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Geomorphological Criteria for Evaluating Liquefaction Potential Considering the Level-2 Ground Motion in Japan

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GEOMORPHOLOGICAL CRITERIA FOR EVALUATING LIQUEFACTION POTENTIAL CONSIDERING THE LEVEL-2 GROUND MOTION IN JAPAN

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ABSTRACT

In response to a bitter experience in the 1995 Hyogo-ken Nambu (Kobe) earthquake, the level-2 ground motion, extraordinarily strong shaking motion that would be caused by an earthquake directly under the area such as the 1995 earthquake, has been considered in seismic design of various kind of structures in Japan, in addition to the level-1 general ground motion. Geomorphological criteria in the manual for zonation on liquefaction hazard issued by Land Planning Agency, which have been used a qualitative estimate of liquefaction potential were demanded to keep up with the above-mentioned trend of the time. The purpose of this study is to develop geomorphological criteria for evaluating liquefaction potential for the level-2 ground motion as well as the level-1 ground motion based on case histories in the past earthquakes. The newly developed criteria are applied to the 1948 Fukui earthquake that induced the level-2 destructive motion. A liquefaction potential map is drawn up for the Fukui Plain affected by the earthquake. The result of the assessment based on the criteria was consistent with the actual performance of the ground during the 1948 event.

INTRODUCTION

In the 1995 Hyogo-ken Nambu (Kobe) earthquake, extraordinarily strong ground motion was experienced in Kobe and its neighboring cities, which was greater than assumed under seismic design codes and standards for various structures. The Hyogo-ken Nambu earthquake also caused extensive liquefaction-related damage in a wider area than predicted by existing liquefaction potential maps. In response, a committee consisting of specialists from related disciplines was assembled by the National Land Agency to revise the "Manual for Liquefaction Hazard Mapping Procedures [Disaster Prevention Bureau of the National Land Agency, 1992]" and also to discuss a method to evaluate liquefaction potential for ground motions as great as those in the Hyogo-ken Nambu earthquake. This paper presents the new liquefaction evaluation criteria based on geomorphology, which were introduced in the revised manual. These evaluation criteria are based on the results of a new survey with special emphasis on two factors: intensity of ground motion and the correlation between past liquefaction sites and geomorphological conditions in Japan. This survey included not only Level-1 normal ground motion but also Level-2 ground motion, which was experienced during the 1995 Hyogo-ken Nambu earthquake, but not previously taken into consideration. These criteria were applied to the Fukui Plain, and discussions on their validity were conducted by comparing the predicted results with the actual performance of the ground during the 1948 Fukui earthquake.

THE FRAMEWORK OF THE MANUAL FOR ZONATION ON SOIL LIQUEFACTION IN JAPAN

This liquefaction-zoning manual covers both Level-1 ground motion, which corresponds to normal earthquake force that may occur once or twice during the life span of a structure, and the stronger Level-2 ground motion caused by earthquakes directly above their hypocenter or by interplate great earthquakes, which have a lesser chance of occurrence than normal earthquakes. To facilitate its use, the manual consists of three grades of approach to zonation, enabling it to be used for either simple or full-scale evaluation methods. These three grades, along with the relevant survey methods, are outlined in Table 1. The "Geomorphological Criteria for Evaluating Liquefaction Potential" cited in this study are to be used with the Grade-2 method in Table 1.

RELATIONSHIP BETWEEN THE OCCURRENCE OF LIQUEFACTION IN PAST EARTHQUAKES AND GROUND-MOTION LEVELS

Wakamatsu [1997] evaluated geomorphological conditions and seismic intensity at sites of liquefaction in the past Japanese earthquakes which can be assumed to have caused Level-2 ground motion in a relatively wide area, and showed that the

