4th International Conference on
Earthquake Geotechnical Engineering
June 25-28, 2007
Paper No. 1297

NUMERICAL AND EXPERIMENTAL ASSESSMENT OF LIQUEFACTION AND FOUNDATION UPLIFTING

Nourredine MEZOUER[1], Akila MESSAOUDI[2], Chikahiro MINOWA[3]

ABSTRACT

Liquefaction has been recognized as the main reason for collapse of earth dams and slopes, failure of foundations and lifelines and its early detection might be of great interest.
A one-dimensional dynamic analysis program for saturated soils is developed in this study. The theoretical formulation is based on the Kim et al (2000) work, which is an extension of Biot's two-phase theory. The analytical formulation leads to a coupled system of equations (soil-water), solved by Newmark's method.
In a first part, we try to detect liquefaction phenomenon regarding induced pore water pressure and shear stress due to the earthquake. This procedure needs strong motion records. The corrected records of Chokubetsu station (HK086) are used. During the excitation, the pore pressure gradually increases and the effective mean pressure decreases until it reaches a zero value. The foundation uplifting starts when the induced force due to water pore pressure acting on the foundation becomes higher than the structural weight. The case of the site of accelerometer foundation and the records situated in Chokubetsu region affected by the Tokachi-Oki earthquake were considered.
In second part, frequency characteristics of Chokubetsu data were analyzed. The attempt of understanding the relation between peak frequency shift and liquefaction was carried. Judging from the spectra of various time areas, the liquefaction of accelerometer foundation excavation soil would be estimated to occur soon after main part (S wave) of the record.

Keywords: Liquefaction, pore water pressure, shear stresses, induced force, uplifting

INTRODUCTION

Liquefaction has been of a primary concern for earthquake engineers since the earthquakes of 1964 in Niigata and Alaska (Seed and Idriss, 1982). These earthquakes triggered a significant amount of research focusing on finding the mechanisms and conditions that lead to liquefaction and its effects due to its occurrence. The research covered three broad categories over the four decades since those earthquakes.

The primary emphasis of the research has been on laboratory testing. This testing includes cyclic triaxial tests, torsional shear tests, shaking table tests, and centrifuge tests. Of particular importance are observations of pore pressure generation and dissipation, acceleration attenuation, changes in shear strength, and deformation mechanisms. The second category of research is theoretical analysis procedures for soil liquefaction and more specifically numerical modeling. These numerical codes are often based on the extension of soil constitutive models to earthquake behavior and specifically the reduction in effective stress that occurs due to the development of excess pore pressure requiring

[1] Researcher, National Earthquake Engineering Research Center (CGS), Algiers, Algeria, mezouer_n@yahoo.fr
[2] Assistant, National Polytechnic School of Architecture and Urbanism (EPAU) Algiers, Algeria
[3] Professor, National research Institute for Earth Science and Disaster Prevention (NIED), Tsukuba, Japan

coupled models for solid fluid interaction. In last years, a number of ground motion records from liquefied-soil sites have been obtained. The third category of research begins with the verification of theoretical analysis procedures for soil liquefaction and detection of liquefaction and induced effects from the strong motion records.

The ground motion parameters from liquefied-soil sites were examined in a number of studies (Kostadinov, 2001) and some of them were employed in several methods for liquefaction judgment from the strong motion records. In the present paper, our interest is to assess the liquefaction and estimate the uplifting by using finite element procedure. This procedure needs strong ground motion records and soil characteristics. The geotechnical data of the site of accelerometer foundation and the signals recorded in Chokubetsu region affected by the Tokachi-Oki earthquake of 2003 are used. The soil investigation was carried out by Kiso-Jiban Consultants (Kiso, 2005). The corrected records of Chokubetsu station (HK086) are exploited. Using the program developed, a tentative to detect liquefaction from strong motion records is done. The records show that the horizontal ground acceleration alters uniquely after the onset of liquefaction while the vertical acceleration is rather stable. This alteration of the horizontal acceleration is triggered by the decreasing of the soil shear modulus as a consequence of the pore-water pressure buildup under un-drained condition. The Paper was written as the study report of JICA Training Course, and revised.

