P- and S-Wave Velocities of the Ground in Japan

Vitesses des P-et S-Ondes dans la Terre au Japon

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SYNOPSIS In recent years, it has become more and more necessary to make clear the dynamic properties of the ground for engineering purposes. In this way, the in situ measurements of the P- and S-wave velocities of the ground have come to take an important significance. We have been making efforts in the past ten years to establish the in situ measurement technique of the velocities and to accumulate data thereon of the ground, especially soft soil ground of the urban areas in Japan. The measuring method has been established as the PS logging system. And we have derived some interesting facts and helpful informations for the Soil Dynamics from a lot of these data.

INTRODUCTION

The S-wave velocity is very important data in studying the dynamic response or behavior of soil ground and evaluating the dynamic characteristics of the ground for engineering purposes. We have developed a P- and S-wave velocity measuring technique as the PS logging method, a kind of the well shooting method in a borehole. We have carried out these measurements in 244 holes (total length of measuring depth: 10784m, mean depth per hole: 44.2m) in subsurface layers of soft ground of the urban areas in Japan since 1967. (See Fig. 1)
In this paper, we have studied how the velocity of P- and S-wave and Poisson's ratio varys according to geology and soil type, in regard to the Alluvial, Diluvial and Tertiary deposits. We examined the relation of some index value in Soil Mechanics to S-wave velocity and shear modulus.

METHOD OF VELOCITY MEASUREMENT

The PS velocity logging method which we are now practising is schematically shown in Fig. 2. The borehole geophone which containes 3 perpendicular components transducer is specially designed to be clamped at any depth. This method of directly measuring the travel time downward is more useful in soft ground of urban areas than the seismic refraction

