RECONNAISSANCE REPORT ON THE EARTHQUAKE IN OSAKA-FU HOKUBU ON JUNE 18, 2018

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Key Facts:
- Hazard Type: Earthquake
- Date of the disaster: 18 June 2018
- Location of the survey: Takatsuki City, Ibaraki City, Suita City, Osaka City
- Date of the field survey: June 2018
- Survey tools: Digital camera, GPS, Laser Rangefinder, Tape measure
- Key findings:

(1) Strong shaking of JMA seismic intensity 6^{-} was observed, however, there was not destructive damage to buildings and infrastructures.
(2) Pulse-like ground motions were recorded near the source fault, Takatsuki and Ibaraki cities.
(3) Damage due to liquefaction was minor as observed in both the field investigation and numerical analysis with the recorded motion.
(4) This earthquake was a moderate earthquake, but the supply of water and gas was stopped over a wide range.
(5) Osaka monorail required time to completely recover because of failure of the monorail switches to move the complicated monorail lines.
(6) Three people were killed by falling furniture or objects, and two people by collapse of block walls.

Key Words: *earthquake in Osaka–fu Hokubu on 18 June 2018, reconnaissance report, earthquake ground motion, source effect, lifeline damage, civil life*

1. INTRODUCTION

A large earthquake with a magnitude determined by the Japan Meteorological Agency (M_J) of 6.1 occurred in northern Osaka Prefecture at 7:58 on June 18, 2018. The epicenter was located at 34.8°N, 135.6°E at a depth of approximately 13 km.[1)] This earthquake caused strong shaking measured at a Japanese seismic intensity of 6^{-} (JMA seismic intensity scale, hereinafter referred to as JMA seismic intensity) in the Kita Ward of Osaka City, Takatsuki City, Ibaraki City, Minoh City, and Hirakata City, led to five deaths, fully or partially destroyed 285 buildings, and caused physical and functional damage to lifeline systems including railways and roads.[2] Rail and road services were disrupted over a wide area, which posed serious social problems, particularly with regard to commute times.

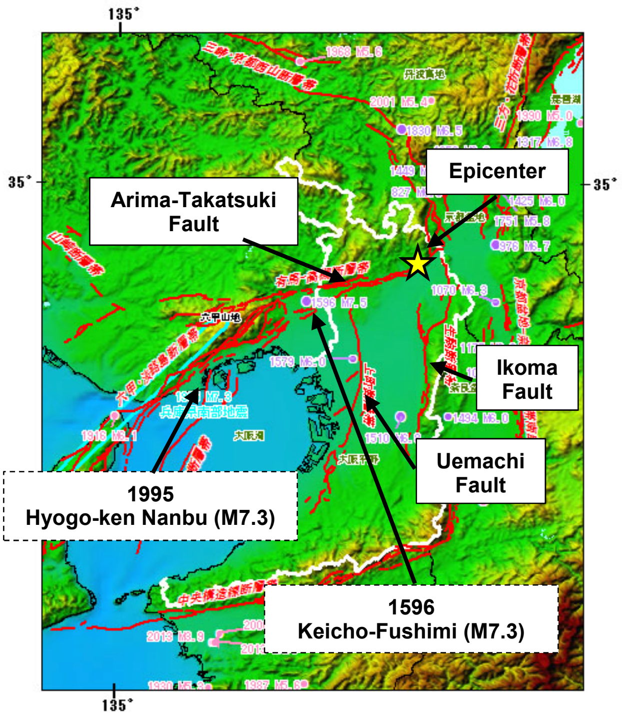

Fig.1 Active faults in the Kinki region and large historical earthquakes (processed from reference[3])

Intra-plate active faults are particularly dense in the Kinki region. Because the epicenter of this earthquake was surrounded by several fault zones (e.g., Arima-Takatsuki, Uemachi, and Ikoma), an earthquake of magnitude class 7 is likely to occur if any of these faults rupture, even though the probability of such an earthquake is not particularly high.[3] Previous intra-plate earthquakes have caused severe damage in Osaka Prefecture, including the 1596 Keicho Fushimi earthquake, 1891 Nobi earthquake, 1927 Kita-Tango earthquake, and 1995 Hyogo-Ken Nanbu earthquake (Kobe Earthquake). Large earthquakes along the Nankai Trough include the 1707 Houei earthquake, 1854 Ansei Tokai earthquake, 1944 Tonankai earthquake, and 1946 Nankai earthquake (**Fig. 1**) [3].

The 1995 Hyogo-Ken Nanbu earthquake was a typical intra-plate earthquake that caused numerous earthquake-induced disasters. More than 6,000 people died and more than 40,000 were injured, approximately 110,000 houses were destroyed and 147,000 partially destroyed, electricity, gas, water, and telecommunication facilities were completely destroyed, and many road and railway bridges collapsed. Following the 2011 Off the Pacific Coast of Tohoku Earthquake, which was an inter-plate earthquake, a tsunami caused large-scale human and physical damage, and severe ground motion (JMA seismic intensity 7) was observed in Tsukidate City, Miyagi Prefecture, close to the epicenter. Large peak accelerations were also observed across the Tohoku and Kanto regions. Long-duration and long-period ground motion was also observed in areas far from the epicenter, including the Tokai, Chukyo, and Kansai regions. Owing to the strong fault activity and intensity of earthquakes and earthquake-induced catastrophes in Japan, it is urgently necessary to consider all aspects of such hazards, which will undoubtedly occur again in the near future. This is particularly true for the Kansai region, where both inter-plate and intra-plate earthquakes can occur at any time, we must obtain valuable information and insight from the inland earthquakes of Hyogo-Ken Nanbu and Osaka-Fu Hokubu.

