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LIQUEFACTION POTENTIAL USING S-WAVE CROSSHOLE TOMOGRAPHY

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SUMMARY

It has been very important to estimate accurate liquefaction potential after 1995 Hyogoken-Nambu Earthquake because of predicting earthquake liquefaction damages. Cyclic triaxial test used to be adopted to evaluate the liquefaction strength after undisturbed tube sampling. However it cannot be avoided disturbance of soil during sampling in case of the dense sand that required accurate liquefaction resistance (R_{L20}). Because of these problems, authors executed the crosshole shear wave tomography in-situ and calculated the liquefaction resistance (R_F) from the measured shear wave velocity. It is compared the liquefaction resistance from the shear wave velocity with the liquefaction resistance from the undrained cyclic triaxial test using tube sampling and in-situ freezing sampling methods. The conclusion is presented to illustrate the usefulness of this method for evaluating liquefaction potential at a site. Liquefaction resistance from shear wave good correspond with these from laboratory tests in alluvium layer. But in diluvium layer, liquefaction resistance has been affected strongly by geological time effect.

INTRODUCTION

Various type of damages occurred in 1995 Hyogoken-nambu Earthquake with buildings and civil structures. Liquefaction damages of ground generated in many places in this earthquake. Earthquake resistant regulations especially for liquefaction characteristics have been started to revise since this earthquake with regard to agencies concerned. The regulation of Specifications for highway Bridges・Part V: Seismic Design[JRA,1996] revised at December 1996 from the view point of very strong input ground motions, liquefaction resistance and the gravely soil which be able to liquefy soil. Earthquake resistant regulations have been tendency to increase treating civil structures. The earth structure like riverbank which has very long length has begun to evaluate liquefaction susceptibility.

Earthquake resistant design has been major part of civil structures design with this intensifying seismic code. There have been needs of high accuracy of the field investigation and the laboratory test with liquefaction potential assessment and simultaneously there have been needs for cost reduction for field and laboratory tests.

This paper was investigated the evaluation of liquefaction resistance using shear wave crosshole tomography under permission to technical committee members of Public Works Research Institute, Ministry of Construction and Japan Geotechnical Association to use experiment data [Matsuo and Tsutsumi, 1996].

The liquefaction assessments have generally been determined by following two type approaches.

- Evaluation of liquefaction resistance by in situ tests. This procedure is due to empirical correlation between in situ soil properties and liquefaction potential during previous earthquakes. These methods include standard penetration test (SPT) which is most frequent use in Japan. The cone penetration tests and shear wave logging in downhole method can be used to evaluate liquefaction potential in Japan.

- Evaluation of liquefaction resistance by means of laboratory cyclic triaxial tests on undisturbed samples.

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This paper was used the procedure (a) and the liquefaction resistance was estimated from shear wave velocity using shear wave crosshole tomography. Moreover the various types of undisturbed sampling included in situ freezing sampling method and laboratory tests were carried in this experiment. The reliable liquefaction resistance can be obtained from these laboratory tests. Discussion was presented with reference to liquefaction resistance from shear wave and form laboratory tests.

REVIEW OF PREVIOUS STUDIES

The studies that assessed liquefaction potentials from shear wave velocity started to research from about ten years ago. Tokimatsu and Yoshimi investigated the liquefaction resistance of gravely soil from shear wave velocity [Tokimatsu and Yoshimi, 1986a]. Tokimatsu et al. developed the correlation curves between the liquefaction resistance and normalized shear modulus from in situ shear wave velocity. They proposed the simplified procedure to estimate liquefaction resistance from shear wave velocity [Tokimatsu and Uchida, 1990]. Furthermore Tokimatsu et al. developed the liquefaction potential evaluation based on rayleigh wave investigation and suggested a correction to amount for fines content of soil [Tokimatsu et al., 1991].

