CHARACTERISTICS OF LIQUEFIED GROUND FLOW AT PLANE RECLAIMED LAND DURING THE 1995 KOBE EARTHQUAKE

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SUMMARY

During the 1995 Kobe earthquake in Japan, extreme liquefaction occurred at the coastal reclaimed land of Hanshin area and the liquefaction-induced large ground displacements were also caused there. This paper deals with the liquefied ground flow at where there is little gradient of ground surface, that is, almost plane ground. Three reclaimed lands, which are located at the southern part of Kobe City, were focused here. The horizontal ground displacements were statistically investigated to clarify the factors that affect the direction and magnitude of displacements. The horizontal ground displacements near the quaywalls were very large and moved toward the sea owing to the seaward movement of quaywalls. However, the displacements in the inland part moved toward the south direction. As a result of analysis, it was clarified that most of liquefied ground in inland part flowed to the south direction under the influence of the inclination of boundary between soil layers and the inertia force by strong ground motion.

INTRODUCTION

Lateral flow of ground induced by soil liquefaction caused severe and extensive damage to structures such as underground foundations and pipelines during the past earthquakes. During the 1995 Kobe earthquake in Japan, extreme liquefaction occurred at the coastal reclaimed land of Hanshin area and the liquefaction-induced large ground displacements were also caused there. Generally, it is considered that liquefied ground flow occurred due to the inclination of ground surface and movement of shore quaywalls [Hamada et al., 1998]. However a few meters of ground displacements were observed at where there is little gradient of ground surface and it is far from the shore during the past earthquakes [Hamada et al., 1992].

This paper deals with the liquefied ground flow at where there is little gradient of ground surface, that is, almost plane ground. The characteristics and mechanism of the occurrence of the horizontal ground displacements induced by the liquefied ground flow were investigated based on a case study of the 1995 Kobe earthquake. First, the characteristics of the horizontal ground displacements that were observed at three reclaimed lands located at the southern part of Kobe City were investigated statistically. The tendency of the magnitude and direction of the horizontal ground displacements that were distributed at each reclaimed land was clarified. Second, the analysis was conducted to clarify the mechanism of horizontal ground displacement induced by soil liquefaction in the inland part of reclaimed land. The relation between the direction of horizontal ground displacements and some factors was investigated. The inclination of ground surface, distribution of liquefiable layer and inertia force by strong ground motion were taken as the factor in this analysis.

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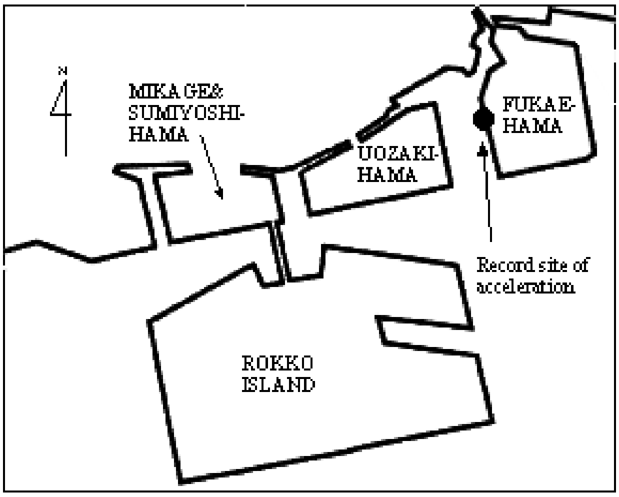
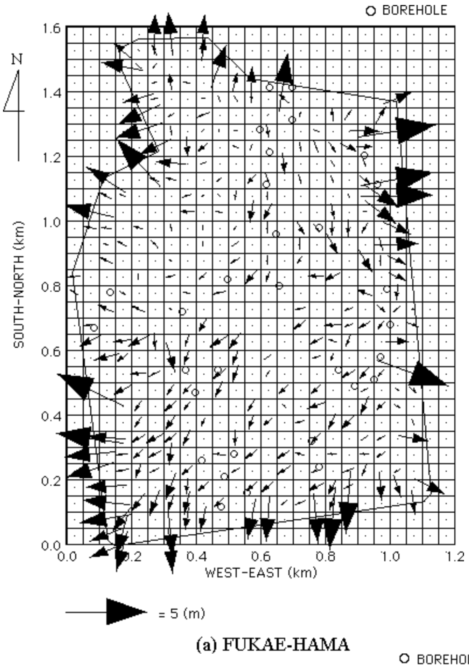
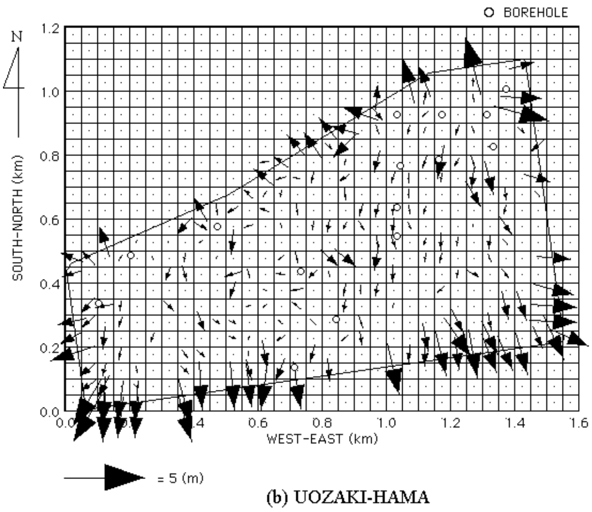


