Seismic hazard in Takamatsu, Japan from a ground database system and palaeo-liquefaction studies

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Abstract: Takamatsu is a harbour city of 330,000 people on the northern shore of Shikoku Island, southwest Japan. Downtown Takamatsu is located mainly on delta and made ground and was extensively damaged by the tsunami caused by No.16 typhoon in 2004. Earthquakes in the Nankai Trough, typically of magnitude M 8+, have caused extensive damage to the city every hundred years or so, and the next big earthquake is expected to occur before the middle of the 21st century. Downtown Takamatsu is composed of Holocene sandy deltaic sediments. Reclaimed lands have been used for paddy fields and salt pans since the 17th century and the salt pans were in-filled in the 1970's. They are composed of soft sandy and silty deposits, dredged soils and waste materials. Therefore, liquefaction and successive tsumamis (2m+) are a serious threat to the city. We have estimated the potential for liquefaction by using a geo-informatics system. Additional data is derived from paleo-liquefaction studies in the Takamatsu plain. The paper describes liquefaction studies and discusses the implications for seismic hazards in Takamatsu.

Résumé: Takamatsu est une ville de port de 330.000 personnes sur le rivage nordique de l'île de Shikoku, sud-ouest Japon. Takamatsu du centre est situé principalement sur le delta et la terre faite et a été intensivement endommagé par le tsunami provoqué par le non.ouragan 16 en 2004. Les tremblements de terre dans la cuvette de Nankai, typique de la grandeur M 8+, ont causé dommages étendus à la ville au sujet de tous les cent ans et du prochain grand on s'attend à ce que le tremblement de terre se produise avant le milieu du 21ème siècle. Du centre Takamatsu se compose de sédiments deltaïques arénacés holocènes. Les terres reprises ont utilisé pour des rizières et des casseroles de sel depuis le 17ème siècle et le sel les casseroles étaient infilled en quelques années 70. Ils se composent doucement d'arénacé et silty sédiments, sols dragués et déchets. Par conséquent, liquéfaction et le tsumami successif (2m+) sont une menace sérieuse à la ville. Nous avons estimé le potentiel pour la liquéfaction en employant un système au sol de base de données de l'information. Des données additionnelles sont dérivées des études de paleo-liquéfaction à Takamatsu plaine. L'article décrit des études de liquéfaction et discute les implications des résultats pour le risque séismique à Takamatsu.

Keywords: database systems, drilling, earthquakes, geographic information systems, geotechnical maps, liquefaction

INTRODUCTION

Takamatsu is on the northern shore of Shikoku Island, southwest Japan. Shikoku Island is located on the Eurasian Plate. The Philippine Sea plate is subducting beneath the Eurasian Plate at the Nankai trough, 120-180km from the south coast of Shikoku. Earthquakes in the Nankai Trough, typically of magnitude M 8+, have been considered the primary source of seismic hazard for the island and Takamatsu. Takamatsu has been seriously damaged by Earthquakes in the Nankai Trough at intervals of 90 to 150 years (Figure 1). The Japanese Government authority for earthquake research estimated that the Nankai Earthquake has a 50% chance of occurring within 30 years from 2005, and an 80% chance within 50 years.

The plain of Takamatsu City is mainly composed of the alluvial fan and the subordinate flood plains, deltas of the rivers, and landfills along the shore. Therefore it can be said that the alluvium is easy to damage by the amplification of earthquake vibration and the occurrence of liquefaction. In addition, in Takamatsu plain, the paleo-liquefaction has been found at 16 sites until now. Although the alluvial fan is considered to have a low risk of liquefaction, 16 sites of liquefaction were found by archaeological surveys. These paleo-liquefaction sites suggest that detailed investigation of liquefaction is necessary through micro-topography and ground condition information.

This paper first describes the paleo-liquefaction in Takamatsu, and then estimates the risk of liquefaction by using geo-informatics and geographic information systems.