From these studies, major factors to liquefaction resistance consist of (a) mean effective stress, (b) soil type and soil fabric, (c) grain size distribution, (d) relative density, (e) geological time effect, (f) overconsolidation ratio, (g) cyclic shear strain amplitude, (h) stress history. On the other side, the shear velocity or the shear modulus was influenced many factors such as (A) mean effective stress, (B) soil type and soil fabric, (C) void ratio or density, (D) geological time effect, (E) overconsolidation ratio, (F) shear strain amplitude, (G) stress history [Tokimatsu et al., 1986b]. It seems that both factors is the almost same. It can be found that each of these factors which is likely to increase to liquefaction resistance also tends to increase shear modulus [Tokimatsu et al., 1986b].

Tokimatsu and Uchida suggested that the pore pressure generation toward liquefaction be governed by the volume change characteristics of soil at small cyclic shear strain. Besides, the volume change characteristics are governed by the soil fabric and density, and so is the elastic shear modulus. They proposed that the liquefaction resistance could be estimated from shear wave velocity that corresponded to the normalized shear modulus.

Stokoe et al. investigated the correlation between shear wave velocity in situ and surface maximum acceleration dividing into liquefying place or not [Stokoe et al., 1988]. Robertson et al. suggested that the correlation between the liquefaction resistance and the shear velocity normalized by the effective vertical overburden stress[Robertson et al., 1992].

There are two types of procedure to estimate liquefaction resistance from shear wave velocity.

- Methods based on a combination in situ shear wave velocity measurements and laboratory tests from Tokimatsu et al.

- Methods based on in situ shear wave measurement and a correlation between liquefaction resistance and shear wave velocity deduced from the liquefaction degree in the field from Stokoe et al.

This paper used the (a) methods proposed by Tokimatsu et al. The liquefaction resistance in situ (RF) was calculated from the normalized shear modulus based on the shear wave crosshole tomography.

METHODS OF INVESTIGATION

In Situ Test Sites

The tests were carried out at four sites, all of which were located in flood basin of major rivers in Japan. Figure 1 shows the location map of experiment sites. Various investigation were carried out at each sites, i.e. boring, standard penetration test (SPT), tube sampling, self-boring pressuremeter test, crosshole shear wave tomography, cone penetration test (CPT) and Automatic ram sounding within 10m horizontal distance centred at the in situ freezing sampling bore hole which investigated the previous year.

As shown Figure 2, N-vale 30 to 40 clean sand layers were distributed in the depth of 10m bellow, so this sand layers made the target of investigation against the very strong input ground motions. These sand layers consist of

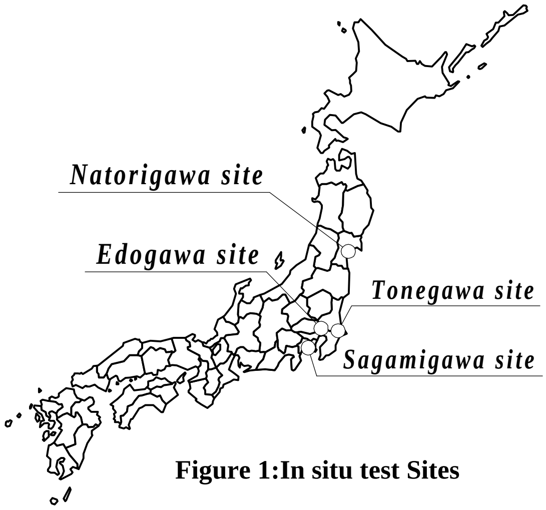

Figure 1:In situ test Sites

clean sand at Tonegawa, Edogawa and Natorigawa site and silty sand at Saganigawa site. This sedimentation age were Pleistocene (diluvial deposit) at Edogawa site and Holocene (alluvial deposit) at Tonegawa, Natorigawa and Sagamigawa sites. Figure 2 shows the soil column, standard penetration tests (95’ and 97’) and shear wave velocity from crosshole tomography (97’) at Edogawa and Natorigawa sites.