Figure 1: Location of reclaimed land





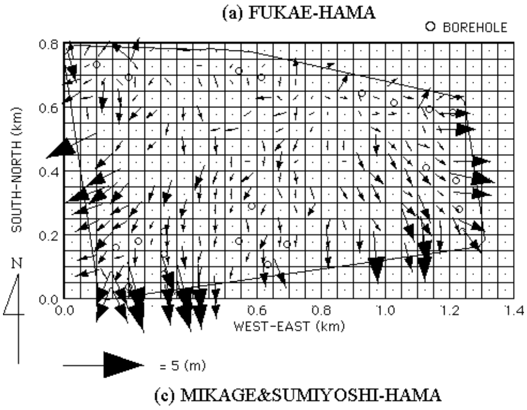


Figure 2: Vectors of horizontal ground displacement and sites of borehole

CHARACTERISTICS OF GROUND DISPLACEMENT

Target Area and Obtained Data

Three reclaimed lands that include Fukae-hama, Uozaki-hama and Mikage&Sumiyoshi-hama were investigated as shown in Figure 1. They are located in the southern coastal area of Higashi-Nada Ward in Kobe City. The landfills were reclaimed in the 1960s by transporting the granite from the Rokko Mountains. These lands are surrounded by the caisson type quaywalls. Many quaywall structures in these areas seriously damaged during the earthquake. The typical failures were movement of caisson seaward with settlement. Furthermore, the ground behind the caisson moved seaward and subsided under the influence of movement of caissons.

Figure 2 shows vectors of horizontal ground displacement and sites where the borehole data were obtained. The number of the boreholes is 31 in Fukae-hama, 15 in Uozaki-hama and 22 in Mikage&Sumiyoshi-hama [Kobe City, 1980]. The data of vector and altitude were used as raster data whose size is 50 m square. Each vector included in a mesh was transformed from the actual displacements which were measured by pre- and post-earthquake aerial surveys [Hamada et al., 1995]. According to the site investigation, it was reported that the large horizontal ground displacements were occurred near the quaywalls. However, they decreased within a range of 50-100 m from quaywalls and mostly unchanged at the outside where was 100 m apart from the quaywalls [Hamada et al., 1998]. It is

