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Determination of shear wave velocity from borehole database in the Osaka Basin, Japan

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ABSTRACT

The shear wave velocity (Vs) provides important information on the properties of subsurface material that has significance in earthquake engineering and in the other works to be carried out in the major cities on alluvial basins. An empirical relationship has been obtained for the Vs with the N value (from standard penetration test) and depth for different geological facies of varying age using the database of 84 investigation boreholes in the Osaka Basin. The calculated and observed shear wave velocities are very close to each other. The obtained equation has been applied to calculate Vs (m/sec) and to draw shear wave velocity profiles across the major sections of the Osaka Basin.

INTRODUCTION

Generally, Standard Penetration Test (SPT) and P- and S-wave (PS) velocity logging are carried out in boreholes. During an earthquake, horizontal vibration causes severe damage of structures on the ground, because the shear wave (S-wave) that creates the horizontal vibrations has larger energy than that of the primary wave (P-wave). Thus, knowledge of the shear wave velocity (Vs) is useful in the field of earthquake engineering and in civil engineering design. It is often necessary to evaluate the soil and rock properties as well as to explore the fluid reservoirs including oil, groundwater, and geothermal fluid (Kitsunezaki 1982). The propagation properties of S-waves are sensitive to conditions of pores and fractures in formations almost regardless of the contained fluid condition, by which the P-wave properties are strongly affected.

Likewise, the main application of the N value in the engineering practice is for estimating the strength and stiffness of the material and also for evaluating the liquefaction potential (Seed et al. 1985). Thus, it is an index of soil liquefaction resistance during earthquake shaking. According to Seed and Lee (1966), the potential for liquefaction of a cohesionless soil is related to the intensity of dynamic loading, in situ stresses, grain size characteristics of soil, shear strength, and relative packing.

In the Osaka-Kobe area, there are about 30,000 boreholes, of which only about 100 are recorded by PS logging. In the present study, the database of only 84 boreholes having all data sets like lithology, N value, and Vs were used (Fig. 1). Besides the value in the engineering field, such a database is useful for the geological interpretation of the seismic exploration data.

MEASUREMENT OF Vs AND SPT

The methods of shear wave velocity logging and measurement technique of N value in standard penetration test are described briefly in the following paragraphs.

Shear wave velocity

The subsurface seismic wave velocity can be measured either by utilising the natural or artificial sources, by

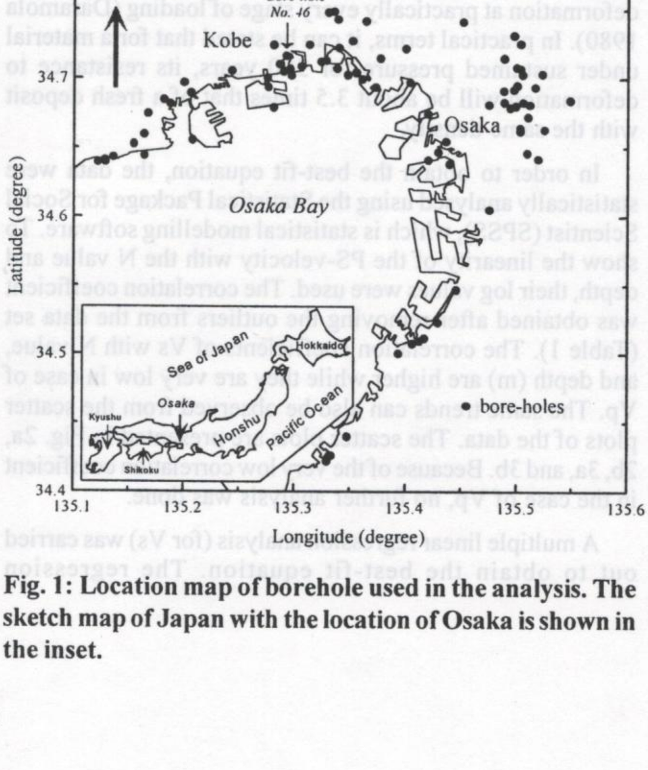

Fig. 1: Location map of borehole used in the analysis. The sketch map of Japan with the location of Osaka is shown in the inset.

observing tremors, or by logging. However, it is to be noted that the PS logging inside the borehole gives a more accurate value, with greater resolving power than that obtained from the observation of tremors. In the down-hole and cross-hole methods of logging, at least one source or one receiver is set in a borehole. However, a suspension type sonde consisting of the source and receivers is widely used (Kitsunezaki 1982). In this study, the seismic wave velocity as measured by borehole logging has been considered. The data were obtained both from the suspension type of sonde as well as the one consisting of only the receivers. As the shear wave, in the down-hole method, was generated manually by means of horizontal hammering, the energy was sufficient only to measure Vs up to the depth of some tens of metres.

Standard penetration test (SPT)

In this method, the number of blows (about 63.5 kg hammer falling freely from a height of 75 cm) required to drive a standard sampling tube (5 cm in outer diameter and 1–2.5 cm in inner diameter) 30 cm into the ground is measured to get the N value of the formation. The N values used during the present analysis were measured in accordance with the Japanese Industrial Standards (JIS).