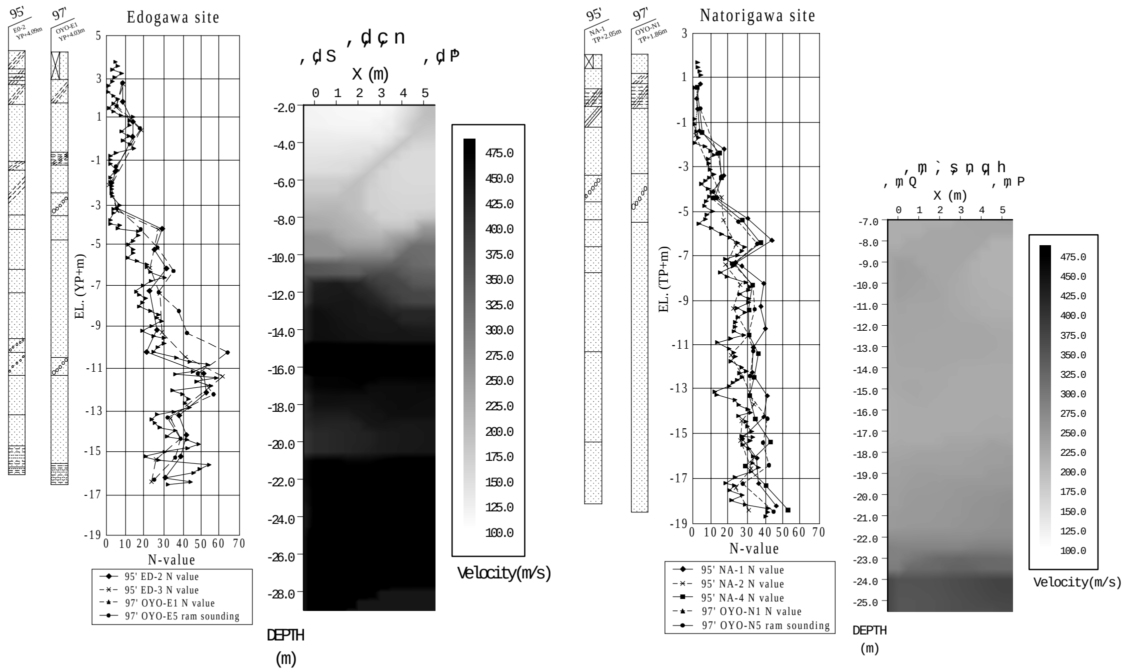

Figure 2: Soil profile, SPT and shear wave velocity at Edogawa and Natorigawa site

Shear Wave Crosshole Tomography Tests

Shear wave crosshole tomography tests were carried out with the shear wave seismic source of Suspension P-S Logging System, which generated SH-waves as the solenoid hammer hits the inside of hitting plate in the sonde. This source was usually used in single hole logging therefore its power not so large. However, because the bore holes spacing was small, in which borehole spacing is about 5m at the four experiment sites, we could apply this source to this investigation. The receivers were Borehole Shttle that contains three component geophones (1 vertical and 2 horizontal; the natural frequency is 10Hz). These receivers are type of four-levels and possible to fix themselves to the wall of bore hole by locking arms.

Figure 3 shows the flow chart of data pre-processing, editing, and analysis of shear wave velocity tomography. First, a couple of horizontal waveform data from every data file was selected as data pre-processing. Next, the first arrival times of shear wave from edited waveform data were picked up. In the tomography analysis, the target section was divided into square cells 50cm by 50cm, and the velocity values of each cell were determined. Then, the theoretical traveltimes by raytracing was calculated by Back Projection Technique (BPT). The residual times between observed traveltimes and the theoretical ones were calculated, and the velocity model was modified by using Simultaneous Interactive Reconstruction Technique (SIRT), so ad to reduce residuals. After 10 times of iteration, the residuals did not reduce so mach and the procedures were converged.

