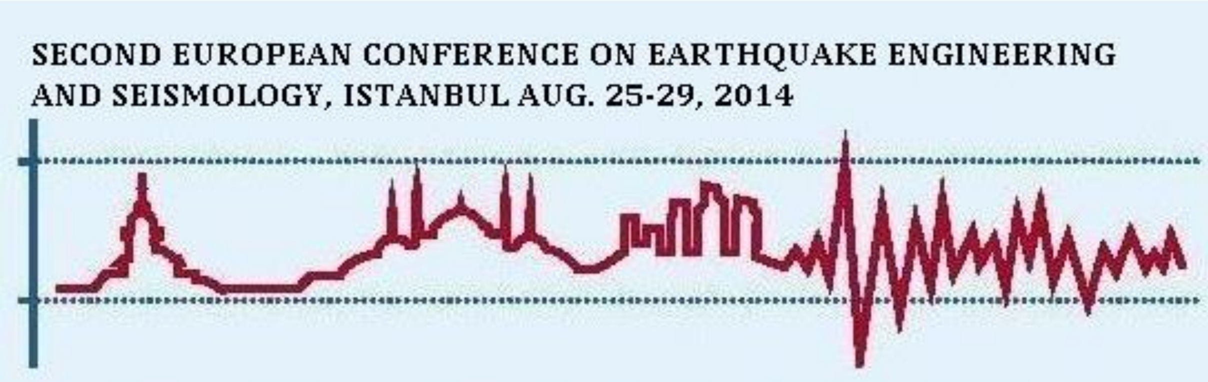


# THE EFFECTS OF VARIOUS GEOTECHNICAL PROFILES ON LIQUEFACTION-INDUCED DAMAGE AT A RECLAIMED LAND

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## ABSTRACT

The degree of liquefaction at a reclaimed land layer is not uniform. There are some reasons for this phenomenon, and the variations in the characteristics of the alluvial clay layer below the reclaimed land could be one of them. In this paper, the liquefaction damage in Urayasu City is investigated, focusing on the profile of the alluvial clay layer. The analysis revealed that the damage caused by liquefaction was more severe with higher thicknesses in the alluvial clay layer. Thus, the results indicate that it is necessary to consider the characteristics of the clay layer in the evaluation of liquefaction damage at a reclaimed land.

## INTRODUCTION

On March 11, 2011, a big earthquake occurred off the east coast of Japan. As a result of this earthquake, liquefaction-induced damage occurred on reclaimed land in Urayasu City, Chiba Prefecture. This is one of the typical disasters in the earthquake. In the liquefied area, the thickness of the alluvial clay layer varied with the location as shown in Figure1. The relationship between the thickness of the clay layer and the liquefaction damage has not yet been clarified. Therefore, in this study we examine the variations in the liquefaction characteristics of the reclaimed land by analyzing the liquefaction damage data prepared by Urayasu City Office (2012).

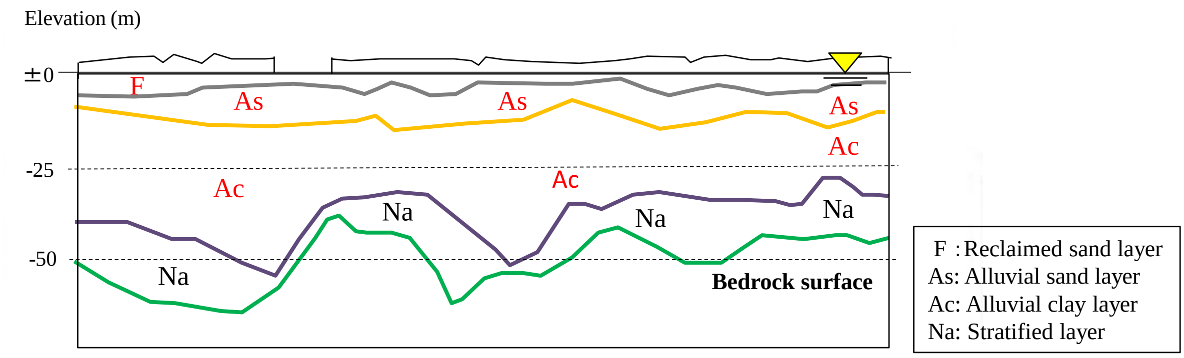


Figure 1. Soil profiles of the liquefied sites. (After Urayasu City Office)

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## METHOD OF ANALYSIS

In general, ground characteristics such as the bedrock surface elevation, the reclamation history, the groundwater level, and the thickness of a sandy layer can have a profound influence on liquefaction damage. In this study, in addition to the ground characteristics mentioned above, the influence of the thickness of the alluvial clay layer on liquefaction damage was investigated.