DATA ANALYSIS AND PREPARATION OF BEST-FIT EQUATION

The borehole database consisted of the data on primary wave velocity (Vp), shear wave velocity (Vs), and N value (from SPT test) of different geological facies at varying depths. It was broadly subdivided into the Holocene and Pleistocene groups. Further subdivisions into clay and silt, sand, and gravel subgroups were made based on sediment facies. The major subdivisions based on age were necessary because the sustained pressure increases the resistance to deformation at practically every stage of loading (Daramola 1980). In practical terms, it can be stated that for a material under sustained pressure for 300 years, its resistance to deformation will be about 3.5 times that of a fresh deposit with the same density.

In order to obtain the best-fit equation, the data were statistically analysed using the Statistical Package for Social Scientist (SPSS), which is statistical modelling software. To show the linearity of the PS-velocity with the N value and depth, their log values were used. The correlation coefficient was obtained after removing the outliers from the data set (Table 1). The correlation coefficients of Vs with N value, and depth (m) are higher while they are very low in case of Vp. The same trends can also be observed from the scatter plots of the data. The scatter plots are presented in Fig. 2a, 2b, 3a, and 3b. Because of the very low correlation coefficient in the case of Vp, no further analysis was done.

A multiple linear regression analysis (for Vs) was carried out to obtain the best-fit equation. The regression coefficients for the Holocene groups lie between 0.83 and 0.91, while it is between 0.70 and 0.87 for the Pleistocene sediments (Table 2). The relationship obtained from the analysis can be represented by the equation given below.

$$Vs = a \times N^b \times D^c \qquad (1)$$

where Vs = shear wave velocity in m/sec,

N = N value,

D = Depth in m,

a = constant of the equation,

b = coefficient of N, and

c = coefficient of D.

From the analysis, a, b, and c values were obtained for each facies of both groups. Thus obtained equation was used to calculate Vs and compared with the observed Vs. The process was repeated till the observed and calculated values were very close. The values of a, b, and c (Equation 1) that give the closest calculated value of Vs (m/sec) to the observed Vs (m/sec) are given in Table 3.

A comparison of the calculated and observed values for the present equation as well as for the other existing equations prepared by various authors (Ohta and Goto 1976; Tajime et al. 1978; Nogishi et al. 1983) has been made (Fig. 4). It shows that the equation obtained from the present analysis has the calculated Vs values very close to the observed ones. Similarly, the equations were applied to the whole data set and the scatter plots were obtained between the observed and calculated values. The result shows that the highest correlation coefficient (0.735) is obtained from the present equation (Fig. 5). However, the other equations were derived using the borehole database of different localities that have different geological conditions and sedimentation history.

The equation was applied to calculate the shear wave velocity profile using the available borehole database (which do not have observed Vs data) across the major sections in the Osaka Basin (Fig. 6). They include the Osaka City as well as the Kobe City. The representative profiles showing the shear wave velocity structure are presented in Fig. 7 and 8 for the Osaka area, and in Fig. 9 for the Kobe area. It has been found that Vs at the shallow depth is below 200 m/sec while it increases with depth. The shear wave velocity is found directly related to the effective grain size, overburden pressure, and age of the sediments.

The very low correlation coefficient for Vp can be explained with the help of the experimental finding of Kitsunezaki (1986) who concluded that the shallow sand layers below the water table were characterised by very low velocity and extremely high attenuation of P-wave probably caused by the small amount of gas bubbles contained in sand layer almost saturated with water.

Table 1: Correlation coefficients for Vs (m/sec) and Vp (m/sec)

Velocity	Facies	Holocene		Pleistocene	
		log N	log D (m)	log N	log D (m)
log (Vs) m/sec	Clay and silt	0.808	0.831	0.820	0.653
	Sand	0.730	0.741	0.625	0.579
	Gravel	0.803	0.723	0.603	0.720
log (Vp) m/sec	Clay and silt	0.307	0.148	0.329	0.206
	Sand	0.576	0.504	0.140	0.041
	Gravel	0.543	0.751	0.266	0.044

