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ROAD BRIDGE DAMAGE DUE TO LIQUEFACTION DURING LEVEL-2 EARTHQUAKE IN KOBE

Sub-Committee on Liquefaction by Level-2 Earthquakes, Japan Society of Civil Engineers
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ABSTRACT: Level-2 earthquakes such as the 1995 Kobe earthquake are defined scarce to occur during the lifespan of structures but necessary to consider by performance-based design. During the Level-2 earthquake, ground becomes more susceptible to liquefaction, resulting in larger settlement, uplifting and lateral spreading. With this back-ground in mind, the Committee for Liquefaction in the Level-2 Earthquake carried out data collections, sample analyses and made discussions based on them. Among major results obtained, the definition of liquefaction for Level-2 earthquake and case history studies on road bridge damage during level-2 Kobe earthquake are addressed.

Key Words: Liquefaction, Level-2 earthquakes, Performance-based design, Settlement, Lateral spreading, Road bridge foundation.

BACKGROUNDS

The 1995 Kobe earthquake posed a number of geotechnical problems on seismic design of urban civil structures mainly because it attacked areas which had not been considered highly seismic with unprecedented seismic intensity. We were thereafter obliged to redefine design seismic motions in two levels for non-nuclear civil structures, too (JSCE 1996);

Level-1 earthquake; Highly probable to occur once or twice during the lifespan of structures.

Level-2 earthquakes; Scarce to occur during the lifespan of structures but necessary to consider for designing those of particular importance from viewpoints of human lives and economy.

The Kobe earthquake is considered to be categorized as Level-2. Some of historically devastating earthquakes in Japan may belong to Level-2; they include 1891 Nobi earthquake (M_J=8.0), 1927 Tango earthquake (M_J=7.3), 1930 Kita-Izu earthquake (M_J=7.3), 1943 Tottori earthquake (M_J=7.2), 1948 Fukui earthquake (M_J=7.1). Recent overseas earthquakes as follows may also belong to the same category; 1994 Northridge earthquake in USA (M_W=6.7), 1999 Kocaeli earthquake in Turkey (M_S=7.4) and 1999 Chi-Chi earthquake in Taiwan (M_S=7.6).

The performance-based design for the Level-2 earthquakes was also proposed according to the importance and the required level of safety of specific civil structures considering several post-earthquake damage levels from total collapse to repairable damage. The performance-based design is increasingly employed in civil or architectural engineering in Japan. In the design, the evaluation of soil behavior such as ground settlement or horizontal displacement during strong earthquakes is critical to during and post-earthquake deformation of superstructures resting on it. In this context, soil liquefaction is really the problem. During the Level-2 earthquake, ground becomes more susceptible to liquefaction, resulting in large settlement, uplifting and lateral spreading.

Liquefaction susceptibility of sandy soils has been comprehensively studied in these three decades, disclosing most of its mechanisms. However, post-liquefaction behavior in order to evaluate settlement, uplifting and lateral spreading has hardly been understood. No reliable tool has been established for evaluating residual settlements, uplifts or lateral displacements in liquefied ground. Not only the post-liquefaction soil behavior but also soil-structure interaction or soil-pile interaction for structures resting on liquefied ground is still least understood for reliable design. It is immensely important therefore for employing the performance-based design to understand post-liquefaction soil behavior or soil-structure interaction in liquefied ground during Level-2 strong earthquakes. With this back-ground in mind, the Committee for Liquefaction in the Level-2 Earthquake set 4 major topics concerning liquefaction behavior during Level-2 earthquakes to be discussed in 4 individual Working Groups.

WG-1: Characterization of liquefaction during Level-2 earthquakes from viewpoints of soil behavior and laboratory tests.
WG-2: Characterization of liquefaction-related damage during Level-2 earthquakes
WG-3: Soil-pile interaction in dense sand liquefied during Level-2 earthquakes.
WG-4: Effect of soil compaction as a liquefaction countermeasure during Level-2 earthquakes.