Table 1. Summary of three level of zonation

	Grade-1	Grade-2	Grade-3
Data used	Simplified geomorphological land classification map	Detailed geomorphological land classification map	Site specific geotechnical data (bore hole log data and in-situ and laboratory tests data)
Target earthquake motion	Not specify	Level-1, Level-2	Level-1, Level-2
Susceptibility or potential assessed	Liquefaction susceptibility	Qualitative liquefaction potential	Quantitative liquefaction potential
Depth estimated	Around 0-5 meters from ground surface	Around 0-5 meters from ground surface	0-20 meters from ground surface
Technique used	Simplified Geomorphological criteria	Detailed Geomorphological criteria	Liquefaction potential index Criteria based on thickness of liquefiable layer and overlying unliquefiable layer
Recommend scale of mapping	1:200,000-1:50,000	1:50,000-1:25,000	1:25,000-1:10,000
Types of denotation	Area	Area	Cell
Designation of liquefaction hazard	Defferencination between susceptibility and non susceptibility	For Level-1ground motion: high, low, very low and none For Level-2 ground motion: very high, high, low and none	Liquefaction effects based on liquefaction Potential Index: very severe, severe and minor. Surface manifestation of liquefaction effects based on relationship between thickness of liquefiable layer and overlying unliquefiable layer: significant and insignificant

Table 2 Seismic intensity that generates liquefaction in a geomorphological unit [Wakamatsu, 1997]

Seismic intensity on the J.M.A. scale	Geomorphological unit
Units liquefied in excess of 5	Natural levee, Point bar, Former river channel, Lower slope of sand dune, Lowland between dunes, Interlevee lowland, Delta, Landfill, Reclaimed land, Back marsh, Valley plain consisting of sandy soil
Units liquefied in excess of 6	Gentle-sloped alluvial fan, Sand bar
Units liquefied in excess of 7	Steep-sloped alluvial fan, Valley plain consisting of cobble or gravel, Gravel bar, Lower terrace, Hollow
Units unliquefied at intensity7	Mountain, Hills, Beach, Top of sand dune with high elevation

minimum seismic intensity that generates liquefaction in a geomorphological unit is almost the same as shown in Table 2, regardless of region or earthquake.

Furthermore, Wakamatsu [2000] analyzed seismic intensities at past liquefaction sites in 75 earthquakes that occurred in throughout Japan over the 112 years from 1885 to 1997, and showed that liquefaction was generally induced in areas underlain by liquefiable Holocene sediments by seismic shaking with an intensity in excess of 5 on the Japan Meteorological Agency (J.M.A.) scale, or 8 on the Modified Mercalli (M.M.) scale. In several cases, however, liquefaction occurred at less than 5 on the J.M.A. scale. She also investigated the geomorphological units at the sites where liquefaction was induced at less than 5 on the J.M.A. scale. The results are plotted in Fig. 1, in which all of the geomorphological units are previously considered to be the most liquefiable types such as landfill and former river channels.

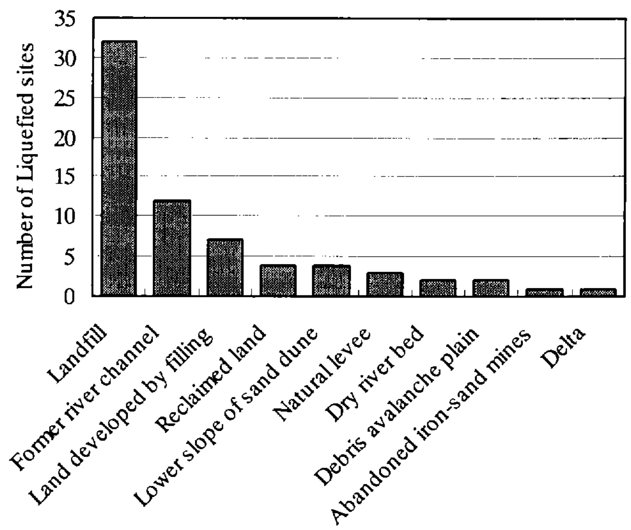

Fig. 1 Geomorphological conditions at sites where liquefaction was induced at less than intensity 5 on the J.M.A. Scale [Wakamatsu, 2000]

Table 3. Geomorphological criteria for evaluating qualitative liquefaction potential

