EVALUATION OF LIQUEFACTION POTENTIAL IN TERMS OF SURFACE WAVE METHOD

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ABSTRACT :

As one kind of ground failure, soil liquefaction often had been observed after strong earthquake. Now, in many countries, judgment of liquefaction potential is considered in seismic code, and the standard penetration tests (SPT) is usually performed for the soil liquefaction potential situation. But, according to the cost, limited time, unsuitable site condition, traditional method often couldn't meet the user's demands. As an attempt, an alternate method in terms of Surface Wave Method (SWM) had been used in recent years. In this paper, based on the Niigata Chuetsu-Oki earthquake (M6.8, July 16, 2007), SWM method and further comparison with active method had been carried out for the valuation of liquefaction potential. Compared with the traditional method, SWM method is easy, inexpensively and nondestructive to evaluate liquefaction potential.

KEYWORDS: **Liquefaction potential, Valuation, SWM method**

1. INTRODUCTION

SWM method is based on the analysis of the dispersion of surface waves. And the vertical distribution of the dynamic shear modulus in the subsoil can be obtained by this method. Main steps for this method are estimating the dispersive characteristics of a site by means of acquisition and processing of seismic data, further inverting the data for estimate of the subsoil properties. At last, the vertical profile of the shear wave velocity is obtained. In order to recognize the various propagation characteristics of the seismic wave field, Multi–channel analysis of surface waves (MASW) method (Park et al., 1999a; Xia et al., 1999; Miller et al., 1999) is utilized, which employs multiple receivers equally placed along a linear survey line with seismic waves generated by an impulsive source. Hayashi and Suzuki (2004) proposed Common Mid-Point (CMP) cross-correlation analysis of multi–channel surface wave method to give accurate phase velocity curves, and enable us to reconstruct 2D (two dimensional) velocity structures with high resolution.
For the judgment of soil liquefaction potential, a simplified procedure is the judgment of soil liquefaction potential based on the Standard Penetration Test (SPT). And the cyclic stress ratio (CSR) is used to represent the seismic load on the soil. This method had been developed several times after 1971 (Seed 1979; Seed and Idriss 1982; Seed at al 1983; Seed at al 1985). Now, comparing with SPT method, some simple, easy methods are carried out, such as the Cone Penetration Test (CPT) and small strain shear wave velocity Vs measurement, which had been reviewed by the National Research Council (NRC, 1995) and Youd and Idriss (1997). Especially, the liquefaction evaluation method based on Vs had been recommended by Dobry et al. 1981, Seed et al. 1983, Stoke et al. 1988, Tokimatsu and Uchida 1990. According to feasibility, easy and simple operation, non-destructiveness, it had been developed very fast.

2. LIQUEFACTION JUDGMENT BY SURFACE WAVE METHOD

In field studies, survey lines were performed to construct the shear wave velocity profile down to 20 m of the site using MASW technique. And then the factor of safety against liquefaction could be calculated by shear wave velocity (Vs).

1.1. Test method and procedure

1.1.1 Surface wave measurement

Based on the MASW method, the data had been acquired. The schematic view of a surface wave method is shown in Fig. 1, and the equipment for this survey (Fig. 2) is composed from:

- Data logger: OYO McSEIS-SXW
- Seismometers: geophones with 4.5 Hz frequency
- Source: Sledgehammer

In this figure, Twenty four geo-phones of 4.5 Hz resonant frequency are deployed at 1 m spacing along a survey line with receivers connected to multi-channel recording device. 10 kg sledgehammer is used as the active source placed with 1 to 2m intervals.

