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HAZARD EVALUATION OF LIQUEFACTION CAUSED BY AN EARTHQUAKE: - FOR A CASE IN HIROSHIMA CITY -

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SUMMARY

In order to investigate possibilities of liquefaction in Hiroshima-city, Japan during an earthquake, a series of dynamic analysis were performed by using the program of "YUSAYUSA", in which the variation of effective stress within soil caused by the earthquake is considered. The calculations were made at 181 sites where soil profile and N-value had been made obvious based on boring and standard penetration test. Three input motions were applied for the analysis. One of them is the Geiyo Input Motion (GIM) with a maximum speed of approximate 10cm/sec which was back-calculated from the acceleration recorded at the depth of 36m in the site of the Fire-fighting Flying Corps Base when Geiyo-earthquake happened on March 24th 2001. The others are the standardized waves of GIM with a maximum speed of 25kine (GIMv25) and pseudo-seismic wave BCJ-L1 of 25kine (0.9L1v25) which has been recommended by The Building Center of Japan. It is found out from the calculated results that in case of GIM liquefied places would be dotted in a wide area, especially in the nearer seaside area, on the condition that the excess pore water pressure ratio of 0.97 was regarded as the ultimate value for liquefaction. As the calculated results using GIMv25 and 0.9L1v25 as input seismic motions, furthermore, the liquefactions occur all over the city. In this paper, a liquefaction danger index Y was proposed, which is defined as the integration with respect to thickness and depth of liquefied layer. By this judgment, it can be seen that the potentially liquefied sites decreased and the danger of liquefaction in inland ground is comparatively lower than in coastal district.

INTRODUCTION

Liquefaction will occur when effective stresses in soil reducing to zero during an earthquake, and suddenly bring about loss of bearing capacity of foundation supporting a structure, reaching to tilt and failure of the structure. Generally, liquefaction can be identified by appearance of sand boil on ground surface after an earthquake. However, non-appearance of sand boil does not denote that liquefactions did not occur in the site. Furthermore, even if complete liquefaction does not occur during an earthquake, bearing capacity of soil would be also weakened with the decrease of effective stresses due to the growth of pore water pressure.

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Hiroshima-city was suffered from the Geiyo-earthquake with Magnitude 6.7 in JMA scale on March 24th 2001, at Aki-nada, southeast of Hiroshima-city. The recorded maximum acceleration on ground surface is about 250gal in Hiroshima-city. According to previous study [1], it had anticipated that liquefactions might occur at most places in Hiroshima-city if the maximum acceleration on ground surface exceeds 100gal. In spite of 150-200gal recorded during 2001 Geiyo-earthquake, however sand boils were only observed at limited sites, including the reclaimed land along the coast as shown in Fig.1. Furthermore, except at the places like Mitsubishi Heavy Industries Ground (MHIG), Wood Port (WP) and Dejima West Park (DWP), the scales of sand boil were smaller than expected. From such a background, it is thought that liquefaction or near liquefaction might occur in the areas where no sand boil had been observed on the ground surface.

