A study on new soil investigation method using seismic waves generated by dynamic penetration blows

Hideki Saito[1)]

Abstract: In order to obtain more reliable data for the information on the ground, a new site investigation method is proposed, in which seismic waves (S-waves) generated by the Swedish Ram Sounding Test (SRS) are used. It is indicated that the energy transferred from the hammer to the rod in SRS's is much more stable, compared to SPT's. A series of SRS with measurements of seismic waves at the ground surface were carried out to clarify the characteristics of seismic wave propagation in the ground. As the results of comparison between seismic S-wave amplitudes and N_d (blow count for 20 cm penetration in SRS), it was found that amplitudes of S-waves generated by SRS correlate well with N_d. The amplitude of the S-wave is thought to be more adequate parameter for the soil strength and rigidity than N_d.
Keywords: dynamic penetration, *N*-value, SPT, SRS, S-wave, amplitude

1. Introduciton

The Standard Penetration Test (SPT) has been widely used in Japan for soil investigations. However, the SPT is considered to be a crude in-situ testing because the driving energy of SPT may change depending on type of drilling apparatus, operator and falling method of hammer and so on (e.g. Fujita *et al.*, 2002). In order to obtain more reliable data for soil properties, a new site investigation method is investigated, in which seismic waves generated by dynamic penetration blows are used. Since the blow direction is restricted in vertical, it must be confirmed that the generated seismic waves include shear waves or not.

In the present study, a series of SPT and SRS (Swedish Ram Sounding) were performed at in-situ with measurements of seismic waves on the ground surface. From the test results, the generation of S-waves by dynamic penetration was confirmed. However, many other waves were also observed at the geophones, the development of the brief specifying methods will be required. In addition, it is found that the correlation between the blow counts such as *N*-value and the amplitude of S-wave are very well. The possibility of new interpretation of soil investigation was suggested.

In the present study, two types of dynamic penetration test were compared, SPT and SRS. It is demonstrated that the transmitted energy from the hammer to the rod in SRS's is much more stable compared with SPT's. It is also shown that the amount of transmitted energy is almost same in SPT and SRS. The correlation between SPT-N and SRS-N_{20} are also discussed.

2. Site investigation

(1) Test site

A series of SPT and SRS were carried out on Joso-terrace in Tsukuba city, Ibaraki, Japan. The soil profile is shown in Fig. 1. Almost all layers deposited in Pleistocene Era. Near the surface, the *N*-value is small and the

1) Oyo Corp., Technical Center, 43 Miyukigaoka, Tsukuba, Ibaraki 305-0841, Japan
E-mail: saito-hideki@oyonet.oyo.co.jp

volcanic sedimentary soil, which is called Kanto-loam, and alternative layer of silty sand and tuffy clay are located at the surface to 9 m in depth.

The N-value indicates over 50 times in the fine sand layer from the depth of 9 m to 14 m, and the fine uniform sand with gravels are observed at 11 m to 14 m deep is laid.

The N-value shows variety at the deeper layer of 14 m to 21 m in depth, because the layer consists of alternative strata of sand, partially stiffened sand and clay. From the depth of 21 m to 33 m, there is sandy silt layer with 10 to 20 of N-values. The deeper of this sandy silt layer, the amount of sand increases. From the depth of 33 m, the fine sand layer is located and the N-value shows over 50 times. The water level is 6.5 m depth below the surface during these site investigations.

(2) Comparison of SPT and SRS

The comparison in the configuration of testing apparatus of SPT and SRS is shown in Table 1. The split barrel sampler is used in SPT. On the other hand, the solid cone with 90 degrees tip is used in SRS. The projected area of the split barrel sampler is 43.2 cm^2, and the corresponding area of SRS's cone is 63.6 cm^2.

The projected area ratio of the split barrel and cone is about 1.0:1.5. The amount of penetration for measurement of SPT-N and SRS-N_{20}, are 30 cm and 20 cm, respectively. The ratio of penetration for SPT and SRS is 1.5:1.0. If it can be assumed that the penetration resistance is proportion to above two items: the projected tip area and penetration for measurement, the differences between SPT and SRS are neglected each other.