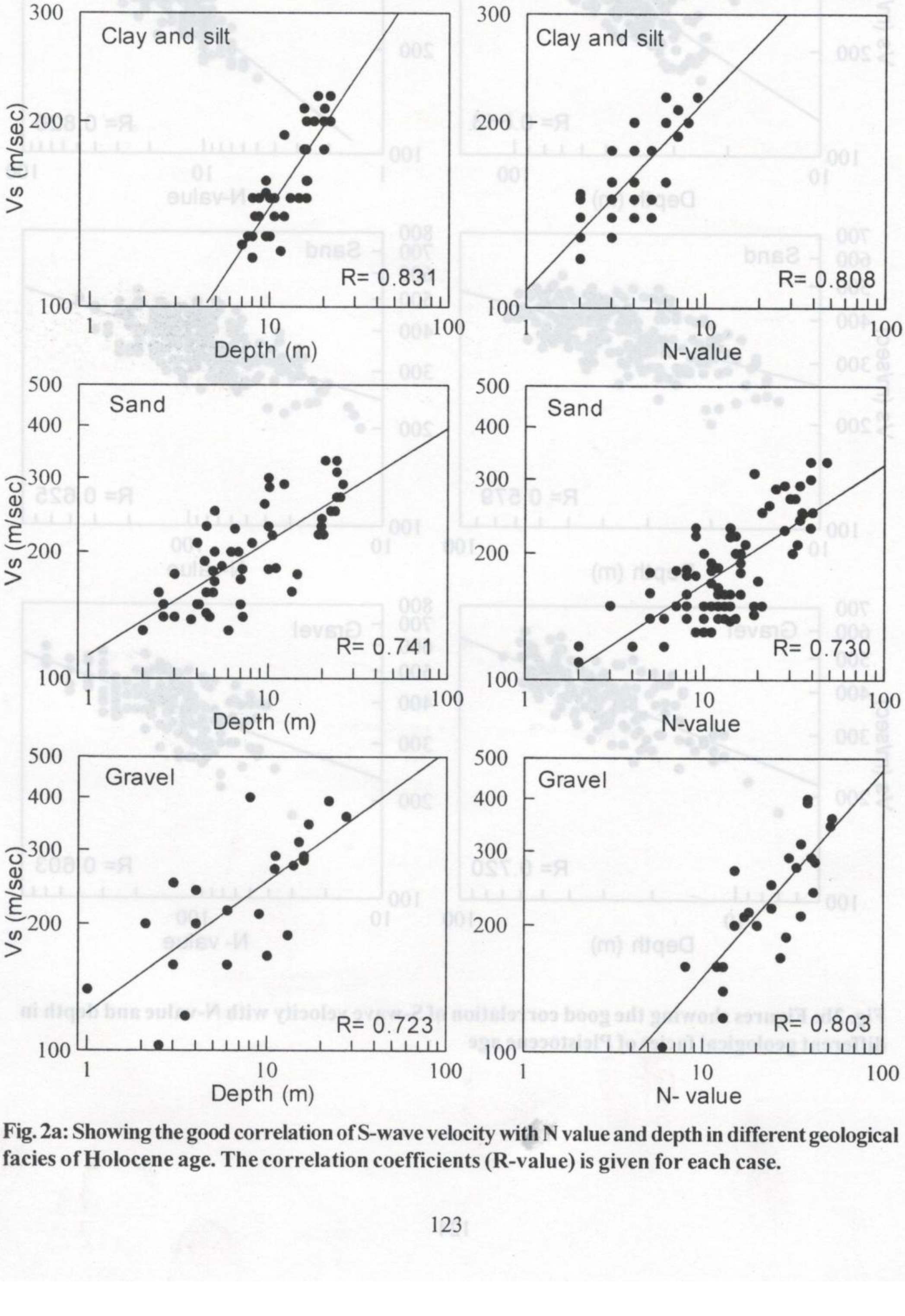

Fig. 2a: Showing the good correlation of S-wave velocity with N value and depth in different geological facies of Holocene age. The correlation coefficients (R-value) is given for each case.