For the damage induced by the liquefaction, two key factors were analyzed: 1) Observed pile foundation uplift, and 2) Variation in the ground level before and after the earthquake. Figure 2 shows the distribution of the observed pile foundation uplift. The pile foundation uplift refers to the generated difference in height between the structure supported by a pile foundation and the surrounding ground. The numbers of damage points of pile foundation uplifts were 833 in total. Figure 3 shows the contour map of the variations in the ground level before and after the earthquake. When the liquefaction occurred, the ground settled due to the boiling of sand and the drainage of pore water by the generated excess pore water pressures. Therefore, the liquefaction may have occurred at the point where settlement occurred.

In order to obtain the relationship between the ground characteristics and the pile foundation uplift, we superimposed the counter maps of the ground characteristics and the distribution map of the pile foundation uplift. The analysis method is shown in Figure 4.

The variations in the ground were analyzed by using a mesh map. These characteristics at each cross point of the mesh can be read by superimposing the mesh map, the counter map of the variations in the ground, and the counter maps of the ground characteristics. There were 300 mesh intersection points in total. The analysis method is shown in Figure 5.

In addition, in this study the relationship between the pile foundation uplift and the inclination at the bottom of the alluvial clay layer was analyzed. This is because some research has indicated that the inclination at the bottom of the layer affects the input motions, and thus the liquefaction level is correlated to the inclination at the bottom layer (Asaoka. 2012). Figure 6 portrays the inclination at the bottom of the alluvial clay layer in the position of the pile foundation. An example of the calculation is shown in Figure 7. The inclination was calculated so that a straight line crosses the pile location and intersects the contour lines at the both ends in the shortest distance (i.e., as the maximum value of the inclination).

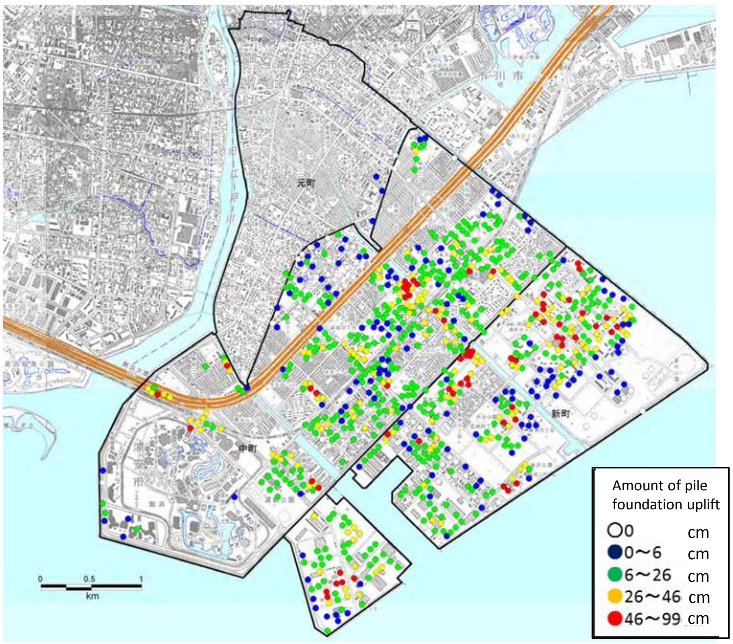


Figure 2. Distribution of observed pile foundation uplift. (After Urayasu City Office, 2011)