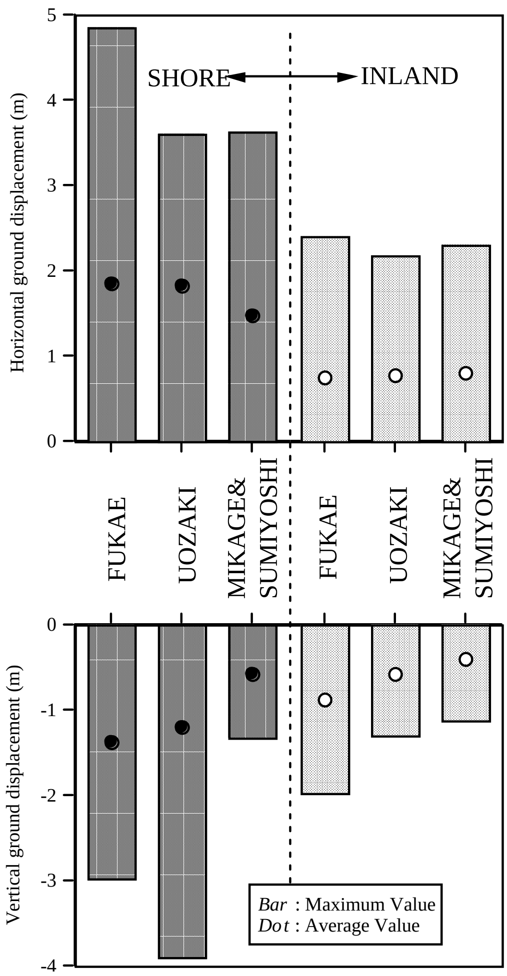


Figure 3: Maximum and average

revetment line. Therefore, the area is divided into two parts by the distance from the revetment line. One part is the area within 100 m from the revetment line that is called as the shore, the other is called as the inland.

Horizontal and Vertical Ground Displacements

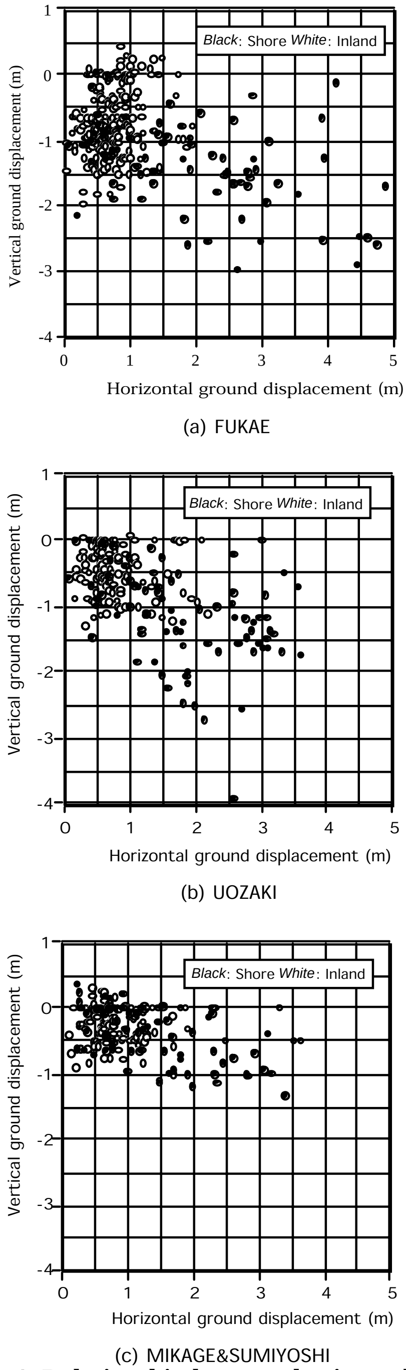


Figure 4: Relationship between horizontal and vertical ground displacements

Figure 3 shows the maximum and average values of horizontal and vertical ground displacements. The vertical displacement gives the settlement of ground surface. The maximum horizontal displacement was about 5 m and the maximum vertical displacement was about 4 m in the shore part, while both of them were 2 m in the inland part. So it seems that the large deformation occurred relatively in the inland part from this figure. Although there is no big difference of magnitude of horizontal displacement in any area, the magnitude of vertical displacement are uneven. Figure 4 shows the relationship between the horizontal and vertical ground displacements. Although it indicates clearly that the vertical displacements increase with an increase in the horizontal displacements in case of shore part, the significant relation between them can not be seen in case of inland part. The mechanism of ground deformation is relatively obvious in the shore part as if the ground surface subsided owing to the movement of caisson. However, this figure suggests that the mechanism of deformation in the inland part is very complex.