LIQUEFACTION ASSESSMENT AND UPLIFTING ESTIMATION USING SHAKUBETSU RECORDS

On September 26, 2003 at 04:50 local time, a big earthquake struck off the south coast of Hokkaido island, Japan (Tokachi-Oki earthquake) (Figure1). The peak ground accelerations after the K-net observation were very important, for example, 784.9 gal in Chokubetsu station (HK086) and 261.2 gal in Shakubetsu (HK094) (Yagi, 2004). The largest damage was inflected to lifelines, embankments and roads. Large ground displacements and related damage occurred mostly in man-made earth structures, reclaimed soils and artificial fills. Several manholes were up-lifted as much as 1.2-1.8 m above the ground surface. Signs of liquefaction were evident along the collapsed ground over buried pipelines and near uplifted manholes.

The accelerometer foundation, situated at Chokubetsu K-net site, was affected by the excavation soil liquefaction. The Kiso-Jiban Consultants Company and NIED made the soil investigations of the site in Figure 2. All the data for this study are taken from the investigation report. The area of accelerometer foundation was excavated in order to estimate the real displacement of the accelerometer foundation. An important uplifting, rotation and tilt occurred in the foundation, as shown in Figure 3.

Based on the static consideration, the balance between the foundation weight and the buoyancy due to the liquefied soil is used as equation for determination of the uplift displacement. The scheme of equilibrium system is given in Figure 4. The calculated result gives an uplifting displacement of about 30cm-40cm, while basing on the displacement occurred since the onset of the liquefaction (figure12). These values approximately agree with the observed data in Z direction of Table 1.

Recent research revealed existence of coupling between the deformations of the solid and the liquid phases of saturated soil. Many studies are focused on this phenomenon. Indeed Biot 1956, who proposed the two-phase model, as an extension to this, followed by others (Zienkiewicz and Shiomi, 1984; Lewis and Schrefler, 1998; Zienkiewicz et al., 1999, Hoon et al., 2000, Kim and al, 2000).

In this paper, according to the latest work of Kim and al, 2000, the seismic responses, such as total stress and pore water pressure for a saturated porous soil layer, were calculated. Matlab program was used for the numerical calculation. The soil profile of 12 layers for the numerical calculations is shown in Figure 5. The investigated soil profile is shown in Figure 6. Each layer for the numerical calculation has thickness of 1m. All the characteristics needed by the model are given in Table 2.