Liquefaction potential		Geomorphological classification
Level-1 ground motion	Level-2 ground motion	
High	Very high	Landfill, Land developed by filling[a], Former river channel, Former pond, Point bar, Dry river bed consisting of sandy soil, Artificial beach, Lowland between dunes and/or bar, Spring
Low	High	Natural levee[b], Marsh and swamp, Sand bar, Back marsh, Delta, Reclaimed land, Gentle-sloped alluvial fan with vertical gradient of less than 0.5%, Valley plain consisting of sandy soils
Very low	Low	Steep-sloped alluvial fan with vertical gradient of larger than 0.5%, Dry river bed consisting of gravel, Gravel bar, Sand dune[c], Beach, Valley plain consisting of gravel and/or cobble
None	None	Plateau or Terrace[d], Hill, Mountain

a) "filling" indicates filling adjacent to cliff, or filling on marsh, swamp, reclaimed land and valley.

b) In the cases of edge of natural levee, natural levee with small elevation and high groundwater level (2-3 m below the ground surface), liquefaction potential is upgraded one rank.

c) In the case of lower slope of dune with high groundwater level, liquefaction potential is upgraded two ranks.

d) Even if in plateau or Terrace, hollow with high groundwater level has liquefaction potential.

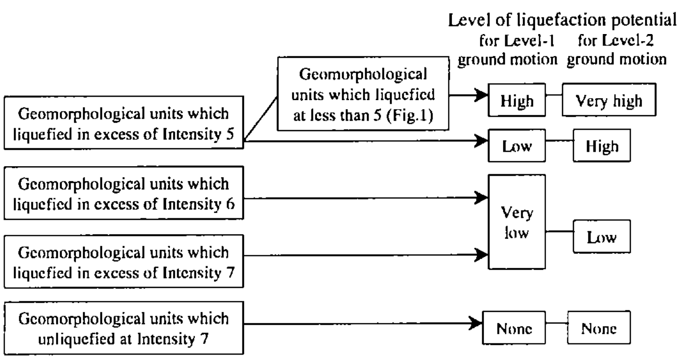

Fig. 2 Routine for the determination of the level of liquefaction potential based on Table 2 and Fig. 1

CRITERIA FOR EVALUATING LIQUEFACTION POTENTIAL CONSIDERING LEVEL-2 GROUND MOTION

Based on Table 2 and Fig. 1, geomorphology-based criteria for estimating qualitative liquefaction potential were developed with reference to the criteria for an earthquake with a J.M.A. seismic intensity of 5 [Disaster Prevention Bureau of the National Land Agency, Japan, 1992; Technical Committee for Earthquake Engineering, TC4, ISSMGE, 1993]. Liquefaction potential on the ground surface was classified into four levels for both Level-1 ground motion ("high," "low," "very low," and "none") and Level-2 ground motion ("very high," "high," "low," and "none"). The conversion from Table 2 and Fig.1 to Table 3 basically follows the routine outlined in Fig. 2. However, the geomorphological units listed in Table 3 are limited to those generally encountered in Japan; local geomorphological units such as the debris-avalanche alluvial plains and small-scale artificially transformed landforms such as abandoned iron-sand mines in Fig.1 were excluded from this discussion. It should be noted, in addition, that detailed characteristics within a single geomorphological unit (e.g., improved ground conditions, landfill materials, time elapsed since construction, and differences in construction methods in a landfill) should be examined independently for each area.

RELATIONSHIP BETWEEN LEVEL OF LIQUEFACTION POTENTIAL AND THE RATIOS OF LIQUEFACTION AREA

The level of liquefaction potential (e.g., "very high" and "high") outlined in Table 3 may cause some uncertainty depending on the individual making the evaluation. Therefore, a guideline for the surface area affected by liquefaction, which corresponds to liquefaction level such as "very high", is outlined below. Below, the ratio of area affected by liquefaction will be defined as the ratio of the area affected by a single occurrence of liquefaction to the total surface area of each geomorphological unit.

In Fig. 3 and 4, the ratio of area affected by liquefaction in the 1964 Niigata earthquake and the 1995 Hyogo-ken Nambu earthquake is shown respectively for the Niigata Plain and the Kobe and its neighboring cities. Here, the intensity of ground motion during the earthquakes is considered to correspond to Levels 1 and 2, respectively. In the Niigata earthquake in which a peak acceleration of approximately 0.15G was recorded at Kawagishi-cho, Niigata, and assumed to have caused Level-1 ground motion, the ratio of area affected by liquefaction is as high as 25% in former river channels. However, in the case of the Hyogo-ken Nambu earthquake, in which more than 0.5G was observed at many sites in Kobe and its neighboring cities, and considered to have caused Level-2 ground motion, the highest ratio (approximately 25%) occurred in landfill. This value is the same as that seen in former river channels in Niigata. It should be specially noted that the ratio of area affected by liquefaction in former river channels in the Hyogo-ken Nambu earthquakes was 2%, a very low value in light of the values seen for the Niigata earthquake. This may be due to differences in grain size characteristics and thickness of liquefiable soil, even if the geomorphological units of the two areas are the same.