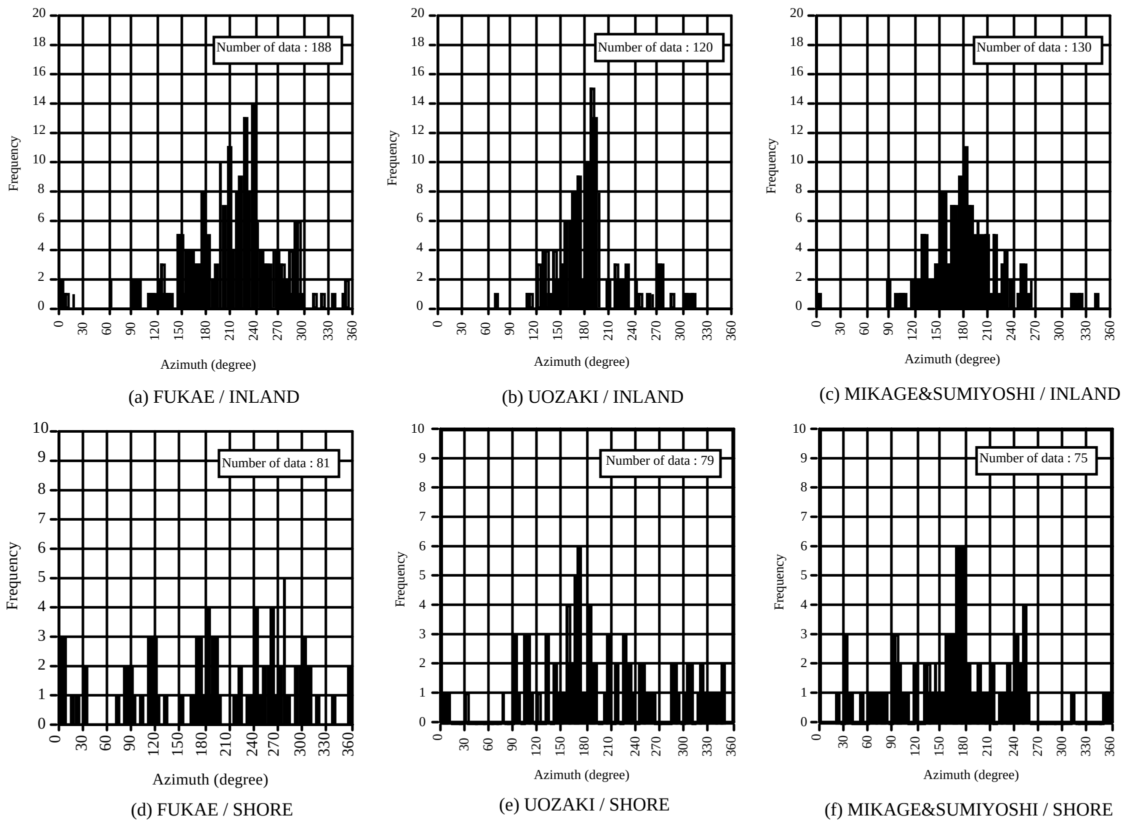


Figure 5 : Azimuth of Horizontal Ground Displacement

Figure 5 shows the frequency of azimuth for the vector of horizontal ground displacement. There is one peak around 180 degrees in the inland part as shown in Figure 5 (a) to (c). It indicates that almost all displacements moved from north to south. However, the frequency is distributed uniformly in the shore part as shown in Figure 5 (d) to (f). Since the length of quaywall line along the north-south direction in Fukae-hama and along the east-west direction in Uozaki-hama and Mikage&Sumiyoshi-hama is longer than the other direction, there is a small peak in the shore part. Although the ground in the shore part moved toward the sea by the movement of caisson quaywalls, it supposed that the directions of displacement in the inland part were influenced by other factors.

FACTORS ON DIRECTION OF HORIZONTAL GROUND DISPLACEMENT

As mentioned above, it is clear that the horizontal ground displacements occurred in the inland part owing to other factors except the movement of caisson. It is investigated here whether the factors such as the inclination of ground surface, distribution of liquefied layer and inertia force of strong ground motion affect the direction of horizontal ground displacement in the inland part.