To address this problem, the Kansai branch of the Japan Society of Civil Engineers organized a reconnaissance team immediately after the Osaka-Fu Hokubu earthquake and conducted an emergency disaster investigation. Here we report the reconnaissance activities and obtained findings, including a description of surveyed ground motion, liquefaction, damage to lifelines, and influence on society.

2. OUTLINE OF EARTHQUAKE AND DAMAGE

On June 18, 2018 in northern Osaka Prefecture, M_J6.1 ground motions with a JMA seismic intensity of 6^- were observed in six cities (Kita Ward in Osaka City, Takatsuki City, Ibaraki City, Minoh City, and Hirakata City) with peak accelerations of the north–south, east–west, and up–down components recorded by K-NET Takatsuki of 512, 794, and 238 cm/s^2, respectively. **Fig.2** shows the EW-component acceleration response spectra from Takatsuki City and three cities in Osaka and Hyogo Prefecture (Higashi-yodogawa Ward in Osaka City, Toyonaka City, and Nishinomiya City) at differing distances from the epicenter.

Takatsuki City (blue line in **Fig.2**) had the most severe response, with a period of 0.2–0.4 s. The frequency component from Higashi-yodogawa Ward in Osaka City was similar to that in Takatsuki City, but the amplitude was considerably smaller. The predominant periods of Toyonaka City and Nishinomiya

City are estimated to have been 0.6 and 0.4 s, respectively. The spectra show an apparently complicated relationship with ground conditions and distance from the epicenter.

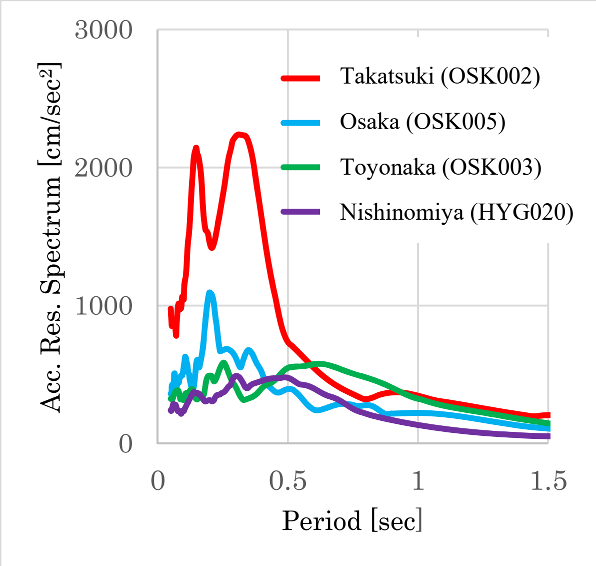

Fig.2 Response spectra of four cities for the Osaka-Fu Hokubu earthquake

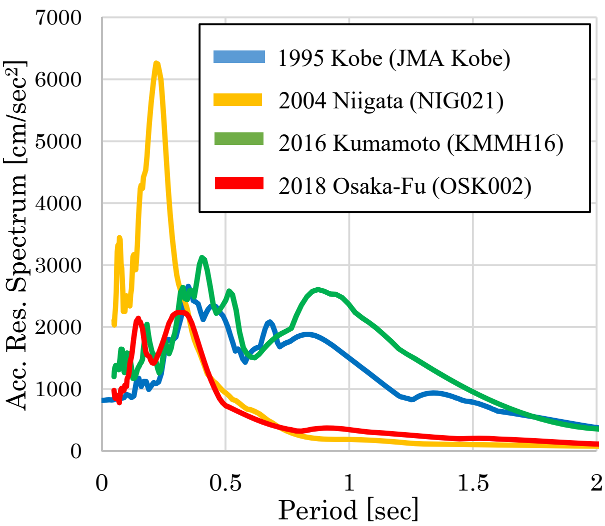

Fig.3 Comparison of response spectra of past earthquakes

Fig.3 compares the acceleration response spectra of K-NET Takatsuki and those of past destructive earthquakes, including those obtained at observation sites of the Kobe Marine Meteorological Observatory from the 1995 Hyogo-Ken Nanbu earthquake, Tokamachi data from the 2004 Niigata Ken Chuetsu earthquake, and Mashiki data from the 2016 Kumamoto earthquake. The horizontal component of the observed records, which shows the maximum acceleration, was used to calculate the response spectrum with a 5% damping factor. The dominant frequency range of Takatsuki City (red) and Tokamachi (yellow) are similar, but their amplitudes are several times different. In comparison with the Kobe Marine Meteorological Observatory (blue) and Mashiki (green), the ~1 s components, which cause serious damage to wooden houses, of the Osaka-Fu Hokubu earthquake differ greatly from those of the other records. However, this earthquake still caused five deaths, extensive building damage, and material and functional damage to lifelines including railways and roads. **Table 1** lists the human and building damage extracted from statistical data [1)] of the Fire and Disaster Management Agency.

Table 1 Casualties and building damage due to the Osaka-Fu Hokubu earthquake

(as of Feb 12, 2019)

Prefecture Name	Casualty			Residential Building			Non-residential Building	
	Fatality	Injury		destroyed	half destroyed	Partially damaged	Public	Others
		serious	slight					
	number of persons			number of houses				
Mie		1	1					
Shiga			3			3		
Kyoto		1	24		9	3,323	17	3
Osaka	6	56	329	20	443	53,368	708	22
Hyogo		4	38	1	2	152	32	
Nara			4			27		
Tokushima			1					
Total	6	62	400	21	454	56,873	757	15

An outline of the damage and lifeline restoration, including railways and roads, is given as follows and described in greater detail in sections 5 and 6.