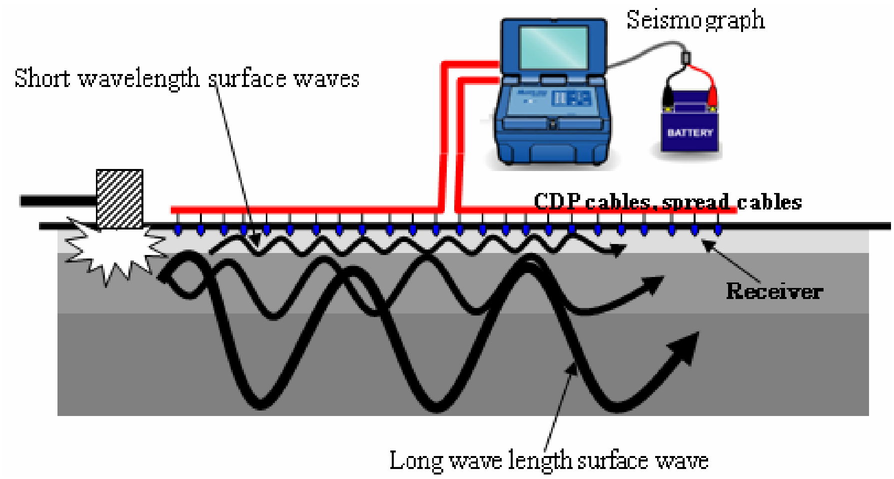

Figure 1 Diagram of data acquisition system for MASW method

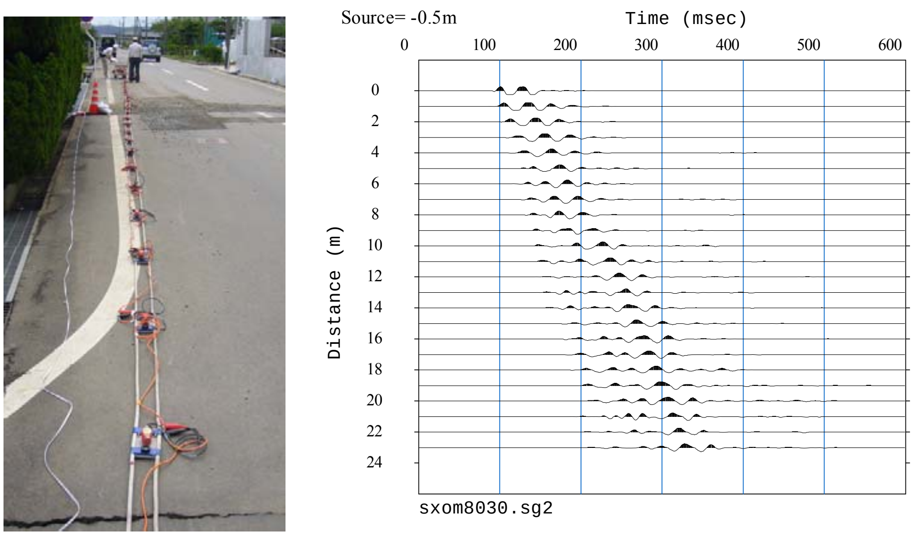

Figure 2 Survey line and obtained data

1.1.2 Data processing

In this step, the CMP cross-correlations analysis will be applied to multi-channel and multi-shot surface wave data. And based on nonlinear least squares inversion, a 2D surface wave velocity profile is reconstructed. The procedure of the CMP cross-correlations analysis is summarized in the following points.

- For every pair of traces, cross-correlations are calculated in each shot gather.

- The correlation traces with a common mid-point are gathered, and those traces having equal spacing are stacked in the time domain. The resultant cross-correlation gathers resemble shot gathers and are referred to as CMP cross–correlation gathers.
- For calculating phase velocities of surface waves, a multi–channel analysis is applied to the CMP cross–correlation gathers.
- By non-linear least squares inversion, a 2D S–wave velocity profile is reconstructed.