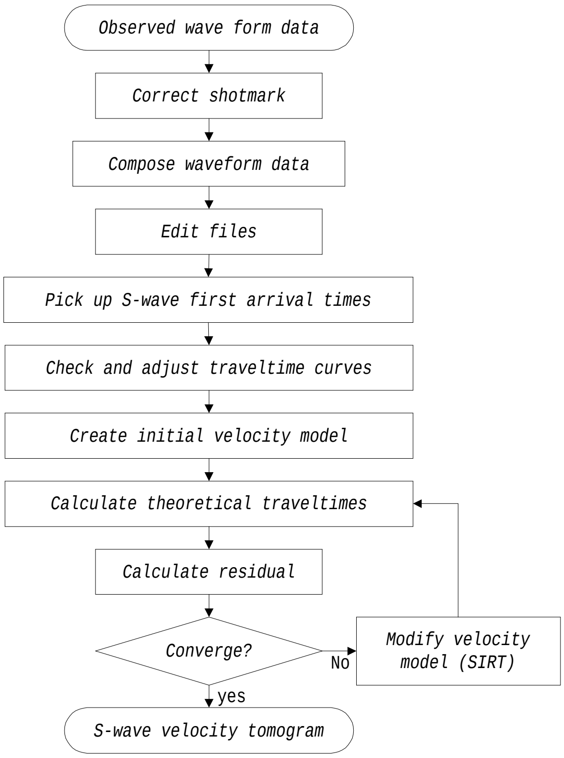

Figure 3: Analysis Flow chart of Shear wave tomography

Estimation Procedure of Liquefaction Resistance

Liquefaction Resistance in situ (R_F) was calculated from shear velocity (Vs) developed by Tokimatsu and Uchida [Tokimatsu and Uchida, 1990].

This method is following:

Determination of the elastic shear modulus in situ (G_F) by the next equation base on the dynamic soil properties.

$$G_F = \rho Vs^2 \qquad (1)$$

In this ρ is the mass density. And then calculated the normalized shear modulus (G_N) following equations:

$$G_N = G_F / [F(e_{\min}) \cdot (\sigma_m'/Pa)^{2/3}] \qquad (2)$$

$$F(e_{\min}) = (2.17 - e_{\min})^2 / (1 + e_{\min}) \qquad (3)$$

$$\sigma_m' = (1 + 2K_0) \cdot \sigma_v' / 3 \qquad (4)$$

$$e_{\min} = 0.65 \sim 0.95 \qquad (5)$$

$$K_0 = 0.75 \qquad (6)$$

in which $e_{\min}$ is the minimum void ratio, *Pa* is reference stress 98.1kPa (1kgf/cm^2), σ_m' is the mean effective confining pressure, σ_v' is the effective overburden pressure and K_0 is the earth pressure coefficient.

And then the stress ratio to cause liquefaction DA=5% in 15 cycles (R_{L15}) is evaluated using the correlation between R_{L15} and normalized shear modulus.

$$R_{L15} = 8.127 \times 10^{-9} G_N{}^3 - 7.956 \times 10^{-6} G_N{}^2 + 3.219 \times 10^{-3} G_N - 0.3369 \quad (@G_N \le 1{,}000) \qquad (7)$$

Because of the comparison of the laboratory tests result in this experiment, R_{L15} is converted the stress ratio to cause liquefaction DA=5% in 20 cycles R_{L20} , Furthermore R_{L20} converted the stress ratio to cause liquefaction for field K_0 conditions and for the factor of the effects of multidirectional shaking to the liquefaction resistance in situ (R_F).

$$R_{L20} = 1/1.05 \times R_{L15} \tag{8}$$

$$R_F = 0.9 \times (1+2K_0)/3 \times R_{L20} \tag{9}$$

The liquefaction resistance in situ (R_F) was calculated from shear wave velocity in crosshole tomography using equations (1), (2), (7), (8) and (9).

