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EVALUATION OF LIQUEFIED GROUND FLOW BASED ON ESTIMATION OF SPATIAL LIQUEFACTION POTENTIAL

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ABSTRACT

The present paper deals with a method for estimation of a spatial liquefaction potential, that is, three-dimensional liquefiable area. This method was applied to estimate the spatial liquefiable area after 1964 Niigata earthquake. Furthermore, the relation between the estimated spatial liquefiable area and permanent ground displacements induced by liquefied ground flow was investigated. As a result, an important geotechnical factor was found out when the displacement of the liquefied ground flow could be evaluated.

KEYWORDS

Estimation of liquefaction potential; F_L-value; geostatistical procedure; ground flow; Kriging technique; 1964 Niigata earthquake; permanent ground displacement; SPT N-value

INTRODUCTION

Lateral and vertical ground displacements induced by soil liquefaction caused severe and extensive damage to many structures such as underground foundations and pipelines during the past earthquakes. During the 1995 Hyogoken-nambu earthquake in Japan, extreme liquefaction occurred at the coastal reclaimed lands of Hanshin area. At the shore line, concrete caissons tilted toward the sea and the filled materials behind the caissons extensively settled and moved horizontally. As a result, the permanent ground displacements occurred over a wide area, for example, the shore line in Port Island moved 2.7 m horizontally and settled 1.3 m vertically in average.

It is important in seismic design to evaluate the displacement and force acting on structures induced by liquefied ground flow. When the displacement of liquefied ground flow will be precisely evaluated, the estimation of the spatial liquefiable area is indispensable. The authors have proposed a method to estimate the spatial liquefaction potential and clarify some factors which affect the accuracy of estimation (Yoshida *et al.*, 1995). This method is based upon a geostatistical procedure which is called as the Kriging technique using the semi-variogram (e.g. Matheron, 1963). It can estimate the three-dimensional liquefaction potential at the points where borehole data do not exist. The present paper discusses the relation between the estimated spatial liquefiable area and permanent ground displacements after the 1964 Niigata earthquake to clarify factors which will be required to predict the displacements.

ANALYTICAL METHOD

An estimation procedure of a spatial liquefiable area in this study is as follows. First of all, the factor of safety against liquefaction, F_L-value, is calculated at each depth using some existing borehole data. The procedure for evaluating F_L-value is described in the Japanese design code of highway bridge (1991). Second, two-dimensional distribution of F_L-value at a horizontal plane is estimated by the Kriging technique using an index called as the semi-variogram. Third, three-dimensional distribution of F_L-value is estimated by superposing some two-dimensional distributions of estimated F_L-value.

Kriging technique

The Kriging technique is a geostatistical procedure which predicts a sample field at non-observation points on condition that an estimated field coincides with the sample values at observation points. An unknown value is estimated by the weighted mean value of known values that exist in the area close to the unknown value. The weighted mean value is expressed as follows:

$$\hat{Z}(x) = \sum_{i=1}^{n} \lambda_i Z(x_i) \tag{1}$$

in which $\hat{Z}(x_0)$ is a value estimated at x_0, $Z(x_i)$ is an observed value at x_i, n is a number of samples, λ_i is a weight for $Z(x_i)$, respectively. The weight λ_i is determined by two conditions using the Laglange multiplier method as follows.

$$\sum_{i=1}^{n} \lambda_i = 1 \tag{2}$$

$$\sigma^2{}_E = E\left[\left\{\hat{Z}(x) - Z(x)\right\}^2\right] \rightarrow \text{minimum} \tag{3}$$

Eq.2 means a non-biased condition of the estimated value and Eq.3 indicates minimization of the variance of estimation error. The optimum estimated value can be obtained by substitution of the weight to Eq.1. The variance of estimation error for the optimum solution is given as follows:

$$\sigma_k^2 = \sum_{i=1}^{n} \lambda_i \gamma\,(h_{i0}) + \mu \tag{4}$$

where, h_{i0} is the distance between x_i and x_0, $\gamma\,(h_{i0})$ is the semi-variogram, μ is the Laglange multiplier.