Inclination of Ground Surface

The gradients of ground surface were calculated by using the difference of altitude between two adjacent meshes apart from 50 m. They were obtained along the north-south and east-west directions. Positive values for horizontal ground displacement were measured upward on the ordinate when the ground moved to north or east. Positive values for the gradient of ground surface were measured to the right on the abscissa when the ground surface went down to south or west. Figure 6 shows the relationship between the gradient of ground surface and the horizontal ground displacement. The figures from (a) to (c) give the relation along the east-west direction and the figures from (d) to (f) give the relation along the south-north direction. There is no significant correlation between them along both directions. The maximum value of the gradient of ground surface is about

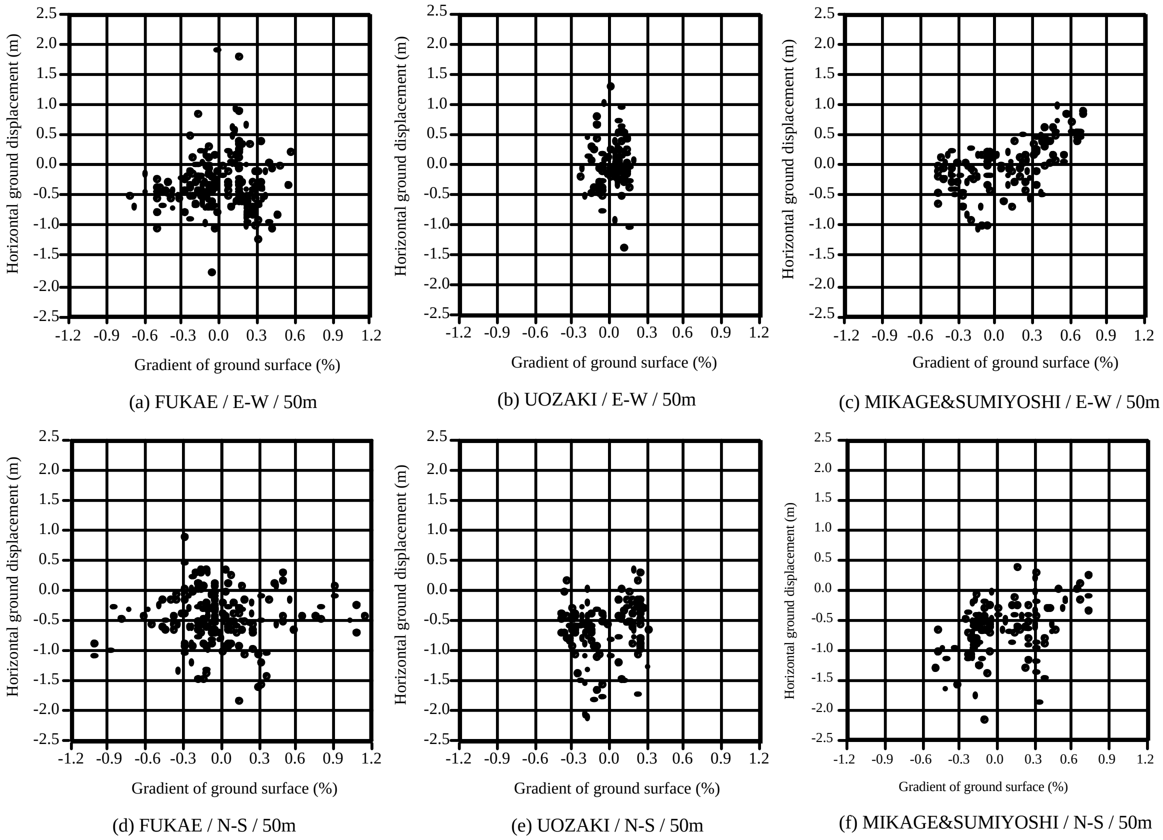


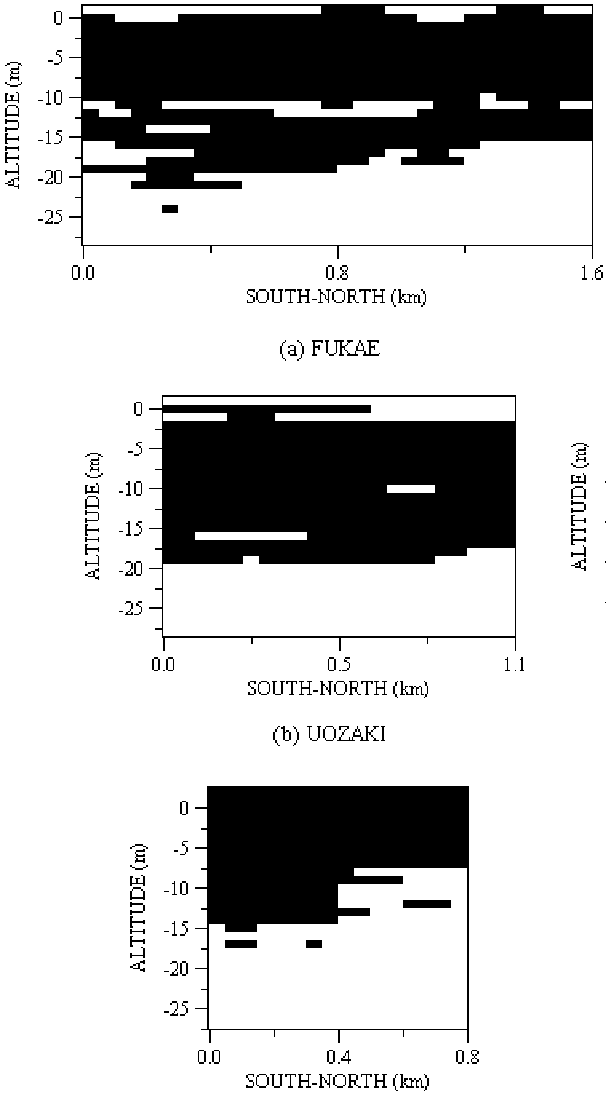
Figure 6: Relationship between gradient of ground surface and horizontal ground displacement

1% in these lands. This gradient is judged as almost plane in the engineering filed. Therefore, it is considered that almost displacements were not influenced by the inclination of ground surface in its small range.

Distribution of Liquefiable Layer

The authors have proposed a method to estimate the spatial liquefaction potential [Yoshida et al., 1995] that is based upon a geostatistical procedure called as the Kriging technique using the variogram [Edward et al., 1989]. The process of estimation of the spatial liquefaction potential in this analysis is as follows. First, the factor of liquefaction resistance, that is, F_L-value [Japan Road Association, 1996] is calculated at each depth using some existing borehole