However, as shown in Table 1, the dropping height of hammer is different, though the weight of hammer is same. Then, the potential energy of drop hammer are 467 J in SPT, 311 J in SRS, and its ratio of SPT:SRS is 1.5:1.0. Although it is recognized empirically that the SPT-N and SRS-N_{20} show almost same value, according to above difference, it is expected that the SPT-N is smaller than SRS-N_{20}. The shapes of sampling

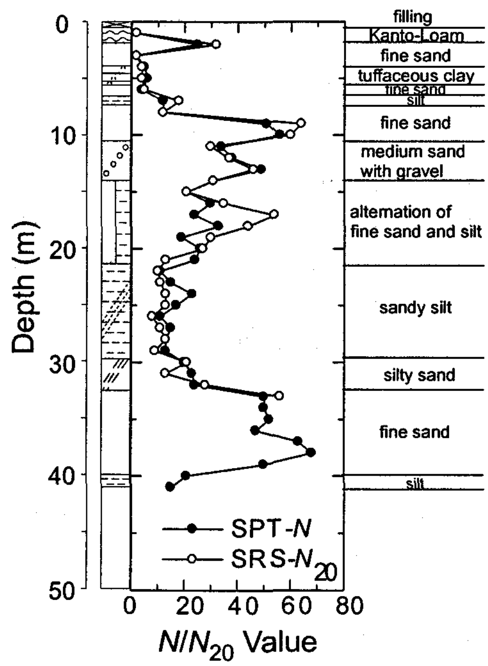

Fig. 1. Soil profile and N and N_{20} values at the test site located in Tsukuba city, Ibaraki, Japan.

Table 1. Configuration of SPT and SRS.

	falling height	sampler	sampling rod
SPT	0.75 m	split barrel inner dia. 35.0 mm outer dia. 51.0 mm	hollow inner dia. 31.0 mm outer dia. 40.5 mm
SRS	0.50 m	solid cone outer dia. 45.0 mm	solid outer dia. 32.0 mm

rod are also different, the hollow rod is used in SPT and the solid thinner rod is used in SRS. It is already confirmed by another test that the rod shape is not concerned with the driving energy.

The SRS- N_{20} is a corrected value depended on the skin friction of cone or rod, and the following empirical correction method is adopted (Sugawara *et al.*, 1997).

$$N_{20} = N_d - \beta M_r \quad (1)$$

where N_d is blow count for 20 cm penetration, β is torque coefficient of 0.0005, M_r is measured torque after blow of 20 cm penetration.

In terms of dropping method of hammer, semi-auto type is used in SPT and automatic in SRS. Although the soil samples cannot be obtained in SRS, it took only one day for depth of 33 m measurements because of its successive driving.

In order to measure the seismic wave generated by dynamic penetration on ground surface, the two component geophones, which have vertical and horizontal (radial) instrumentations, were placed on the ground surface at 5 m to 40 m away from the borehole with every 5 m intervals. The natural frequency of the geophone was 10 Hz.

(3) Test results of SPT and SRS

The SPT-N values were measured at 1.0 m intervals, while the SRS- N_{20} values were obtained each 0.2 m. The two test results for almost the same point are shown in Fig. 1, though the results of SRS are reduced for comparison with SPT. As shown in Fig. 1, the both blow counts of SPT and SRS is very similar.

To obtain the driving efficiency for each dynamic penetration, the transmitted energy to sampling rod was measured in SPT and SRS, by using two-point strain gauge method (Matsumoto *et al.*, 1992). Although the transmitted energy was calculated for each blow, the energy efficiency against the ideal potential energy, which is averaged for each N or N_{20} value, is shown in Fig. 2 with the blow counts. The indicated average efficiency for SPT in Fig. 2(a) shows scattering results compared with SRS's in Fig. 2(b). The average efficiency for SPT is getting smaller as increasing with depth; however, the efficiencies of SRS do not show such tendency.

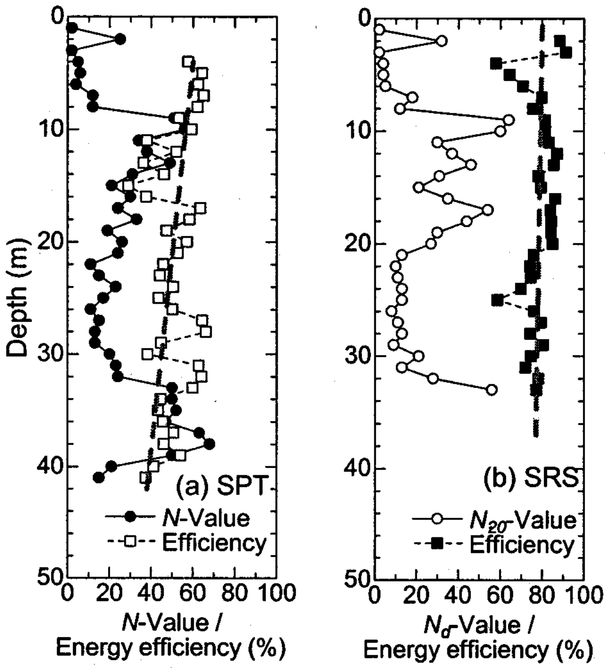

Fig. 2. Average energy efficiency and blow counts of (a) SPT and (b) SRS.