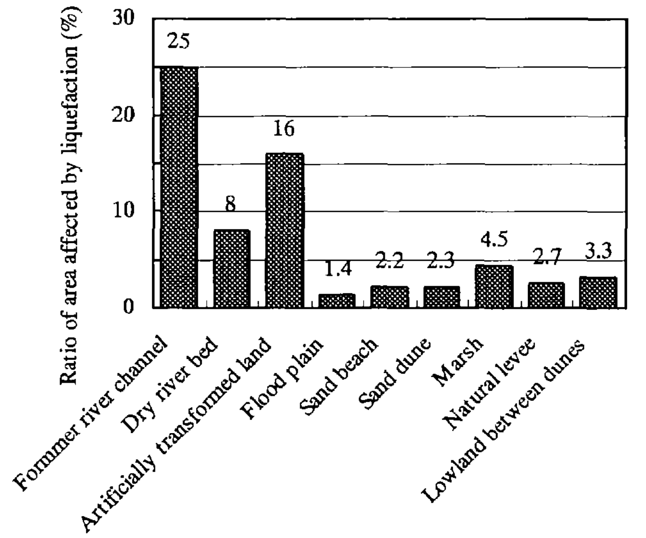

Fig.3 Ratio of area affected by liquefaction within a geomorphological unit in the 1964 Niigata earthquake

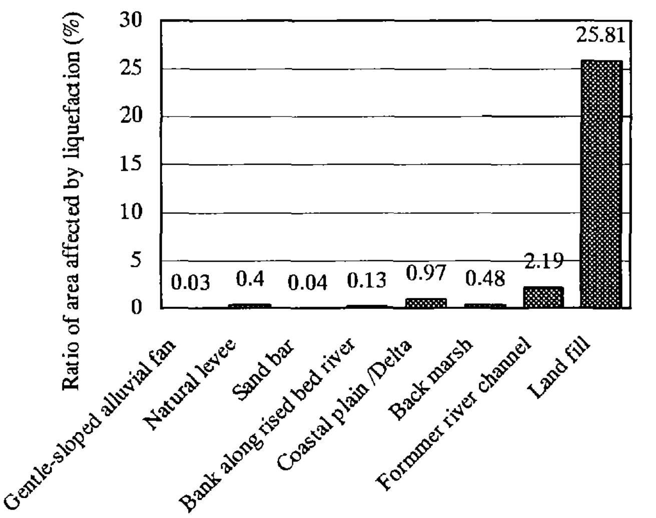

Fig.4 Ratio of area affected by liquefaction within a geomorphological unit in the 1995 Hyogo-ken Nambu earthquake

However, if we observe the ratio of area affected by liquefaction for a single region (a single earthquake event), it is obvious that there is a difference in vulnerability to liquefaction depending on differences in geomorphological conditions (Fig. 3 and 4). Only the case histories due to the two earthquakes have been evaluated for the ratio of area affected by liquefaction according to geomorphology, because distributions of liquefaction effects to calculate the area of liquefaction were uncertain in other earthquake.

It is extremely difficult to obtain a general correlation between level of liquefaction potential and ratios of area affected by liquefaction from these limited case histories alone. To avoid any confusion between "very high" liquefaction potential in Table 3 and total areas of liquefaction in a given geomorphological unit, we referred to the results of the above studies to set the guidelines for correspondence between expected liquefaction potential and the ratio of area affected by liquefaction in Table 4, with reference to a rough estimate from the 1983 Nihonkai-Chubu earthquake [Yasuda and Hamada, 1988], which caused significant liquefaction damage along the coast of the Japan Sea (epicentral distance: 80~150 km) yields a value of 2-9% for the total area of alluvial plain.