METHOD

The objective of this study is to publish a liquefaction hazard map in order to reduce the disaster of Nankai earthquakes. Firstly, the database was constructed from about 2500 borehole logs and established using G-Cube (Integration ground information management system by Chuo Kaihatsu Co., Ltd.). The ground conditions were classified by land classification of micro-topography and micro-tremor observations. The liquefaction risk was based on P_L-value under the condition of the observed ground water table, and a liquefaction hazard map was proposed (Figure 2).

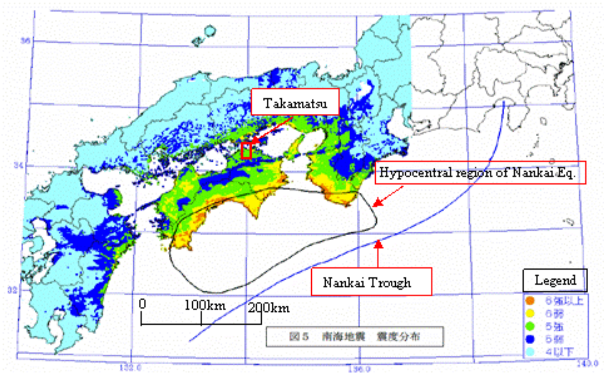


Figure 1. Estimation of Seismic intensity of future Nankai Earthquakes (modified from the central disaster prevention council, 2003)

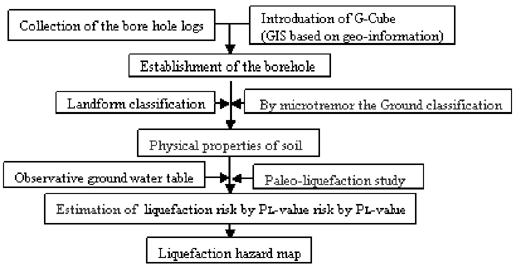


Figure 2. Flow chart of the research

TOPOGRAPHY AND SURFACE GEOLOGY

Figure 3 shows the topography of the Takamatsu area. The Takamatsu plain consists of the alluvial fan of the Koto River, the subordinate flood plains of the Shin, Kasuga and Honzu Rivers, deltas of these rivers, and landfills along the shore. Downtown Takamatsu city is located on deltaic deposits and the urban areas are developed on the fan around the Koto River, the flood plains of other rivers and reclaimed lands.

This fan was formed in the glacial age and consists of gravels and sand. The surface of the fan is covered with thin sandy and silty deposits of Holocene age. Several paleo-channels have been recognized by micro-topography and archaeology.

The flood plains of minor rivers consist of soft sandy and muddy deposits. The delta is mainly composed of soft sandy and silty deposits of Holocene age. The delta deposits are less than 10m in thickness (Kawamura,2000) and cover the Pleistocene Fan deposits of the Koto River.

Reclaimed lands have formed paddy fields and salt pans since the 17th century and the salt pans were filled up in 1970s. These area are composed of soft sandy deposits, dredged soils and waste materials. The surrounding hills are composed of late Cretaceous granitic rocks and middle Miocene volcanic rocks.

HISTORICAL DESTRUCTIVE EARTHQUAKES

The earthquakes along the Nankai trough (Nankai Earthquakes) have been documented since 684AD. The mean recurrence time of the Nankai earthquakes is about 200 years before 1605AD and about 100 years after 1605. However, recent paleo-seismological studies using pale-liquefaction data have revealed that there is a possibility of undocumented Nankai earthquakes before 1605. The historical record of destructive earthquakes on this plate boundary is particularly well described since 1596 in Takamatsu. Historical destructive earthquakes in the Takamatsu area are shown in Table 1.

Historical records show that every Nankai earthquake caused severe damage to downtown, the area of the delta and the fan deposits. On the contrary, Ansei-Nankai Earthquakes caused liquefaction in reclaimed land, salt fields and landfills

PALEO-LIQUEFACTION SITES

The 16 paleo-liquefaction sites in Takamatsu plain have been reported by archaeologists (Kinoshita, 2000, and Oshima, 1996). According to these reports, 9 sites of paleo-liquefaction are located on the Koto Fan and 7 sites are located on the delta (see Figure 3 and Table 2). It is interesting to note that the paleo-liquefaction sites are concentrated on the eastern part of the Koto Fan. Detailed surveys of micro-topography and archaeology show that most of the paleo-liquefaction sites are located at the paleo-channels, reclaimed land or back marshes on the fan.