Data collections, sample analyses and discussions were carried out by the working group members. Among major results obtained, the definition of liquefaction for Level-2 earthquake and case history studies on road bridge damage during level-2 Kobe earthquake are addressed here more in detail.

DEFINITION OF LIQUEFACTION FOR LEVEL-2 EARTHQUAKES

Under very strong motions of the Level-2 earthquakes, not only loose sands, loose non-cohesive silts or loose gravels but also dense sands, dense gravels or cohesive soils may build up excess pore-pressure and be considered as potentially liquefiable soils. Cyclic mobility in dense sands and gravels, cyclic softening in cohesive soils and other related phenomena are to be considered in definition of the term "*liquefaction*". The followings are the terminology the Committee proposes for describing liquefaction related phenomena for the Level-2 earthquakes.

1) The term "*liquefaction*" is classified into "*liquefaction in strict definition*" and "*liquefaction in broader definition*". The former should be named simply "*liquefaction*" in the geotechnical profession.
2) "*Liquefaction in strict definition*" means that loose cohesionless soils; sands or gravels develop 100% pore-pressure build-up due to seismic cyclic loading or other causes, lose the shear resistance and eventually behaves like liquid with flow potential.
3) "*Liquefaction in broader definition*" means that a variety of soils such as dense sands, dense gravels or even cohesive soils develop excess pore-pressure due to cyclic loading or various causes and lose a part of strength or stiffness leading to hazardous settlement or deformation. Not only saturated soils but also unsaturated soils, though its mechanism is still poorly understood, have a potential for liquefaction in this category.

CASE HISTORY OF ROAD BRIDGE DUE TO LIQUEFACTION DURING KOBE EQ.

Introduction

Since the 1995 Kobe earthquake, quite a few case history studies have been carried out in structural or geotechnical aspects for various facilities. However, comprehensive studies covering performance of superstructures and substructures during and after soil liquefaction have not been carried out so much. In the Committee, the performance of buildings, tanks, bridges, etc. during the Kobe earthquake has been focused on in the light of geotechnical or substructural characterization. In this paper, the performances of road bridges are specifically discussed among other facilities. The performance of buildings is discussed in other

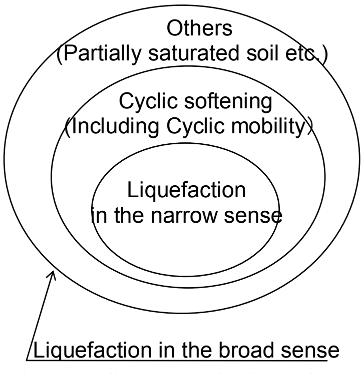


Fig.1 Definition of "*liquefaction*"

literature (Wakamatsu and Numata 2004).

Locations of Road Bridges and their damage.

Fig.2 shows the locations of road bridges investigated and their features of damage to superstructures as well as to the foundations. All the bridges belong to Route No.3 (Kobe Route) or Route No.5 (Coast Route) of the Hanshin Express Way Corporation; the former passes through inland stiff soil ground while the latter passes through soft reclaimed lands along the coast line. The design of Route No.3 was based on an old version of the bridge design code in 1964, in which liquefaction and lateral bearing capacity of piles were not considered, while that of Route No.5 was made based on the newer one of either 1980 or 1990.

Route No.3 suffered considerable damage in superstructures such as fallen bridge girders and collapsed or tilted piers whereas the influence on the foundations was relatively minor. The foundation ground was mostly stable without liquefaction and only small cracks and settlement occurred.

In contrast, extensive liquefaction took place along Route No.5 causing lateral spreads and lateral pile displacements of bridge piers near shorelines retained by concrete caissons. This caused considerable damage in bridge foundations but only minor damage in superstructures in general except for some long span bridges. The 80% of Route No.5 was of pile foundations, most of which was cast in place piles of 1.5-2 m diameter. During the Kobe earthquake, liquefaction took place almost exclusively in decomposed granite soils (locally named Masa Soil) of reclaimed ground along coasts or in man-made islands. This should be borne in mind in considering liquefaction in the Kobe earthquake.