Semi-variogram

The semi-variogram is evaluated in consideration of disposition and value of samples to understand the characteristics of sample distribution. Let $Z(x)$ be a sample value observed at a point x of a geometrical field V, the theoretical semi-variogram $\gamma(h)$ is as follows:

$$\gamma(h) = \frac{1}{2V}\iiint_V \left[Z(x+h) - Z(x)\right]^2 dV \tag{5}$$

where, h is the distance between the points. This equation represents characteristics of distribution of sample values. $\gamma^*(h)$ which is called as an experimental semi-variogram is actually used in calculation as follows:

$$\gamma^*(h) = \frac{1}{2N}\sum_{i=1}^{N}\left\{Z(x_i + \bar{h}) - Z(x_i)\right\}^2$$
$$\bar{h} = h \pm \Delta h \tag{6}$$

where, N is number of sets of samples at a distance of $\bar{h}$ each other, Δh is the interval of h when the semi-variogram is calculated. In this study, the experimental semi-variogram $\gamma^*(h)$ is assumed as the following equation by using an exponential function:

$$\gamma(h) = a \cdot (1 - e^{-b \cdot h}) \tag{7}$$

where, a and b mean coefficients of dispersion and auto-correlation between sample values, respectively.

ESTIMATION OF SPATIAL LIQUEFIABLE AREA

Conditions of analysis

The Niigata earthquake, with a magnitude of 7.5, occurred in the Japan sea about 50km north off Niigata city at Niigata prefecture on June 16, 1964, causing severe damage to structures such as buildings, bridges, oil storage tanks and lifeline facilities due to soil liquefaction. A central part of Niigata city located between the Shinano river and the Niigata railway station was focused in this study as shown in Fig.1. The Shinano river is shown at the left-upper side in Fig.1 and it flows from southwest to northeast. The area is 0.6 km long in east-west direction and 1.1 km long in north-south direction. Most of this area has no gradient of the ground surface. Twenty six borehole data were obtained in and around here. The data within an altitude of 3m to -16m were used. The water level in this area was supposed to be equal to the ground surface. The maximum horizontal acceleration of this earthquake in Niigata city was about 0.16g (Hamada, 1992). This acceleration was used to calculate F_L-value in the study.

Fig.2 shows the horizontal and vertical ground displacements after the earthquake. The data were transformed from the actual displacements which were measured by pre- and post-earthquake aerial surveys (Hamada, 1992) to raster data. The maximum permanent ground displacements measured in this area were about 4.0 m of lateral flow, 3.0 m of settlement and 1.4 m of upheaval.

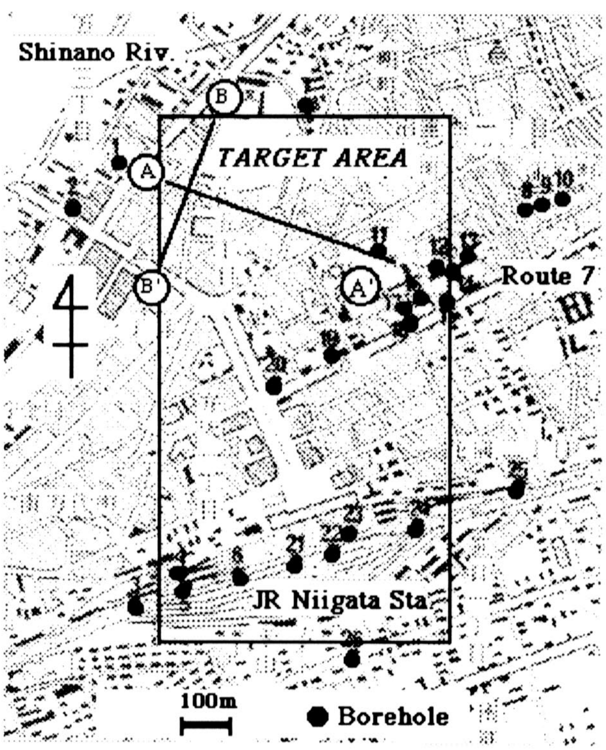

Fig.1 Map of Niigata city and distribution of boreholes.