data. The water level in this area was supposed to be equal to the ground surface. The maximum horizontal acceleration to calculate F_L-value was 327 gal which was recorded at Higashi-Kobe bridge (see Figure 1). Second, two-dimensional distribution of F_L-value at horizontal plane is estimated by the Kriging technique. Third, three-dimensional distribution of F_L-value is estimated by superposing some two-dimensional distribution of estimated F_L-value.

As whole area of ground liquefied according to the results of estimation, the liquefied area was divided into two parts. One part whose F_L-value is less than or equal to 0.5, is defined as the strong liquefied area. Figure 7 and Figure 8 show the distribution of the strong liquefied area along south-north section and east-west section, respectively. The black-painted area in these figures gives F_L-value less than or equal to 0.5. It seems that the depth of strong liquefied area in the left side is thicker than that in the right side as shown in Figure 7. So it can be seen that there is a inclination of boundary between the bottom of strong liquefied area and the top of the area below it. The left side in Figure 7 means the southern direction and most horizontal displacements moved to this direction. However, there is no tendency as mentioned above along the west-east direction in Figure 8. Consequently, it was clarified that the horizontal ground displacement moved under the influence of the direction of inclination of boundary between the strong liquefied layer and the other It is considered that the difference of distribution between these figures was caused by the soil layer condition. For example, it is clear that the bottom of reclaimed layer and alluvial clay layer incline toward the southern direction [Yoshida et al., 1999].