Damage level

Table 1 shows the damage classification of bridge foundations, **a** to **d** corresponding to the degree of damage. This classification in the present study was originally used in the Road Bridge Earthquake Countermeasures Committee of the Kobe Earthquake and also based on the Handbook on Earthquake Countermeasures of Roads (Restoration Volume). Table 2 shows similar damage classifications for superstructures. The damage survey was centered on bridge foundations with greater damage, though some of those without significant damage were also investigated by random sampling. In addition to

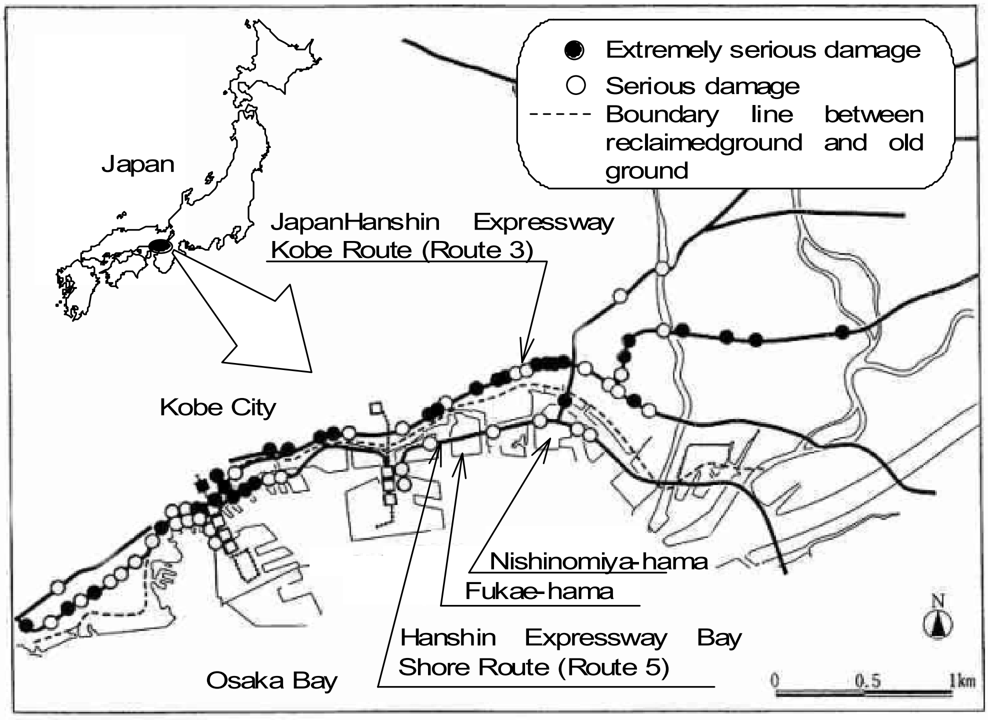


Fig.2. Location of investigated highway bridges and damage of piers and superstructures

Table 1 Categorization of damage to pile foundation

Damage Degree	Definition
a	Settlement of the foundation accompanied by considerable residual horizontal displacement
b	Considerable residual horizontal displacement of the foundation Bending cracking of the pile body
c	Minor bending cracking of the pile body
d	No damage to the pile on slight bending cracking

Table 2 Categorization of damage to pier

Damage Degree	Definition
As	Collapsed. Extremely serious damage or deformation.
A	Cracking, buckling, broken reinforcement, or similar damage, or serious deformation.
B	Partial buckling of reinforcement or deformation of members. Partial breakage or bulging out of reinforcement, and partial peeling and cracking of the protective concrete covering.
C	Localized light buckling or deformation of reinforcement. Cracking or localized peeling of the protective concrete covering.
D	No damage, or if there is, extremely minor damage that will not effect the load bearing capacity.