RESULT

Liquefaction Resistance from Shear Wave Velocity

The liquefaction resistance could be calculated at four experiment sites and Figure 4 contains two sites at Edogawa and Natorigawa. The normalized shear modulus (G_N) in Edogawa site was exceeded 98.1Mpa (1,000kgf/cm^2) which was equivalent for shear wave velocity about 250m/sec, so equation (7) cannot be applied to this sand layer. That high velocity sand layer in Edigawa site corresponds to diluvial deposit. Figure 4 shows the normalized shear modulus greater than G_N>98.1Mpa (1,000kgf/cm^2) was represented the liquefaction resistance in situ greater than R_F>2.2.

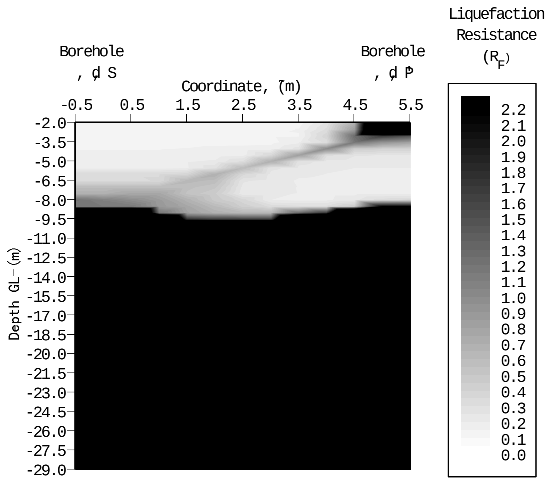

Figure 4(a): Liquefaction resistance from shear wave tomography at Edogawa site

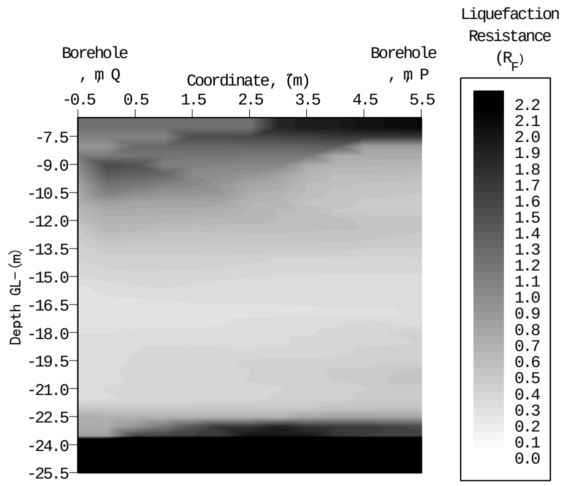

Figure 4(b): Liquefaction resistance from shear wave tomography at Natorigawa site

Liquefaction Resistance from Laboratory Tests

The liquefaction resistance from shear wave velocity could be compared with the undrained cyclic triaxial tests on in situ freezing samples and tube samples. This procedure was that the correlation between the normarized shear modulus (G_N) from shear velocity in situ and the liquefaction resistance in situ (R_F) that calculated from equation (9) with the stress ratio (R_{L20}) to cause liquefaction in cyclic triaxial tests were examined at the same sampling depth.

Figure 5 shows the correlation between the liquefaction resistance in situ (R_F) and the normalized shear modulus (G_N). It can be seen that the liquefaction resistance is too small especially in Edogawa site. It may be inferred from this data that the one of the reasons is the diluvial deposit at Edogawa site. It is possible to deduce that the tube samples and the in situ freezing samples are both disturbed in sampling. The data was still more scattered in the portion of the high normalized shear modulus from the regression curve in equation (7) .

DISCUSSION

There are many factors to affect the shear wave in situ. It has been recognized to the geological time effect. Many researchers have been investigated on the effect of the geological time effect to the shear wave velocity.