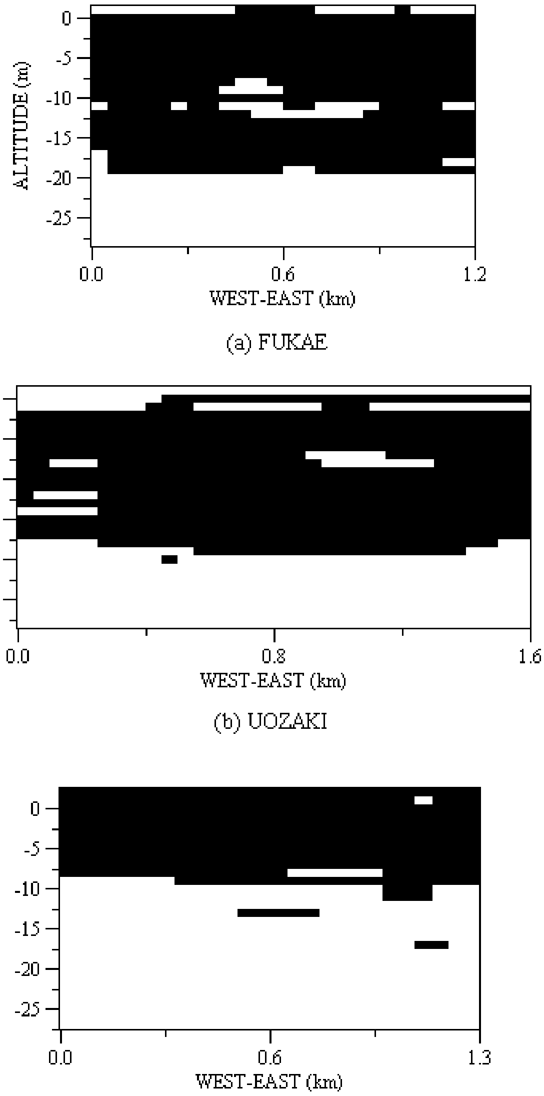


(a) FUKAE

(b) UOZAKI

(c) MIKAGE&SUMIYOSHI

Figure 7: Cross section of F_L-value less than or



(a) FUKAE

(b) UOZAKI

(c) MIKAGE&SUMIYOSHI

Figure 8: Cross section of F_L-value less than or

3.3 Inertia Force by Strong Ground Motion

Figure 9 shows the horizontal orbits of acceleration larger than 150 gal. This acceleration was recorded at the site as shown in Figure 1. It can be seen from this figure that peaks of distribution are distinguished along the directions of north-south and northwest-southeast. Especially, the points of large acceleration are distributed near the southeast direction. It is almost the same direction as the horizontal ground displacements in the inland part. If the horizontal ground displacements were caused by residual displacement owing to the strong ground motion, it is considered that the direction of inertia force affected the direction of displacement.

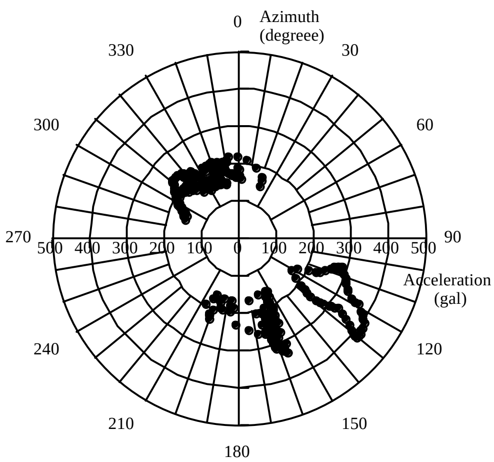


Figure 9: Orbit of acceleration

CONCLUSIONS

This paper deals with the liquefied ground flow at where there is little gradient of ground surface, that is, almost plane reclaimed land. The characteristics and mechanism of the occurrence of the horizontal ground displacements induced by the liquefied ground flow were investigated based on a case study of the 1995 Kobe earthquake. The following conclusions may be drawn from the present study. Large horizontal and vertical ground displacements occurred in the shore part and the strong correlation was observed between them. Although most horizontal displacements moved seaward owing to the movement of quaywalls, the horizontal displacements in the inland part moved toward the south direction regardless of the direction of quaywalls. It was clarified that this direction coincided with the direction of inclination of boundary between strong liquefied layer and the other, and the inertia force by strong ground motion.

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