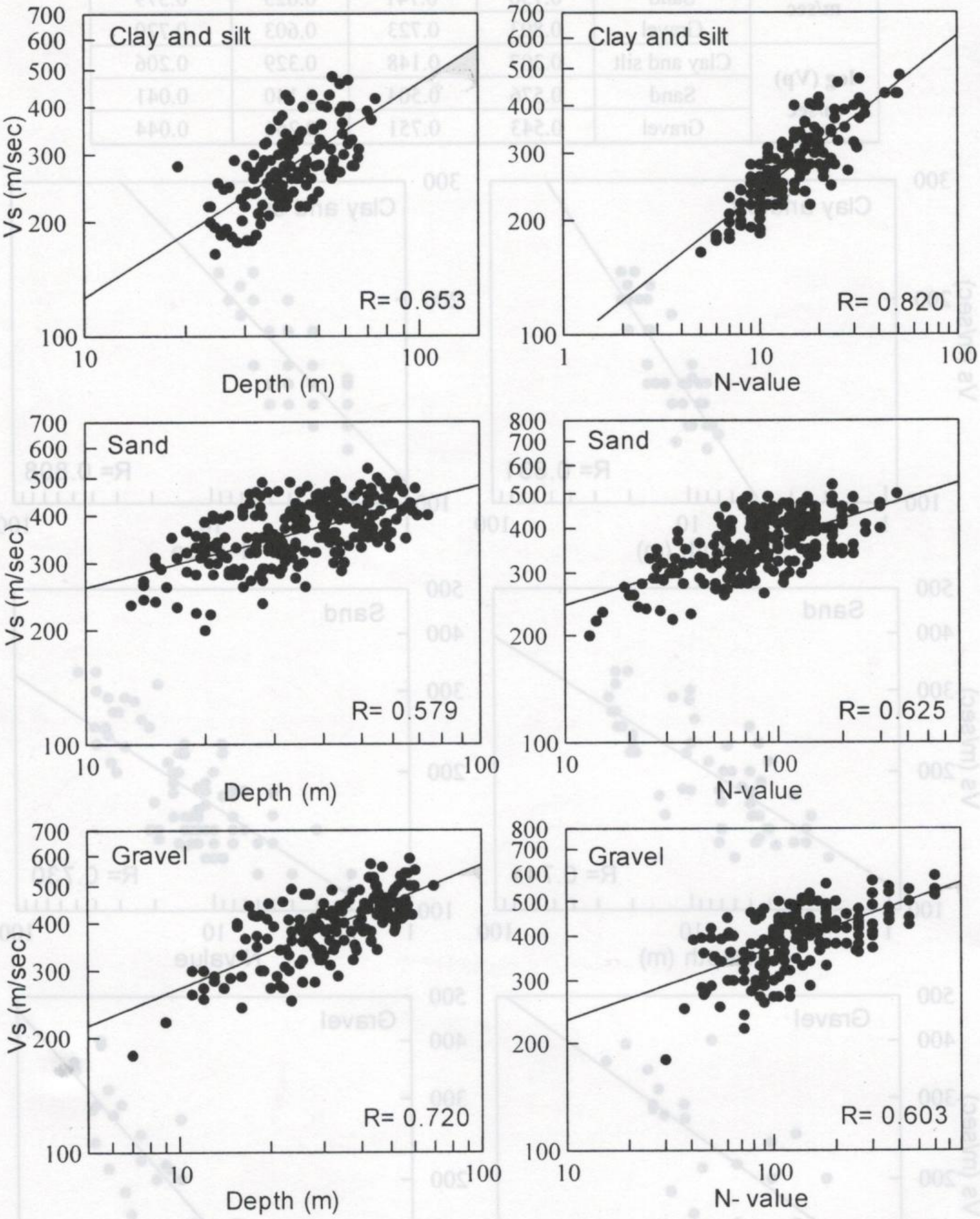

Fig. 2b: Figures showing the good correlation of S-wave velocity with N-value and depth in different geological facies of Pleistocene age

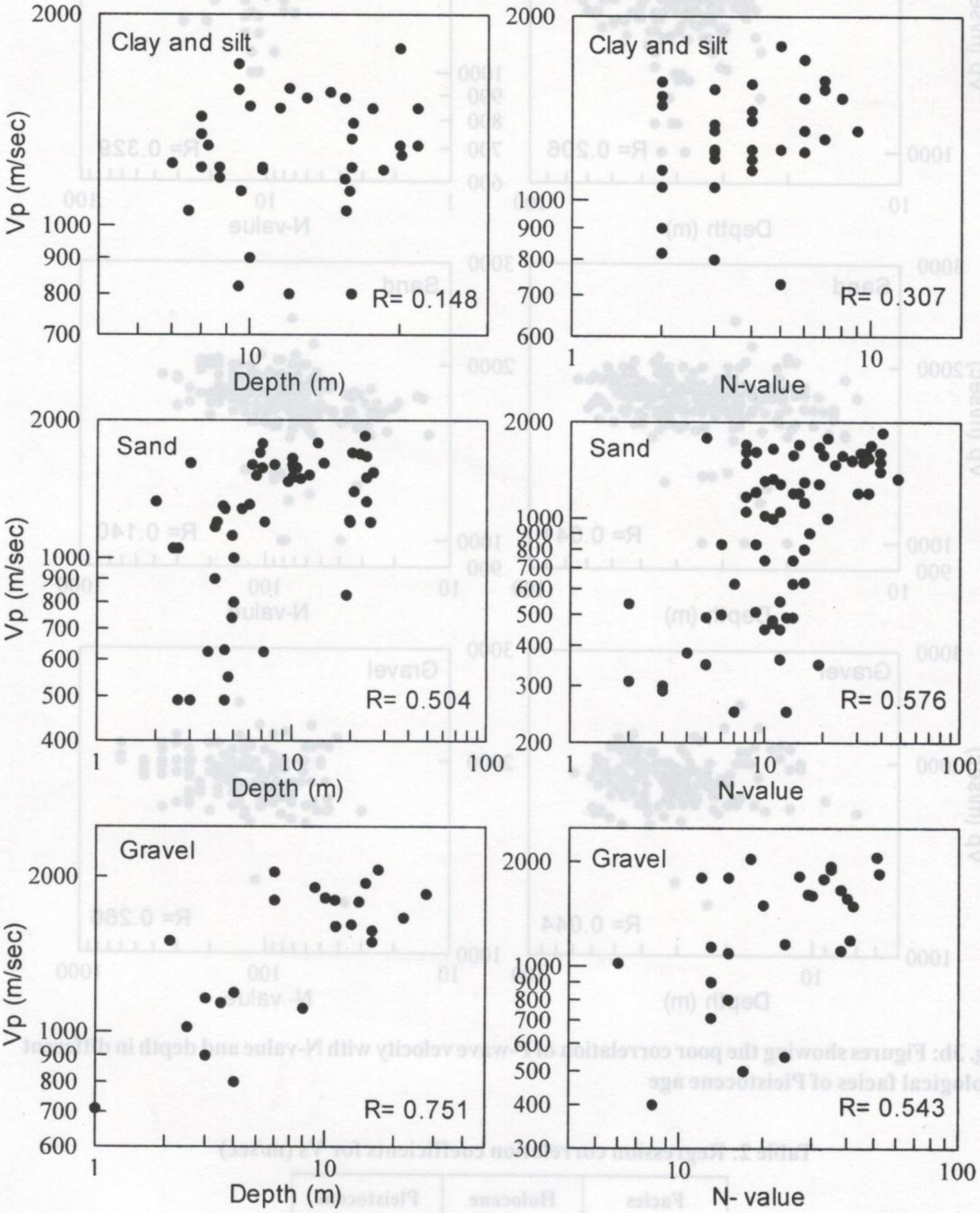

Fig. 3a: Figures showing the poor correlation of P-wave velocity with N-value and depth in different geological facies of Holocene age