The age of sand dikes estimate the period of the Nankai earthquake. The age of liquefied gravels at two sites is middle Yayoi period (about 200 B.C. – 50 A.D.). This liquefaction is estimated to have been caused by an earthquake on the MTL (Median Tectonic Line: M 8 class earthquake in Yayoi period; Hasegawa and Finn, 2002).

Figure 4 shows recordings of the trench excavation at Kagawa University on the eastern part of the Koto Fan, about 40m north of the Loc.10 paleo-liquefaction site. The paleo-liquefaction layer is correlative with well-sorted sand layers of loose to medium size, and is covered with soft silty deposits. The water table is near the ground surface. Figure 5 (a) and (b) show grain size accumulation curves in samples A and B. Sample A is classified as sand (S), and B is classified as sandy gravelly fine soil (GS). According to the Harbor Office of the Ministry of Transport both sample A and B can be judged as possible sources of liquefaction.

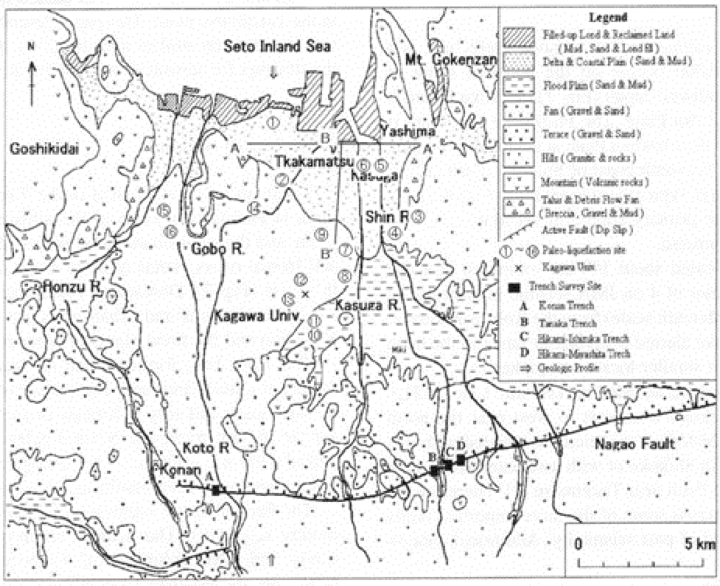


Figure 3. Outline of topography of the Takamatsu area, including liquefaction sites shown in Table 2

Table 1. Historical destructive earthquakes

Date	Name of earthquake	Magnitude	Epicenter	JMA seismic intensity	Description
1596.9.6	Keicho-Kinki	7.5±1/4	Kyoto (Arima-Takatuki Fault)	5	Collapse of shines and temples
1707.10.28	Hoei	8.4	Nankai Trough 33°2'N 135°9'E	6	Collapse of Mt.Gokenzan, Liquefaction, Tsunami 1.8m
1854.12.24	Ansei-Nankai	8.4	Nankai Trough 33°0'N 135°E	6	Liquefaction, Tsunami 0.3m
1946.12.21	Showa-Nankai	8	Nankai Trough 33°02'N 135°37'E	5	Liquefaction, Settlement Tsunami 1.0m

THE MICROTREMOR OBSERVATION

Micro-tremors have been observed at about 400 points in the Takamatsu plain (Saito et al,2005) The predominant period of the ground is estimated by the period of the maximum ratio of the H/V spectrum. The ground type was judged by the predominant period (Table 3).

The ground type at the Takamatsu plane can be described as follows. The Class-I ground is the mountainous district, the hills and parts of the alluvial fan. The Class-II ground is the old reclaimed land, the old delta belt, the alluvial fan, the natural levee and the talus. The Class-III ground is the new reclaimed land, the modification land, a new delta belt and parts of the alluvial fan.