Table 3 Damage degree to pile foundations (Number of piers)

Road	Damage Degree									
	a		b		c		d		totals	
No.3 Kobe line, Hanshin Expressway	0	(0%)	0	(0%)	17	(16%)	92	(84%)	109	(100%)
No.5 Bay Shore Line, Hanshin Expressway	0	(0%)	17	(11%)	57	(37%)	79	(52%)	153	(100%)

non-destructive impulse wave test, bore holes were drilled in piles and their inner walls were scanned by bore-hole cameras. Table 3 summarizes the number of damage of pile foundations. In Route No.5, relatively serious damage of class-b comprising about 10% of the total number took place by large lateral ground displacement caused by liquefaction induced lateral spread near collapsed retaining sea walls in reclaimed lands. The rest of the pile foundations suffered relatively minor damage with small fissures or no damage particularly in Route No.3. It is also noted that the most serious damage of class-a, associated with large settlement and lateral displacement at the same time, was not found despite extensive liquefaction and spreading.

Liquefaction Susceptibility and Damage Characterization

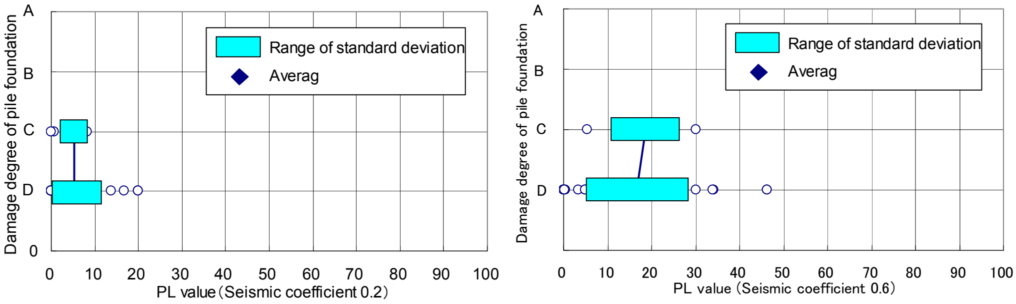
In order to investigate a relationship between the intensity of liquefaction and the degree of damage, a parameter P_L was introduced by integrating the liquefaction resistance F_L multiplied by the weight of depth as;

$$P_L = \int_0^{20} (1 - F_L)(10 - 0.5z)\,dz$$

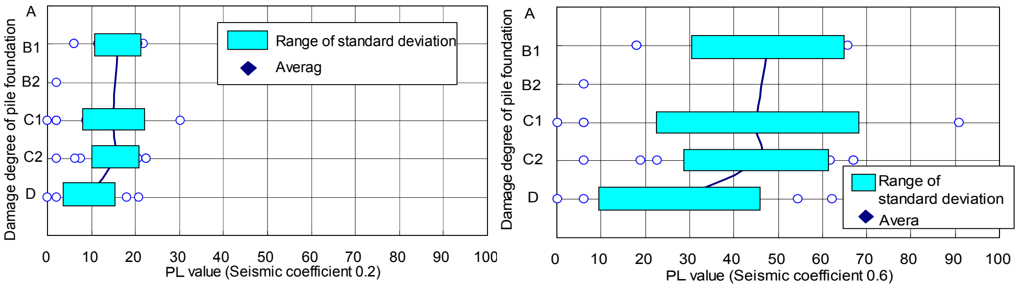
$$F_L = R/L$$

where R =shear strength ratio, L =seismic shear stress ratio and z =depth in meter. P_L is considered to represent the intensity of liquefaction so that $P_L \leq 5$ and $P_L \geq 15$ generally indicate minor and serious damage, respectively. P_L was evaluated for two seismic intensities k=0.2 corresponding to the Level-1 earthquake and 0.6 corresponding to the Level-2 earthquake.