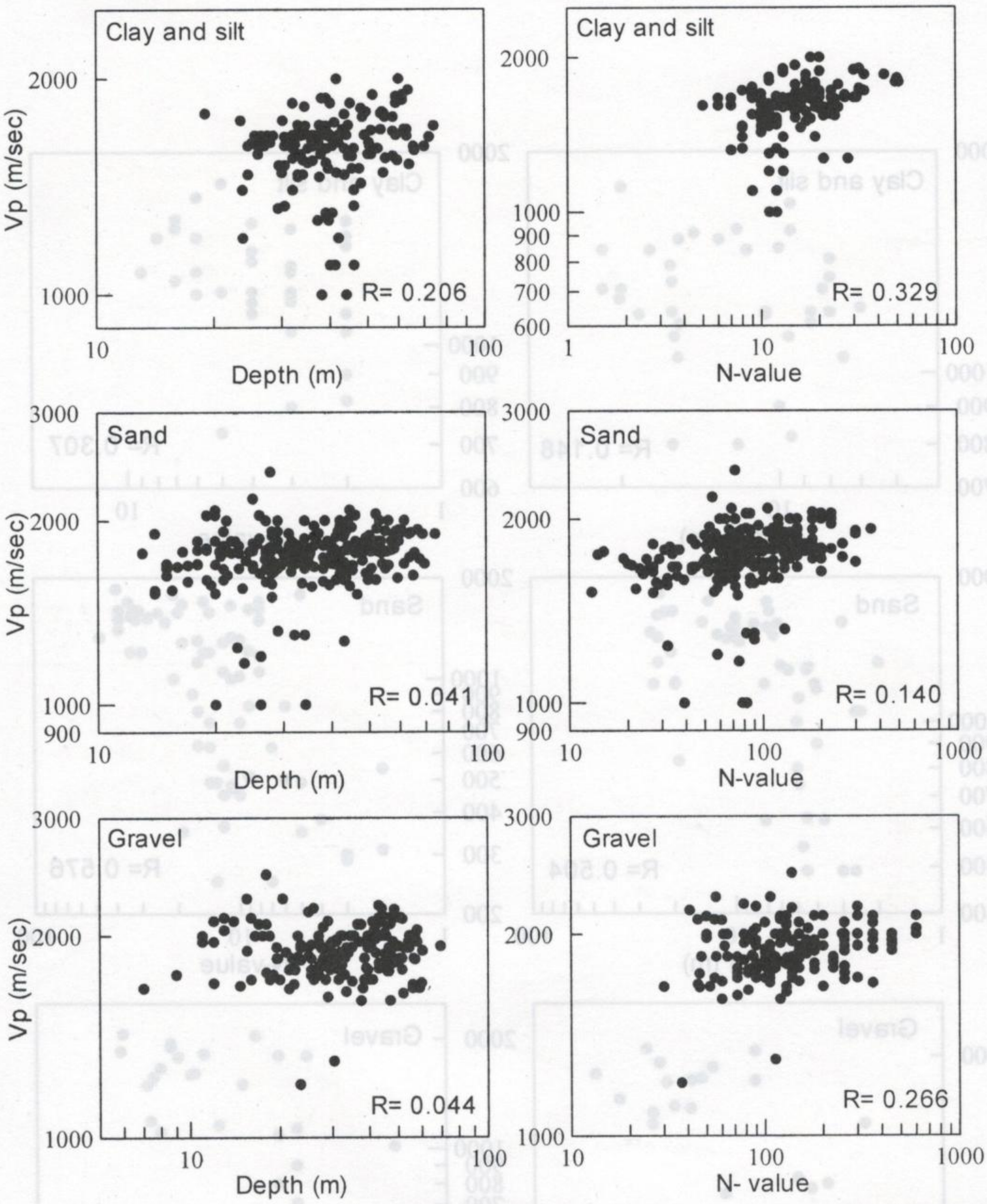

Fig. 3b: Figures showing the poor correlation of P-wave velocity with N-value and depth in different geological facies of Pleistocene age

Table 2: Regression correlation coefficients for Vs (m/sec)

Facies	Holocene	Pleistocene
Clay and silt	0.914	0.871
Sand	0.833	0.707
Gravel	0.853	0.783

Dependent variable: log (Vs), m/sec
Independent variables: log (N) and log (depth), m

Table 3: Coefficients of equation obtained from multiple linear regression

Age	Facies	Coefficients		
		a	b	c
Holocene	Clay and silt	63.973	0.191	0.266
	Sand	73.114	0.208	0.199
	Gravel	46.559	0.431	0.107
Pleistocene	Clay and silt	39.628	0.327	0.258
	Sand	107.642	0.135	0.172
	Gravel	90.365	0.117	0.496