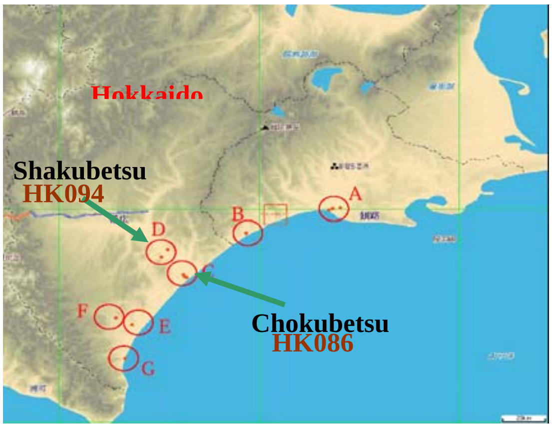


Figure 1: General map indicating the location

Figure 2: The investigation work

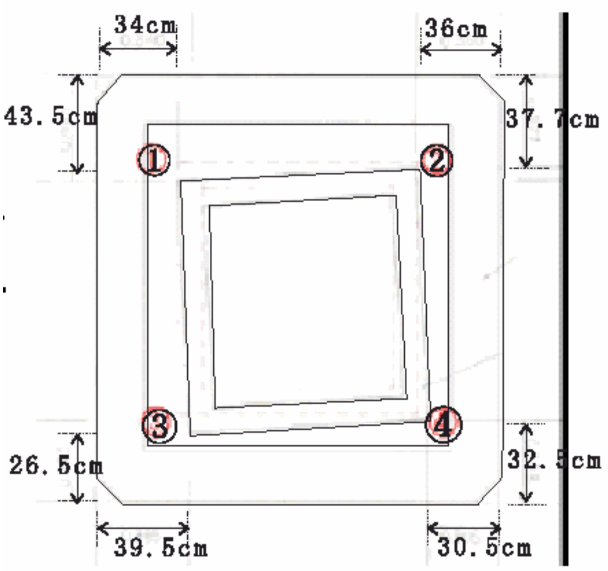


Figure 3: Final configuration of the accelerometer foundation

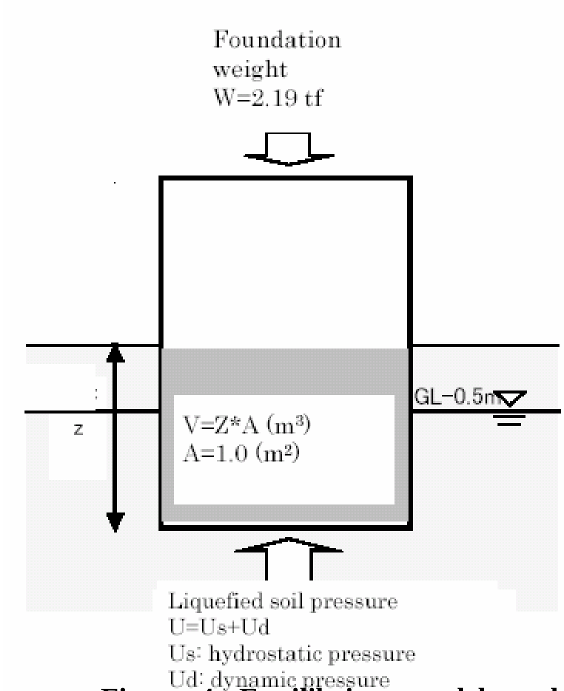


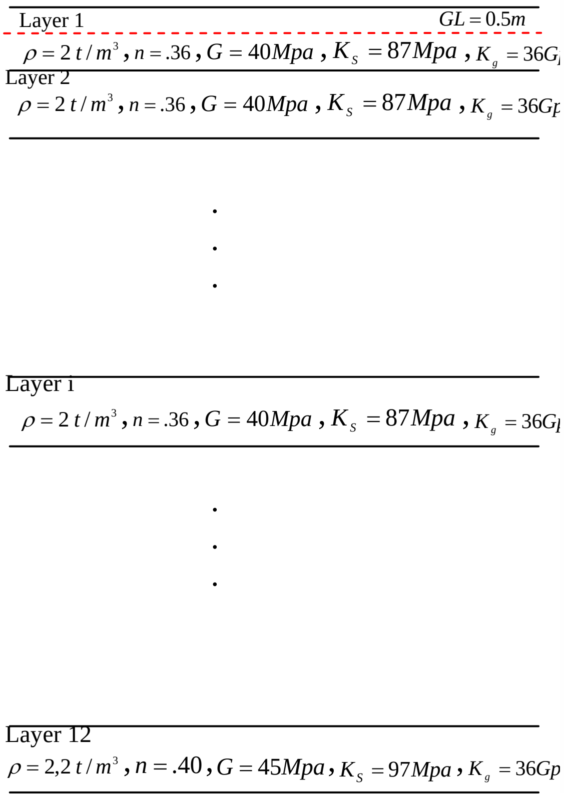
Figure 4: Equilibrium model used for uplift estimation

Table 1: Observed displacements (cm) of the accelerometer foundation

	X	Y	Z
Corner 1	-1.0	-8.5	30.5
Corner 2	-1.0	-2.7	30.8
Corner 3	4.5	-8.5	26.3
Corner 4	4.5	-2.7	26.8

Table 2: Other needed Soil profile characteristics

Bulk modulus of water (GPa)	2.2
Bulk modulus of solid grain (GPa)	36
Permeability	10^{-11}
Viscosity of water (Ns/m^2)	10^{-3}