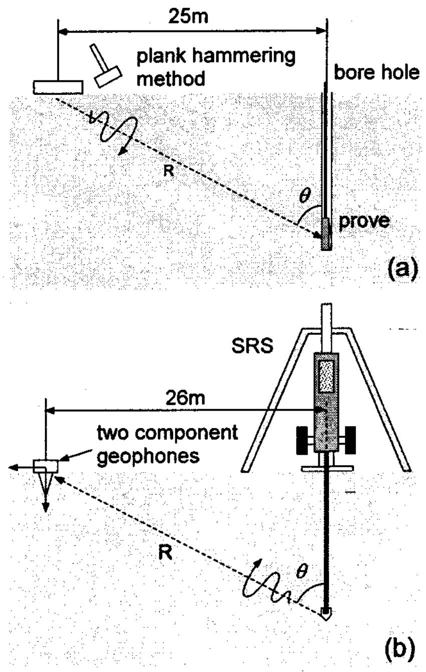

Fig. 3. Measurements configurations.
(a) Downhole SH-wave logging with plank hammering source.
(b) SRS measurements with surface seismic observation.

The whole average of energy efficiency for SPT is 51 %, and for SRS is 78 %. Since the ideal energy is 467 J and 311 J for SPT and SRS, respectively, the effective energy is 239 J and 242 J for SPT and SRS. This result supports above experience that SPT-N and SRS-N_{20} are equivalent.
From these comparisons of SPT and SRS, it is found that the driving efficiency of SRS is better than SPT's, and stable for depth.

3. Seismic waves generated by dynamic penetration blows

(1) Seismic waves generated by dynamic penetration and downhole velocity logging

The downhole velocity logging was performed by putting a plank hammering source at 25 m point from the borehole, as shown in Fig. 3(a). To compare with the result of velocity logging, the seismic wave records of the geophone, which was set on 26 m point from the borehole as shown in Fig. 3(b), are picked up and shown in Fig. 4(b). The results of normal velocity logging and SRS-N_{20} are also presented in Fig. 4(c) and Fig. 4(d), respectively. The displayed waveforms by SRS are composite waves of vertical and horizontal components, i.e. the data are same with waves in 45 ° direction against horizontal, though the composite should be done in direction of the cone tip to the geophone.

Since both of traveltime curves by SRS and velocity logging are very similar, it is confirmed that the composite waves by SRS express shear waves. Although no data is shown in the present paper, if only one component data is applied to traveltime curve, the primary waves are also mixed. Additionally, in case that the position of geophone is too close to borehole, the primary wave tends to mix, even if the two components data was combined in 45 ° direction.

It is possible to execute the velocity logging such as up-hole method by using dynamic penetration, however, it is necessary for easy practical use to investigate the optimized position of geophones. Otherwise many geophones will be required. And it is very interesting that the velocity logging is available in spite of the complex layer condition.