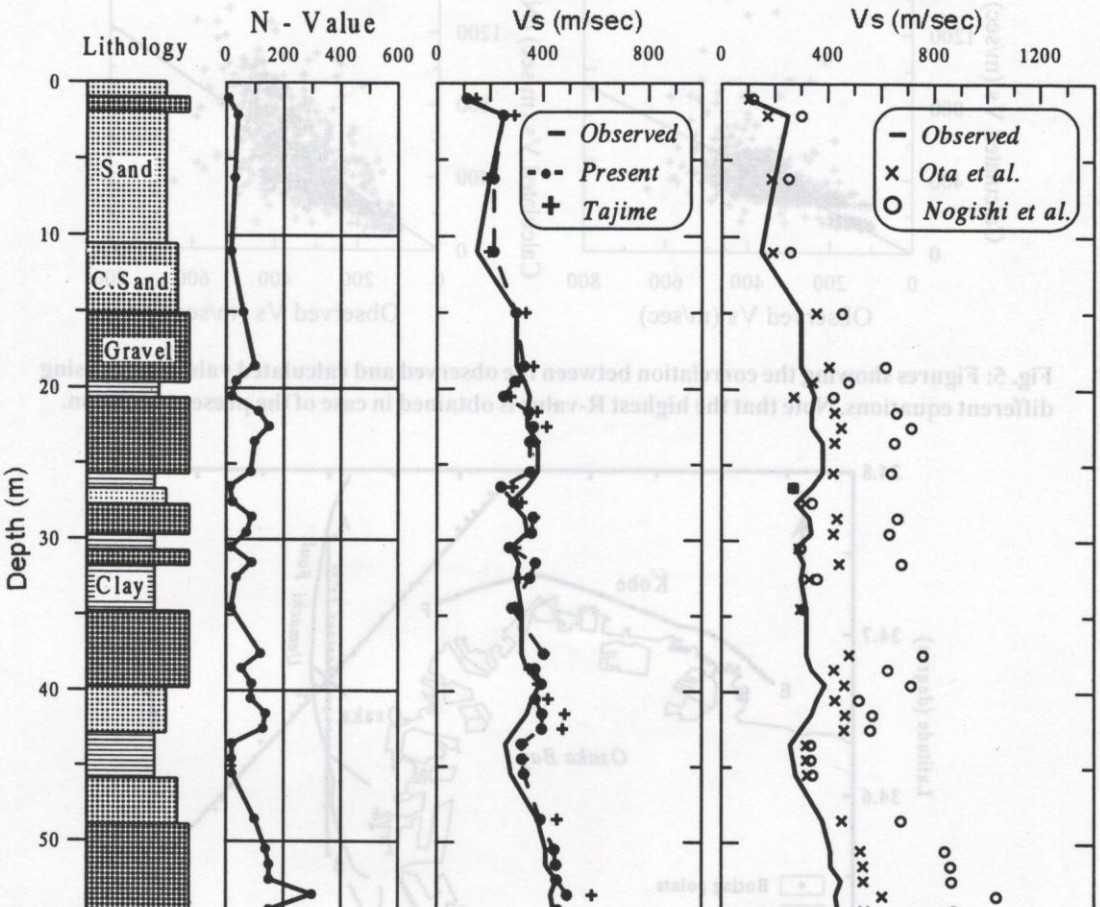

Fig. 4: Comparison between the observed and calculated Vs (m/sec) as applied in borehole No. 46 (Fig. 1). It is clear that the values of Vs calculated by using the present equation are closest to the observed ones.