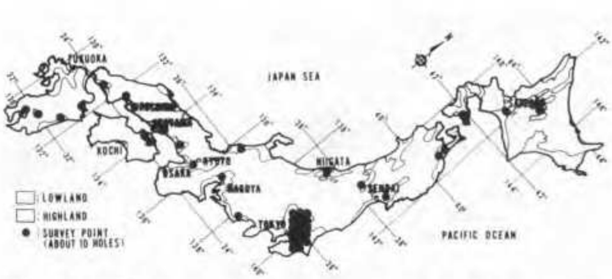

Fig. 1 Survey Point distribution in Japan

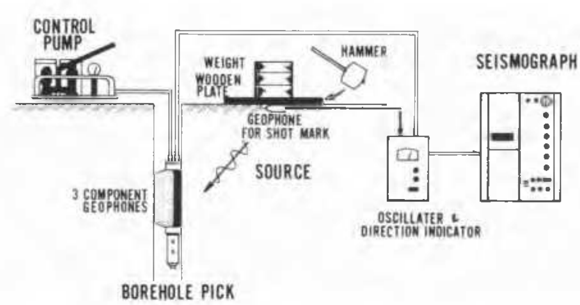

Fig. 2 Measurement System of Velocity Logging

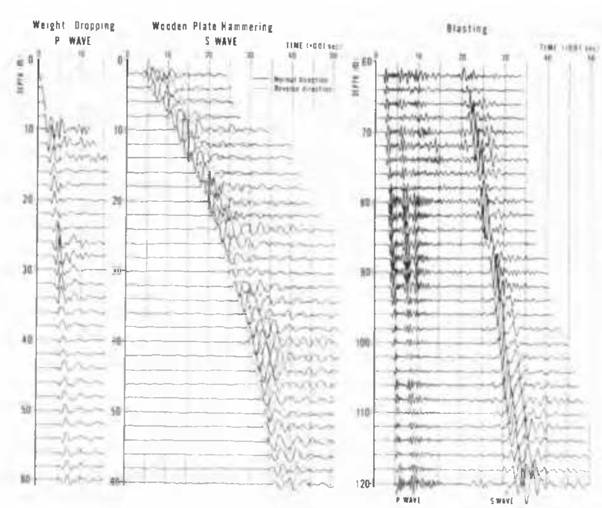

Fig. 3 Examples of P-&S-wave Logging Records

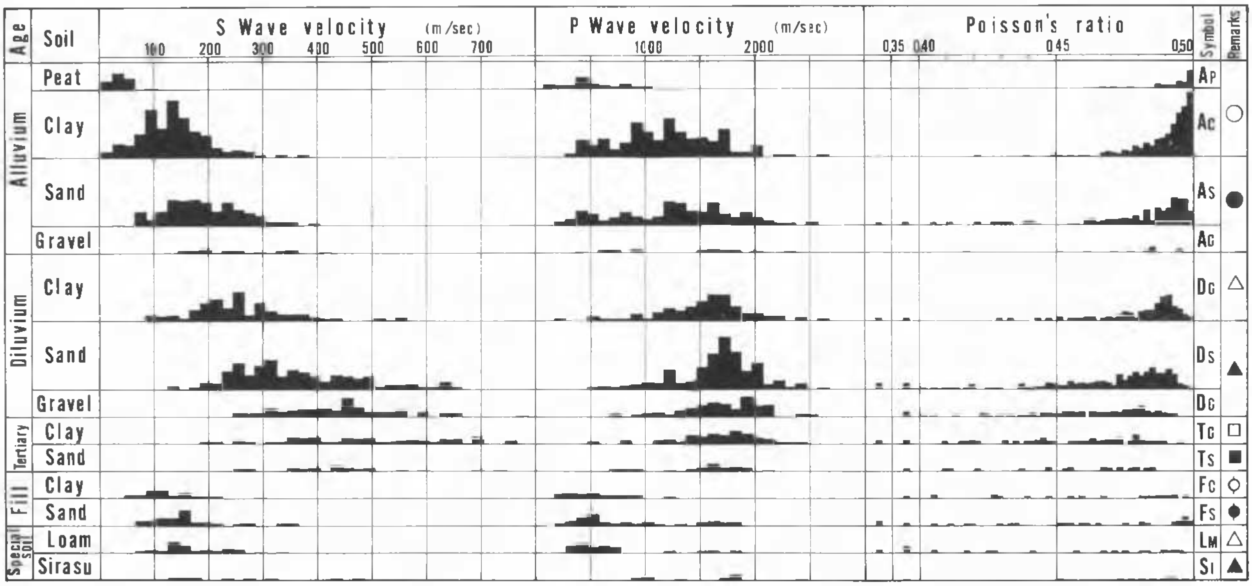

Fig. 4 Distributions of Velocities and Poisson's Ratio in Soil

prospecting and the cross-hole method. The velocities of soil layers can be determined with an easy operation in limited working space of any ground by this method.
It is not affected by any surface waves, and large wave-generating energy or long space for geophone array is not necessary. It is applicable to any velocity layering, including intercalating low velocity layers. The measurement is done repeatedly with the adequate depth interval of 1 to 2m. As the wave generating method, wooden plate hammering, weight dropping and blasting are used.
Fig.3 shows example records by these method.

VELOCITIES AND POISSON'S RATIO OF GROUND SOIL

On the basis of above-mentioned data, we have studied the distribution patterns and extents of the P- and S-wave velocities of soils according to geological ages and soil types. They are shown in Fig.4, which indicate the frequency of appearances of velocity values. Judging from these results, in each categories the velocity values take a fairly large extent, and the difference of the distribution pattern by soil, geology and P- or S-wave is discernible. In the P-wave velocity, it is classified in three types as follows.

- Type-1 : Peak velocity < 1000m/s such as peat, fill clay and loam
- Type-2 : Peak velocity > 1000m/s such as diluvial, tertiary and sirasu
- Type-3 : Both peaks as above mentioned such as alluvial sand & clay

In the S-wave velocity, these may be found a tendency of characteristic consistense for each soil type except old deposits. It is possible to recognize a certain corresponding relation between the S-wave velocity and the soil type, but in the P-wave, the contrary is the case and other factors are more prevalent.
This tendency is, again, more clear when we compare the velocity distribution in each hole. In case of P-wave velocity Vp, clear contrast is often found between above and below the underground water level. On the other hand, in case of S-wave velocity Vs, there is a good correlation with mechanical properties of the soil layers. These facts supported the general explanation that, though Vp depends on bulk modulus of soil skeleton and pore water, Vs depends on structural elasticity of soil skeleton.