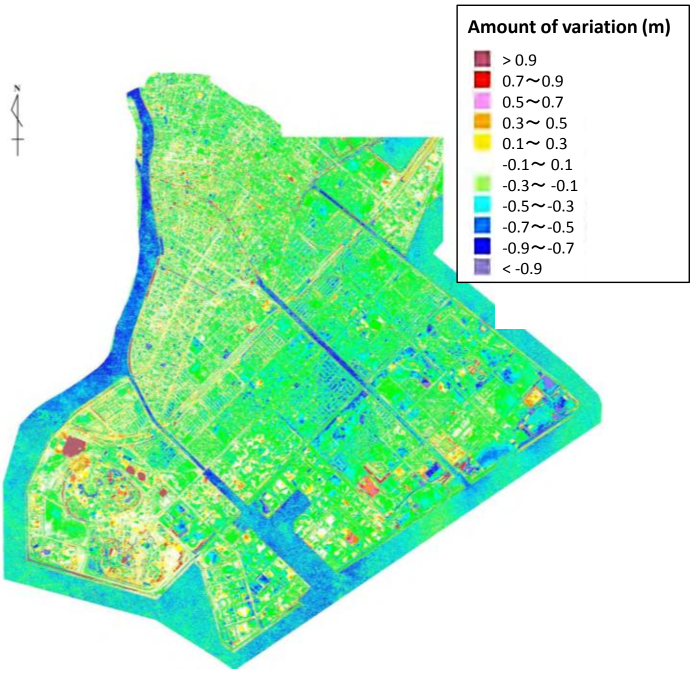


Figure 3. Contour map of the variations in the ground level. (After Urayasu City Office, 2011)

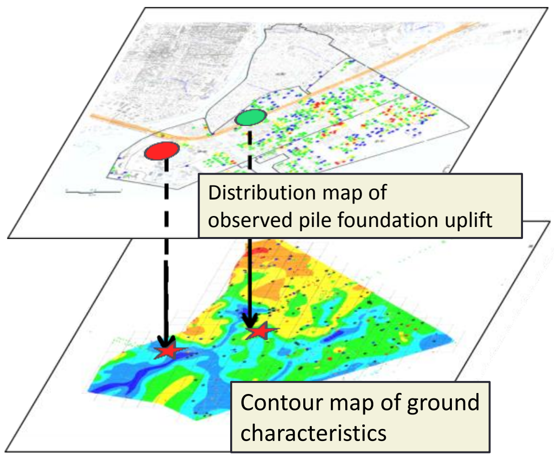


Figure 4. Analysis of the pile foundation uplift.

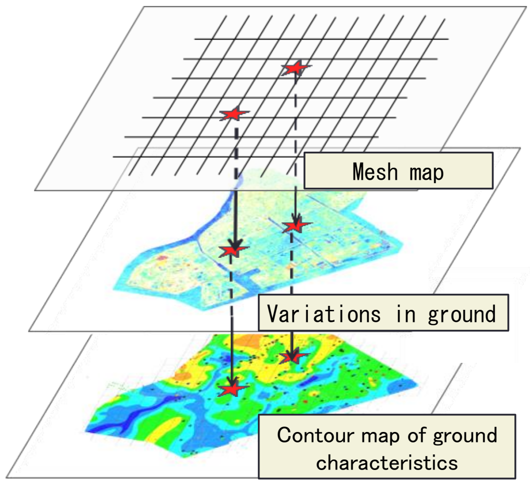


Figure 5. Analysis of the variations in ground level.

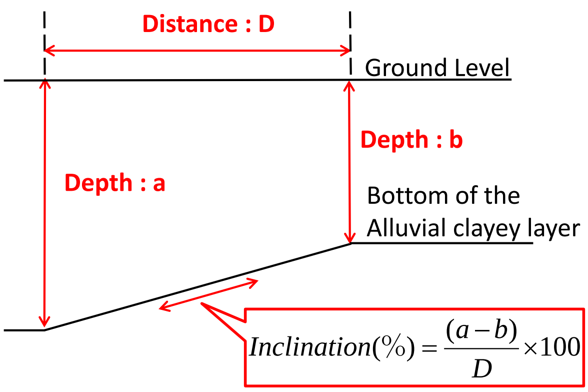


Figure 6. The inclination at the bottom of the layer.

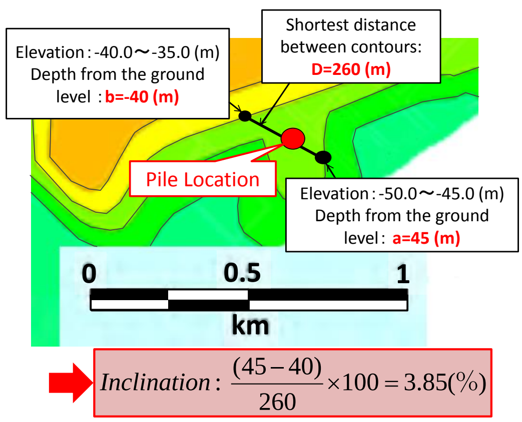


Figure 7. An example of the inclination calculation.