Fig.3 indicates a relationship between the damage class of the road bridge and the P_L-value in terms of



(a) Hanshin Expressway Kobe Route (Route 3)



(b) Hanshin Expressway Bay Shore Route (Route 5)

Fig.3 Relationship between damage degree of pile foundation and P_L value

average values and standard deviations. Route No.3 (Fig.3(a)) shows small P_L-values or large resistance against liquefaction. P_L-values are small not only for k=0.2 but also for k=0.6 because the ground mostly consisted of medium dense soils. P_L-values for k=0.6 are evaluated slightly over 15 however no liquefaction occurred actually and the damage class were c or d. Route No.5 (Fig.5(a)) mostly shows larger P_L-values exceeding 15 for k=0.2, indicating much higher liquefaction susceptibility. For k=0.6 P_L-values far exceeded 15, being consistent with the occurrence of the damage class b and c.

Fig.4 shows a relationship between the damage classes of piles and bridge piers. In Route No.3 (Fig.4(a)), serious damage in piers occurred continuously in a few hundred meters where the total super structure was collapsed down, in contrast to minor damage in piles. This may indicate that less-liquefiable soil actually transmitted larger seismic inertia force to bridge piers, which collapsed without applying excessive bending moments to foundation piles. In Route No.5 (Fig.4(b)), most bridge piers suffered far lighter damage than foundations except some piers supporting Higashi-Kobe-Ohashi and others where the damage class was B. Route No.5 passes mostly through reclaimed land where extensive liquefaction and pile damage by kinematic effect of liquefied ground resulted in smaller seismic excitation of bridge piers and saved the superstructures. The similar trend can also be found in private houses in that liquefaction or foundation damage resulted in minor superstructure damage while heavier damage in houses is accompanied by minor foundation damage.

Foundation damage due to lateral spreading

Pile damage due to lateral spread in liquefied ground was investigated inland and in the vicinity of seawalls. Fig.5 indicates distribution of cracks along depth in piles of inland and near seawalls for Route No.5. In this figure, the number of cracks are summed up in every 1 m depth interval for each bridge pier and compared with typical soil profiles there. The cracks include both separate cracks indicated with dotted lines and non-separate cracks.

Near seawalls shown in Fig.5(a), cracks concentrates within 1 m from the top but also spreads in the upper part of Layer B. Cracks also concentrates in 4 m interval near the boundary between B and Ac. A smaller number of cracks are also found near the boundary between Dsg nd Dg.

In the inland areas shown in Fig.5(b), the cracks distribute in the similar manner although they are more