We can obtain the Poisson's ratio ν from the knowledge of Vp and Vs by following equation.

$$\nu=\frac{1-2(Vs/Vp)^2}{2-2(Vs/Vp)^2} \quad \text{----------} \quad (1)$$

Fig.4 shows the distribution of Poisson's ratio of soil. Fig.5 shows the relation between Vp and ν. According to these results , it can be said that the distribution of ν can be understood as the cross pattern of velocity distribution, and the Poisson's ratio obtained by this method can be understood as a state value which is influenced by the elasticity of skeleton structure and the degree of saturation, in the medium consisting of the soil skeleton and the pore water.

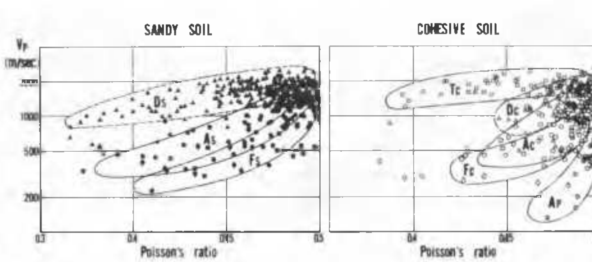

Fig.5 P-wave Velocity and Poisson's Ratio

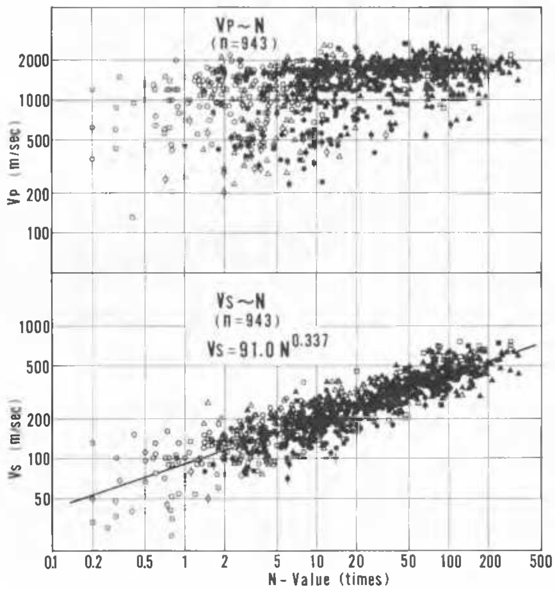

Fig. 6 Velocities and N-value (Total Data)

VELOCITIES AND SOIL PROPERTIES

We will, next, examine the relations between the elastic wave velocity and various index properties of soils. In the soil mechanics, the mechanical properties can be obtained from various in-situ or laboratory test and

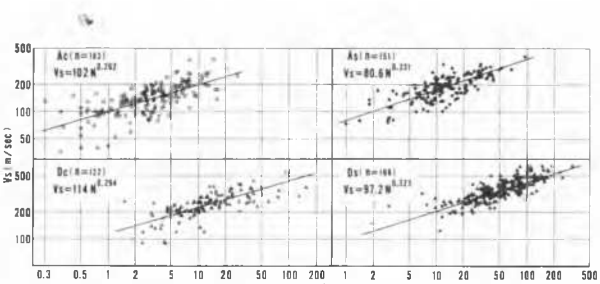

Fig. 7 S-wave Velocity and N-value (Selected Data)

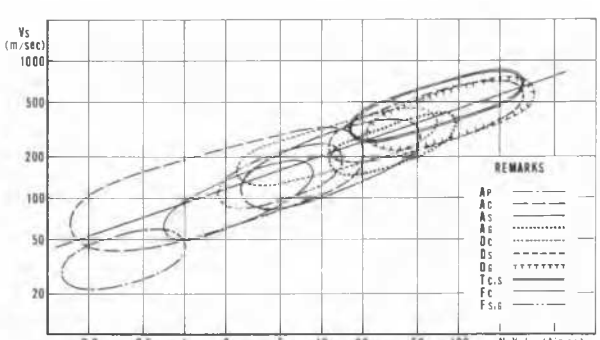

Fig. 8 Summarized Relation of Vs to N

can be shown as various index value of strength and deformation characteristics. What is quite common and indispensable among them from the standpoint of design is N value for the standard penetration test.