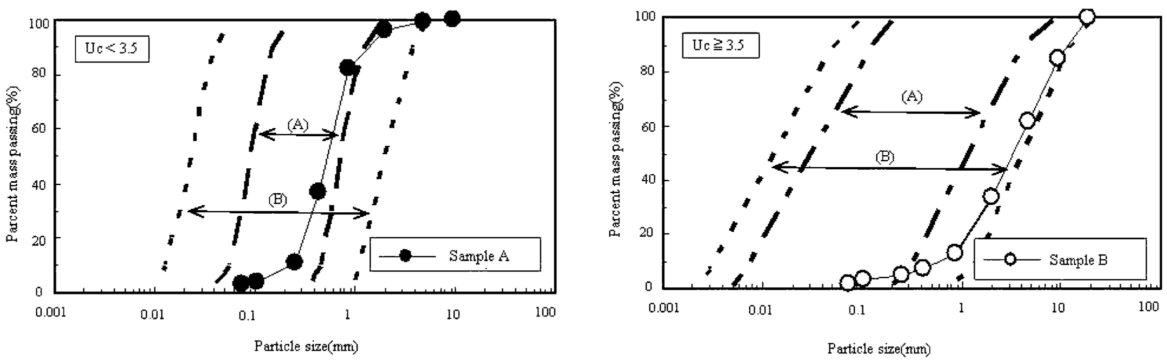
PREPARATION OF GEO-INFORMATICS

The geo-informatics constructed on GIS consist of information on geography, geology, subsoil, N-value, and ground water (Nishie et al, 2000).

Figure 6 shows the locality of borehole logs in the database for the Takamatsu area. Many borehole log data are in distributed ground around the urban areas and on national highways including the seaside. With the cooperation of public institutions, such as the Ministry of Land, Infrastructure and Transport and Takamatsu City Office, it was possible to collect data from about 1500 boreholes.

Table2. Paleo-liquefaction in the Takamatsu area (modified from Hasegawa and Finn,2002,)

No.	Type	Site (name of ruins)	Age	Topography (micro topography)	Possible earthquake
1	Sand dike	Takamatujyo	Before 1600 A.D.	Delta (ancient shore)	?
2	Sand dike	Hisgashinakasuji	1200-1450 A.D.	Fan (back swamp)	?
3	Sand dike	Hisamoto	900-1100 A.D.	Fan (margin)	?
4	Sand dike	Kumeike	Before 1600 A.D.	Delta (ancient shore)	?
5	Sand dike	Kawaminami-higashi	ca. 1700-1800 A.D.	Delta (ancient shore)	1707 Hoei?
6	Sand dike	Kawaminami-nishi	1450-1800 A.D.	Delta (ancient shore)	1707 Hoei?
7	Sand dike	Rokujyo-Josho	Before 1600 A.D.	Fan (margin)	Nankai
8	Sand dike	Rokujyo-gesho	Before 1600 A.D.	Fun (back swamp)	?
9	Sand dike	Gufukujiryo	ca. 400 B.C. -300 A.D.	Fun (buried channel)	Nankai
10	Sand dike	Kukoatochi	1600-1850 A.D.	Fun (buried channel)	1707 Hoei? 1854 Ansei?
11	Gravel dike	Ikkaku	50-300 A.D.	Fun (buried channel)	MTL
12	Sand dike	Hikkonbara	300-1500 A.D.	Fun (buried channel)	Nankai
13	Gravel dike	Matsubayashi	200 B.C. -50 A.D.	Fun (back swamp)	MTL
14	Sand dike	Nishihaze-doi	200 B.C. -300 A.D.	Fan (back swamp)	?
15	Sand dike	Tsuzukijo	Before 1800 A.D.	Fun (back swamp)	?
16	Sand dike	Aoki	After 1200 A.D.	Fun (back swamp)	?



(a) Grain size accumulation curve of sample A (b) Grain size accumulation curve of sample B

Figure 5. Grain size accumulation curves of sample A and B
(A): high risk of liquefaction.
(B): possibility of liquefaction.