## RESULTS OF STATISTICAL ANALYSIS

As the ground characteristics, total 6 indexes: reclamation year, depth to water level, bedrock surface elevation, thickness of reclaimed sand layer, thickness of alluvial sand layer and thickness of alluvial clay layer were focused. At first, statistical analysis was conducted.

### Correlation coefficients

The correlation coefficients among the ground characteristic data are shown in Table 1 and Table 2. The definition of the correlation coefficients is shown in Eq. (1).

$$\rho_{xy} = \frac{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \bar{y})^2}} \tag{1}$$

where, $\rho_{xy}$ is the correlation coefficient, $x_i$ and $y_i$ ( $i = 1,2,\cdots n$ ) are the data and average of variables $\bar{x}$ , $\bar{y}$ are expressed as $\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$ , $\bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i$ .

Table 1. Correlation coefficients among ground characteristic data related to the pile foundation uplift.

| | Reclamation year | Depth to water level | Bedrocksurface elevation | Thickness of reclaimed sand layer | Thickness of alluvial sand layer | Thickness of alluvial clay layer |
|---|---|---|---|---|---|---|
| Reclamation year | — | — | — | — | — | — |
| Depth to water level | 0.1915 | — | — | — | — | — |
| Bedrock surface elevation | -0.3373 | -0.0198 | — | — | — | — |
| Thickness of reclaimed sand layer | 0.3013 | 0.068 | -0.1485 | — | — | — |
| Thickness of alluvial sand layer | 0.2005 | 0.3025 | -0.0142 | -0.0757 | — | — |
| Thickness of alluvial clay layer | 0.2436 | 0.1164 | -0.4717 | 0.1336 | 0.1564 | — |

Table 2. Correlation coefficients among ground characteristic data related to the variations in ground level.

| | Reclamation year | Depth to water level | Bedrocksurface elevation | Thickness of reclaimed sand layer | Thickness of alluvial sand layer | Thickness of alluvial clay layer |
|---|---|---|---|---|---|---|
| Reclamation year | — | — | — | — | — | — |
| Depth to water level | 0.1183 | — | — | — | — | — |
| Bedrock surface elevation | -0.2963 | 0.1529 | — | — | — | — |
| Thickness of reclaimed sand layer | 0.2488 | -0.0572 | -0.2395 | — | — | — |
| Thickness of alluvial sand layer | 0.2713 | 0.2358 | -0.0660 | -0.0930 | — | — |
| Thickness of alluvial clay layer | 0.2760 | -0.0710 | -0.5153 | 0.1120 | 0.0540 | — |

Table 3. Results of multiple regression analysis. P values for the explanatory variables

| | Variations in the ground | Pile foundation uplift |
|---|---|---|
| Coefficient of determination $R^2$ | 0.0758 | 0.0417 |
| Reclamation year | 0.3649 | 0.1438 |
| Depth to water level | 0.1261 | 0.9073 |
| Bedrock surface elevation | 0.4659 | 0.1763 |
| Thickness of reclaimed sand layer | 0.0050** | 0.0002** |
| Thickness of alluvial sand layer | 0.0134* | 0.9124 |
| Thickness of alluvial clay layer | 0.0651 | 0.0020** |

Significance level **:1% *:5%

It is said that there is a significant correlation when the correlation coefficient is close to 1. However, in the correlation coefficients among the ground characteristic data, there were no numbers close to 1. Thus, no significant correlations were observed in the ground characteristics data.

**Results of multiple regression analysis**

Multiple regression analysis was done to examine the effects of differences in ground characteristics on the differences of the liquefaction damage. Table 2 shows the results of multiple regression analysis. The ground characteristic data were used as explanatory variables, and the liquefaction damage data were used as dependent variable. As shown in Table 2, the thickness of reclaimed sand layer and the thickness of alluvial sand layer affect the variations in the ground. In regard to the damage of pile foundation uplift, it is affected by the thickness of reclaimed sand layer and the thickness of alluvial clay layer.

## RELATIONSHIP BETWEEN LIQUEFACTION DAMAGES AND GROUND CHARACTERISTICS

The relationship between liquefaction damage data and ground characteristic data were carefully examined to check the results of multiple regression analysis.