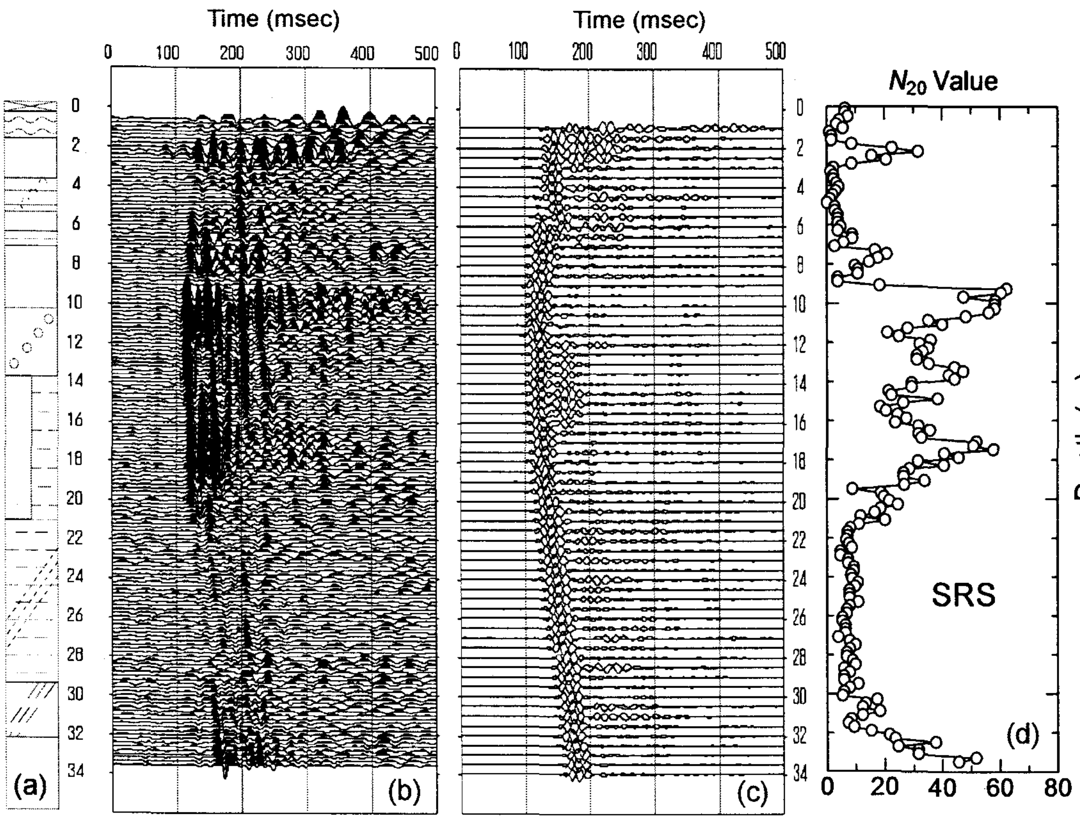

Fig. 4. (a) Soil profile at the test site. (b) Measured seismic waves generated by SRS blow at every 20 cm interval. Acquisition was carried out by the configuration in Fig. 3(b). (c) Downhole SH-waveform records (normalized by the maximum amplitude) at every 50 cm reception as shown in Fig. 3(a). (d) N_{20} value measured by SRS at every 20 cm interval.

(2) Amplitude of measured seismic waves and blow count

From the comparison of SRS- N_{20} values and the maximum amplitude of composite waves in Fig. 4(b), it is recognized that the correlation between them are very high; i.e. as the SRS- N_{20} value is larger, the maximum amplitude is also getting larger. Therefore, the relation between corrected blow counts (penetration resistance) and the amplitude by each blow was investigated.

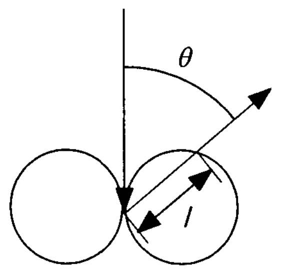

Fig. 5. Schematic diagram of assumed radiation pattern of SV-waves when the bottom of a borehole is hit vertically.

So far the SRS- N_{20} values are used for discussion, however, in order to obtain the corresponding value to SRS- N_{20} from one blow, the N_d values are corrected by using amount of penetration (equivalent N_d = 20 cm/amount of penetration for each blow). The maximum amplitude was also corrected by geometrical spreading with the distance between penetrating point and the geophone and the radiation pattern of seismic source. After correction by distance, the amplitude is offset based on the radiation pattern by vertical force of dynamic penetration, as shown in Fig. 5 (Rector, 1990). In this correction, it is assumed that the body waves are transmitted to the geophone directly and linearly. The formula for the correction is as follows.

$$a_N = a_0 \frac{R}{\sin\theta} \tag{2}$$

where a_N is normalized amplitude at 1 m away from the source, a_0 is the observed amplitude at the distance R, R is the distance between cone tip and geophone (m), θ is radiation angle in Fig. 5. The normalized amplitude, a_N, of 100,000 is corresponding to 0.6 mkine of particle velocity.