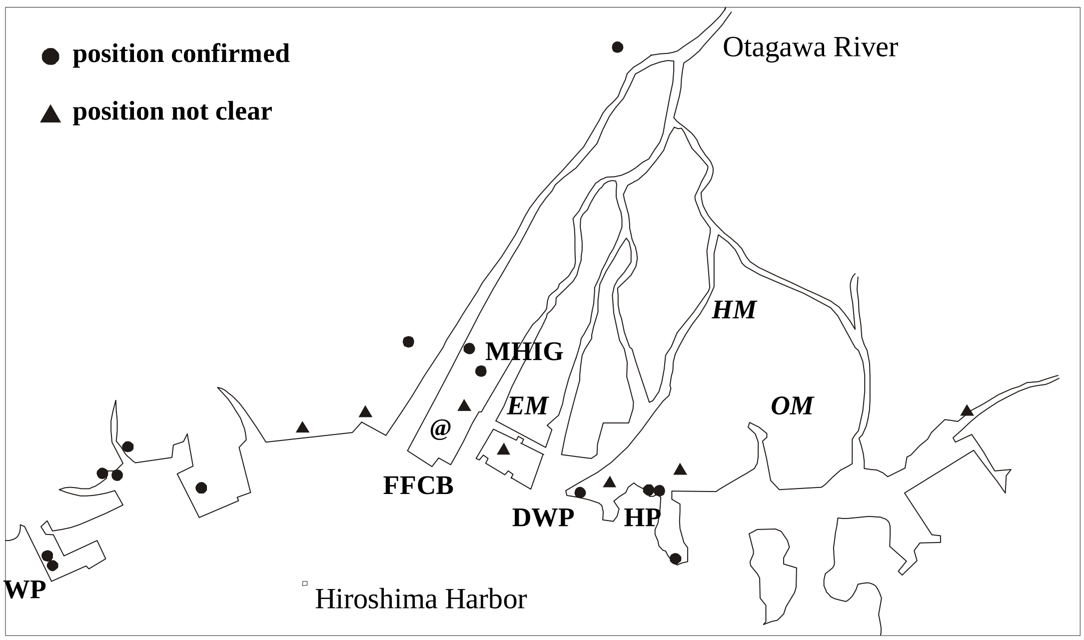


Fig.1 Sand Boil Sites when Geiyo-earthquake, 2001

Anyway, the influence of liquefaction or effective stress reduction on foundation structures cannot be disregarded. In order to analyze the effect and to offer the information to guide engineers in the design of foundation for mitigating the destruction caused by liquefaction, it is necessary to evaluate the level of liquefaction in different soil conditions under different seismic intensity. The aim of this paper is to propose a method of hazard evaluation of liquefaction, which is depend on a liquefaction danger index, in Hiroshima-city on the basis of effective stress analysis.

OUTLINE OF HIROSHIMA CITY GROUND AND GEIYO-EARTHQUAKE RECORD

Outline of Soil Profile in Hiroshima-City

The central part of Hiroshima-city is laying spread on Hiroshima lowland, which is divided into the upstream side and the lower streamside of the Otagawa River. The upstream side area belongs to the Otagawa flood residual flat, and the lower stream area is the Otagawa Delta. The later is moreover classified into natural emergence delta and seaside reclaimed land. The ground characteristics change roughly from the pivot of the delta toward the sea continuously. For example, authors find out by calculation that the resonance period of the ground is shorter in upstream side and longer on seaside-reclaimed land. Since there are some past islands in this area, such as the Hiji Mountain (HM), the Ougon Mountain (OM) and the Enami Mountain (EM) as shown in Fig.1, the locality is strong and the resonance periods of the ground of this area are short than 0.6sec. Moreover, the reclaimed lands have been made and developed for many years, and the whole distribution of the soil profile and properties are comparatively complicated, as shown in Fig.2 [2].

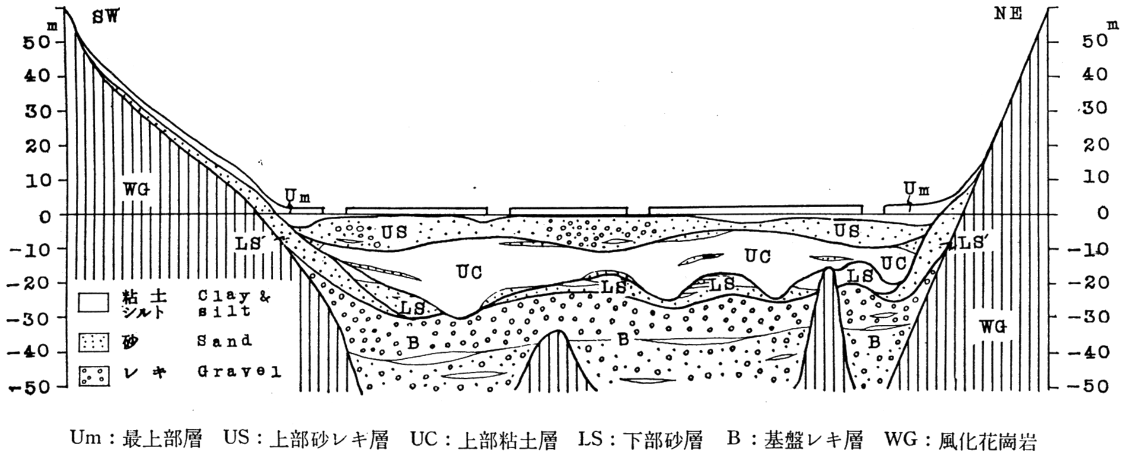


Fig.2 Typical Geological Profile of Otagawa Delta [2]