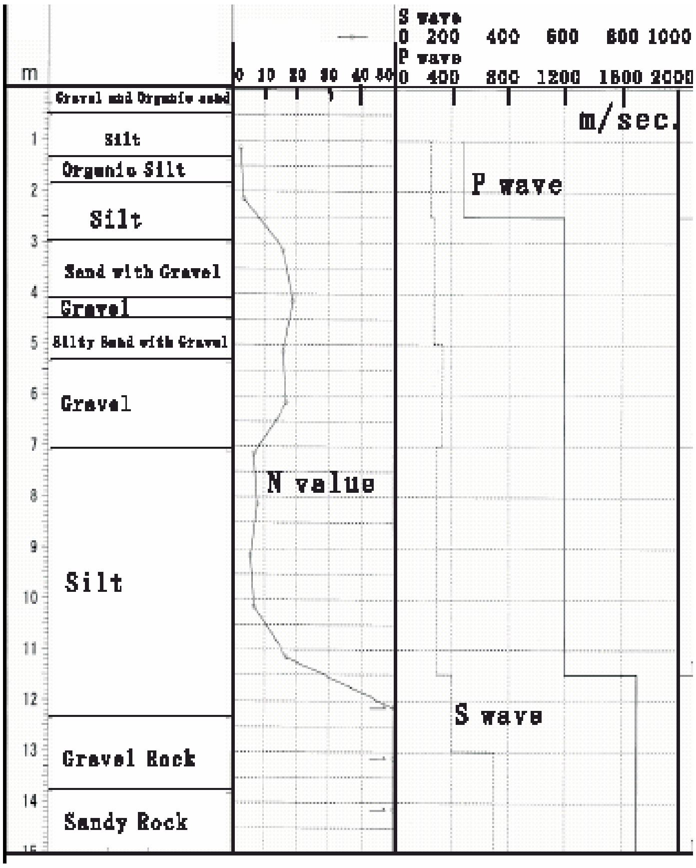


Figure 5: Soil profile model for calculation. Figure 6: PS logging result of K-net Chokubetsu

First, we investigate pore water pressure and shear stress induced in a saturated layered soil by Tokachi-Oki acceleration. The three components recorded in Chokubetsu station are given in Figure 7. The excavation soil of this station was liquefied.

Figure 8 shows the E-W component of the Shakubetsu station, North 5km, West 3Km from Chokubetsu, where the soil was not liquefied. The Shakubetsu record is used as an input motion to the model to calculate seismic responses, such as total stress and pore water pressure of a saturated porous layered profile given in figure4. The Shakubetsu site is judged as a rock, the record is taken as a base rock motion for the model of Chokubetsu site.

Figure 9 shows the shear stress induced. It appears only with the strong part of acceleration. The maximum calculated shear stress shows the values around 100KPa. Figure 10 shows the calculated pore water pressure. The maximum value shows also around 100KPa. During the earthquake, the pore pressure gradually increases and the effective mean pressure decreases until it reaches a zero value. As the mean effective pressure approaches zero, large shear strains are developed in the excavation soil. The shear deformations in the soil accumulate due to shear stress cycles during the earthquake shakings. Figure 11 shows the decreasing of effective shear resistance with increasing of pore water pressure. The first mean decreasing peak in effective stress is occurred around 32 seconds. The effective shear stress becomes zero at 34 seconds. Figure 12 shows the uplift of the accelerometer foundation. The foundation uplifting starts when the induced force due to water pore pressure acting on the foundation becomes higher than the structure weight. The comparing relation between the increasing the induced force and the foundation weight gives the uplifting and the vertical permanent displacement of the foundation. The calculated peak value of uplifting displacement is 42 cm. The average displacement in Figure 12 is 35 cm at the end of main shaking. The foundation tries to recover its equilibrium. Some settlement occurs and the final permanent displacement will be less than 35 cm. The post earthquake investigations give the value of 30.8 cm.

