An attempting research on evaluating grain-size characteristics based on acoustic properties of soil for liquefaction assessment by Swedish Ram Sounding

Suguru Yamada i) and Akihiko Oshima ii)

i) Associate Professor, Department of Urban Engineering, Osaka City University, 3-3-137 Sugimoto, Sumiyoshi-ku, Osaka 558-8585, Japan.
ii) Professor, Department of Urban Engineering, Osaka City University, 3-3-137 Sugimoto, Sumiyoshi-ku, Osaka 558-8585, Japan.

ABSTRACT

In order to achieve the economical assessment of liquefaction safeness for an individual residential property by Swedish Ram Sounding (SRS), an attempting research on evaluating the grain-size properties of strata employing acoustic properties of soils was carried out. The sounds generated by friction between soils and stainless-steel metal during direct shear testing and SRS were recorded. And then, their acoustic properties were compared with grain size properties of soils. As results of examination on their relationships, the possibility was discovered that the fines content, Fc, at certain stratum and presence or non-presence of plasticity of fines would be able to estimate based on the spectrum shape of frictional sound. The trends were also observed that the frictional sound of soils without plastic fines has narrow spectrum width and its peak frequency might be affected by particle size.

Keywords: Swedish ram sounding, soil investigation, direct shear test, soil classification

1. INTRODUCTION

The demand for applying measures against liquefaction to residential properties has been risen up in response to liquefaction-caused severe damages in residential ground during the 2011 off the Pacific coast of Tohoku Earthquake in Japan. Since a soil sample is not collected from certain soil stratum by common soil investigation techniques for residential properties, the Swedish Weight Sounding and the Swedish Ram Sounding (SRS) have been practically used in Japan, it is not simple to assess the safeness against liquefaction of a residential property with applying FL method in which grain size characteristics, e.g. fines content, is required. Therefore, in order to achieve applying the FL method to residential properties, it was attempted in this study that grain size characteristics of soil strata were evaluated by employing acoustic properties of the sound which were generated by the friction between the periphery of penetration cone of SRS and surrounding soils instead of collecting soil samples.

As a part of SRS process, the torque is measured by rotating a rod at each 0.2m in penetration depth with a purpose to use it in correction of the $N_d$ value. SRS cone which is of stainless-steel with a diameter of 45mm is made 2 turns at an angular velocity approximately 47 deg/sec in the ground during torque measurement. Meanwhile, the frictional sound generated was recorded and the power-spectrum was calculated, then the shape of the spectrum (spectrum width) was compared to grain size properties of soil obtained from the SPT samples. Additionally, a series of direct shear test on the Silica sand with various fines content was performed to determine the acoustic properties of friction sound generated by the shear involved between soils and the stainless-steel which is a material of SRS cone.

2 APPARATUS AND EXPERIMENTAL PROCEDURE

2.1 Direct shear test

Testing was performed using a standard type direct shear apparatus (JGS 0560-2000). An upper shear box of a direct shear apparatus was switched to a plate of stainless-steel (SUS304) with a condenser microphone built-in. The frictional sound generated by shearing between soils and stainless-steel was recorded. A schematic of upper and lower box of direct shear apparatus used is shown in Fig.1. A condenser microphone 9.4mm in diameter was installed in the microphone compartment 10mm in diameter provided in the center just above the circular specimen with a diameter of 60mm. The epoxy resin was filled in a gap between the microphone and the compartment then the compartment was caped in order to hold down the microphone slightly to the plate.

Soils used for direct shear tests were Silica sands which were prepared so that their fines content to be 0, 10, 20, 50 and 100% by mixing 2 kinds of...
commercially available Silica sands, which were Silica No.5 and Fine Silica, whose fines content were 2% and 98%, respectively. The both sands were produced in Gihu prefecture, Japan. Soil samples were given IDs as SM0, SM10, SM20, SM50 and SM100 in ascending order of fines contents.

The specimens of 10mm in height and 60mm in diameter were prepared by a method conforms to the testing method for minimum density of sand (JIS A 124: 2009), i.e. the air-dried soil sample was filled up the hopper and pluviated into lower shear box keeping the dropping height nil, and top surface was made smooth. Table 1 highlights fines contents, $F_c$ and dry densities at after consolidation, $\rho_{dc}$, of tested specimen, also consolidation pressures, $\sigma_c$, and shear rate in the direct shear tests.