Geiyo-earthquake Record

During 2001 Geiyo-earthquake, the degree 5 in the JMA scale was adjudged in Otagawa Delta area, and a maximum acceleration of 250gal on ground surface was recorded. The earthquake record used for analysis was obtained from the Fire-fighting Flying Corps Base (FFCB), a vertical array observation station shown in Fig.1, which is recorded at a depth of 36m where the SPT *N*-value is large than 50. The soil profile in the site is shown in Fig.3. The observed EW direction acceleration record and its Fourier spectrum are shown in Fig.4 [3].

INPUT SEISMIC WAVES FOR ANALYSIS

Calculation of Geiyo Input Motion (GIM)

The equivalent elastic analysis program DYNEQ [4] was used to calculate the input motion on the free bedrock of 2E from the record observed in FFCB. This equivalent elastic analysis is the same as SHAKE under the condition that dispersion damping is not taken into consideration. Obtained 2E wave is shown in Fig.5. By comparing the calculated results with the measured accelerations in different depths on this site, good agreement between field observation and calculation was confirmed, as shown in Fig.6. Furthermore, the dynamic

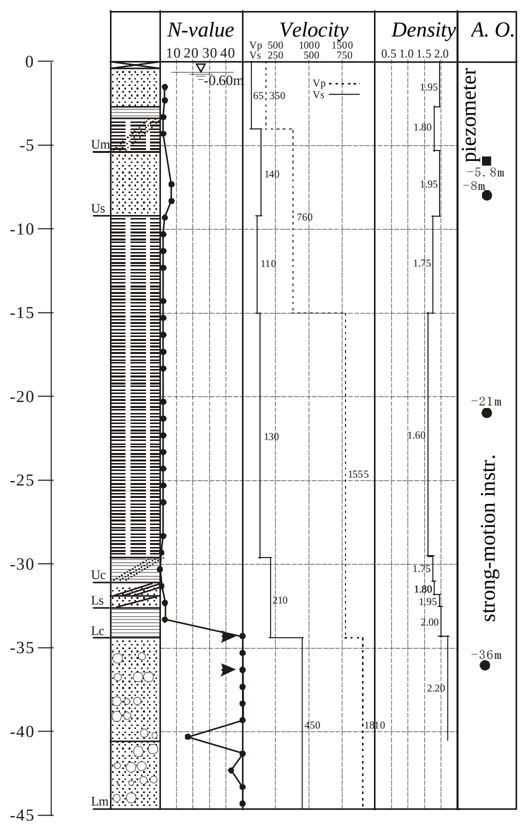


Fig.3 Borehole Log at FFCB Site [3]

analysis considering the effective stress, which will be discussed in detail later, for FFCB and for another array observation station of Minori Park (MP), in the west of the Otagawa Delta, also shows that the calculated and measured acceleration waves are coincident with each other, and that the calculated excess pore water pressure ratios at the depth of 3.3m at MP and at the depth of 5.8m at FFCB are fairly near to measured values (respectively 55% to 40-70% and 65% to 30-40%). Consequently, it is adequate that the calculated 2E wave is used as one of the input seismic waves for effective stress analysis, and is defined as Geiyo Input Motion (GIM).