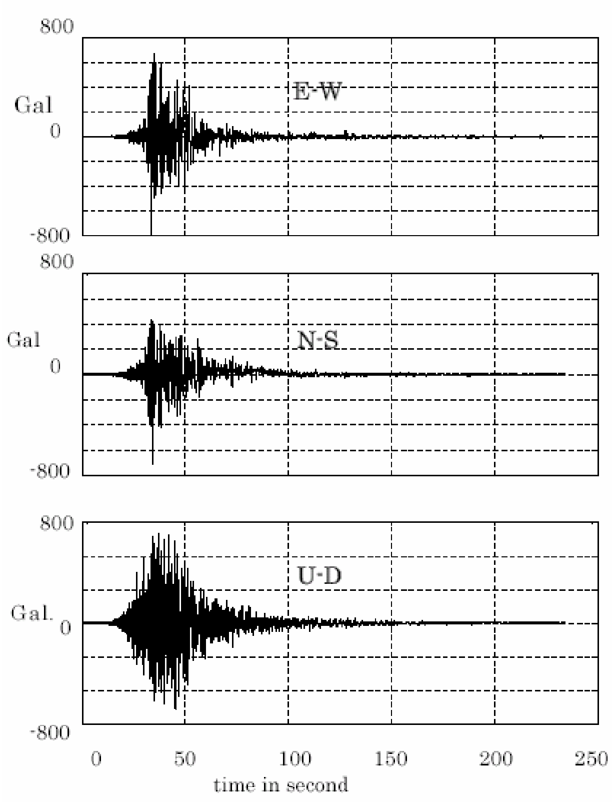


Figure 7:Corrected K-net Chokubetsu Records

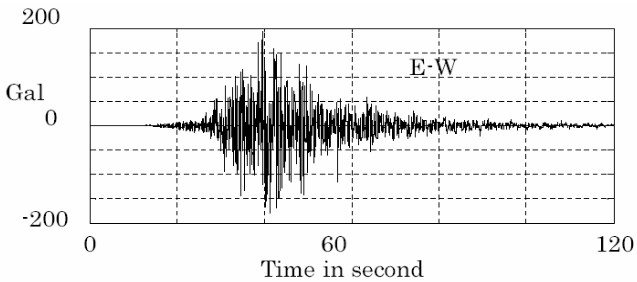


Figure 8: JMA Shakubetsu Record

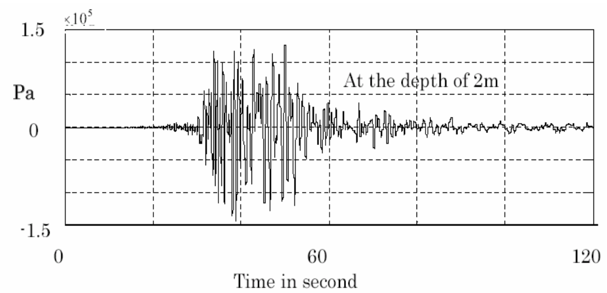


Figure 9: Shear stress due to Shakubetsu E-W

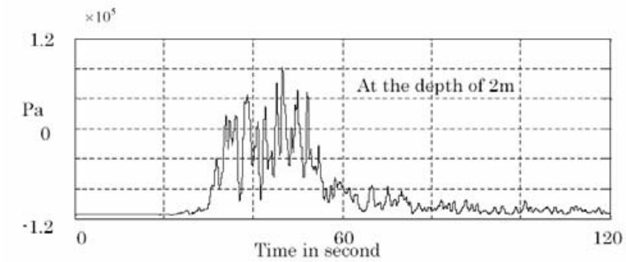


Figure 10: Pore water pressure due to Shakubetsu E-W

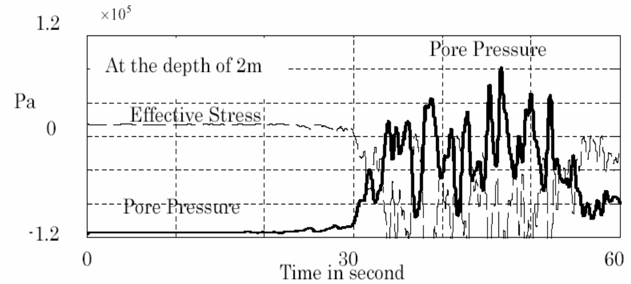


Figure 11: Pore water pressure due to Shakubetsu E-W

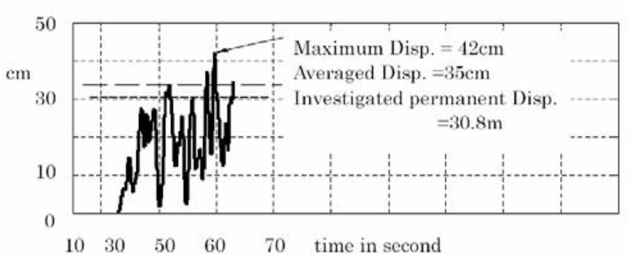


Figure 12: Uplifting of the foundation due to excavation soil liquefaction in cm

FREQUENCY CHARACTERISTICS OF CHOKUBETSU RECORDS

There are several methods to find the generation of liquefaction. In this section, in order to have to estimate the generation of liquefaction in Chokubetsu site, Fourier analysis of Chokubetsu records was conducted. The dominant frequencies in spectra would change from the onset of liquefaction generation. The results are compared to those of no liquefaction site of Shakubetsu.