**The reclamation year**

As for the reclamation year, the ratio of the level in the pile foundation uplift is shown in Fig. 8, and the ratio of the variations in the ground level is shown in Fig. 9. Generally, it can be said that the N values of the ground increase with years after reclamation, and the liquefaction resistance also increases. However, such trends cannot be found in Fig. 8 or Fig. 9. This could be because liquefaction countermeasures, such as ground improvements, had been done in the same places reclaimed after 1970.

**The depth to water level**

As for the depth to water level, the ratio of the level in the pile foundation uplift is shown in Fig. 10, and the ratio of the variation in the ground level is shown in Fig. 11. Generally, liquefaction is likely to occur as the depth to water level is shallow. However, such trends cannot be seen in Fig. 10 or Fig. 11. One reason for this is probably that the contour map used to examine the depth to water level does not show the exact data at the time just before the earthquake. In fact, the contour map of the water level was drawn by the measured water level at a different time. The water level varies for many reasons such as seasonal changes and the influence of rainfall. There is a possibility that the water level data used in this study was not correct. It implies the difficulty of using adequate data of water level for liquefaction susceptivity assessment.

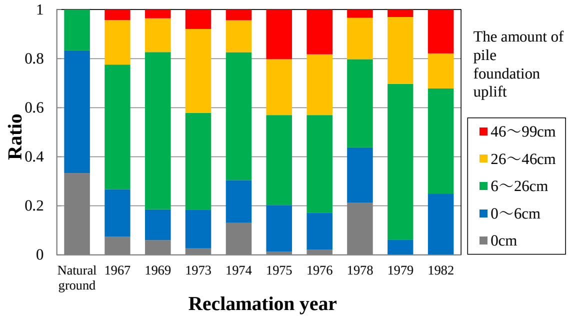


Figure 8. Relationship between the reclamation year and the level of the pile foundation uplift.

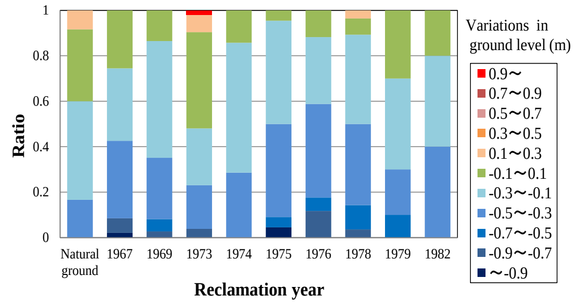


Figure 9. Relationship between the reclamation year and the variations in the ground level.

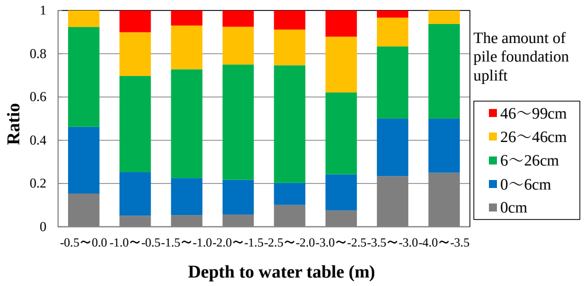


Figure 10. Relationship between the depth to water level and the level of the pile foundation uplift.

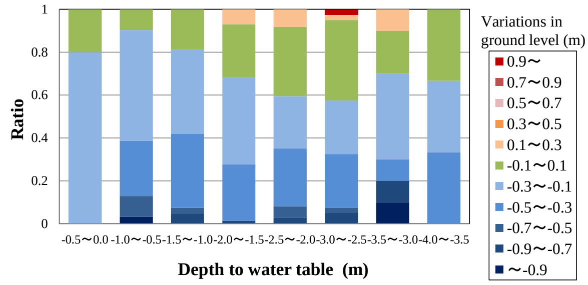


Figure 11. Relationship between the depth to water level and the variations in the ground level.

### The bedrock surface elevation

As for the bedrock surface elevation, the ratio of the level in the pile foundation uplift is shown in Fig. 12, and the ratio of the variation in the ground level is shown in Fig. 13. It has been reported that less liquefaction damage was observed in the shallow bedrock region (Urayasu City Office, 2011). However, such a trend cannot be seen in Fig. 12 or Fig. 13. The reason of this difference is not clear so far, and more detailed discussion is necessary.