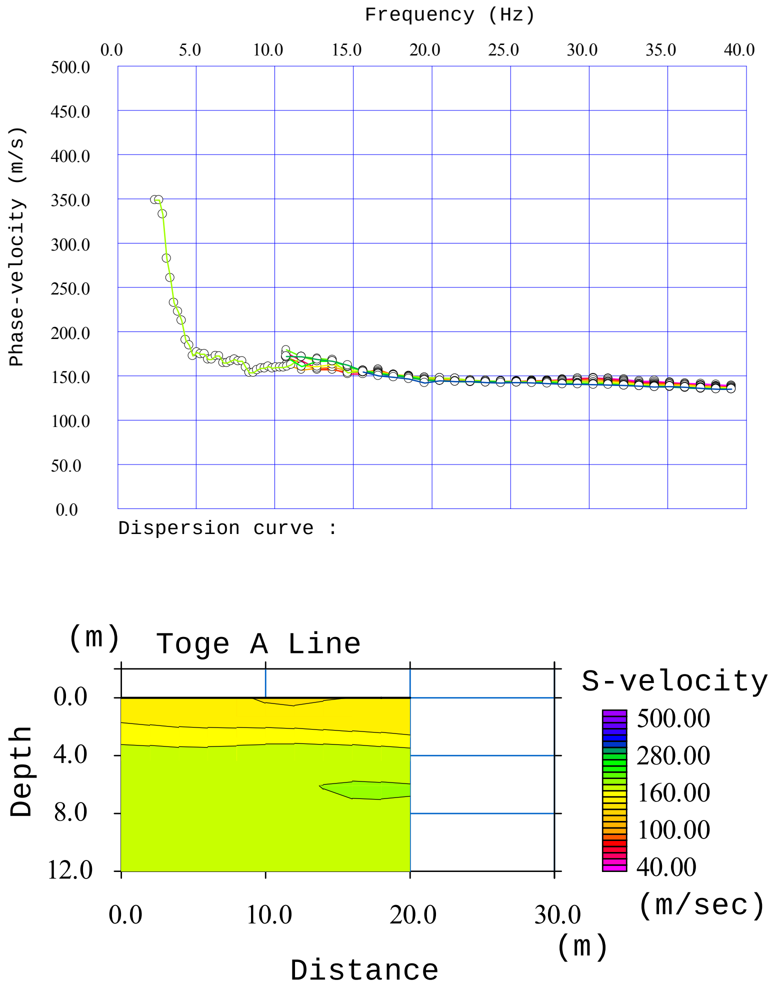

Figure 3 Dispersion curve and Vs structure of survey line

1.2. Calculation of liquefaction potential

1.2.1 Safety factor (F_s)

In judgment of liquefaction potential based on Shear wave velocity (V_s), the safety factor against liquefaction of a soil at a particular depth in a soil deposit is defined as Eqn. 2.1.

$$F_s = \frac{CRR}{CSR} \tag{2.1}$$

Where, *CRR* is the resistance of the soil, which is expressed as the cyclic resistance ratio (*CRR*). And *CSR* is the loading induced by an earthquake which is expressed as the cyclic stress ratio (*CSR*). If the F_s is less than 1, the occurrence of liquefaction is predicted.

For *CSR* is generally expressed as Eqn. 2.2 (Seed and Idriss 1971).

$$CSR = 0.65\frac{\sigma_\upsilon}{\sigma_\upsilon^{/}}\cdot\left(\frac{a_{\max}}{g}\right)\cdot\frac{r_d}{MSF} \tag{2.2}$$

Where, σ_υ is total overburden stress at the depth in question, [kN/m2]; $\sigma_\upsilon^{/}$ is initial effective overburden stress at the same depth, [kn/m2]; $a_{\max}$ is peak horizontal ground surface acceleration, [gal]; g is acceleration of gravity, [980cm/s2]; r_d is shear stress reduction factor to adjust for flexibility of the soil profile. The value r_d at the depth of z can be calculated using Eqn. 2.3 (Liao et al. 1988; Robertson and Wride, 1998).

$$\begin{aligned} r_d &= 1-0.00765z && for && z \le 9.15m \\ r_d &= 1.174-0.0267z && for && 9.15m \le z \le 23m \\ r_d &= 0.744-0.008z && for && 23m \le z \le 30m \end{aligned} \tag{2.3}$$