Fig. 6 shows the relations between N value and Vp or Vs, using the total data (n=943). The N value here used is the average value in the same velocity layer. N value over 50 or under 1 are converted from the penetrating length at the time of 50 or 1 blows into the number of blows necessary for penetration as deep as 30cm. As stated before, Vs shows fairly better correlations with N value except the extent of $N < 1$, than Vp. Tentatively trying to find an empirical formula by all data, the formula is as shown by the full line in Fig. 6

$$Vs = 91.0\ N^{0.337} \quad - - - - - (2)$$

The coefficient of correlation r is 0.889.

We continue to discuss the above relations in detail by the categories of geological ages and soil types. Fig. 7 shows some representative results. It is seen from this figure that there are wide differences of coverages of Vs and N value, and that sandy soil has the better consistence in this relation and higher gradient than cohesive soil. Also, diluvial soils show the higher Vs at same N value than alluvial soils. Fig. 8 shows above discussed results as summarized relations of Vs to N value in each category.

Now, we show some results of our studies regarding the relations between mechanical properties often used in soil mechanics and the S-wave velocity Vs. Fig. 9 shows the relations between Vs and specific coefficient of soil reaction ko, preload Py and unconfined compressive strength qu. ko can be obtained from the gradient of load-displacement curve by the Lateral Load Tester (LLT) in borehole, and is a numerical value necessary for estimation of behavior under horizontal force of the pile foundation. In these relations, a fairly good correlation is to be found except very soft clay. These relations between mechanical properties important from the viewpoint of soil mechanics and Vs do not show much difference according to geological ages and soil types. We have thus obtained an empirical formula for each. At any rate it may be consequently said that the importance of Vs in terms of its utilization in engineering has been made clear.

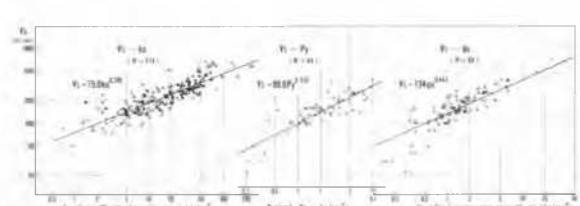

Fig. 9 S-wave Velocity and Soil Test Results

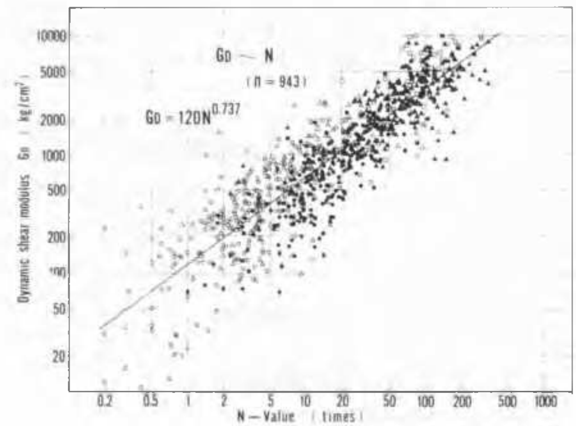

Fig. 10 Dynamic Shear Modulus and N Value (Total Data)

SHEAR MODULUS OF SOIL

We show the relationship between shear modulus Go obtained from Vs and N value in Fig.10 (total data) and Fig.11 (by soil type). It is seen here that shear modulus and N value are well correlated, and the coefficient of correlation of total data is 0.888. Fig.12 compares shear modulus determined by PS logging in which shear strain levels are approximately in a range of 10^{-6} to 10^{-7} or less,