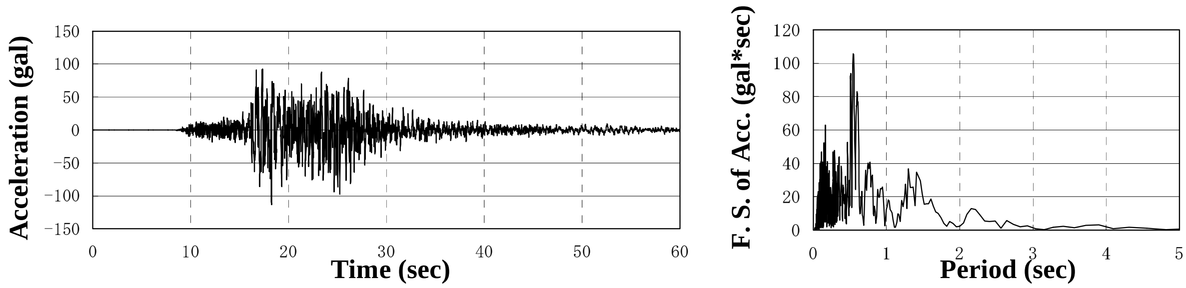


Fig.4 Acceleration Record of Geiyo-earthquake at FFCB, in Depth of 36m, EW Direction

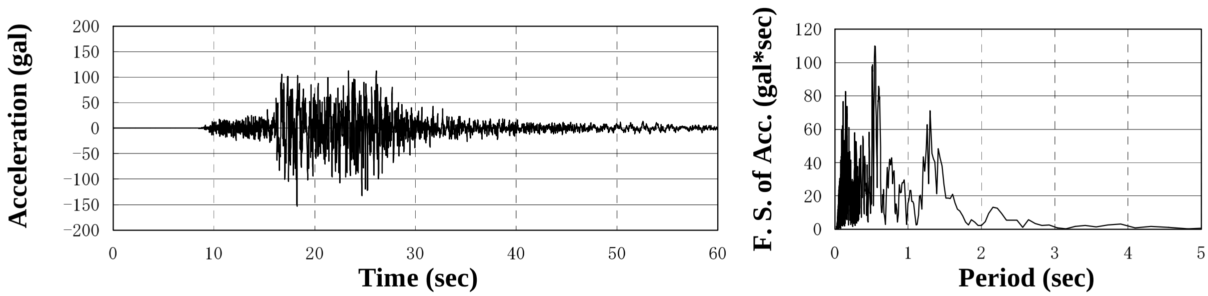


Fig.5 Input Motion on the Free Bedrock of 2E (GIM)