As a characteristic of the ground shaking intensity, $a_{\max}$ is defined as the peak value in a horizontal ground acceleration record. Peak acceleration is commonly estimated using empirical attenuation relationships of $a_{\max}$, as a function of earthquake magnitude, distance from the energy source, and local site conditions. And the densities of the various soil layers and characteristics of the ground water (unit, meter) would be used in the calculation of σ_v and $\sigma_v^{'}$. The magnitude of earthquake is used in the calculation of *MSF* which can be expressed in Eqn. 2.4.

$$MSF = \left(\frac{M_w}{7.5}\right)^n \tag{2.4}$$

Where: M_w moment magnitude of the earthquake. The lower bound for the range of magnitude scaling factor recommended by the 1996 NCEER workshop is defined with 2.56 (Idriss personal communication to T.L.Youd, 1995) for earthquakes with magnitude ≤7.5. The upper bound of the recommended range is defined with 3.3 Andrus and Stokoe, 1997) for earthquakes with magnitude ≤7.5. For earthquakes with magnitude >7.5, the recommended factors are defined with 2.56.
The *CRR* expressed as the cyclic resistance is generally established by separating liquefied cases from non liquefied cases. Eqn. 2.5 defined by Andrus et al. (1999).

$$CRR = \left[a\left(\frac{V_{s1}}{100}\right)^2 + b\left(\frac{1}{c-V_{s1}}\right) - \frac{1}{c}\right] \tag{2.5}$$

Where, a, b, c are curse fitting parameters ($a = 0.022,\ \ b = 2.8,\ \ c = 200 \sim 215\,{}^{m}\!/_{s}$); V_{s1} is overburden stress corrected shear wave velocity (m/s), which is defined in Eqn. 2.6.

$$V_{s1} = V_s\cdot\left(\frac{P_a}{\sigma_\upsilon^{/}}\right)^{0.25} \tag{2.6}$$

Where, V_s is the measured shear wave velocity, (m/s); Pa: reference stress (100kPa); $\sigma_\upsilon^{/}$ is initial effective overburden stress, (kPa). The parameter c in the Eqn.6 represents the limiting upper value of V_{s1} for liquefaction occurrence.

1.2.2 Liquefaction Index (P_L)

The liquefaction index is calculated using Eqn.7:

$$P_L = \int_0^{20} F \cdot w(x)\, dx \qquad (2.7)$$

Where, $F_L < 1.0,\ F = 1 - F_L$; $F_L \geq 1.0,\ F = 0$, $w(x)$ is weighted function value, $w(x) = 10 - 0.5x$ and x is the depth from surface.

3. FIELD STUDY

During the field studies, total 40 survey lines had been selected for surface wave method application. According to the damage due to soil liquefaction, 28 MSAW data had been acquired in Niigata area. As examples, some results are shown in the below.