- ✓ Electricity: Maximum of 170,000 power outages in the immediate aftermath. Resolved at 10:43 on June 18.
- ✓ Gas: The supply stopped owing to an automatic shutdown of the medium- to low-pressure governor for 111,951 units. Supply obstruction was resolved at 22:00 on June 24.
- ✓ Water supply: Destruction occurred in some old pipelines including the Hirakata pipe bridge air valve and Takatsuki City water pipe. All water cutoffs were resolved by June 19. Takatsuki City's water outage or pressure reduction affected a maximum of 194,000 people (86,000 residences) and was resolved by 15:00 on June 19. The water cutoff affected a maximum of 20,000 people (0.8 million units) in some areas of Minoh City was resolved by 16:00 on June 19. The Suita shutdown in Suita City affected 30 houses and was resolved by June 18.
- ✓ Railway/Road: Many of the railway companies in the Kansai area were forced to cease

operations owing to the excess shaking above the reference seismic intensity. Highway companies also blocked all lines or partial sections. A considerable amount of time was spent on inspection and restoration. The Osaka monorail suffered damage, including splitter damage, insulator breakage, vehicle stabilization wheel damage, and rubber block damage, but all lines eventually resumed operation on June 25.

3. GROUND MOTION

The Osaka-Fu Hokubu earthquake was an inland crustal earthquake of *Mj*6.1 (*Mw*5.6) with an epicenter near Takatsuki City (**Fig. 4**). There are numerous active faults in the area, including the Arima-Takatsuki, Ikoma, and Uemachi fault zones near the epicenter. However, the evaluation by the Earthquake Research Promotion Headquarters did not present any conclusions regarding the relationship between the earthquake and these fault zones. [4]

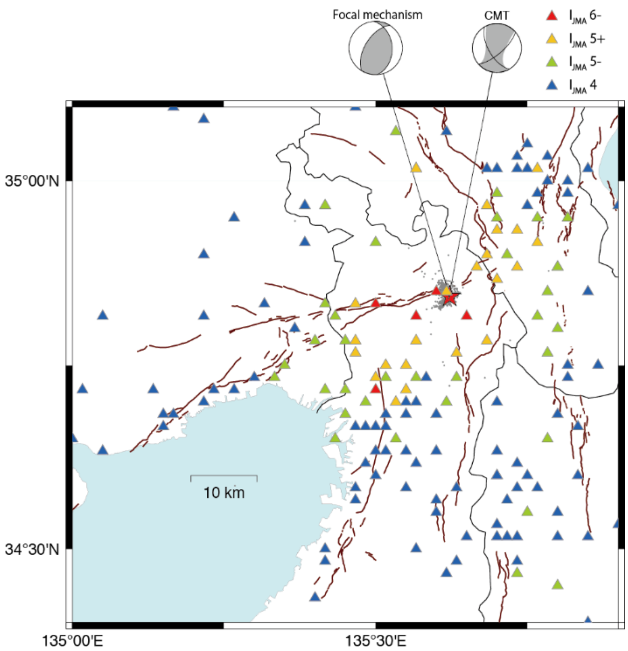

Fig.4 Distribution of the epicenter, focal mechanism, and seismic intensity of the Osaka-Fu Hokubu earthquake. The red lines show the surface trace of the active fault [6] and the gray dots shows the distribution of aftershocks the following day

The initial focal mechanism shows that rupture occurred on a reverse fault via east–west compression with a north–south strike direction. The centroid moment tensor (CMT) solution shows that it is a right-lateral strike-slip fault with a non-double couple component, even though the compression axis is east–west. This means that multiple fault planes ruptured. Reverse fault motion first occurred north of the source, followed by a strike-slip fault rupture south of the initial source. Detailed aftershock data show aftershocks distributed on the eastward-inclined surface in the north and nearly vertically on the south side.[5] This implies that the reverse fault is north of the ruptured fault and the strike slip fault is to the south.

Strong ground motion owing to the earthquake was observed mainly in the Hokusetsu region. A maximum seismic intensity of 6^- was observed in Takatsuki City, Ibaraki City, Hirakata City, Minoh City, and Kita Ward in Osaka City. The area with a seismic intensity of 5^+ spread elliptically, with its long axis in the northeast–southwest direction (**Fig.4**).

Fig.5 shows the horizontal peak velocity at the seismic observation point near the epicenter, covering the records of the K-NET, National Meteorological Agency Seismic Intensity Meter, Committee of Earthquake Observation and Research in the Kansai Area (CEORKA), Osaka prefectural seismic intensity meter, and Osaka monorail at the Expo Base station. The aftershock distribution for one day following the mainshock is also shown, which represents the fault extent that was destroyed at the time of the mainshock. The Takatsuki observation point of the Meteorological Agency is located just above the fault; however, observation points not above the source recorded a larger horizontal peak velocity.

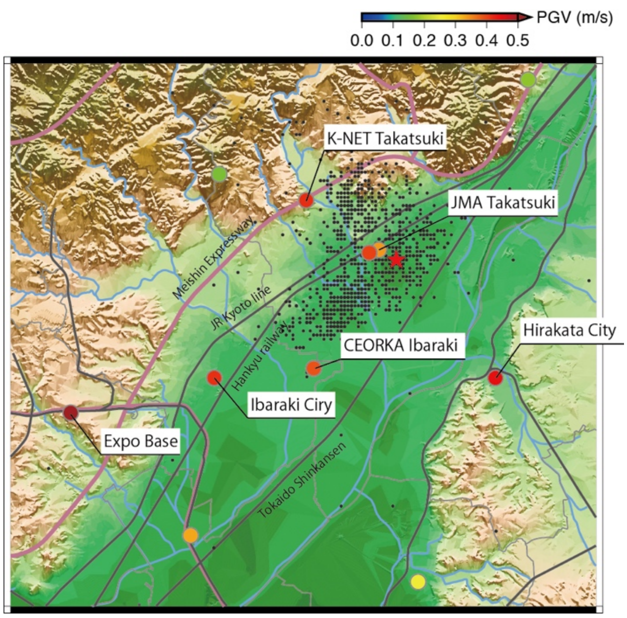

Fig.5 Seismic observation point near the source and horizontal peak velocity. The black dots show the distribution of aftershocks for the day following the mainshock.