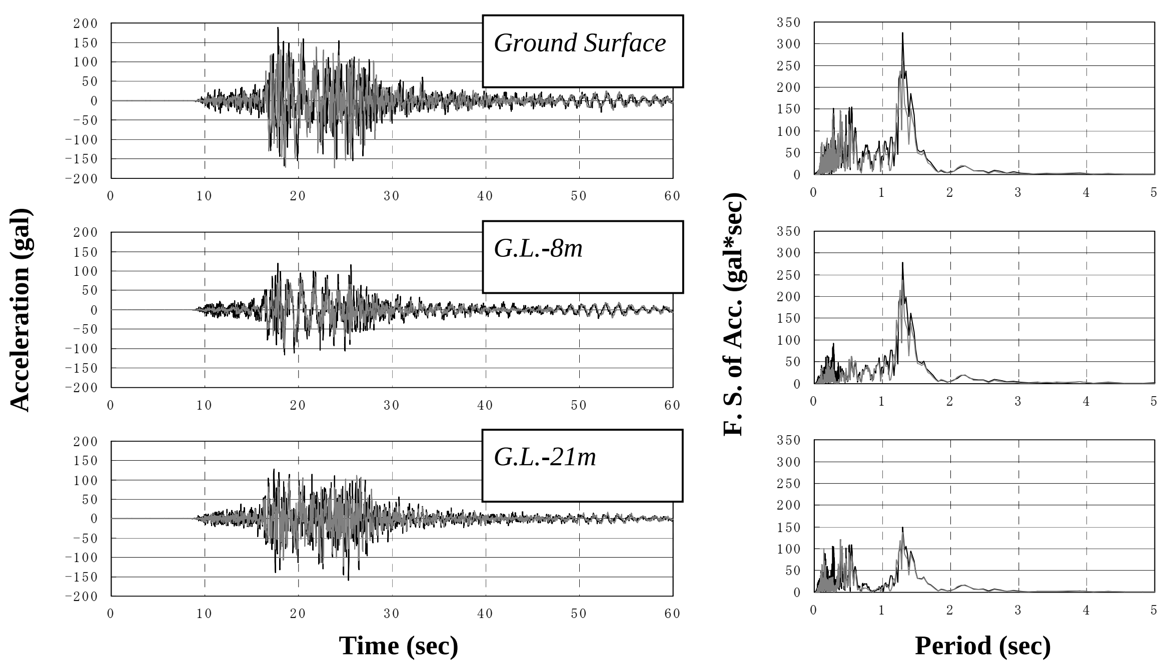


Fig.6 Comparing of Accelerations at FFCB Site (Black:measured; Gray:calculated)

Standardized Wave of GIM and of the Imitation Wave BCJ-L1 with 25kine

The GIM wave should have a maximum speed of about 10kine. Besides the GIM wave, the standardized wave of GIM and an imitation seismic wave BCJ-L1 with a maximum speed of 25kine, GIMv25 and 0.9L1v25 shown in Fig.7, were also used for the effective stress analysis as parameters of seismic intensity and periodic characteristics. BCJ-L1 is the input motion on free bedrock defined by the Building Center of Japan [5]. It can be seen from Fig.5 and Fig.7 that GIM shows the feature of shorter period than BCJ-L1.

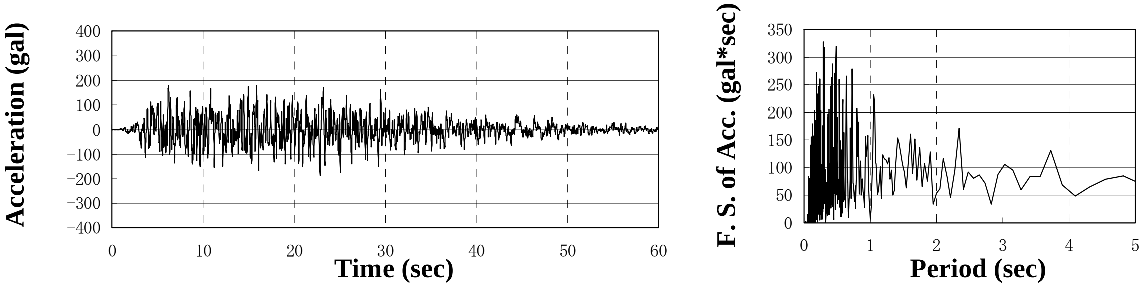


Fig.7 Input Motion of 0.9L1v25

EFFECTIVE STRESS ANALYSIS

Dynamic analysis for earthquake responses considering the effective stress was executed to investigate the change of excess pore water pressures ratio at 181 sites spread in the Otagawa Delta. The computer program used for the analysis is YUSAYUSA [6]. This program is widely used in the field of seismic engineering for soil and foundation in Japan, and its validity has already been confirmed. In addition to the site of FFCB, the constants of soil properties for analysis in the rest sites were determined by the soil boring logs published by 97' Hiroshima Geotechnical Engineering Map [7]. The distribution of the calculated maximum excess pore water pressure ratios was plotted in vertical direction for each site. Since it is difficult to express all the results in one graph, only 18 sites are chosen representatively here for discussion. These sites are plotted in Fig.8, and their distributions of the maximum excess pore water pressure ratio are indicated in Fig.9 a) to r).

For the case of GIM excited on bedrock, the sites where the maximum excess pore water pressure ratio reached 97% as the supremum in the effective stress analysis (defined as complete liquefaction) exist without asking on the sea or the inland side. However, they appear different in thickness and depth. The increasing degree of excess pore water pressure at each site is also different. At the sites along the coast (Tq61 as example) and the sites near the coastal district (TpIII17 as example), the layer where the rising of pore water pressure occurs is thick and its upper border is shallow comparatively. For the inland sites contrastively, they show such a tendency that the pore water pressure rises thinly only near the lower border of the layer in which liquefaction may occur (UpI44 as example), and even the case with less than 50% of the maximum excess pore water pressure ratio (To28 as example) exists.