### The thickness of the sand layers

As for the thickness of the reclaimed sand layer, the ratio of the level in the pile foundation uplift is shown in Fig. 14, and the ratio of the variation in the ground level is shown in Fig. 15. Also, as for the thickness of the alluvial sand layer, the ratio of the level in the pile foundation uplift is shown in Fig. 16, and the ratio of the variation in the ground level is shown in Fig. 17. Generally, liquefaction easily occurs in soft sand. Therefore, it is thought that the thickness of the sand layer affects the liquefaction damage. As shown in Fig. 14 and Fig. 15, regarding the relationship between the thickness of the reclaimed sand layer and the level of the liquefaction damage, it can be seen that the degree of liquefaction damage increased as the thickness increased. However, as shown in Fig. 16 and Fig. 17, such a trend cannot be seen in the relationship between the thickness of the alluvial sand layer and the layer of the liquefaction damage. In the investigation reports of Urayasu City, it was reported that the N values of the alluvial sand layer were higher than those of the reclaimed sand layer. Thus, it is thought that the thickness of the reclaimed sand layer was the major part of the liquefaction.

### The thickness and inclination of the alluvial clay layer

As for the alluvial clay layer, the ratio of the level in the pile foundation uplift is shown in Fig. 18, and the ratio of the variation in the ground level is shown in Fig. 19. As shown in these figures, the liquefaction damage was serious when there was a thick alluvial clay layer. These results indicate that the thickness of the alluvial clay layer affected the level of the liquefaction damage significantly.

The relationship between the inclination at the bottom of the alluvial clay layer and the level of pile foundation uplift is shown in Fig. 20. It is found that these data do not correlate. The relationship between the inclination at the bottom of the alluvial clay layer and the variations in the ground level was not investigated at this time because the data processing was too complex.

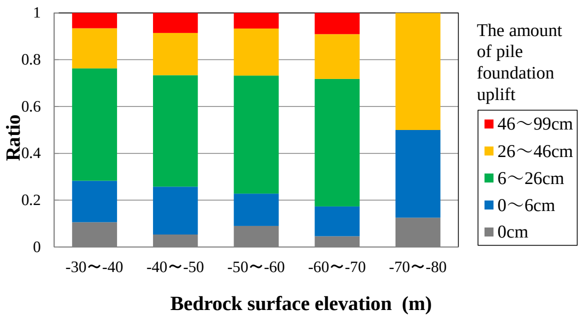


Figure 12. Relationship between the bedrock surface elevation and the level of the pile foundation uplift.

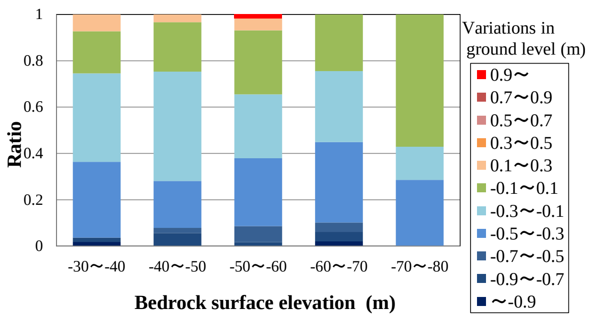


Figure 13. Relationship between the bedrock surface elevation and the variations in the ground level.

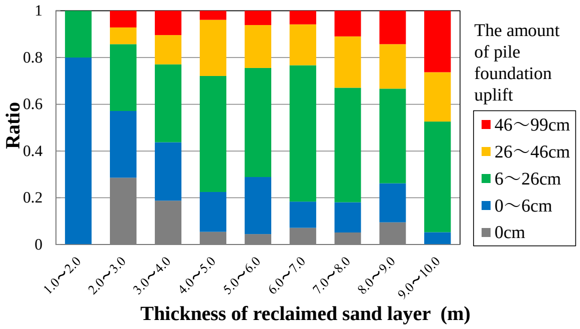


Figure 14. Relationship between the thickness of the reclaimed sand layer and the level of the pile foundation uplift.

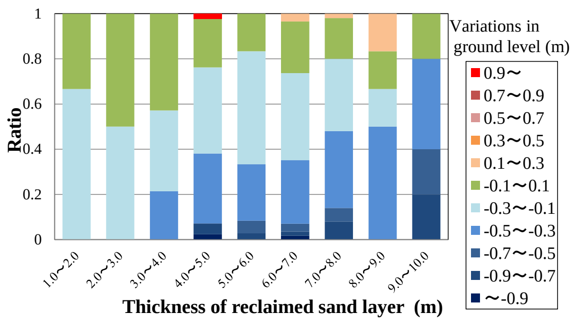


Figure 15. Relationship between the thickness of the reclaimed sand layer and the variations in the ground level.