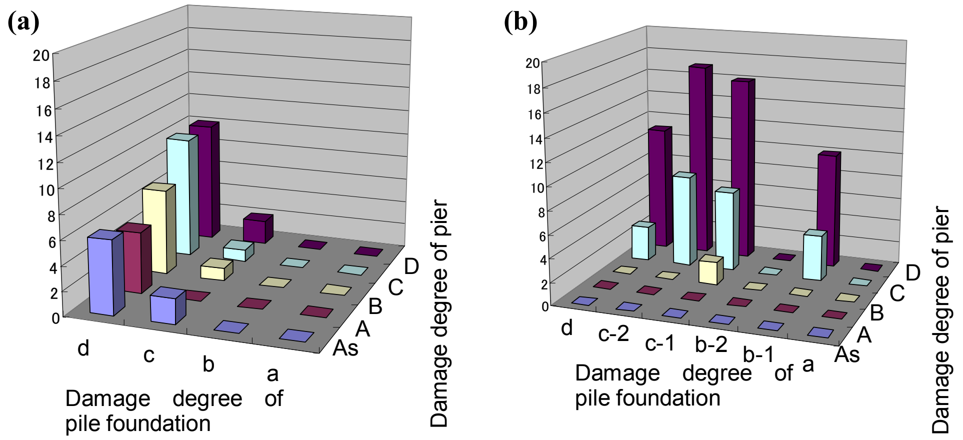


Fig. 4 Relationship between damage degree of pile foundation and pile

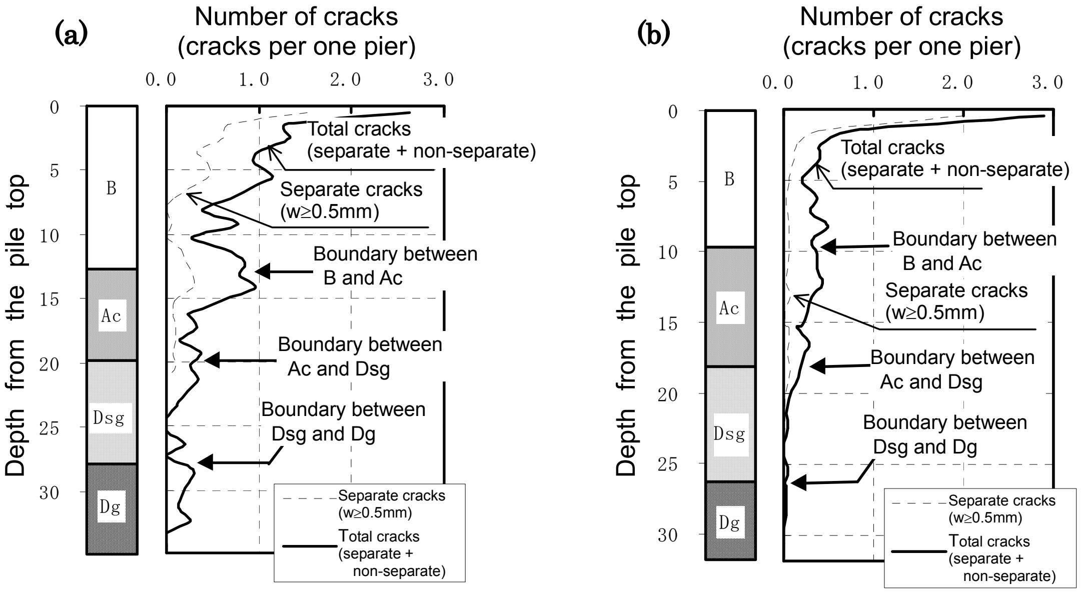


Fig.5 Relationship between depth and number of cracks of pile foundation

concentrated in the pile top than the boundary between B and Ac. This indicates that the effect of lateral spreading is dominant near seawalls, inducing larger bending moment in deeper sections of piles.

The pile damage mechanism may be explained in two ways; firstly by inertia effect of superstructures as well as kinematic ground deformation during earthquake shaking and secondly by ground deformation due to lateral spreading mostly after shaking. Cracks at the pile tops were commonly found both inland and near seawalls, indicating that the inertia effect of the superstructure prevailed everywhere.

Fig.6 shows the total amount of crack openings per a pile plotted versus the shortest distance of piles from the shoreline. The total crack opening is evidently larger within 200 m distance from the shoreline, indicating a greater effect of lateral spreading near the shore. In areas more distant from the shore, lateral spreading does not seem to affect the performance of piles.

Foundation damage without lateral spreading in liquefied ground

Foundation damage in areas more than 400 m far from the shoreline where the effect of lateral spreading seems minimal according to Fig.6, was investigated to understand its causes. Fig.7 shows the locations of bridge piers in Nishinomiyahama and Fukaehama investigated here, where the maximum accelerations