Table 3. Classification of ground type by predominant period

Classification	Property value TG	Relative Hardness	Predominant period (sec)
Class-I	TG<0.2	Hardness	about 0.1
Class-II	0.2≤TG<0.6	medium	about 0.4~0.6
Class-III	0.6≤TG	softness	about 0.7~1.0

ESTIMATION OF LIQUEFACTION RISK

The liquefaction risk was judged using potential P_L-values, integrating liquefaction resistance F_L values for the ground depth (JRA, 1996). The liquefaction resistance F_L is obtained using N-values from standard penetration tests.

$$P_L = \int_0^{20} F * (10 - 0.5z)dz \quad \text{(z :depth from the ground) (m)}$$

$$F_L < 1 \Rightarrow F = 1 - F_L, \quad F_L \geq 1 \Rightarrow F = 0$$

The soil properties are shown in Table 4. Because the soil tests could not be conducted on all the borehole data, an average of the soil propertie values was used.

Table 5 shows the criteria for liquefaction risk using P_L-values, following the method of the Public works research institute of the Ministry of Construction (PWRI, 1981). If P_L is larger than 15, the risk of liquefaction in the ground is very high.

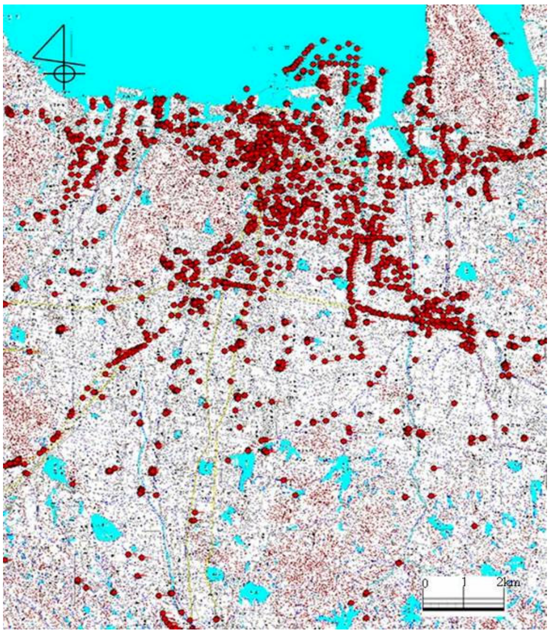
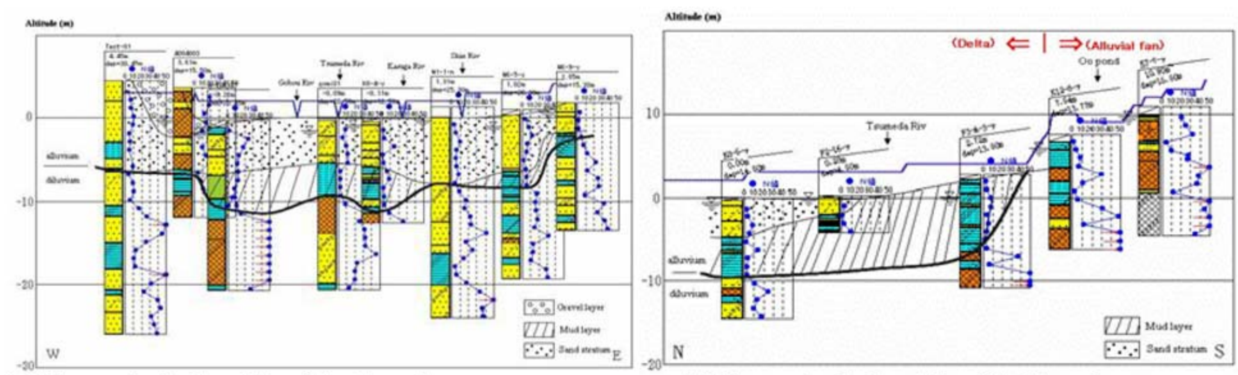


Figure 6. Locality of borehole logs in the Takamatsu plain



(a).The geological profile of A-A' section (b).The geological profile of B-B' section

Figure 7. The geological profile based on the borehole logs database (Locality of sections are shown in Figure 3)

Table 6 shows the standard horizontal seismic coefficient for the following two types of earthquake. Type-I earthquakes are a large-scale earthquake that occur in the plate boundary such as the 1923 Kanto Earthquake and 1946 Nankai Earthquake. Type-II are shallow inland earthquakes such as the 1995 Hyogoken-Nanbu Earthquake. We have used the horizontal seismic coefficient of Type-I earthquakes.