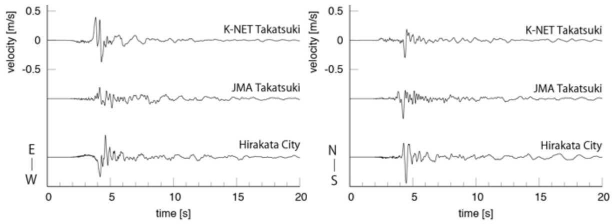

Fig.6 Velocity time histories (Takatsuki-Hirakata trace)

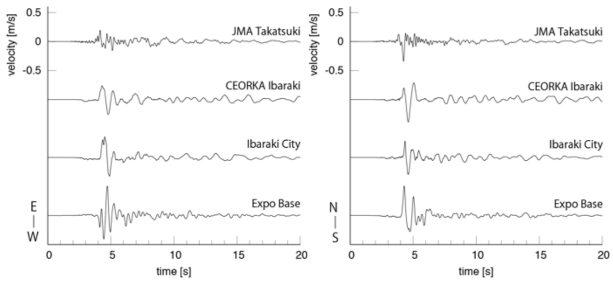

Fig.7 Velocity time histories (Takatsuki-Ibaraki trace).

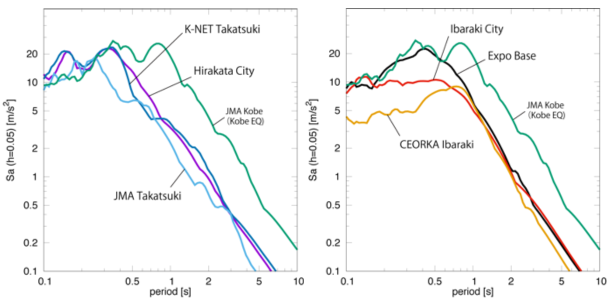

Fig.8 Acceleration response spectrum (damping ratio of 5%)

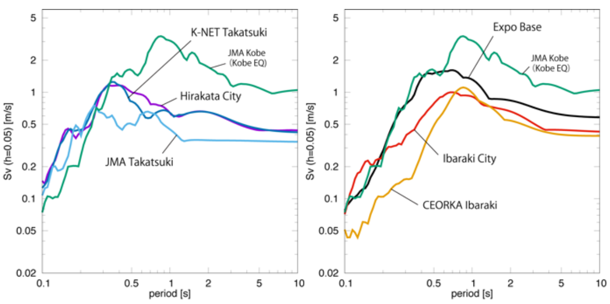

Fig.9 Velocity response spectrum (damping ratio of 5%)

For example, peak velocities of 42 cm/s were recorded at K-NET Takatsuki, 39 cm/s at CEORKA Shirakawa in Ibaraki City, 45 cm/s at Ogaki in Hirakata City, and 42 cm/s at Higashichujo in Ibaraki City, in addition to 57 cm/s at the Osaka Monorail Expo Base station.

Fig.6 shows the velocity waveforms observed from Takatsuki to Hirakata. This is a trace that roughly follows the extension of the earthquake source fault, which is a thrust fault. Each case shows notable short-duration pulsed seismic motion in the north–south component. In K-NET Takatsuki, the S-wave of the east–west component arrives earlier, which highlights the influence of the radiation characteristics owing to the reverse fault. The east–west components from Hirakata City and K-NET Takatsuki appear to be reversed in phase, which can be explained by the radiation characteristics of the right-lateral strike-slip fault. This implies that the K-NET Takatsuki data represent complex earthquake motion affected by the radiation characteristics of both the reverse fault and right-lateral strike-slip fault.

Fig.7 shows the velocity waveforms observed from Takatsuki to Ibaraki. This is a trace roughly along the extension of the earthquake source fault, which is a right-lateral strike-slip fault. The pulse at CEORKA Ibaraki was slightly wider than those shown in **Fig. 6**, but similar pulses were also observed in Higashichujo in Ibaraki City and the Expo Base, thus it is considered to have been influenced by the source mechanism rather than the site conditions. Moreover, the east–west components at the Expo Base appear to have been affected not only by the strike-slip fault but also by the site condition because the frequency component record differs from the others and the phase seems to be inverted.

Fig.8 shows the acceleration response spectra with a damping ratio of 5%, as well as the spectrum from the JMA Kobe marine meteorological station (JMA Kobe) during the Hyogo-ken Nanbu earthquake. In the Takatsuki-Hirakata trace recording (**Fig.6**), the components of the period up to 0.5 s were predominant. The response in that periodic band corresponded to the JMA Kobe wave. The response decreased when the period exceeded than 0.5 s. On the Ibaraki side of the Takatsuki-Ibaraki trace (**Fig.7**), a flat acceleration response is shown with a period of up to approximately 0.8 s. The Expo Base data show a similar response as the JMA Kobe wave for periods slightly above 0.5 s. Differences in the periodic components of such earthquake motions are more clearly seen in the velocity response spectra (**Fig.9**). In K-NET Takatsuki and Hirakata City, the velocity response around 0.4 s was predominant, whereas in the Expo Base and Ibaraki City, the response of period 0.6–0.8 s dominated. In the case of pulsed waves, as in this earthquake, differences in the predominant period of seismic ground motions are thought to be related to rupture directivity. However, further detailed analysis of such fault rupture processes is necessary.