Table 4 Guidelines for correspondence between expected liquefaction potential and ratio of area affected by liquefaction within each geomorphologic unit

Level of liquefaction potential	Ratio of area affected by liquefaction
Very high	In excess of 20 %
High	On the order of 10 %
Low	On the order of 2 %
Very low	Less than 1 %
None	0 %

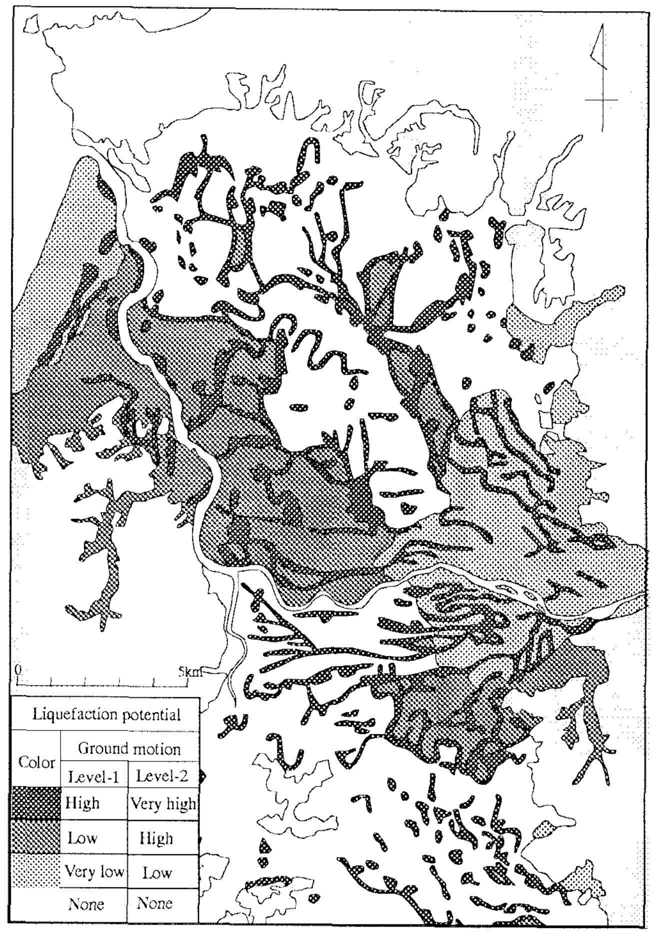

Fig. 5 Liquefaction potential map for the Fukui Plain

CASE STUDY

To evaluate the validity of the newly developed criteria listed in Table3, a liquefaction assessment was performed for the Fukui Plains and results based on our criteria were compared to the distribution of sand boils due to the 1948 Fukui earthquake. First, the geomorphological land classification map was used to

Table 5 Comparison between liquefaction potential for Level-2 ground motion based on the geomorphological criteria in this study and that based on ratio of area affected by liquefaction during the 1948 Fukui Earthquake

Geomorphological units subjected to Level-2 ground motion estimated from damage ratio of wooden buildings	Total surface area (km^2)	Area of non-liquefaction (km^2)	Area of liquefaction (km^2)	Ratio of area affected by liquefaction (%)	Level of liquefaction potential		Result of comparison
					Based on ratio of area affected by liquefaction (Table 4)	Based on Geomorphologica l criteria (Table 3)	
Steep-sloped alluvial fan	4.4739	4.4739	0.0000	—*	—	low	—
Gentle-sloped alluvial fan	20.0637	12.2322	7.8315	39.0	Very high	High	Under-estimation
Natural levee with relatively small elevation	21.1336	17.0369	4.0966	19.4	Very high	Very high	Agree
Point bar	1.5626	0.4772	1.0854	69.5	Very high	Very high	Agree
Delta, Back marsh	185.0891	162.9180	22.1711	12.0	High	High	Agree
Valley plain consisting of sandy soils	8.7226	8.6747	0.0479	—*	—	High	—
Marsh and swamp	7.6400	7.4542	0.1858	2.4	low	High	Over-estimation
Former river channel (distinct)	12.5602	9.2604	3.2998	26.3	Very high	Very high	Agree
Former river channel (indistinct)	26.3424	20.3494	5.9929	22.8	Very high	Very high	Agree
Lower slope of dune	2.8465	2.4059	0.4406	15.5	Very high	Very high	Agree
Lowland between sand dunes	1.3754	0.6828	0.6926	50.4	Very high	Very high	Agree
Dry river bed consisting of sandy soils	5.4805	3.2562	2.2243	40.6	Very high	Very high	Agree
Dry river bed consisting of gravel	3.2998	3.1492	0.1506	4.6	Low	Low	Agree