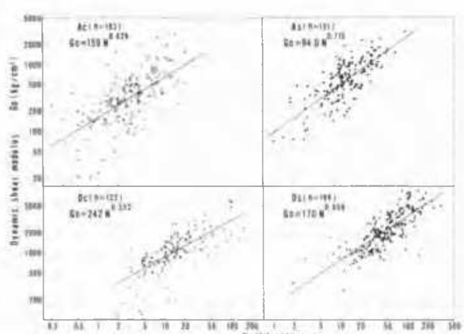

Fig. 11 Dynamic Shear Modulus and N Value (Selected Data)

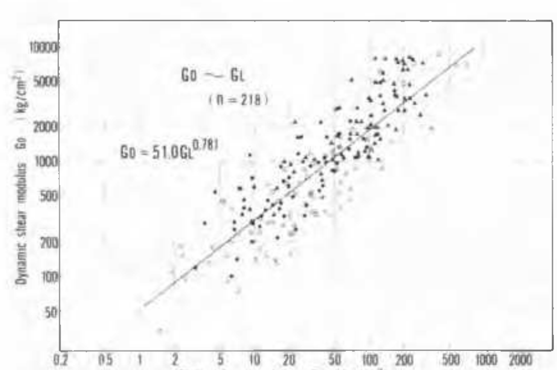

Fig. 12 Dynamic and Static Shear Moduli

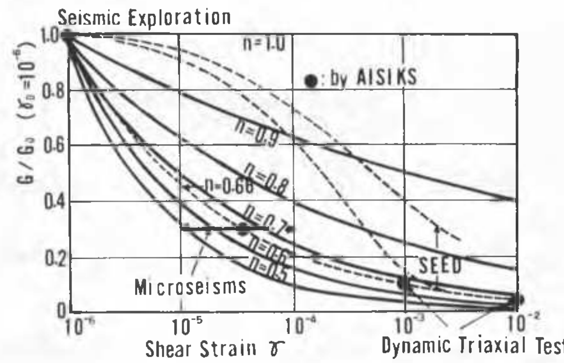

Fig. 13 Valuation of Shear Moduli by Strain Level

with those determined by LLT measurement in a range of 10^{-1} to 10^{-2}. Now, when the stress-strain characteristics of soil may be shown in the following formula $\tau = a\gamma^n$, the ratio of various shear moduli is expressed as a function of the ratio of shear strains in Fig.13.

CONCLUSIONS

As the investigation method of urban area the ground of which is chiefly of the Quarternary deposits, hitherto soil engineering method has been restored to, little use of the geophysical prospecting method being made. But for the earthquake engineering and the soil dynamics, informations on soil elasticity, like the shear modulus and the S-wave velocity, have come to be of importance. The PS logging method for measuring velocity of elastic wave, especially S-wave, described in the present paper is simple and useful for the above stated object.

This velocity information, which is closely connected with mechanical and engineering properties of soil, is indispensable to the evaluation of the dynamic characteristics of ground. Needless to say, the various matters mentioned in this paper have many problems yet to be solved. Accumulation of rich data and close experimental and theoretical verification remain to be made hereafter.

REFERENCES

Aisiks, E.G. and I.W. Tarshansky (1968), "Soil Studies for Seismic Design of San Francisco Tranbay Tube, Vibration Effects of Earthquakes on Soil and Foundation," ASTM Special Technical Publication 450, American Society for Testing and Materials, Philadelphia

Imai, T. et al. (1975), "The Relation of Mechanical Properties of Soils to P- and S-wave Velocities in Japan," Proc. 4th Japan Earthquake Engineering Symposium, pp. 89-96 (in Japanese)

Seed, H.B. (1969), "The Influence of Local Soil Conditions on Earthquake Damage," Preprint of State of the Art Lecture, Soil Dynamics Specialty Conference, 7th Int. Conf. S.M.F.E.