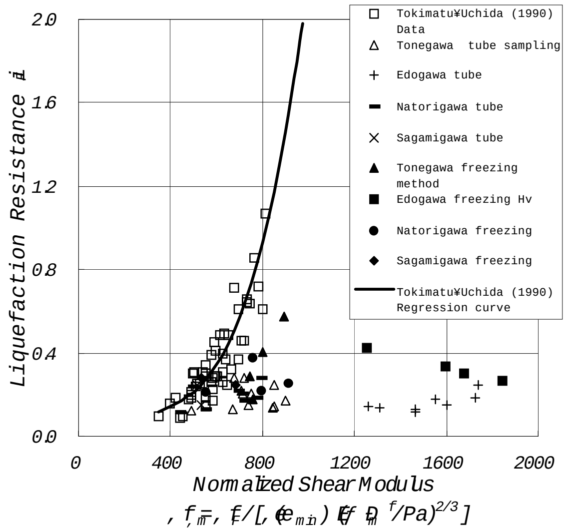

Figure 5: Correlation between liquefaction resistance in situ (R_F) and normalized shear modulus (G_N)

Figure 6: Modification of the normalized shear modulus (G_N) after consideration of the geological time effect

Ohta and Goto investigated the shear wave velocity in terms of characteristic Indices of soil using the quantification theories [Ohta and Goto, 1976]. The results are summarized as the regression equation as follows:

$$Vs(m/\sec) = 69 \times N^{0.17} D^{0.2} \times F_1 \times F_2 \tag{10}$$

Then N shows N values in SPT and D is the depth (m) in the measurement and the F_1 is the coefficient of the effect of geological age. It takes the value from F_1=1.0 for alluvial deposit to F_1=1.3 for diluvial deposit. Also the F2 shows the effect of a sort of soil. This coefficient takes the 1.0 for clay to 1.45 for gravel. It is clearly recognized the geological time effect.

Imai and Tonouch summerized the shear wave velocity and soil properties, in which the total data 1654 was experimented mainly at the Kanto district of Japan where located at the metropolitan area. They proposed the regression equations to the shear wave velocity from PS-logging and the N-value from SPT in every kind of soils and geological age. These regression equations for the alluvial sand and for the diluvial sand as follows:

$$Vs = 87.8 N^{0.292} \quad \text{[For alluvial sand (As)]} \tag{11}$$

$$Vs = 110 N^{0.285} \quad \text{[For diluvial sand (Ds)]} \tag{12}$$

The ratio of the shear modulus in situ between alluvial sand and the diluvial sand could be calculated from equation (11), (12) and (1) in consideration of the appropriate mass density. This equation shows as bellow:

$$G_F(As)/G_F(Ds) = 0.491 \times Vs(Ds)^{0.0491} \tag{13}$$

The normalized shear modulus in Figure 5 could be modified from equation (13). Figure 6 shows the modification of the normalized shear modulus (G_N) after consideration of geological time effect. It suggest that the modification of the normalized shear modulus (G_N) is effective but the liquefaction resistance in situ (R_F) is still disturbed and appears the low resistance. There is the point of further discussion. This investigation could be reached the conclusion that the shear wave velocity in situ at Edogawa site is affected the geological time effect.

CONCLUSIONS

The liquefaction resistance in situ from shear wave crosshole tomography was estimated at four experiment sites in Japan. The investigation was developed to the comparison with the liquefaction resistance in situ from shear wave crosshole tomography and the liquefaction resistance from the undraind cyclic triaxial tests in the laboratory on undisturbed tube and in situ freezing samples. The conclusions as follows:

1. There is good correspondence of the liquefaction resistance between in situ and the laboratory in the alluvial sand.
2. The liquefaction resistance between in situ and the laboratory cannot be agreed in the diluvial sand. It may be possible to think that the sampling is disturbed in the diluvial deposit.
3. The normalized shear modulus can be correct using the existing equations between shear wave velocity and the N value in SPT.
4. The liquefaction resistance can be estimated from shear wave crosshole tomography in the cross sections. It may be expected that this method will use frequently in the liquefaction assessment.

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