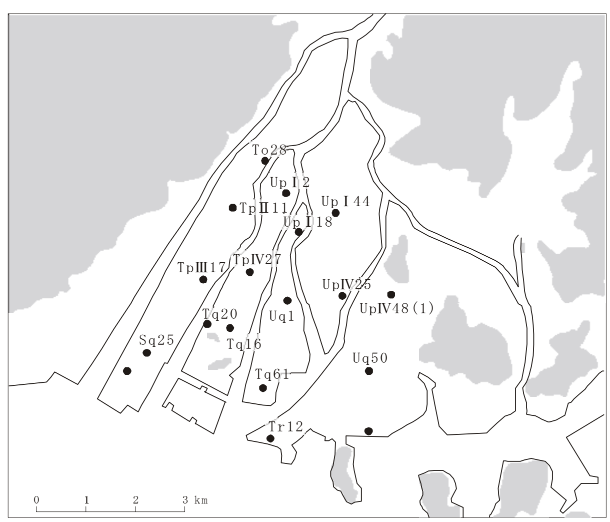


Fig.8 Analysis Sites

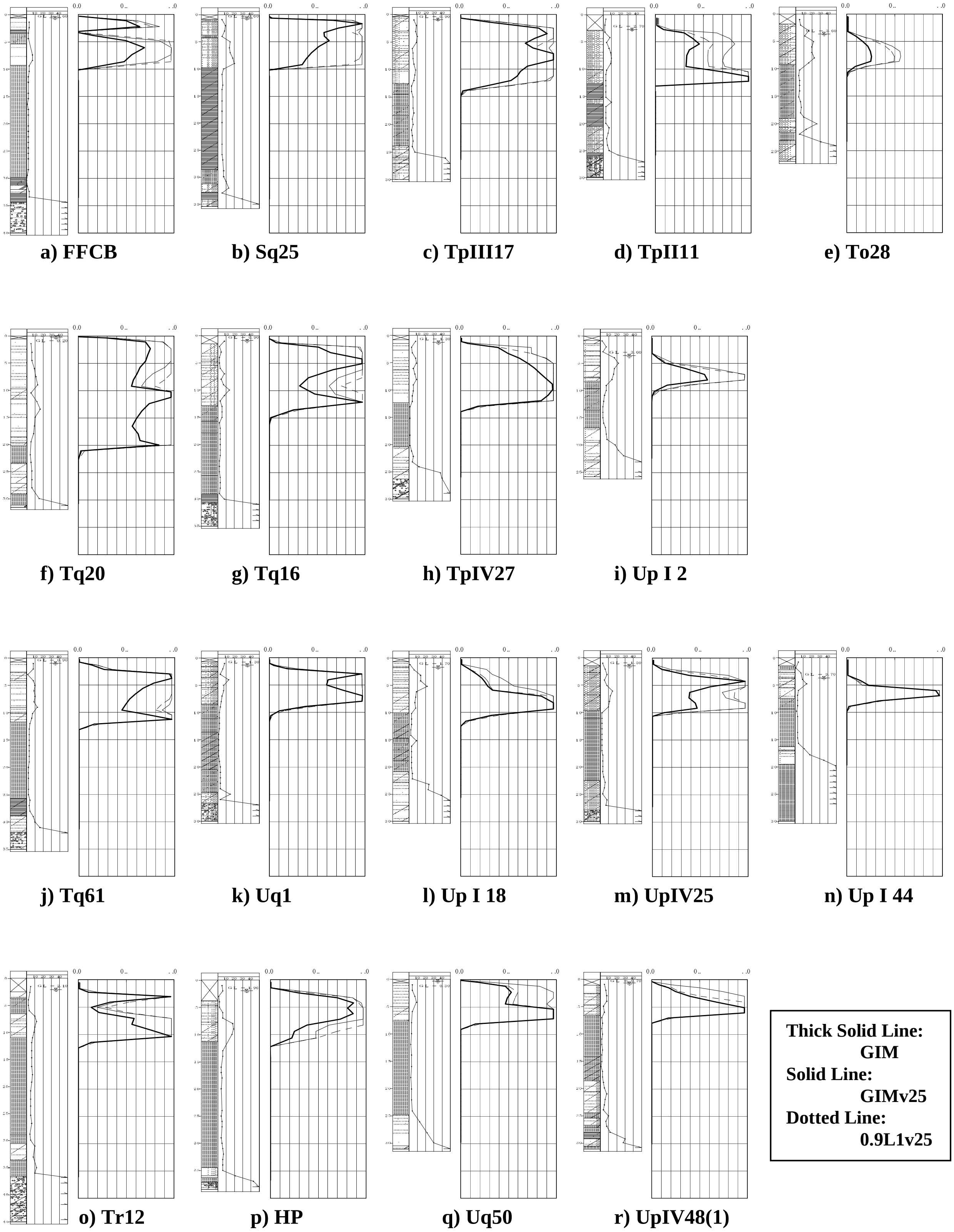


Fig.9 Distributions of the Maximum Excessive Pore Water Pressure Ratio in Depth

When GIMv25 and 0.9L1v25 are used as input motions, most layers in which liquefaction may occur have reached complete liquefaction at almost all sites other than the inland site of To28. On the other hand, at an inland site, pore water pressure develops only near the lower end of the layer for liquefaction, and the pressure rising in its upper part of the layer is held back in many cases.

HAZARD EVALUATION OF LIQUEFACTION

Method of Liquefaction Judgment

In this paper, direct judgment of liquefaction danger was conducted based on the excess pore water pressure obtained by the effective stress analysis, in which two indices were utilized. One is the maximum excess pore water pressure ratio X_{max} (%). When X_{max} reaches 97% in some layer at a site where the deformation of soil increase rapidly, the site is recognized as complete liquefaction no matter what the depth and the thickness of the liquefied layer will be. The value of X_{max} presents the danger of liquefaction directly. In order to take account of the depth and the thickness of the liquefied layer, that is, the shallower and the thicker layer, the more dangerous for liquefaction, another index Y is modeled like the calculation formula of a liquefaction index P_L value, just as:

$$Y = \int_0^{20} X(10 - 0.5z)dz \qquad \cdots (1)$$

where z is the depth and X denotes the distribution of the maximum excess pore water pressure ratio along depth. Y is a depth weighted integration value, defined as the liquefaction danger index. The depth weight is indicated in Fig.10. The larger the Y-value is, the bigger the liquefaction danger will be. Y-value is used to verify the local adaptability for liquefaction danger evaluation, and further examination will not be conducted in this paper.