All specimens were subjected to one dimensional consolidation at 100kPa after which shear load was applied to upper box until shear displacement reached to 15mm. The frictional sound was recorded continuously during shearing. It should be mentioned that shear rate on each test indicated in Table 1 are slightly different. It is because that shear force was applied to specimens by rotating handle of screw jack with an aim to reduce mechanical noises as much as possible which will be recorded together with frictional sound.

### 2.2 SRS test

Swedish Ram Sounding (SRS) tests, which is categorized as DPSH-A according to ISO 22476-2, were performed at 3 sites in Japan, where Urayasu city (Chiba prefecture), Katori city (Chiba prefecture) and Karatsu city (Shiga prefecture). The sites in Urayasu and Katori are located at the areas at which significant liquefaction-damage were observed during the 2011 off the Pacific coast of Tohoku Earthquake. A schematic of a microphone embedded penetration cone used for recording of frictional sound during SRS test. A condenser microphone which is same one as that used for direct shear test installed into a mic-chamber. In order to prevent the microphone from coming off during SRS test, the gap between microphone and the mic-chamber was filled by epoxy resin and mic-cap was fixed to the stainless-steel plate with screws. Additionally, the mic-cap was held down by spring to prevent screws from to be loosened by blow shock during SRS test. The cone was screwed to the rod. Therefore, they were able to rotate together underground during torque measurement. The torque was measured at each 0.2m of penetration depth by rotating a rod. The sound recording was continued while each 1m penetration would be completed.

### 3 FRICTION SOUND ANALYSIS

The sound sensed by a microphone was amplified by a mic-amplifier then recorded at a sampling

---

Table 1. Soils and testing conditions for direct shear tests.

| Soil name       | $F_c$(%) | $\rho_{dc}$(g/cm$^3$) | $\sigma_c$(kN/m$^2$) | Shear rate (mm/sec) |
|-----------------|----------|------------------------|----------------------|---------------------|
| SM0 (Silica No.5) | 0        | 1.55                   | 100                  | 0.16                |
| SM10            | 9.8      | 1.50                   | 100                  | 0.18                |
| SM20            | 19.6     | 1.58                   | 100                  | 0.19                |
| SM50            | 49.0     | 1.47                   | 100                  | 0.17                |
| SM100 (Fine Silica) | 98.0    | 1.72                   | 100                  | 0.17                |

---

Fig. 1. Shear box used for sound recording in direct shear tests.

Fig. 2. Cone used for sound recording in SRS tests.
frequency of 44.1 kHz using PC software in both testing cases of the direct shear tests and SRS tests. A recorded sound by SRS test performed at Urayasu city as an example, the method of analyzing the frictional sound is described below.

Fig. 3 shows a waveform of sound which was recorded continuously during the 1 m of SRS operation, corresponding depth was from 10.4 m to 11.4 m. The corresponding process of SRS and the position (depth) of microphone (cone) to the waveform are presented in the figure. Where, the meaning of “blow” and “rev” are the dynamic penetration process and the torque measurement process, respectively. All amplitude of sounds recorded during dynamic penetration was over the range of recordable volume. It can be understood from the figure that almost constant amplitudes were observed during torque measurements. Considering the facts that cone was stationary in the ground and almost no signal was observed at the time that from after dynamic penetration to before torque measurement, the sound recorded during torque measurement is able to be determined the one which was generated by friction between outer periphery of a cone of stainless-steel and surrounded ground.

In the present study, the shape of power spectrum was considered as a parameter which represents acoustic property of friction sound, and it was used in examination on relations between grain size properties of the ground. The below are description on the method for evaluating a shape of power spectrum of frictional sound.