As shown in **Fig.5**, spatially dense earthquake records were obtained from this earthquake, but these may not be sufficient to investigate the earthquake ground motion distribution in detail. We therefore surveyed the falling rate of tombstones from Takatsuki City to Ibaraki City. The survey was conducted on June 26–27, 2018, but also included some results from the day following the main shock and other later days. For general tombstone types, the toppling rate is defined as the number of tombstones with a pole stone that toppled divided by the total number of tombstones in the target graveyard. **Fig.10** shows the tombstone toppling rate on the map. Although Takatsuki City is thought to be immediately above the hypocenter, tombstone tumbling was practically negligible there (almost 0% toppling rate). Conversely, the toppling rate in the central part of Ibaraki City was 10%–30%. Furthermore, areas with high toppling rates do not always overlap with back marsh, [7] which is regarded as soft ground. This implies that it is difficult to understand the earthquake ground motion near the hypocenter only by seismic distance and simple site amplification. The influence of the radiation characteristics as the source mechanism and particularly directivity can therefore not be ignored.

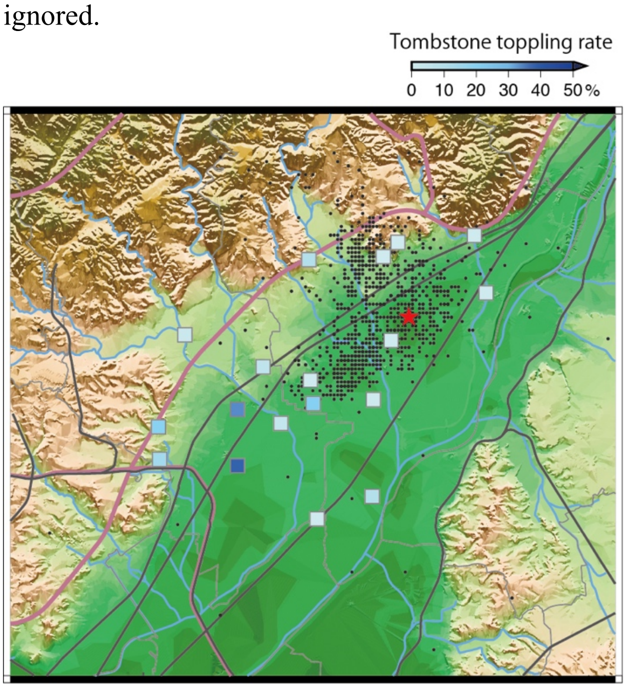

Fig.10 Tombstone toppling rate near the hypocenter

4. DAMAGE DUE TO LIQUEFACTION

Longitudinal cracks were reported at 14 river embankments in the Yodogawa river system. Most of these cracks were several centimeters in width and the early response was made by lime injection, emulsion capping, and blue sheet curing[8]. Three sandboiling craters owing to liquefaction were confirmed in the Yodogawa riverbed[9]. Three cases of water leakage owing to the deterioration of aged buried underground pipes and one case of air valve damage of a water pipe bridge was reported [10]. This damage was reportedly not related to liquefaction. Additional damage, including water leakage from buried pipes, was reported several days following the earthquake [10].

Although some areas with large ground motion were observed with a JMA seismic intensity of 6^-, no large damage was reported related to liquefaction. In this section, we numerically investigate the occurrence of liquefaction in the Yodogawa riverbed from the strong motion records.

(1) Numerical method

An effective stress analysis method with multiple shear mechanisms as a constitutive model (FLIP Rose, Ver 7.2.3) [11] [12] was used for the liquefaction analysis. The analyzed location was chosen near the 22 kilopost on the waterside of the right-hand-side levee of the Yodogawa (**Figs.11, 12**). According to the borehole data at this point, there is an alluvial sand layer (“As”) with a layer thickness of approximately 6 m under the capsoil (layer B) with a layer thickness of approximately 2 m[13]. Below that is an alluvial clay layer (“As” layer) with a thickness of approximately 11 m, followed by a 2-m-thick “Tcs” layer and a “Tg” layer with a layer thickness of 2 m or more. The groundwater level (GL) is approximately −4 m. According to the borehole data from a cross section of the levee shown in **Fig.12**, a stratified structure can be assumed to exist deeper than the “As” layer. The SPT N-value of the “As” layer (with a thickness of approximately 4 m) below the groundwater level is 8–13, and potential liquefaction in this layer poses a concern when large earthquakes occur.

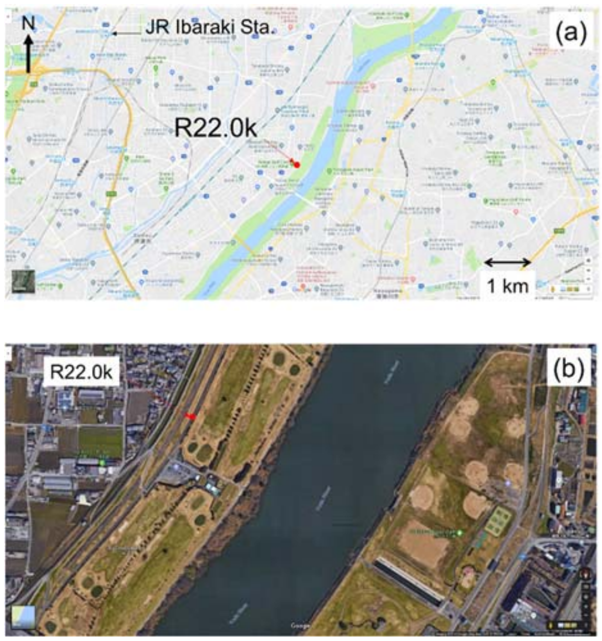

Fig.11 (a), (b) Location of the analyzed site (near Hashiramoto in Takatsuki City, Google Maps)