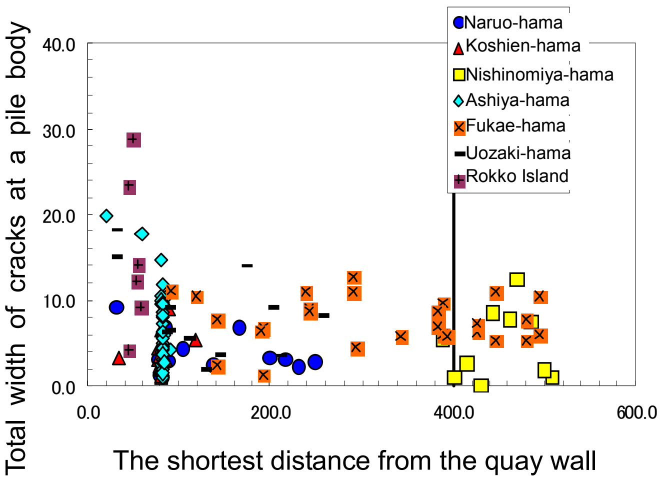
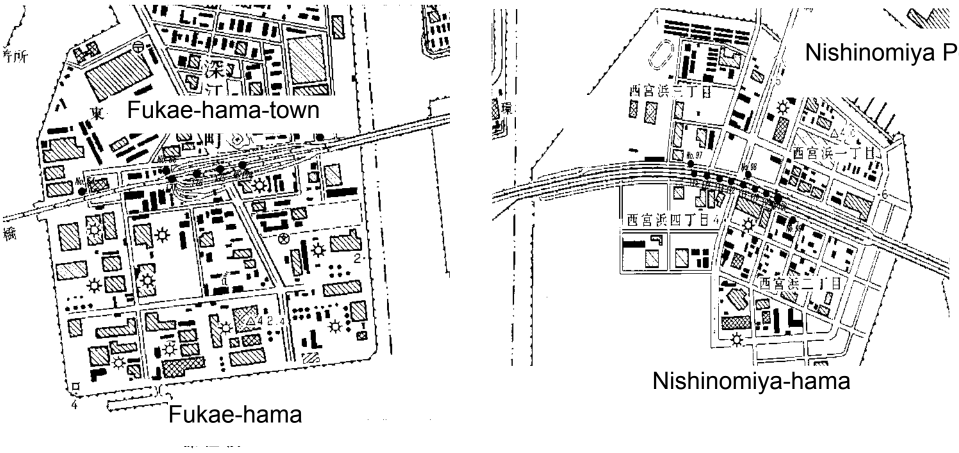


Fig. 6 Relationship between the distance from the quay wall and total width of cracks at a pile body



（a） Fukae-hama (570gal)　　（b） Nishinomiya-hama (490gal)

Fig.7 Location of pier not affected liquefaction-induced ground displacement

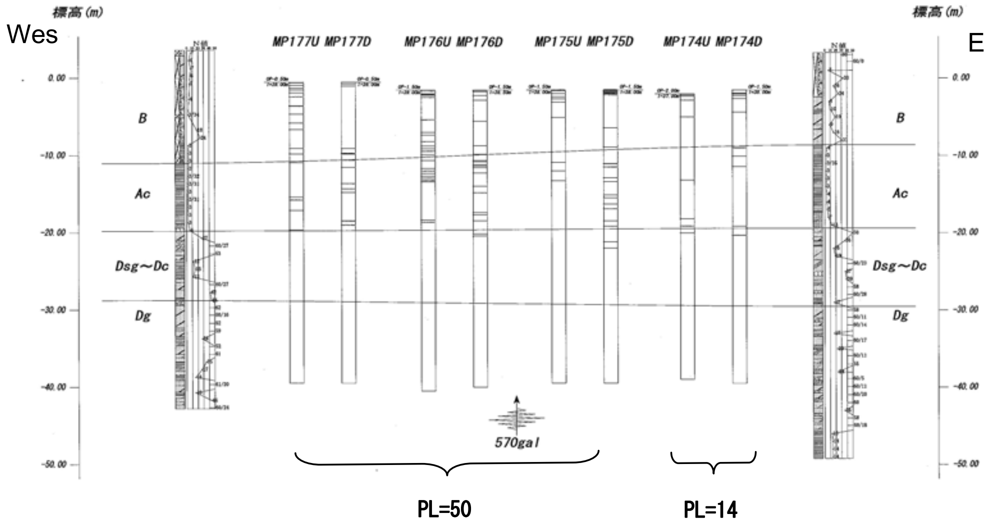
were 490 cm/s^2 and 570 cm/s^2, respectively. Fig.8 depicts crack distributions of piles in the areas. This indicates that piles suffered more cracks in Fukaehama where the acceleration was larger. The difference is more evident in Layer Ac (Alluvial clay) despite almost the same soil and structural conditions, implying that the larger acceleration exerted larger shear strain in the soft clay layer which caused more cracks in the piles. The same figure also indicates that the degree of damage tends to be greater for larger P_L- values in Fukaehama. No such correlation can be seen in Nishinomiyahama, where the foundation damage was lighter despite the appearance of larger number of sand boils.