1) Denoising: the signal of frictional sound was extracted from recorded sound by applying the spectral subtraction (Boll 1979 and Saeed 2000) to which data of 2 seconds before the start of torque measurement were applied as a noise sample. Note that in the case of direct shear test, data of 2 seconds before and after shearing were used as a noise sample for the spectral subtraction. The time histories of sound pressure before and after denoising are shown in Fig. 4(a) and (b), respectively. The both are corresponding data to that of 10.6 m in depth shown in Fig. 3. It can be found that while the noise having constant amplitude of approximately 0.08 Pa was observed before and after torque measurement in Fig. 4(a), they has been removed in Fig. 4(b). Additionally, Fig. 4(b) shows the stable amplitude with approximately 65 dB through the torque measurement, therefore it can be understood that the variation in amplitude of frictional sound is small.

2) Short Term Fourier Transform (STFT): A data unit of frictional sound which the noise had been removed was divided into many data units which have 4096 plots (approximately 0.0929 sec) while sifted 2048 plots (approximately 0.0464 sec) from the beginning. Then, the power spectrums were calculated on each divided sound data unit. This is a same idea with Short Term Fourier Transform which is one of major technique...
(3) Normalized Power Spectrum: A normalized power spectrum was obtained for each divided data unit by dividing each power spectrum by its maximum value. The data from 4 to 5sec which are parts of the time-history of sound pressure shown in Fig 4(b) are presented in Fig. 5. Dividing the data of Fig. 5 and applying STFT on each data unit, normalized power spectrums were obtained as shown Fig. 6. Normalized power spectrums for 9 data units which are corresponding to 43008plots (0-0.4644sec) from beginning of the data of Fig. 5 are illustrated in Fig. 6. Since approximately same frequency at maximum peak and similar sketch was observed from every spectrum, it can be thought that the frictional sound generated during torque measurement has uniform frequency property. Finally, single normalized power spectrum which represents frequency property of entire frictional sound was calculated by taking average of all normalized power spectrum was averaged and dividing it by its maximum value. Note, while 9 normalized power spectrums obtained from data for 1sec are illustrated as an example in Fig. 6, STFT was applied to entire frictional sound in analyses performed in this study. It should be mentioned that the entire frictional sound was defined as follows; the sound data recorded during single torque measurement (approximately 15.3sec) for SRS, and that recorded during shearing until shear displacement reached to 15mm for direct shear test. Fig. 7 shows a normalized power spectrum which was obtained as a mean from 328 divided data shown Fig. 4(b). It is found from Fig. 7 that the spectrum indicates a maximum power at around 400Hz and three larger peaks between 200Hz to 15 kHz.

As parameters represent the shape of normalized power spectrum of entire frictional sound, 2 parameters were defined and used in following discussion. The one is the peak frequency which is a frequency at which maximum power appeared. Another is the spectrum width that is the range of frequency the normalized power, \( NP \), indicated above 0.2.

### 4 EXPERIMENTAL RESULT

#### 4.1 Direct shear test

Normalized power spectrums of frictional sound obtained from direct shear tests are shown in Fig. 8. It is observed from the figure that spectrums of SM0 (Silica No.5), SM10 and SM100 (Fine Silica) indicate single peak and spread within narrow band. On the other hand, spectrums of SM20 and SM50 indicate several larger peaks. In addition to that these two spectrums have broader band in comparison with the other three soils. And more, it is found that every soils have different the peak frequency. Note that although...
small peaks were observed at the frequency within 100Hz and 200Hz on the spectrums of SM0 and SM100, they are considered to be a component of the noise which could not be sufficiently removed.

Reading peak frequency and spectrum width defined above out from each normalized spectrum shown in Fig. 8, relationships between fines content of tested soils are shown in Fig. 9. No good correlation among peak frequency and fines content was observed from the figure. SM10, SM20 and SM50 show higher or lower peak frequency than Silica No.5 (SM0) and Fine Silica (SM100), even though they are mixture of them. On the other hand, clear differ was observed on the spectrum width of soils with various fines content. In particular, SM20 and SM50 have much broader spectrum width than the others. Although both Silica No.5 (SM0) and Fine Silica (SM100) consist of almost single-sized particle, the mixtures of them have wide-spread grain size distribution curves. Therefore, it is examined that the frequency band of frictional sound became broader because various sized sand particles could have much chance of friction with stainless-steel plate in the case of mixtures. It is also considered that the peak frequency is affected by grain size distributions. However, the effect has not been clear yet. The other conceivable effects are density, consolidation pressure, shear rate, etc. should be examined by continuous research.

