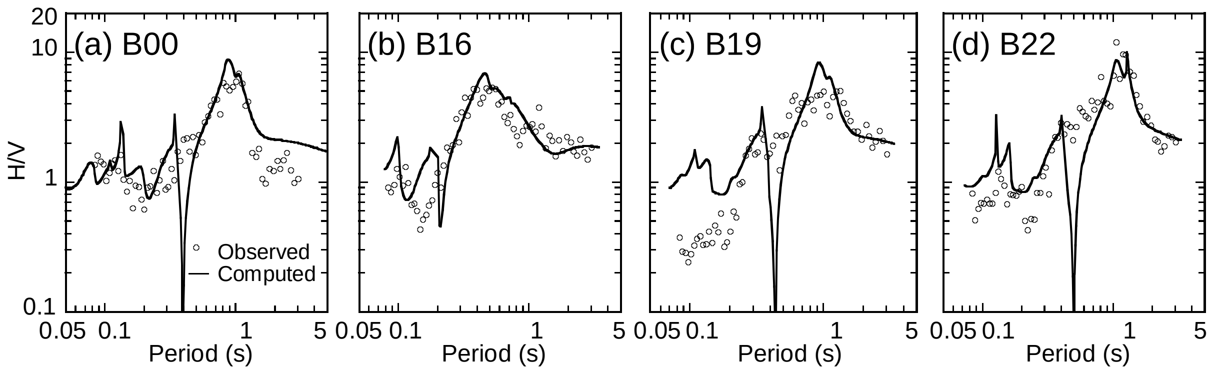


Figure 8: Selected H/V spectra along Line B

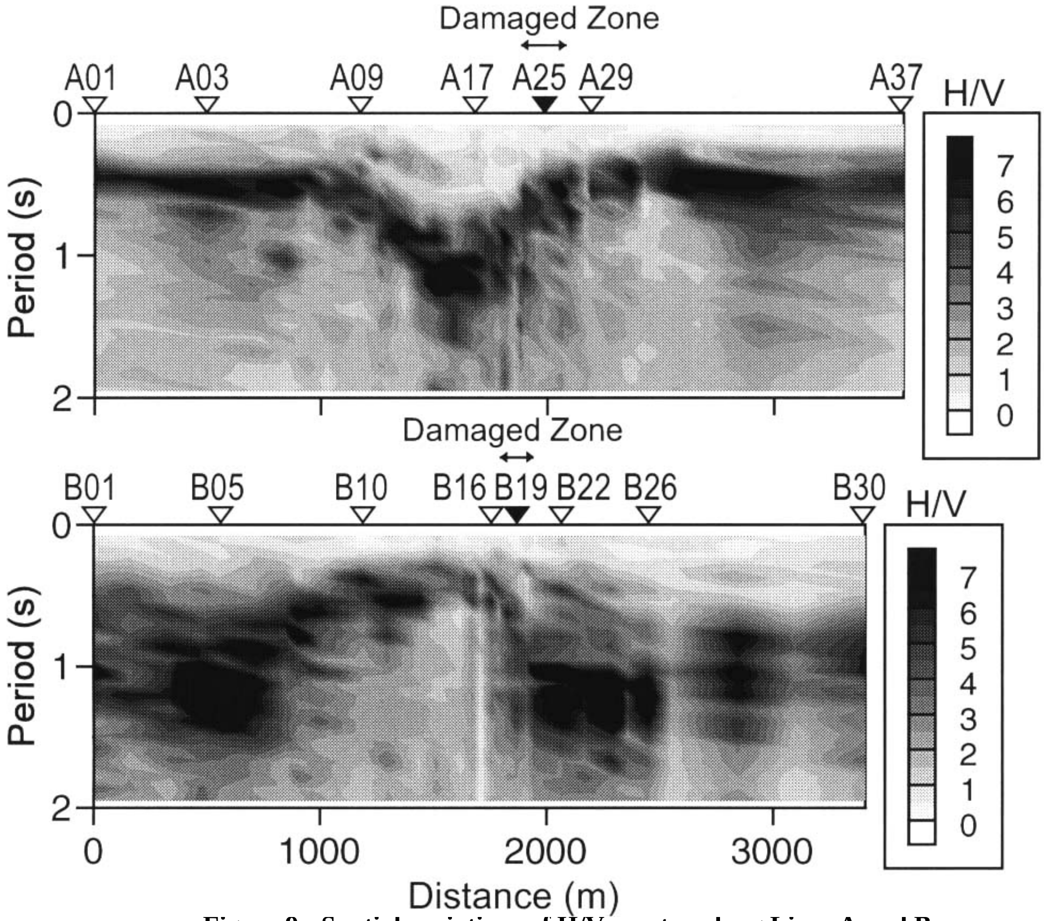


Figure 9: Spatial variations of H/V spectra along Lines A and B

SHEAR WAVE STRUCTURES ESTIMATED FROM MICROTREMOR H/V SPECTRA

According to the inverse analysis proposed by Arai and Tokimatsu (1998), two-dimensional shear wave velocity profiles along the two lines are estimated. In the inverse analysis, it is assumed that the observed microtremor H/V ratios correspond to those of surface waves and are defined by the formulas presented by Tokimatsu and Arai (1998), and that the soil deposit below the site is horizontally stratified. In addition, the amplitude ratio between Love and Rayleigh waves in microtremor horizontal motions is assumed to be 0.7 for all periods. Figure 7(a) compares the observed and theoretical H/V spectra at Site A00 of which shear wave velocity profile is given in Fig. 3 (a). A good agreement between the observed and theoretical H/V spectra confirms that microtremors represent the characteristics of surface waves.

An inverse analysis is performed so that misfits between observed and theoretical H/V spectra are minimized. A four-layer model is used throughout the study. The shear wave velocities of all layers are predetermined to the values described previously, and only the thicknesses of the top three layers are sought provided that the forth layer with Vs = 1600 m/s occurs at a depth of 100 m.. Further details of the inverse analysis has been presented by Arai and Tokimatsu (1998).

Figure 10 shows the two-dimensional shear wave velocity structures thus inverted for Lines A and B. The broken lines in Figs. 7 and 8 are the computed H/V spectra of surface waves for the inverted shear wave profiles. The inversion made for Site B00 indicates that the depth of the Tertiary Urahoro Group with Vs = 800 m/s is 51 m, which is consistent with a known bedrock depth of 54 m. The good agreement in spectral shape and peak period as well as in the depth of Tertiary Rock suggests that the inverted structures could be reasonably reliable.

The depth where the layer with Vs = 800 m/s occurs varies form 25-72 m, which is consistent with the previous study [Okazaki et al., 1966]. The irregularly stratified layer with Vs = 800 m/s creates hidden valleys below the sedimentary deposits with level ground surface. Probably, these valleys were formed by stream erosion