The Fourier transform of Figure 13 is about whole area of E-W Chokubetsu records. Figure13 shows peak frequencies in band area around 0.1-2 Hz. In order to obtain the peak frequency shift characteristics, FFT analysis of moved area were done. The spectra are shown in Figure 14. The peak frequency band area in the spectra shifted to low frequencies with the elapsed time. The dominant frequency of analysis area up to 20 second was around 3Hz, and up to 34 second it was around 1Hz.

The integral velocity waves of original (raw) Chokubetsu data in Figure 15 show the divergent properties from 37 second. The divergent properties in Chokubetsu waves were assumed to be induced by the liquefaction of excavation soil.

Figure 16 is the Fourier spectrum of the E-W component of Shakubetsu record. Shakubetsu station was on the bedrock in west-northern part of Chokubetsu. Shakubetsu record has the similar peaks 0.3Hz and 0.7Hz in low frequency region to those of Chokubetsu record. The Fourier amplitudes of frequencies 2Hz-8Hz in Figure 16 are stronger in comparison with those of Chokubetsu data in Figure 13. The Shoukubetsu record shows the typical frequency characteristics of bedrock.

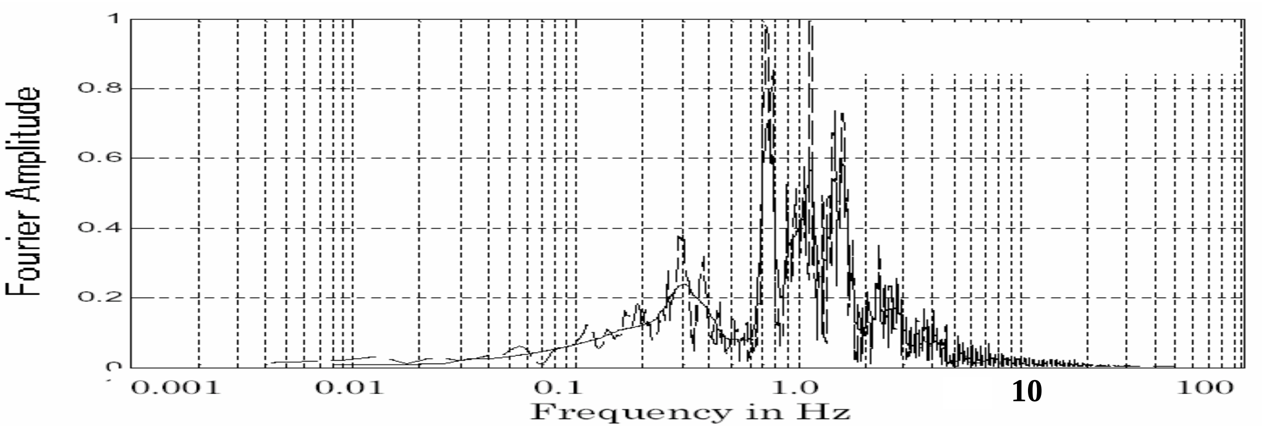


Figure 13: Fourier amplitude of E-W Chokubetsu whole area

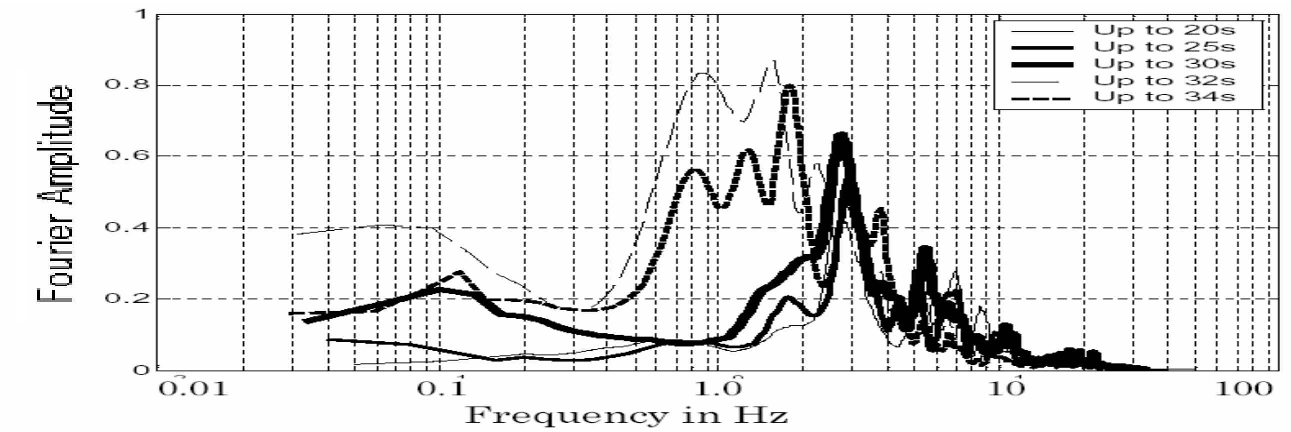


Figure 14: Fourier amplitude comparison for different time area of E-W Chokubetsu

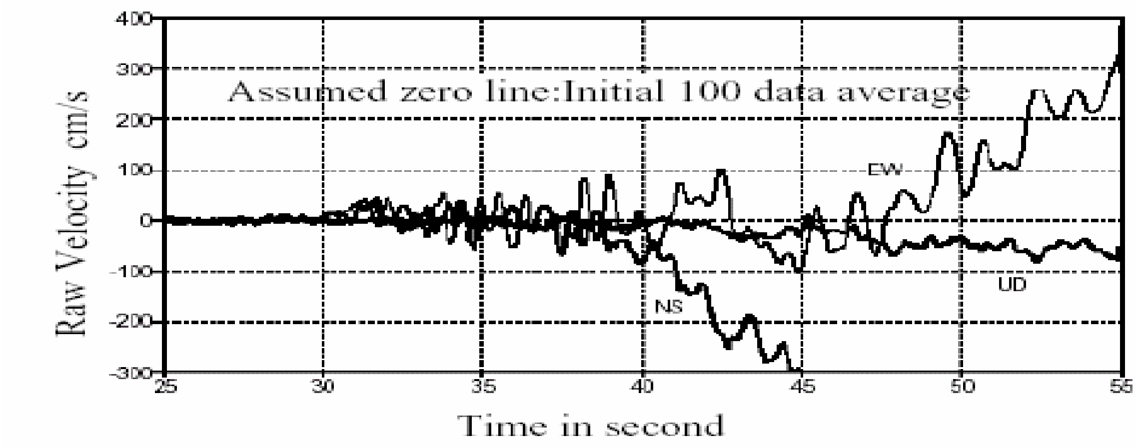


Figure 15: Divergent characteristics of one time integral velocity waves of Chokubetsu records.