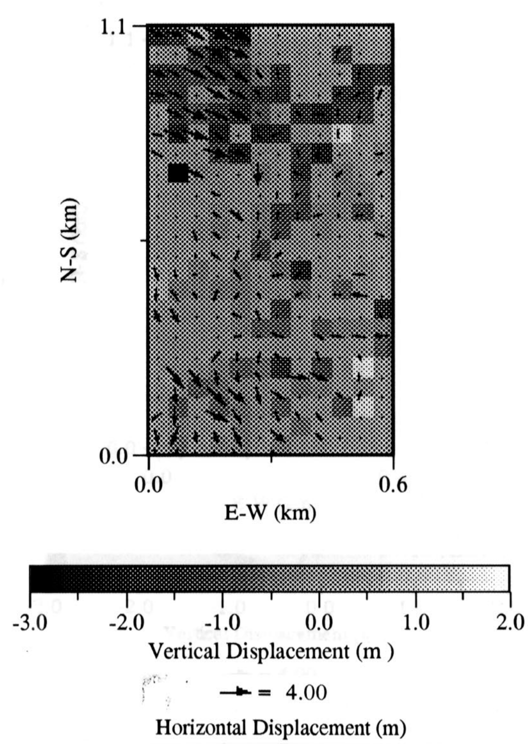

Fig.2 Horizontal and vertical permanent ground displacements.

Results of estimation

Fig.3 shows the three-dimensional view of liquefiable portion made by superposing some two-dimensional planes of estimated F_L-value. The two-dimensional planes were calculated at interval of 50 m along the north-south and east-west directions, and at interval of 0.5 m vertically. The opaque area means that F_L-values are less than or equal to 1.0, that is, liquefiable area. It can be obtained from this figure the thickness and inclination of liquefied layer and whole shape of liquefiable portion roughly. Although the liquefiable layer exists above 10 m in depth, liquefaction does not occur at very shallow layer because of soil type The thickest liquefiable layer exists on the northwesterly area along the right bank of the Shinano river, and its thickness gradually decreases towards the southeasterly direction. The boundary between the liquefied layer and the upper non-liquefied layer is inclined from northwesterly area toward the northeasterly direction with the maximum gradient of about 3 %. This direction corresponds with the large vectors of horizontal displacement at the northwesterly area as shown in Fig.2.

As mentioned above, information of very shallow layer which moved actually, could not be seen from Fig.3. Therefore, SPT N-value was investigated because N-value expresses the stiffness of soil and affects the deformation of ground. The estimation of distribution of N-value was, therefore, carried out in much the same way as that of F_L-value. In this case, two-dimensional planes were calculated at interval of 1 m vertically. Fig.4 shows the three-dimensional view of N-value of less than or equal to 5. This is a simple index to estimate liquefaction as same as F_L-value. The loose soil layer with N-value of less than or equal to 5, exists in a part of the surface layer. Although F_L-value can give the information of liquefaction potential, the information of non-liquefiable area can not be obtained. The estimation of spatial softness area evaluated by N-value can give the important information of non-liquefiable area.

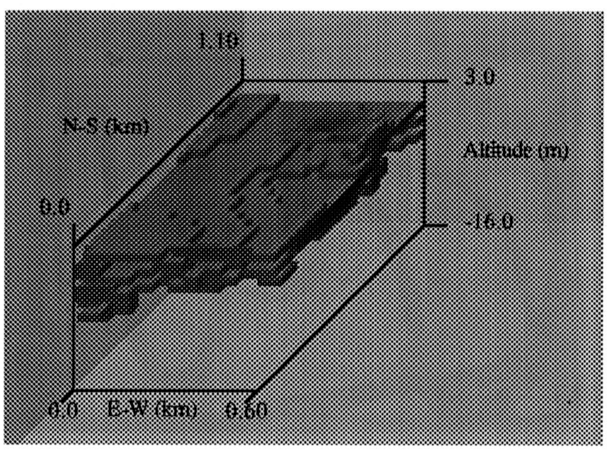

Fig.3 Three-dimensional view of F_L-value of less than or equal to 1.0.

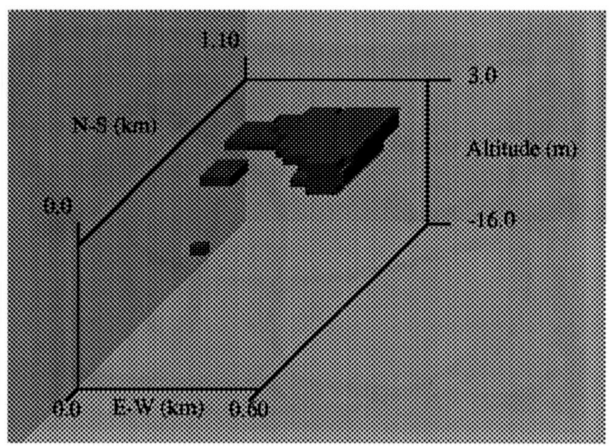

Fig.4 Three-dimensional view of N-value of less than or equal to 5.