The regional correction coefficient has divided Japan into three regions (A, B, and C), prefecture, city, and county. Takamatsu City in Kagawa Prefecture is classified into regional division B. The regional correction coefficient of division B, C_Z, is 0.85.

Table 4. Typical solid property values (JRA, 1996)

Soil classification	γ_{sat} (kN/m^3)	γ_t (kN/m^3)	D_{50} (mm)	F_c(%)
surface soil	16.66	14.70	0.020	80
silt	17.15	15.19	0.025	75
arenaceous silt	17.64	15.68	0.040	65
silty fine sand	17.64	15.68	0.070	50
very fine sand	18.13	16.17	0.100	40
fine sand	19.11	17.15	0.150	30
medium sand	19.60	17.64	0.350	10
coarse sand	19.60	17.64	0.600	0
gravel	20.58	18.62	2.000	0
clay	16.66	14.70	0.010	0
out of object, sandy soil	19.11	17.15	0.000	0
out of object, rest	19.60	17.64	0.000	0
bedrock	20.58	18.62	0.000	0

Table 5. Criteria of liquefaction risk using P_L values (PWRI, 1981)

P_L value	Rank	Judgment of liquefaction occurrence
$15 < P_L$	A	A risk of the liquefaction is very high.
$5 < P_L \leq 15$	B	A risk of the liquefaction is high.
$0 < P_L \leq 5$	C	A risk of the liquefaction is low.
$P_L = 0$	D	A risk of the liquefaction is very low.

Table 6. Standard horizontal seismic coefficient (JRA, 1996)

Ground Type Classification	Earthquake	
	Type-I	Type-II
Class-I	0.30	0.80
Class-II	0.35	0.70
Class-III	0.40	0.60

LIQUEFACTION RISK OF TAKAMATSU CITY

The P_L-value of the paleo-liquefaction sites in the Takamatsu area shown in Figure 6. Figure 8 shows the borehole log data at the Faculty of Eng., Kagawa University (No.10, Kukoatochi in Table 2). This area is located on the eastern part of the Koto-fan and consists of loose sand of low-N-value near the surface. The P_L-value of this site is 21.32, and the liquefaction risk is classified as A. This estimation coincides with the evidence of the paleo-liquefaction.

About 1000 borehole logs were used for the calculation of the P_L-value. Figure 9 shows the liquefaction risk of the micro-topographic zone. Liquefaction risk is very high in the delta, the sand bank, natural levee and reclaimed land.

The liquefaction hazard map of Takamatsu city for the Type-I earthquake in shown in Figure 10. The study area is sectioned into meshes of 200m in width. In cases where there are several borehole logs and the result of the different liquefaction risk judgments are different, the highest P_L-value is adopted. The meshes which do not have corresponding borehole logs used the highest rate of liquefaction risk from micro-topography. The map suggests that the risk of liquefaction is very high in areas such as reclaimed land and deltas in the north of the Takamatsu plain. As the urban area is located on the delta and on reclaimed land, the liquefaction risk occurrence for future Nankai Earthquakes is a great threat to Takamatsu city.

CONCLUSION

To make the liquefaction prediction map of the Takamatsu plain the ground information database was built, using data from about 1500 boreholes. The ground information database was used to form a liquefaction prediction map, which assumes that a Nankai earthquake will occur in the near future. Earthquake motion is assumed from the liquefaction trace due to a historical (big) earthquake, and the risk of liquefaction was divided into four ranks from A to D based on P_L values. This judgment is reflected in the observation of ground water levels and ground classification by micro-tremor measurements. As a result, it turned out that the liquefaction risk was high in the following geographical features: reclaimed land and the salt fields in the surrounding coast areas and in the inland parts of the Sin river and Kasuga river. This area had few inhabitants during the historical Nankai earthquake, but is rapidly becoming urbanized, since the 1950s. For this reason, the study was used to show the possibility of a high risk of extensive liquefaction in Takamatsu city from a Nankai earthquake in the near future.