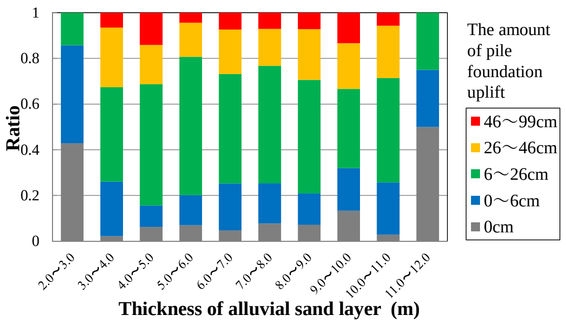


Figure 16. Relationship between the thickness of the alluvial sand layer and the level of the pile foundation uplift.

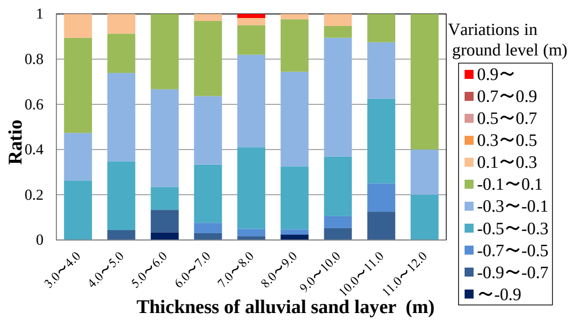


Figure 17. Relationship between the thickness of the alluvial sand layer and the variations in the ground level.

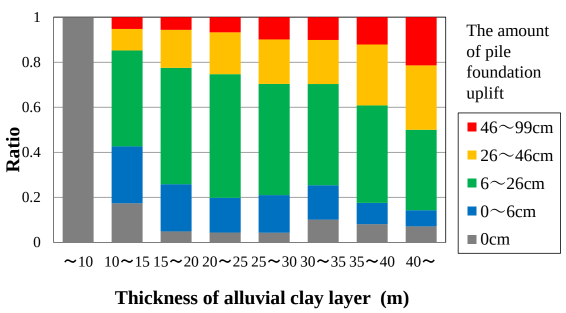


Figure 18. Relationship between the thickness of the alluvial clay layer and the level of the pile foundation uplift.

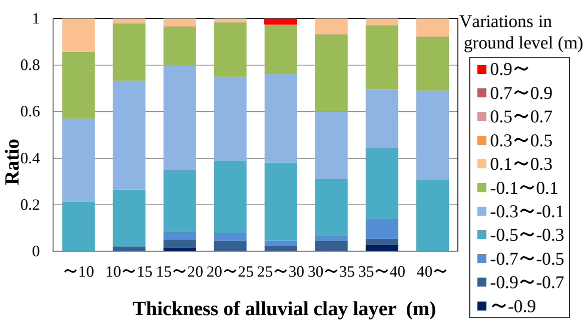


Figure 19. Relationship between the thickness of the alluvial clay layer and the variations in the ground level.

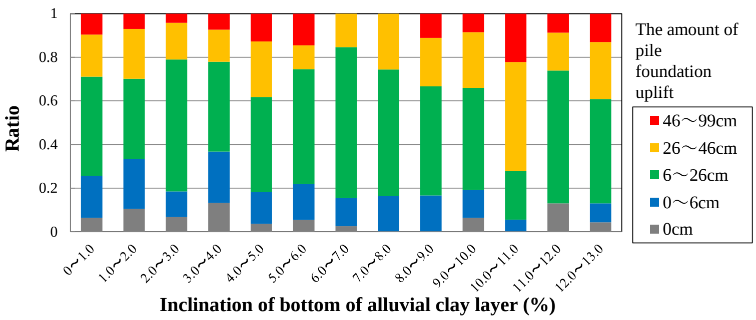


Figure 20. Relationship between the inclination at the bottom of the alluvial clay layer and the level of the pile foundation uplift.

## CONCLUSIONS

The following conclusions can be drawn from this study:

1) Among the ground characteristic data, the thickness of the reclaimed sand layer and the thickness of the alluvial clayey layer affected the level of the liquefaction damage of reclaimed land.
2) Reclamation year, bedrock surface elevation and the inclination at the bottom of the alluvial clay layer have no correlation to the level of the liquefaction damage.

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