Discussion on permanent ground displacement

Fig.2 shows almost all lateral flows moved from northwest to southeast. The large vectors were distributed at the northwesterly area and the maximum displacement was about 4.0 m. Two sections along A-A' and B-B' as shown in Fig.1 were investigated here. These two lines were mutually perpendicular. The ground adjacent the right bank of the Shinano river moved toward the river in a northwesterly direction. However, the area along A-A' moved to the southeast, almost opposite that on the river bank. The direction of horizontal displacements here was unusual as compare with other liquefied areas (Hamada, 1992).

Fig.5 shows the distribution of the estimated F_L-value and the observed permanent ground displacements along A-A' section. Those, along B-B' section, are also shown in Fig.6. These figures of estimated F_L-value along any section were obtained from Fig.3. The dark portion shows the liquefied layer where F_L-values are less than or equal to 1.0. The thickest liquefied layer of about 10 m exists on the left side in Fig.5. The upper and lower boundary of liquefied layer was inclined down from A to A'. It seems that the large horizontal displacements occurred on the left side and the ground moves from A to A' corresponding to thickness and inclination of liquefied layer. Along B-B' section, there are no particular change for thickness and inclination of liquefied layer. Therefore, there is no horizontal displacements in direction along B-B' according to Fig.2. Consequently, the direction of lateral liquefied ground flow is influenced by thickness and inclination of liquefied layer.

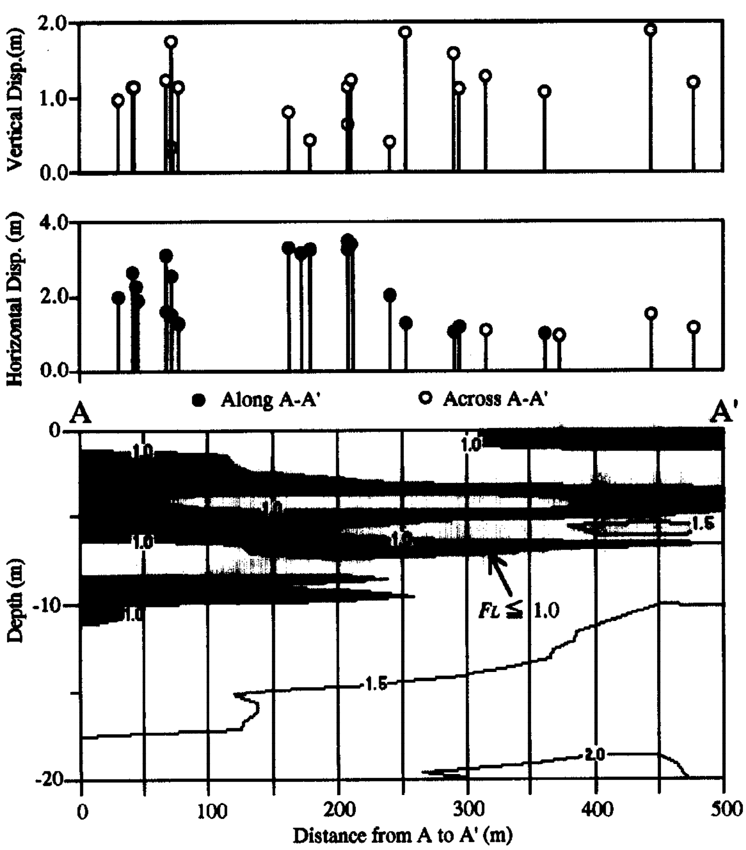

Fig.5 Distribution of estimated F_L-values and permanent ground displacements along A-A' section.