*Reconnaissance investigation in this unit on liquefaction was considered to be insufficient because the aerial photographs were not taken immediately after the shock.

evaluate the liquefaction potential of each geomorphological unit according to Table 3 and to draw up a liquefaction potential zoning map (Fig. 5). The predicted results indicate that the areas with "very high" liquefaction potential under Level-2 ground motion were the natural levees along rivers, former river channels, and lowlands between sand dunes. These results almost coincided with the areas where sand boils were observed during the 1948 Fukui earthquake. Since a precise comparison cannot be made because the levels of ground motions for the studied area are uncertain, the ratio of areas affected by liquefaction was compared for every geomorphological unit.

First, regions assumed to have suffered a seismic intensity of 7 on the J.M.A. scale, which corresponds to Level-2 ground motion in the 1948 Fukui earthquake, were selected based on the ratio of total destruction to wooden [Special Committee for Earthquake Disaster of the Hokuriku Region, 1951]. By utilizing the aforementioned geomorphological map and the distribution of sand boils, the total area, area of liquefaction, area of no liquefaction, and ratio of area affected by liquefaction to total areas were calculated for each geomorphological unit. Based on these calculations, liquefaction potential was estimated from Table 4. An evaluation was also conducted on the level of liquefaction potential for each geomorphologic unit based on Table 3. These results are summarized in Table 5. The total surface areas of the "steep-sloped alluvial fan" and "valley plain consisting of sandy soils" were not included in the regions where aerial photographs were taken immediately after the earthquake to compile the distribution map of sand boils, so the liquefaction data for these two units were inadequate. Therefore, they were excluded from our discussion.

The level of liquefaction potential based on the actual ratio of area affected by liquefaction and our evaluation results based on Table 3 agree for 9 out of 11 geomorphologic units, and are considered to be consistent. However, in the "gentle-sloped alluvial fan" area, our evaluation based on Table 3 gives a lower level of liquefaction than that actually observed in the Fukui earthquake. One reason for this may be that this area is located directly above the hypocenter fault for the Fukui earthquake, where total destruction of wooden-framed housing was 100%; it may thus have experienced stronger ground motions than assumed in our evaluation. On the other hand, Table 3 overestimates the level of liquefaction potential of "marsh", which may be due to the ground of the Fukui Plains being predominantly clay, and therefore less likely to suffer liquefaction.

SUMMARY AND CONCLUSIONS

This paper focuses on the results of a review on correlation between liquefaction sites in past Japanese earthquakes and geomorphological conditions, with a special emphasis on the role of ground motion. Our study included not only Level-1 ground motion, included in previous studies, but also Level-2 ground motion, thus developing a two-stage criterion for evaluating liquefaction potential.

Although the geomorphological criteria generally do not provide us with definitive information for site-specific evaluation, the strong point of liquefaction zoning maps denoted by area based on the criteria is that boundaries can be delineated on features that best reflect the surface ground conditions. This approach is especially effective in small areas such as former river channels and former ponds, where zoning maps drawn using cells, typically around 0.25 × 0.25 km or 0.5 × 0.5 km in size, based on bore hole data cannot express these features.

Our evaluation criteria were verified by applying them to the Fukui Plains, with our results compared to the actual distribution of sand boils observed in the 1948 Fukui earthquake. These new findings were generally consistent with actual performance of the ground, except for some areas of over- and under-estimation. The geomorphological criteria listed in Table 3 will become more effective if they are modified based on more site-specific correlation between past liquefaction sites and geomorphological settings. Nevertheless, this map is useful for preliminary planning purposes in identifying areas where liquefaction may pose a serious threat and where site-specific investigations will be needed for specific projects and land-use decisions.

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