Table 2 Model ground parameters

		B	As1	As	Ac	Tcs	Tg
Uniti weight	tf/m^3	2.092	2.092	2.092	2.092	2.092	2.092
Shear modulus at small strain	kPa	4.306×10^4	5.462×10^4	4.707×10^4	3.075×10^4	1.803×10^5	1.803×10^5
Bulk modulus at small strain	kPa	1.123×10^5	1.424×10^5	1.227×10^5	1.697×10^5	4.703×10^5	4.703×10^5
Ave. eff. Conf. stress	kPa	7.35	36.8	45.3	91.9	150.675	150.975
Friction angle	Deg.	39.6	37.30	36.06	31.10	43.6	43.6
Cohesion	kPa	0	0.0	0.0	0.0	0	0
Max. damping constant	–	0.24	0.24	0.24	0.24	0.24	0.24
Permenability	m/s	0	0	1.0×10^{-4}	0	0	0
Phase trans. angle	Deg.	-	-	28	-	-	-

Liquefaction parameter for the "AS" layer

ε_d^{cm}	$r_{\varepsilon dc}$	$r_{\varepsilon d}$	q_1	q_2	l_k	r_k	S_1	c_1	q_{us}	q_4	r_{gamma}	r_{mtmp}
0.020	0.95	0.25	3.5	0.01	2.0	0.7	0.005	2	0.0	1	0.1	0.5

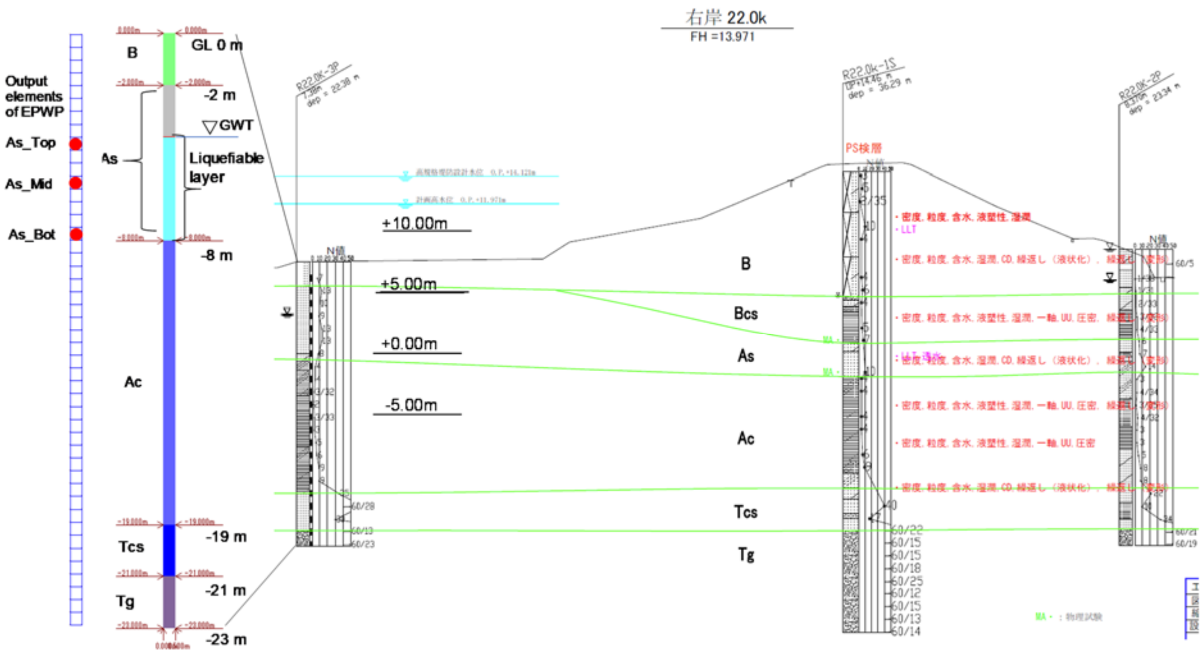

Fig.12 Soil profile at the location near the 22 kilopost: borehole logs of the levee of the Yodogawa, and the finite element mesh after 13).

The model ground parameters used in the analysis were derived by the empirical method using SPT-N values and fines contents (**Table 2**). In this analysis, however, it is assumed that the fines content is 0% and the N-value is averaged in each layer. The liquefaction target layer was set to the "As" layer (GL = −4 to −8 m) below the groundwater level (**Fig.12**). The liquefaction parameter was obtained by fitting to the liquefaction strength curve of Toyoura sand with a relative density of 50% (**Fig.13**). As shown in Fig. 12, The finite element mesh was a square element with a 0.5-m side and modeled up to the depth GL = −23 m where the boring data were obtained. The degrees of freedom at the bottom two nodes were fixed in both the horizontal and vertical directions, and not left unfixed for the other nodes. However, to assume an infinite half space, node displacement at the same depth was restrained to be identical.