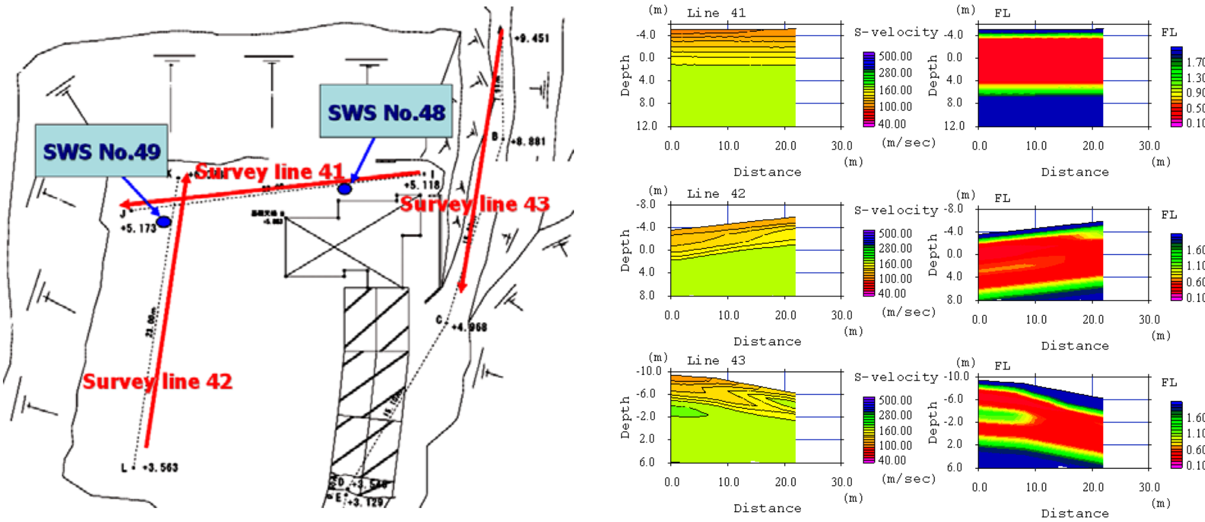

Figure 5 Sketch map of investigation and Vs structure & FL results of survey line 41, 42, 43 in Kariwa, Niigata

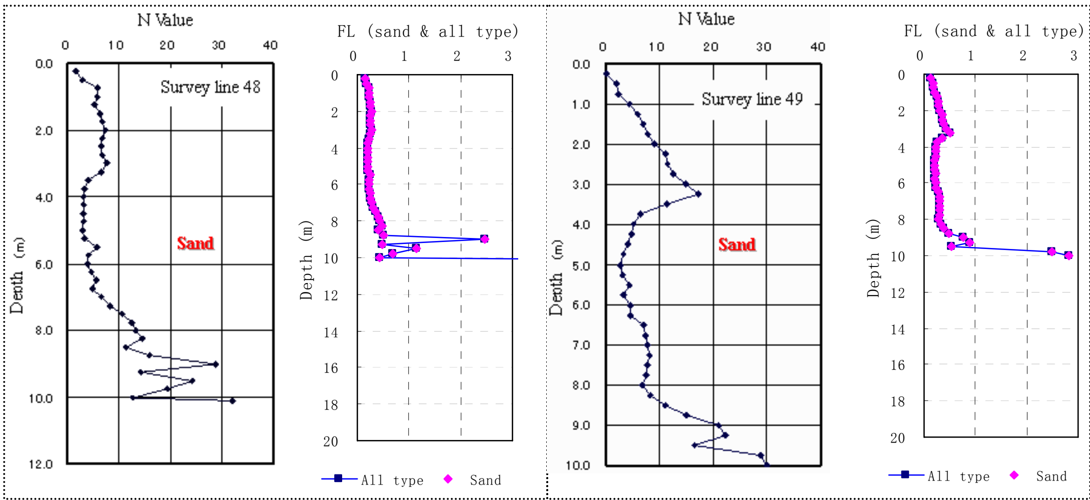

Figure 6 The N value and FL results of SWS data 48, 49 in Kariwa, Niigata

From Fig. 5 and Fig. 6, Vs structure can describe the soil profile more clear than conventional method. Compared with the results of SWS data, SWM method can draw a similar conclusion. From surface down to 8 or 10 meters with covered sand layer, soil stiff is very low and with high dangerousness of liquefaction.

Table 3.1 Results by the traditional method in Matsunami, Niigata

ID	PL			Liquefaction level			Data
	150(gal) M7.5	350(gal) M7.5	667(gal) M6.8	150(gal) M7.5	350(gal) M7.5	667(gal) M6.8	
33	0	3.00	8.64	None	Light	Middle	Borehole
34	0	2.10	7.22	None	Light	Middle	Borehole
50	1.54	23.42	39.44	Light	Serious	Serious	SWS
51	4.38	19.48	31.37	Light	Serious	Serious	SWS
52	2.51	21.28	38.46	Light	Serious	Serious	SWS
53	0	4.96	10.32	None	Light	Middle	SWS