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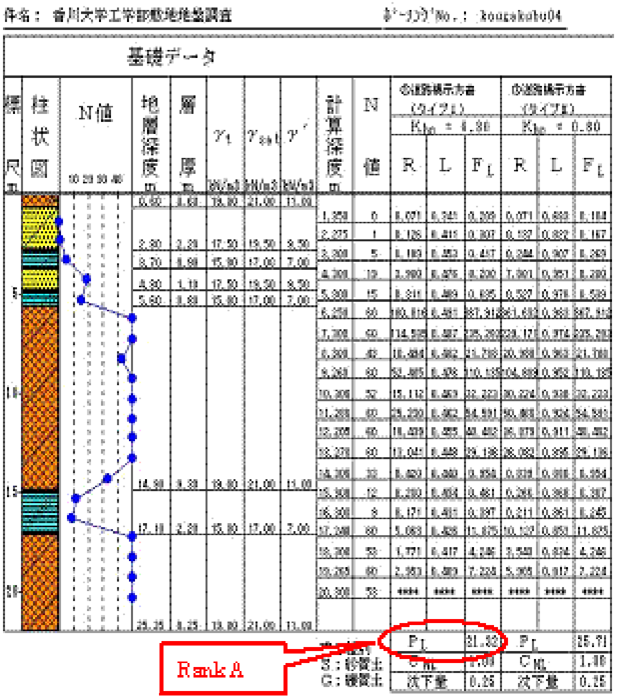

Figure 8. The P_L-value of area at Faculty of Eng., Kagawa University

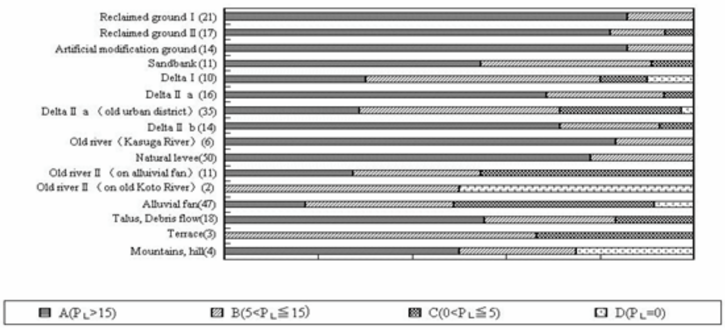

Figure 9. Liquefaction risk of micro-topographic zone

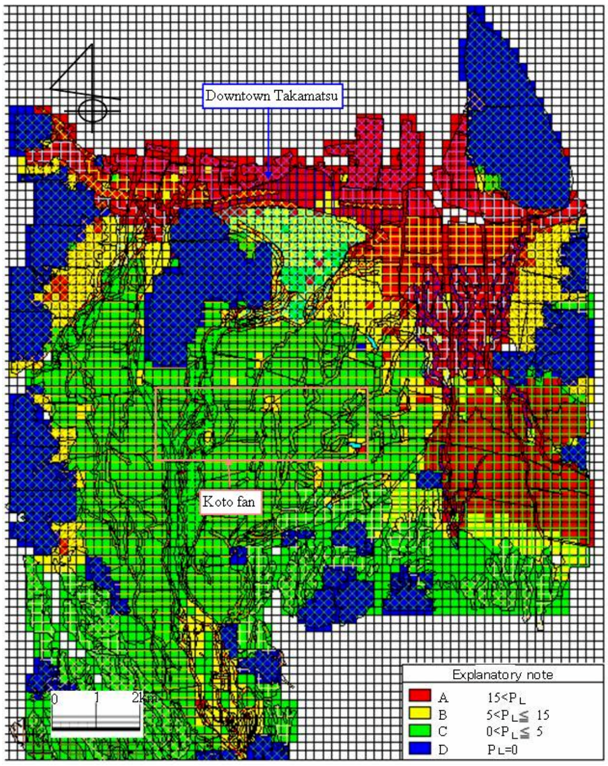

Figure 10. Liquefaction hazard map of Takamatsu city for the Type-I earthquake

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