4.2 SRS

Depth profiles of fines content and the spectrum width of frictional sound recorded Urayasu city, Katori city and Kratsu city in Fig. 10 (a), (b) and (c), respectively. Where, fines contents shown in Fig. 10 were obtained by grain size analysis on soil samples corrected by Standard Penetration Test performed beside of SRS testing point. While there is considerable variation, a certain level of agreement between both depth profiles can be observed. This result might be suggesting that fines content of the certain stratum is able to be estimated by using spectrum width of frictional sound recorded during SRS testing. Focusing on the value of spectrum width, it is found that less than 1000Hz were obtained at most depth of Katori and Karatsu, while that of Urayasu shows large value as 4500Hz in maximum and large variation. It is considered that the difference on the spectrum width is depended on the characteristics of fine particles. It has been known that fines in Urayasu are low plastic silt, and that of Katori and Karatsu are non-plastic silt (Hirata et al.). Therefore, it can be inferred that the frequency band of frictional sound is depended on the plasticity of fines particle even though fines content is same.
In order to compare the spectrum shape of frictional sound for same fines content, normalized power spectrum obtained from several strata with fines content is approximately 20, 60 and 90% are shown in Fig. 11. Note, the result of 11% of fines content is shown in Fig. 11 instead of 90% because there was not stratum has 90% of fines content in Karatsu. In the figure, soil classification symbols are presented along with fines content. Focusing on spectrums of 20% and 60% of fines content, it is found that the spectrums of Urayasu, fine particle is low plastic silt, show several peaks in the broad frequency range from 800 to 5000Hz, while that of Katori and Karatsu, fine particle is non-plastic silt, show single peak in narrow frequency range from 1000 to 2000Hz. It is also found that spectrums with 90% of fines content in Urayasu (low plastic silt) and Katori (high plastic silt), both strata consist of plastic fine particles, indicate several peaks in the broad band. Moreover, some trend is observed in three spectrums of Karatsu, where every stratum contains gravels, that the peak frequency was shifted to lower-frequency area with increase of fines content, while significant difference was not observed in spectrum widths with fines content ranged from 10 to 60%. However, the opposite trend was also observed in comparison on spectrums with 21% and 66% of fines content of Katori, i.e. the peak frequency of 66% of fines content is higher than 21%. Considering that, it can be inferred that the peak frequency of soil without plastic fines would be affected by the size of major particle which consist of the stratum.

5 CONCLUSIONS

As results of a series of direct shear test on Silica sands with various fines content and SRS tests at three sites performed in the present study, a possibility was discovered that the fines content at certain stratum and presence or non-presence of fines would be able to estimate based on the spectrum shape of frictional sound. The trends were also observed that the frictional sound of soils without plastic fines has narrow spectrum width and its peak frequency might be affected by particle size. It is necessary to investigate effects of grain size distributions, density, consolidation pressure, etc. for establishing a method for estimation of grain size characteristics from acoustic properties of the frictional sound.

ACKNOWLEDGEMENTS

This research work has been founded by Japan Science and Technology Agency (JST) and Rent All Scholarship Foundation. We wish to acknowledge their support.

REFERENCES

1) Boll S.F. (1979): Suppression of acoustic noise in speech using spectral subtraction, IEEE Transactions on Acoustics, Speech and Signal Processing, Vol.27, Issue.2, pp. 113–120.
2) International Organization for Standardization (ISO). (2005): Geotechnical investigation and testing –Field testing- Part 2; Dynamic probing, ISO 22476-2: 2005.
3) Hirata et al. (2014): Comparison in method for liquefaction safety assessment based on various ground survey for residential properties, Proc. of 49th JGS conference, paper No. 47. (in Japanese)
4) Japanese Geotechnical Society (JGS). (2000): Method for consolidated constant pressure direct box shear test on soils, JGS 0561-2000.
5) Japanese Geotechnical Society (JGS). (2009): Test method for maximum and minimum densities of sands, JGS 0161-2009 (JIS A 124: 2009). (in Japanese)
6) Saeed V. V. (2000): Advanced Digital Signal Processing and Noise Reduction, Second Edition, Wiley & Sons Ltd, pp.333-354.