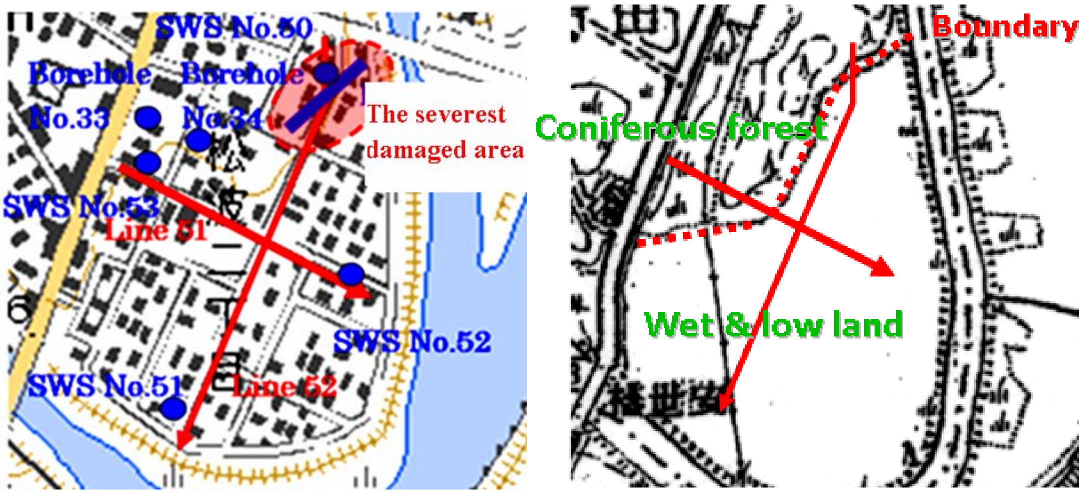

Figure 7 Maps about survey line 51, 52 in Matsunami, Niigata (old map, right)