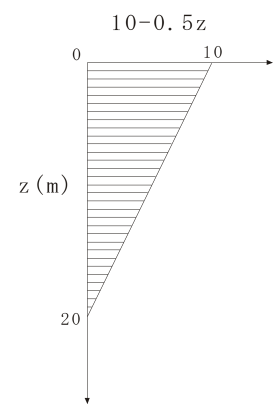


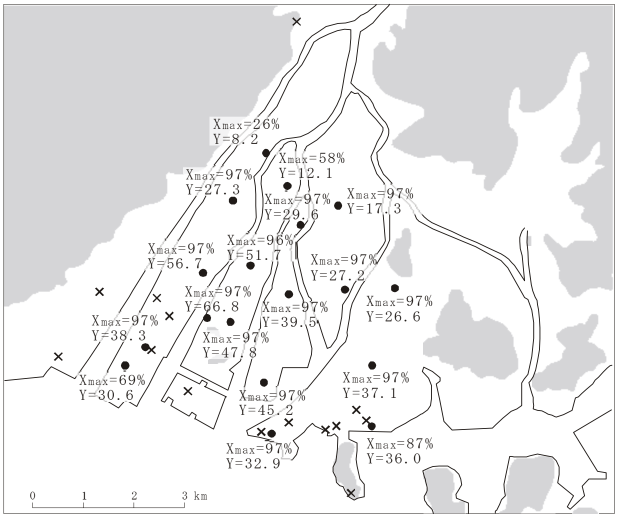
Fig.10 Weight of Depth

Hazard Evaluation of Liquefaction and Discussion

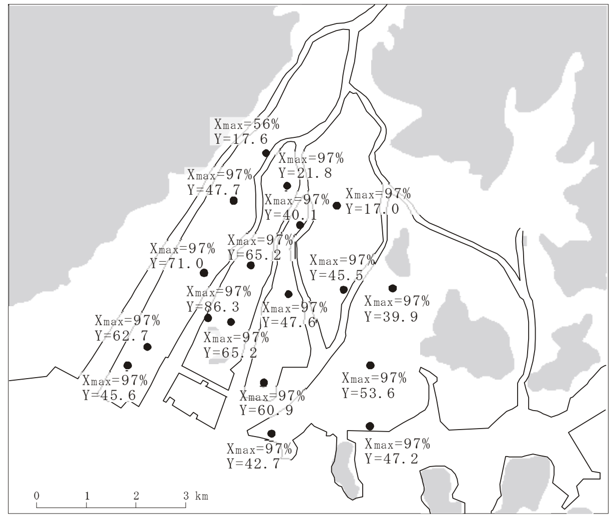
The evaluation of liquefaction danger based on the maximum excess pore water pressure ratio X_{max} and the liquefaction danger index Y was conducted here. For the input motion of GIM, GIMv25 and 0.9L1v25, pairs of X_{max}-value and Y-value at the 18 sites aforementioned were entered in Fig.11 a) to c), respectively. The following things can be clarified based on the data.

In the case of GIM, although it appears, according to the X_{max}-value, that complete liquefaction would occur in the wide area over the Otagawa Delta, danger is relatively lower at inland sites than at ones near coastal district if Y is used as evaluation index. Considering the factor that liquefied layer at inland sites is deeper and thinner, their liquefaction danger may be graded as lower.

On the other hand, in the cases of GIMv25 and 0.9L1v25 with a maximum speed of 25kine, complete liquefaction would happen at almost all sites, and the evaluation based on Y-value remains the same tendency of lower danger at the inland sites. Furthermore, by comparing the Y-values in the both cases, it can be seen that the former corresponds to larger Y-value at inland sites, and the latter corresponds to larger Y-value at coastal side sites contrastively. This phenomenon seems to reflect the influence the different periodic characteristics of input seismic motions. That is, when GIMv25 with the feature of shorter period is as input motion, it increases the excess pore water pressure and amplifies the liquefaction danger index Y at inland sites more than 0.9L1v25, where the resonance period of the ground is shorter than coastal district.

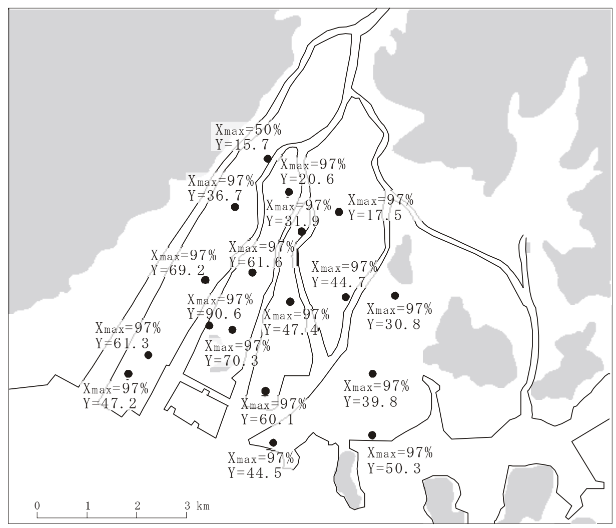


a) When GIM as Input Motion



b) When GIMv25 as Input Motion

Fig.11 X_{max}-value and Y-value at the Analyzed Sites



c) When 0.9L1v25 as Input Motion

CONCLUSION

A series of dynamic effective stress analysis were executed to investigate the excess pore water pressures ratio at 181 sites in Hiroshima-city during 2001 Geiyo-earthquake. Other two standardized seismic waves with a maximum speed of 25kine were also used to examine the effects of seismic intensity and periodic characteristics. Based on these considerations, hazard evaluation of liquefaction was performed for Hiroshima-city. An index Y was proposed for judging the liquefaction danger. Calculated liquefaction danger evaluation reflected well the characteristics of the local ground and the input seismic motions. The calculation agreed well with the filed observation.

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