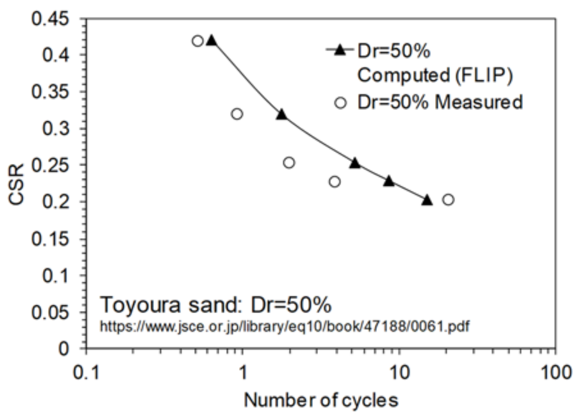

Fig.13 Measured and computed liquefaction strength curves of Toyoura sand with a relative density of 50%

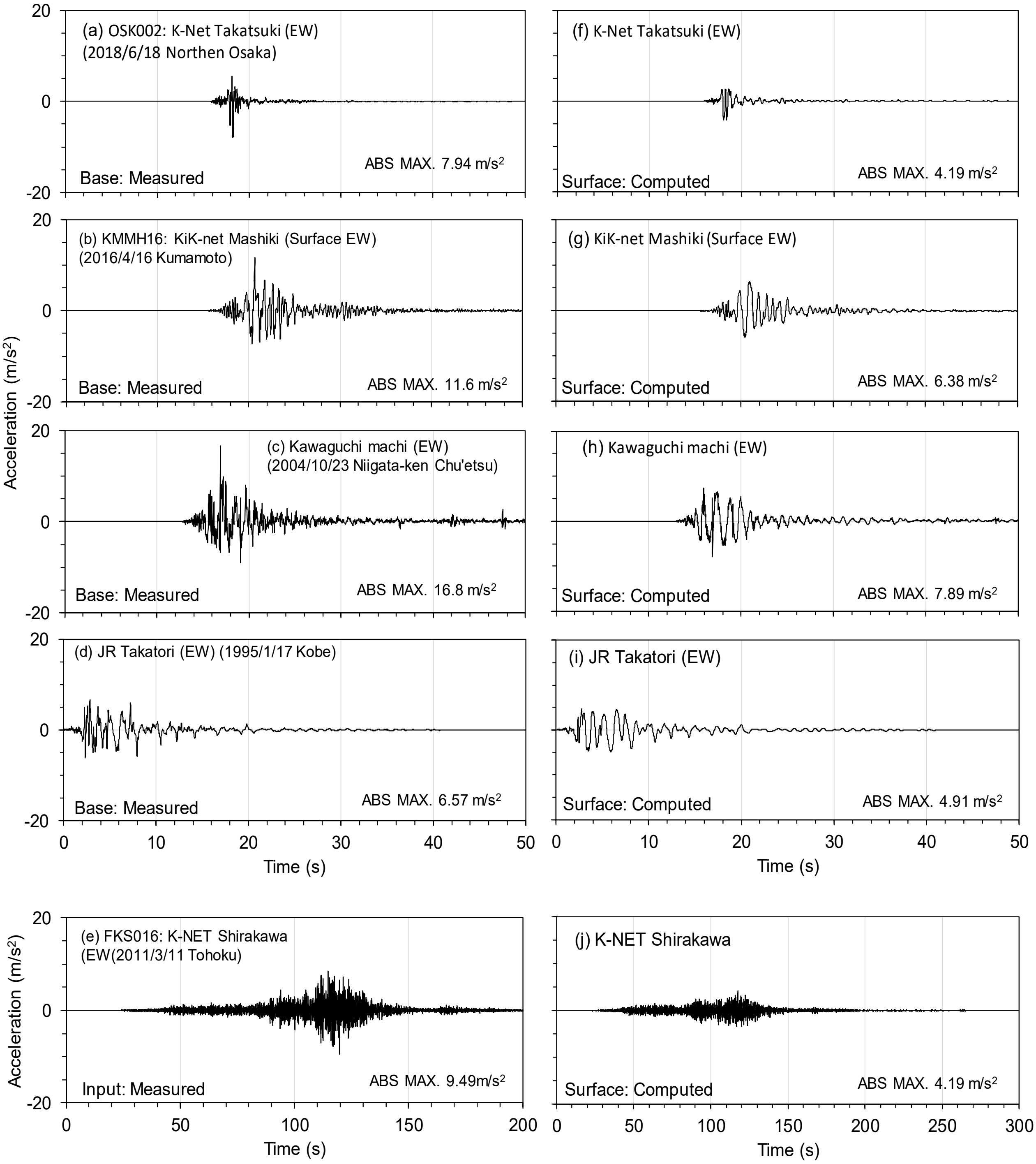

Fig.14 Acceleration time histories of ground motions: (a)–(e) measured input motions; (f)–(j) computed surface responses

Five strong motion records (**Figs.14(a)–14(e)**) were used as the input ground motion. These are the records of the horizontal component on the ground surface of K-NET Takatsuki (OSK002) from the 2018 Osaka earthquake, KiK-Net Masuki (KMMH16) from the 2016 Kumamoto earthquake, Kawaguchi Town office from the 2004 Niigataken Chuetsu earthquake, JR Takatori from the 1995 Hyogo-ken Nanbu earthquake, and the K-NET Shirakawa (FKS016) from the 2011 Tohoku region Pacific offshore earthquake.

Here, the time axis of the 2011 off the Pacific Coast of Tohoku Earthquake is set from 0 to 200 s and the others are set from 0 to 50 s. These strong motions were recorded on the ground surface. However, in this analysis, they are directly input as the horizontal motion to the node at the bottom of the mesh (GL = −23 m). Figure 15a shows the Fourier amplitude spectra of the input motions in which the predominant earthquake ground motion frequency of the 2018 Osaka-fu Hokubu earthquake is approximately 3 Hz, which is higher than the records of the

Kumamoto earthquake, Niigata-ken Chuetsu earthquake, and Hyogo-ken Nanbu earthquake with peaks around 1 Hz. In this case, the killer pulse of the period from 1 to 2 s cannot be seen in the waveform referred above.