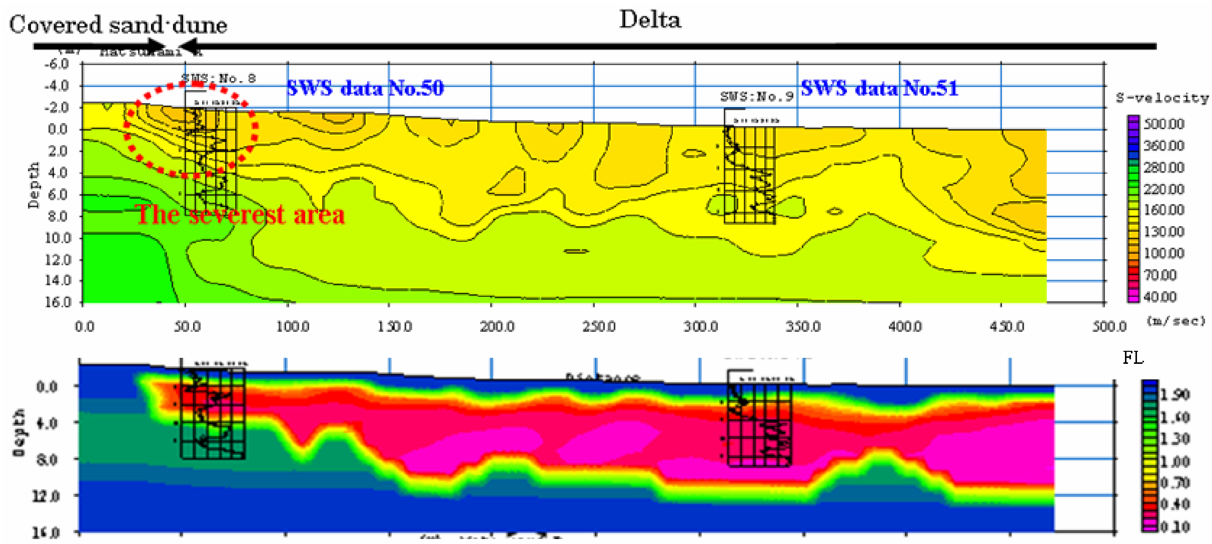

Figure 8 Vs structure and FL value of survey line 52 in Matsunami, Niigata

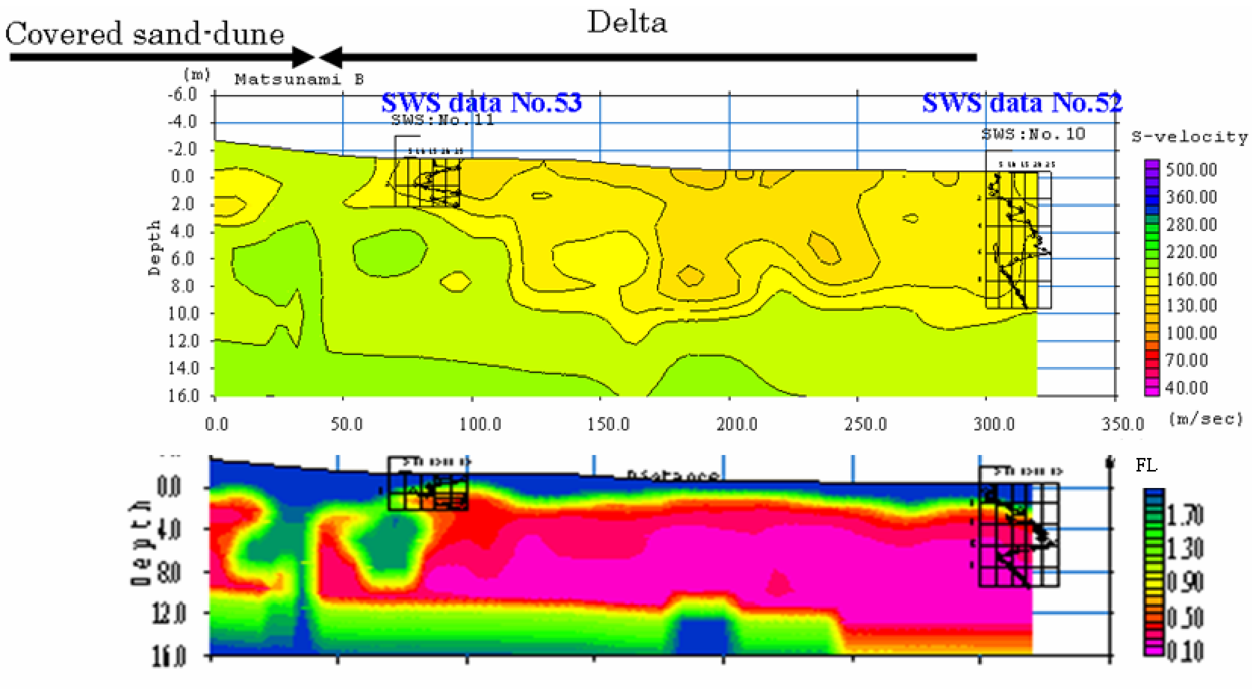

Figure 9 Vs structure and FL value of survey line 51 in Matsunami, Niigata

As another example shown in Fig. 7 to 9 and Tab3.1. Using borehole or SWS data, the results in Tab3.1 are calculated with 150gal, 300gal, 667gal and M7.5, M7.5, M6.8. At point 50, 51, 52, liquefaction level is higher than anthers. In Fig. 7, variation of site is shown by two maps. The point 50, 51, 52 locate in the wet low land of the old map. In Fig. 8 and Fig.9, Vs structure and FL value of survey line 51, 52 in Matsunami, Niigata. The variation of site is deduced by Vs structure chart very well and FL value accord with the damage in fact.

4. CONCLUSIONS

In this paper, the surface wave method has been carried out from surface nondestructively. The shear wave velocity can be obtained by the surface wave method and comparing with exiting data, such as borehole data and Swedish Weight Sounding data, the results calculated based on surface wave method can be used as a new judgment method of liquefaction potential, and explain the damage due to soil liquefaction. The last conclusions are summarized as following:

- Shear wave velocity is more accurate to describe the soil stiffness and confirm the soil profile than the SWS data.
- Compared with active method, surface wave method can obtain more data due to its economical, easy control and nondestructive characteristic.

In order to reduce casualty and economy loss due to earthquake, evaluating safety of site is very important. Compared with the traditional method, the surface wave method has vast vistas to popularize and utilize in the future.

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