SUMMARY

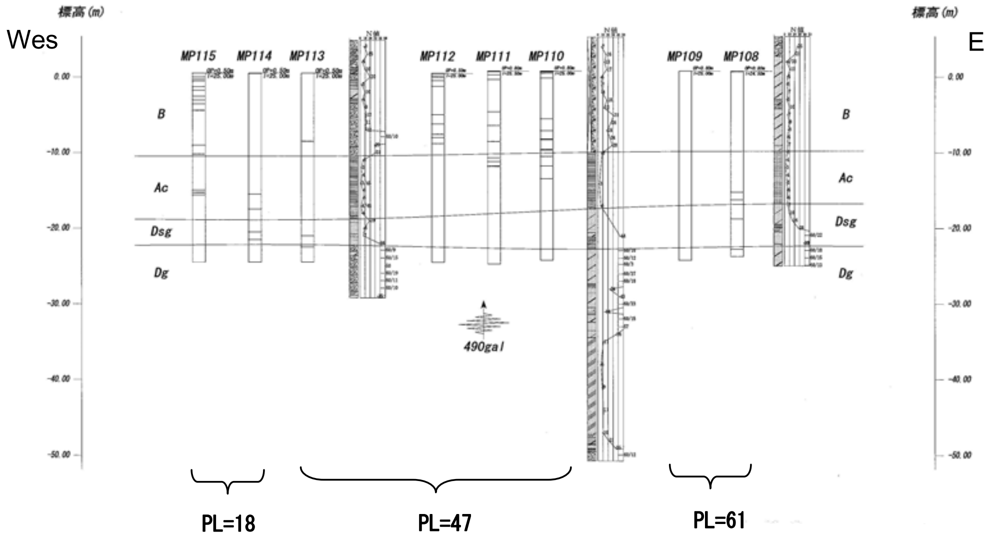
(1) Considering significant effects of Level-2 earthquakes, it is proposed that the term "*liquefaction*" be defined in strict meaning and in broader meaning. In the strict meaning, sand behaves like liquid with flow potential.

(2) Damage data base of road bridges indicates that pile foundations in highly liquefiable ground with large PL-values under Level-1 earthquakes is more prone to damage under Level-2 earthquakes if P_L-values are larger. Piles in less liquefiable soil with small P_L-values under Level-1 earthquakes are less susceptible to damages under Level-2 earthquakes even if P_L-values are as large as 15.

(3) It is demonstrated from damage data during the Level-2 Kobe earthquake that superstructures such as road bridges or houses tend to suffer lighter damage by earthquake shaking if the foundations deteriorates



(a) Fukae-hama



(b) Nishinomiya-hama (490gal)

Fig.8 Distribution of cracks in pile body

road bridges or houses tend to suffer lighter damage by earthquake shaking if the foundations deteriorates due to liquefaction or structural failures. In contrast, foundations tend to suffer little damage if superstructures are heavily damaged.

(4) Piles near retaining seawalls are prone to heavier damage in deeper sections due to lateral spreading in liquefied ground. This effect seams dominant within 200 m and ignorable in areas further than 400 m from the shoreline.

(5) Piles of inland seam to have suffered more heavily under larger acceleration in alluvial clay layers underlying liquefied reclaimed soil if compared in two different areas.

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