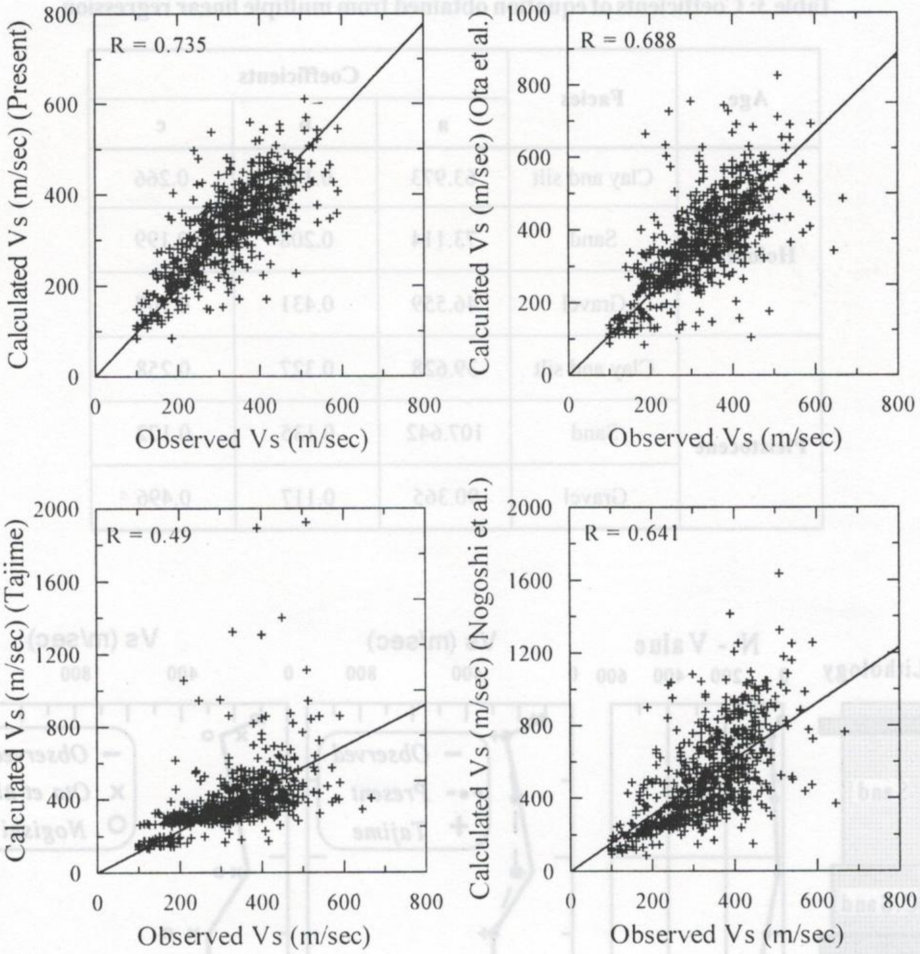

Fig. 5: Figures showing the correlation between the observed and calculated values of Vs using different equations. Note that the highest R-value is obtained in case of the present equation.

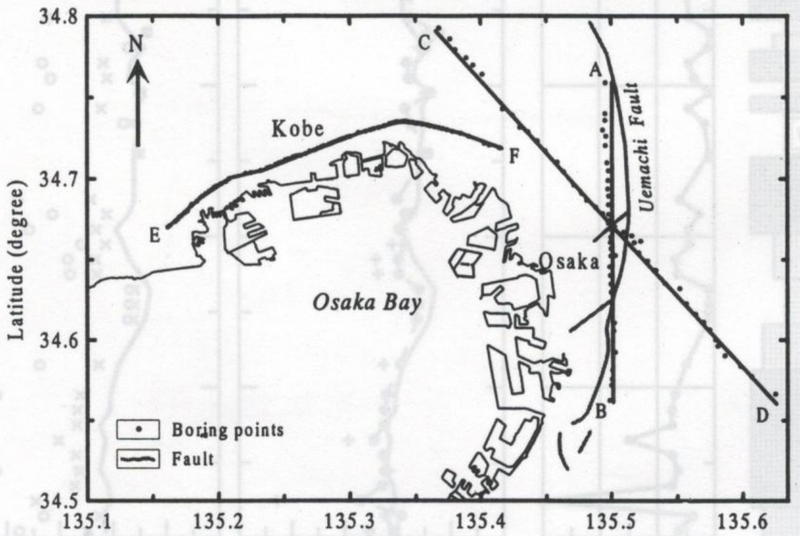

Fig. 6: Profile lines used to estimate the shear wave velocity structure across the Kobe-Osaka area in the Osaka sedimentary basin.

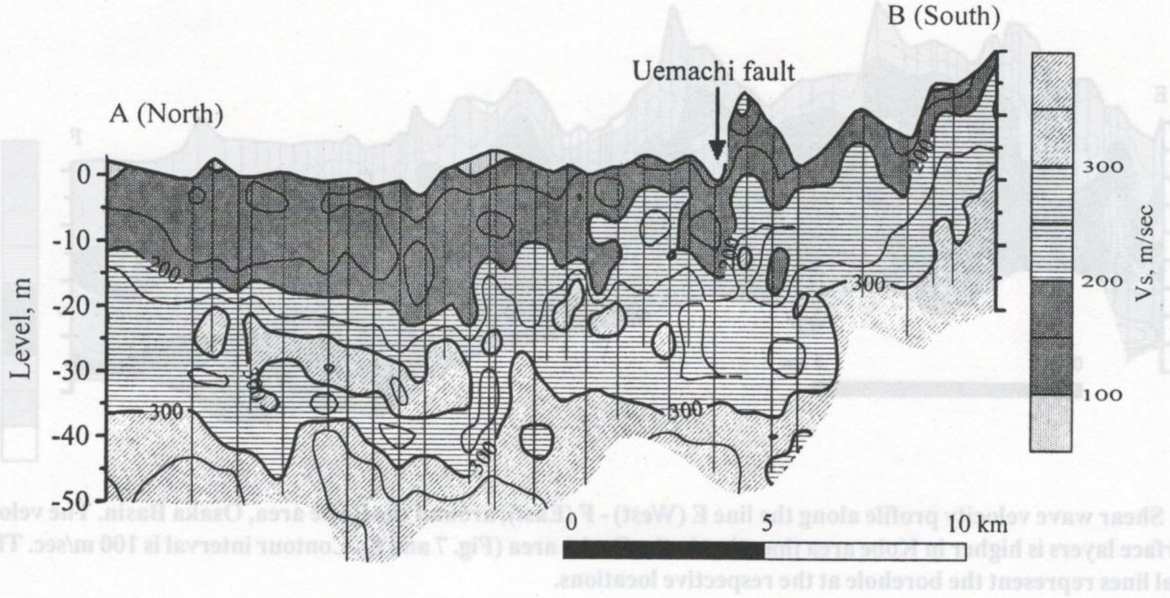

Fig. 7: Shear wave velocity profile along the line A (North) - B (South) in the Osaka Basin. Thickness of the low velocity layers gradually decreases southward of Uemachi fault. The contour interval is 50 m/sec. The thin vertical lines represent the boreholes at the respective locations.