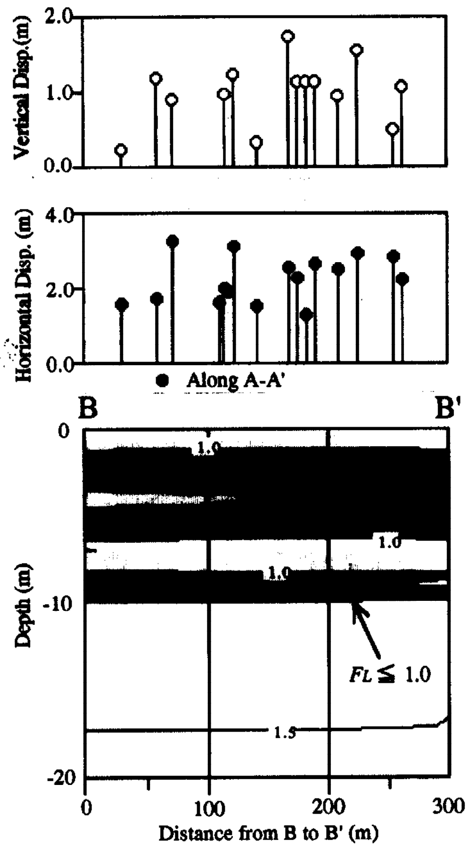

Fig.6 Distribution of estimated F_L-values and permanent ground displacements along B-B' section.

Next, the reasons why the largest ground displacements appeared in this area are investigated. Average N-values up to 5 m in depth were calculated from the estimated N-value. Fig.7 shows the distribution of the average N-values up to 5 m in depth and horizontal ground displacements, and Fig.8 illustrates that of the vertical displacements. According to Fig.7, there is a very soft ground at the downstream of large vectors in the northwesterly part. It seems that the very soft ground at the downstream enlarged the horizontal displacements because of soft boundary condition. Therefore, the direction and magnitude of horizontal displacements are influenced by not only thickness and inclination of liquefied layer but also stiffness of surrounding soil, especially at the downstream of flow. While, it can be seen from Fig.8 that large vertical displacements occurred where the average N-values are relatively small. And the upheaval of ground occurred at the downstream of liquefied ground flow. Therefore, a closely correlation of the occurrences between the horizontal and vertical displacements seems to exist.

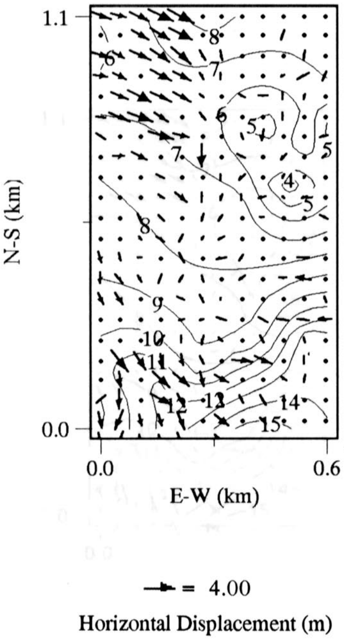

Fig.7 Relationship between average estimated N-values up to 5 m in depth and horizontal permanent displacements.

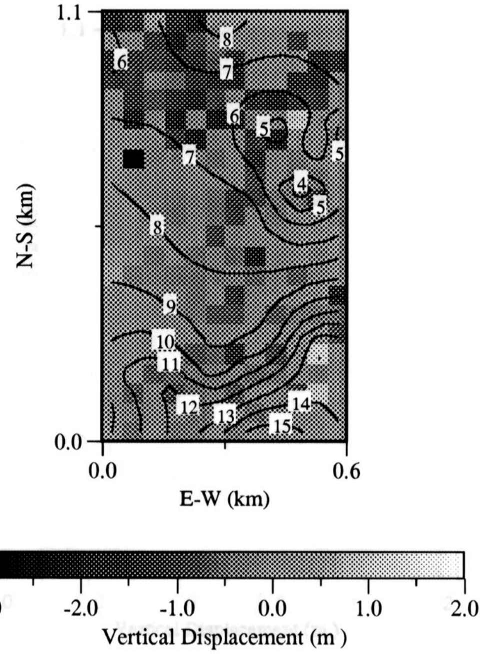

Fig.8 Relationship between average estimated N-values up to 5 m in depth and vertical permanent displacements.

CONCLUSIONS

The present paper investigated the relation between the estimated spatial liquefiable area and observed permanent ground displacements in Niigata city after 1964 Niigata earthquake. Information of not only liquefied area but also soil conditions of the surrounding area can be obtained from the three-dimensional views of liquefiable portion and low SPT N-value area. The following conclusions may be drawn based on the present study. The direction and magnitude of permanent ground displacements were influenced by the thickness and inclination of liquefied layer, as it has been indicated in the past. The soil conditions of the surroundings of liquefied area also affected to the permanent ground displacements as a boundary condition. The spatial estimation of liquefiable area and stiffness of the surrounding ground is, therefore, necessary to predict the magnitude and direction of permanent ground displacements.

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