The relation between the equivalent N_d and the corrected maximum amplitude a_N is shown in Fig. 6. It is found that the above two values have high correlation, even in the case of large variation by thin layers. Meanwhile, the corrected amplitude is likely to be large compared with corresponding N_d, at the depth between 10 m and 18 m where the equivalent N_d shows large value. In these layers, the gravels are mixed in fine sand, therefore, it seems that the equivalent N_d value tends to be large by influence of blowing gravels. This suggests that the corrected amplitude expresses some soil property more properly than the blow counts. Inversely, at the shallow layer until 9 m below surface, the corrected amplitude is larger than the equivalent N_d. It can be thought that this is subjected to the influence of water table of 6.5 m below surface. This influence of water table or saturation is suggested by another study (Matsumoto *et al.*, 2002).

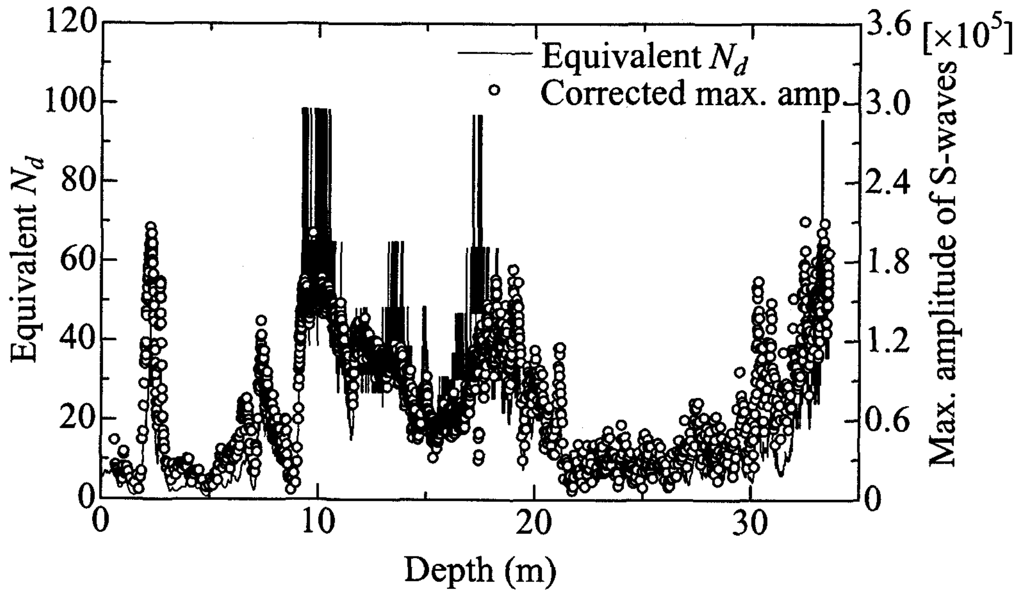

Fig. 6. Correlation between equivalent N_d and corrected amplitude of SV-wave for each penetration blow.

4. Conclusions

The present study is summarized as follows.

1) It is found that the velocity logging using seismic waves generated by dynamic penetration is available, i.e. the shear waves are generated and can be measured, though the blow direction is vertical only.

2) The relation between the equivalent SRS-N_d values and the corrected maximum amplitude measured on ground surface has high correlation. And it is suggested that the new investigation using seismic waves generated by dynamic penetration may express more detail properties of soil compared with blow counts such as SRS-N_{20}.

3) The correlation between average amplitude and SRS-N_{20} is also high; hence there is a possibility that the blow counts, such as SPT-N and SRS- N_{20}, can be estimated from a seismic wave generated by only one blow.

4) It is confirmed that SRS- N_{20} is equivalent to SPT-N by comparison of each configuration and measurements of energy efficiency.

The energy applied by the impact of dynamic penetration will be used for failure of soil partially, and the other might be converted to the seismic waves. Therefore, if the constant energy is always applied during dynamic penetration test, the evaluation of soil may become possible by measurement of the amount of penetration or the energy of generated seismic waves. The SPT or SRS is one of the testing methods based on this assumption.

It is suggested that the energy of seismic waves can be measured by using maximum amplitude picked up on ground surface. However, the transmitted media of the seismic waves are not uniform, then it is expected that the propagated seismic waves must be influenced by the soil layers, which have various attenuation coefficient or transmission factors. The results of in-situ tests do not agree with above expectation. This may show that the differences of energy generated at the bottom of borehole are more effective compared with the varieties of transmit paths. Although the wavelength of the seismic waves is a few meters, it is indicated that the amplitude can evaluate the differences in order of several centimetres.

In the future, the properties of vertical impact in another type of sampler and the mechanism of generation of seismic waves might be cleared. The model tests and numerical simulations may support the clarification of above problems. Then, it will lead to the establishment of a new practical investigation method with high quality compared with using only N-value.

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