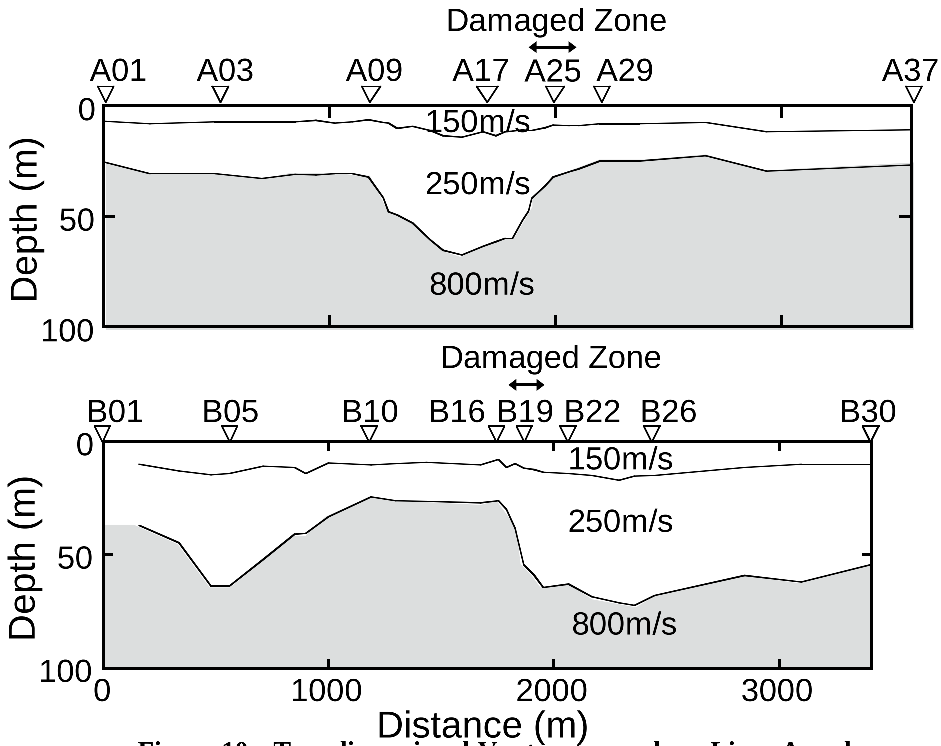


Figure 10: Two-dimensional Vs structures along Lines A and B inverted from microtremor H/V spectra

during ice ages when the sea level was much lower than today's and then buried by stream deposition in the Recent epoch. Also shown in Fig. 10 are the zones of manhole damage. It is interesting to note that the damaged zones are located near the top of the slope of the valley.

DYNAMIC RESPONSE ANALYSES FOR ESTIMATED SHEAR WAVE STRUCTURES

To examine possible causes of the damage concentration, one- and two-dimensional dynamic response analyses were conducted for the inverted shear wave structures using the finite element method [Lysmer et al., 1975]. Nonlinear soil properties were taken into account using the equivalent linear technique. In the one-dimensional analysis, a soil column with the shear wave velocity profile immediately below was assumed for each site. In the two-dimensional analysis, the soil deposits along Lines A and B were modeled as shown in Fig. 11, with transmitting boundaries on both sides and viscous boundaries on the top of the base layer with Vs = 1600 m/s, located at a depth of 100 m. The stronger NS component motions obtained at the Kushiro JMA station during the 1993 Kushiro-oki earthquake [Kashima et al., 1994] was deconvolved to the top of the base layer, and used as an input motion. Only the shear waves with the in-plane particle motion incident vertically from below were considered.

The dashed lines in Fig. 12 shows the distribution of peak ground accelerations computed for the one- and two- dimensional models. In both Lines A and B of both models, the peak ground accelerations show maximum values above the top of the slope of the hidden valley. Figure 13 shows the distribution of peak maximum shear strains developed at a depth of 3 m that corresponds to the average penetration depth of the manholes. In both Lines A and B of both models, the peak maximum shear strains also take maximum values above the top of the slope

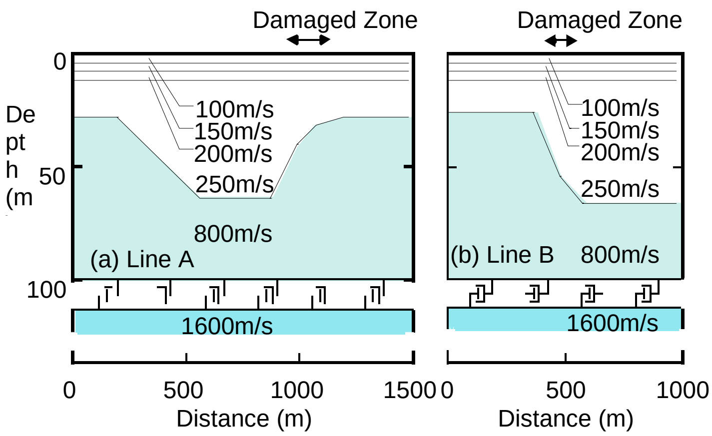


Figure 11: Two-dimensional models for Lines A and B

of the hidden valley.

To discriminate the effects of one- from two-dimensional wave propagation, the relation between peak maximum shear strain and thickness of Holocene deposit for one dimensional case is shown in Fig. 14. The shear strain varies depending on the thickness of soft layers, showing a maximum value at a depth of about 35 m. The depth of maximum shear strain occurs corresponds approximately to the thickness of Holocene deposit of the damaged zones. This indicates that the one-dimensional site amplification partly contributed to the increase in shear strains in the damaged zones and to the concentration of manhole damage. Figures 12 and 13 also suggest that the maximum acceleration and shear strain are generally larger in two-dimensional case than in one-dimensional case. This indicates that the two-dimensional site amplification due to the presence of hidden valleys also contributed to the increase in shear strains in the damaged zones as well as to the concentration of manhole damage.