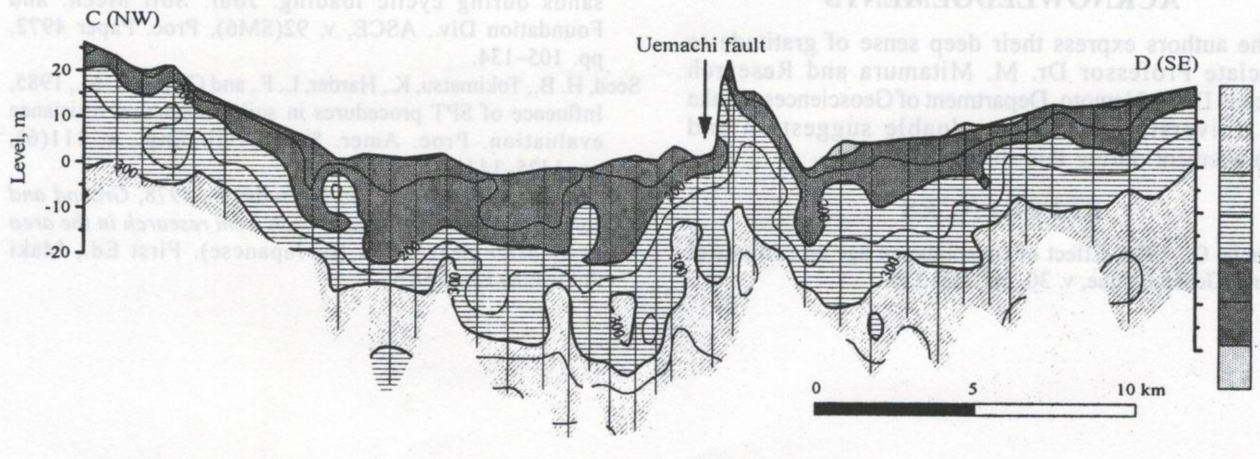

Fig. 8: Shear wave velocity profile along the line C (NW) - D (SE) in the Osaka Basin. Thickness of the low velocity layers is more around the north of Uemachi fault in the section. The contour interval is 50 m/sec. The thin vertical lines represent the boreholes at the respective locations.

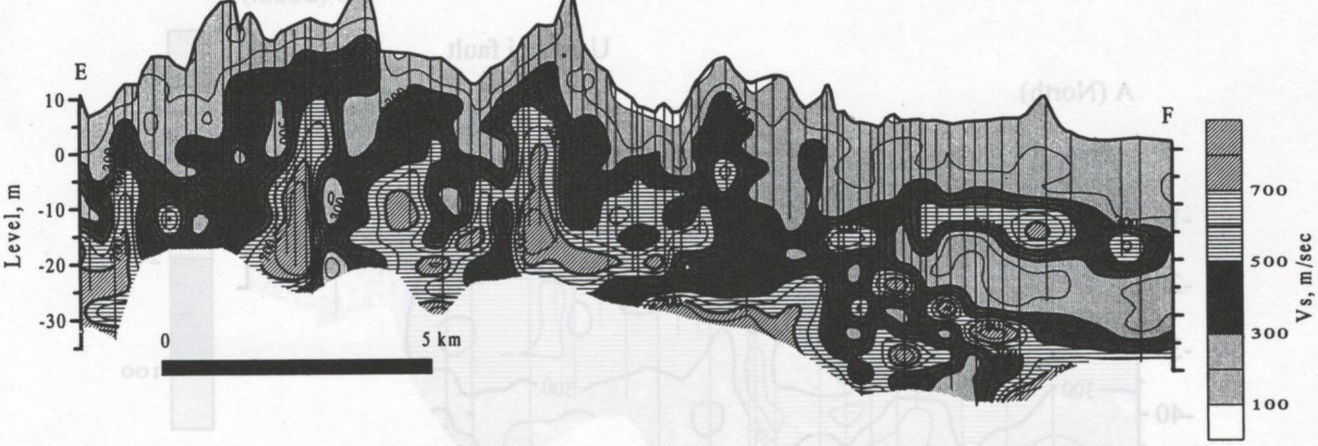

Fig. 9: Shear wave velocity profile along the line E (West) - F (East), around the Kobe area, Osaka Basin. The velocity of subsurface layers is higher in Kobe area than that in the Osaka area (Fig. 7 and 8). Contour interval is 100 m/sec. The thin vertical lines represent the borehole at the respective locations.

CONCLUSIONS

The Vs for unconsolidated sediments of shallow depth in the Osaka Basin can be calculated more correctly using the present equation, which takes into account the N value as well as the depth of sediments of different lithology and geological age. The equation derived gives the calculated value of Vs very close to the observed one. A good correlation exists between the observed Vs, N value, and the depth of unconsolidated sediments of different lithology and age. The very low correlation coefficient in case of the Vp indicates that the velocity of P-wave in shallow subsurface layer varies significantly with respect to the degree of saturation in comparison with that of the S-wave.

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