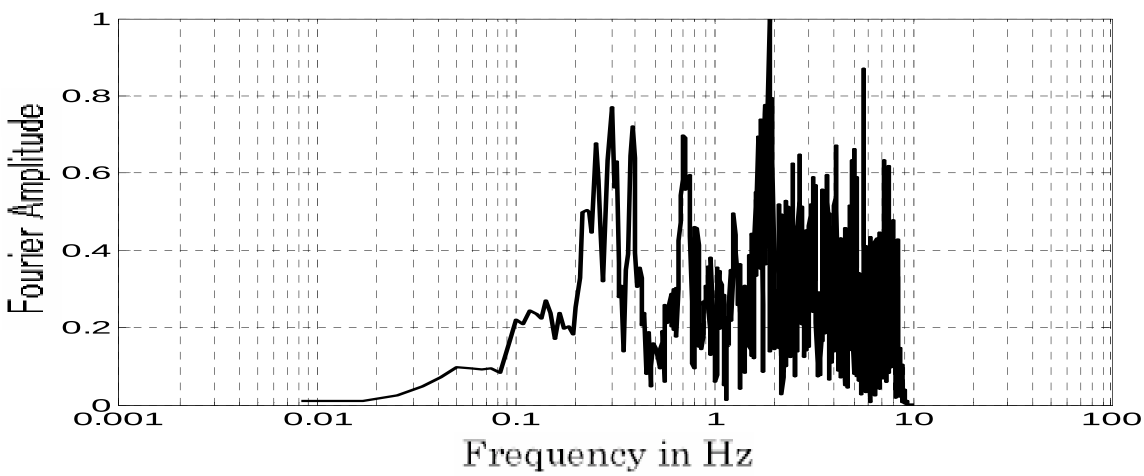


Figure 16: Fourier spectrum of the E-W Shakubetsu record

CONCLUSIONS

In the first part, an estimation of the accelerometer foundation uplifting is done. The corrected records of Shakubetsu station are used. In a second part, in order to have the purpose to estimate the generation of liquefaction in Chokubetsu site, frequency analysis of Chokubetsu data was conducted.
The shear stress developed in soil induces gradual increasing of the pore water pressure and the decreasing of the effective mean pressure. The foundation uplifting starts, when the induced force due to water pore pressure acting on the foundation becomes higher than the structure weight. Comparison between the increasing induced force and the foundation weight gives the uplifting and the vertical permanent displacement of the foundation. The calculated vertical displacement agrees with the post earthquake observed value (30.8 cm).

The dominant frequencies in spectra would change with the onset of liquefaction generation. The results are compared to those of no liquefaction site of Shakubetsu. The Fourier analysis of the E-W component of Chokubetsu recorded on liquefied site shows the peak frequency shift characteristics. The mean frequency of whole area is around 0.1-2 Hz. In accordance with different elapsed time, the peak frequency band is shifted to low frequencies especially after 34 second. The integral velocity waves of original (raw) Chokubetsu data show the divergent properties from the time about 37 second. The divergent properties in Chokubetsu waves were assumed to be induced by the liquefaction of excavation soil and the growth of Fourier amplitude less than 2Hz may be induced by soil rigidity deterioration.

ACKNOWLEDGEMENTS

Co-author Dr. Chikahiro Minowa expresses his sincere deep special thanks to Late Professor Takaaki Kagawa of Wayne State University. The Ultra Laminar Shear Boxes of NIED, Tsukuba and Miki (E-Defense) realized with his assistance.

The investigation of Chokubetsu Site was conducted by Kisojiban Consultant, Dr. Morimoto and Mr. Tochio with the help of Professor Yasuda of Tokyo Denki University. The authors show special Thanks.

REFERENCES

Biot M. A. April “Mechanics of Deformation and Acoustic Propagation in Porous Media,” Journal of Applied Physics. Volume **33**, N° 4, pp 1482-1498, 1962.

Hoon K. and Jin K. “Two Phase Finite Element Procedures for Dynamic Analysis of Saturated Porous,” Media. Engineering Computations. Volume **17**, No.7, pp 758-774, 2000.

Kim Sun-Hoon & Kim Kwang-Jin, “Two Phase Finite Element Procedures for Dynamic Analysis of Saturated Porous Media,” Engineering Computations. Volume **17**, No.7, pp 758-774, 2000

Kiso-Jiban Consultants, “Preliminary reconnaissance report on the 2003 Tokachi-Oki earthquake,” 2003

Kostadinov M.V.and Yamazaki F., “Detection of soil liquefaction from strong motion records,” Earthquake Engng Struct. Dyn., 30 pp.173-193, 2001

Lewis, R.W. and Schrefler, B.A., “The finite element method in the static and dynamic deformation and consolidation in porous media,” John Wiley. Chichester, 1998

Seed H.B., and Idriss I.M., "Ground Motions and Soil Liquefaction During Earthquakes," Earthquake Engineering Research Institute, Berkeley, California, 1982

Yagi Y., “Source rupture process of the 2003 Tokachi-Oki earthquake determined by joint inversion of teleseismic body wave and strong ground motion data,” Earth Planets Space, 56, 311–316, 2004

Zienkiewicz O. C., Chan., Pastor, M., B.A. and Shiomi, T., “Computational Geomechanics with Special Reference to Earthquake Engineering,” John Wiley, Chichester, 1999

Zienkiewicz O. C. and Shiomi, T., “Dynamic behavior of saturated porous media; the generalized Biot formulation and its numerical solution,” Int. J. Number. Anal. Methods Geomech. Vol.**8**, pp.71-96, 1984