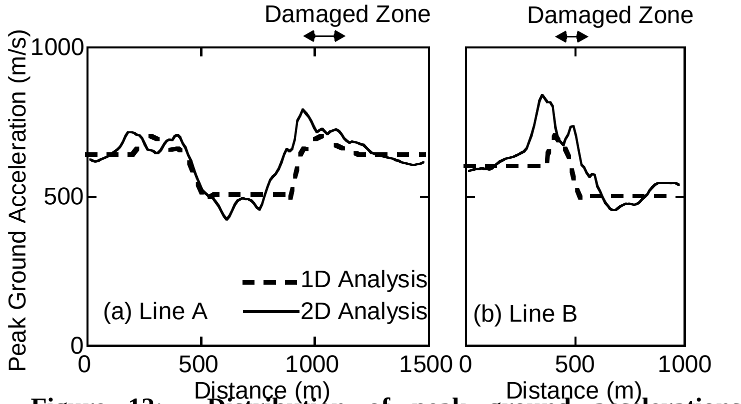


Figure 12: Distribution of peak ground accelerations computed from 1D and 2D analyses

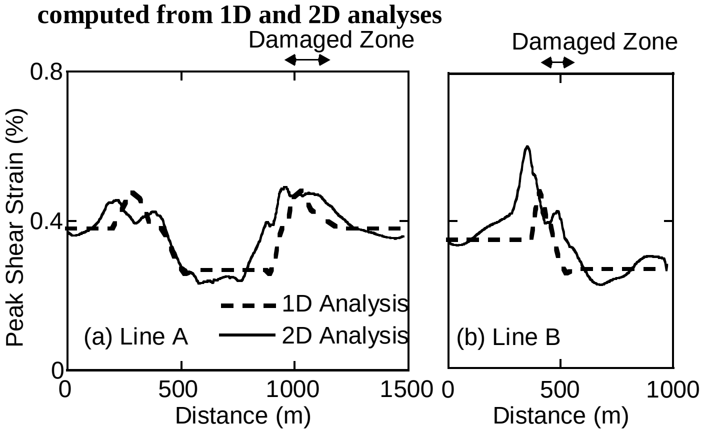


Figure 13: Distribution of peak shear strains at 3-m depth computed from 1 and 2D analyses

CONCLUSIONS

Effects of possible causes on the concentration of manhole damage in Kushiro-cho during the 1993 Kushiro-oki earthquake were investigated, based on microtremor measurements and subsequent analyses. The two-dimensional shear wave velocity structures across the damage zones have been determined from the inversion of microtremor H/V spectra. One- and two-dimensional dynamic response analyses were conducted on the inverted soil profiles. Based on the results of the microtremor measurements and subsequent analyses, the following conclusions may be made.

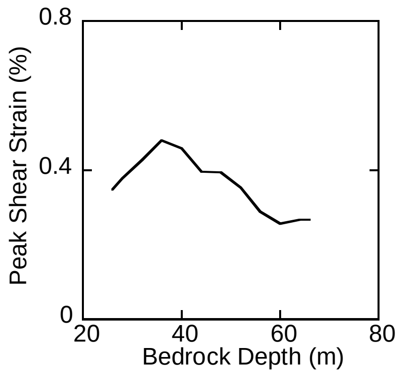


Figure 14: Relation between peak shear strain and thickness of Holocene layer

(1) The microtremor H/V spectral method can be used in estimating two-dimensional shear wave structures including hidden valleys, provided that the impedance ratio between the surface and underlying layers is reasonably high.
(2) The liquefaction-induced manhole damage tends to have concentrated on the ground above the top of the slopes of the hidden valleys.
(3) In addition to one-dimensional site amplification, two dimensional soil amplification arising from the presence of the hidden valleys contributed to the increase in shear strains below the damaged zones as well as to the concentration of manhole damage.

Since only the shear waves with in-plane motions are considered in this study, further studies are required to examine the effects of shear waves with the out-of-plane motions on manhole damage.

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