(2) Results of effective stress analysis

In the following section, attention is paid to the response acceleration of the ground surface and effective stress reduction ratio. As shown in **Figs.14(f)–14(j)**, the maximum amplitude of the surface acceleration is less than the input motion peaks for all of the motions without amplification. Moreover, **Figs. 14(f)–14(i)** show that the waveform has a longer period. This tendency can be seen also in the Fourier amplitude spectrum in **Fig.15(b)**. It is thus presumed that because the excess pore water pressure increased in the liquefied layer, the effective stress decreased and the ground softened.

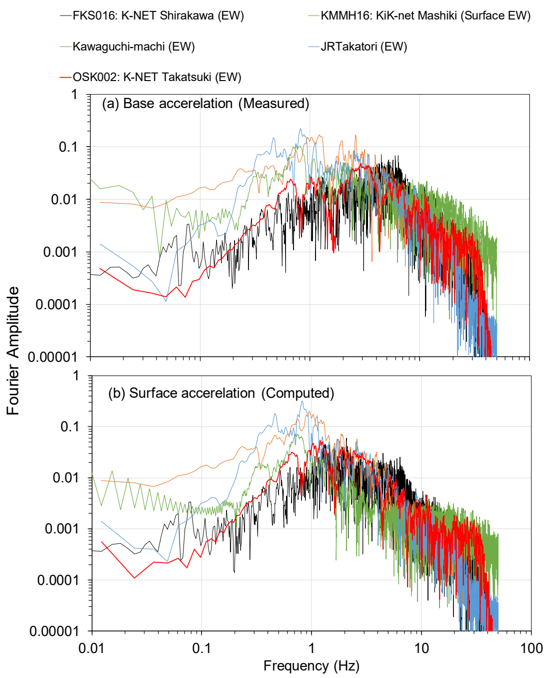

Fig.15 Fourier amplitude spectrum of acceleration: (a) input (measured record), (b) response at the ground surface (computed)

The time histories of the effective stress reduction ratio shown in **Fig.16** correspond to the values of the element indicated by the red markers on the mesh of **Fig.12** (top, middle, and bottom of "As" layer). From the middle part of the "As" layer to the upper layer (**Figs.16(a), 16(b)**), the effective stress reduction ratio exceeds 0.9 for the four earthquake motions excluding the Osaka-fu Hokubu earthquake. At the bottom, the effective stress reduction ratio exceeds 0.9 with three earthquake motions other than Osaka and Tohoku. The maximum effective stress reduction ratio owing to the ground motion in the Osaka-fu Hokubu earthquake is approximately 0.8 at the top end of the "As" layer, ~0.5 in the middle part, and ~0.4 at the bottom. The upper part of the "As" layer does not reach complete liquefaction, even though the ground softens slightly and the dominant period becomes longer.

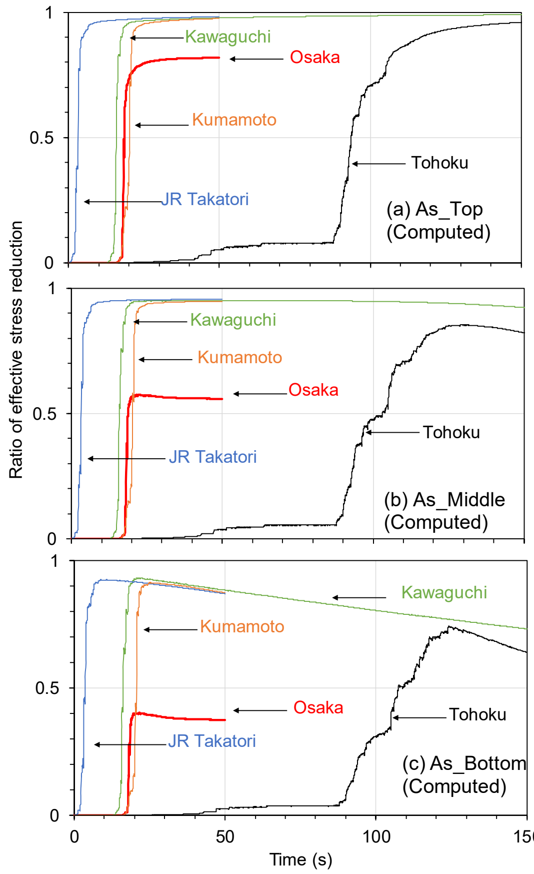

Fig.16 Time histories of the effective stress reduction ratio of the liquefiable layer (As layer): (a) top of the "As" layer, (b) middle, (c) bottom

The ground parameters related to the liquefaction strength used in this study are for Toyoura sand with a relative density of 50%. The average SPT N-value of the liquefiable layer is estimated to be approximately 11 from the borehole log shown in **Fig.12**. The effective confining pressure at the middle of the liquefiable layer is found to be approximately 103 kPa from the density shown in Table 2 and GL = −4 m. Substituting these values into the Mayerhoff formula yields an estimated relative density of approximately 70%. The analysis in this study may therefore possibly overestimate the ground response, and further study using parameters directly obtained from the local soil is needed for better understanding for what happened in reality.

5. LIFELINE DAMAGE AND RECOVERY

(1) Summary of lifeline damage

In this earthquake, a seismic intensity of 6^{-} was observed near the epicenter, but damage to the civil infrastructure was not serious. Because the earthquake occurred during the weekday commuting time in the urban area, it became difficult to return home because of suspended railway service and restricted driving.

Table 3 Overview of damage and recovery of lifeline serviceability functions

	Functional damage	Recover
Electric power	Up to 170,000 households in Osaka and Hyogo prefectures	Restored 3 hours after power outage.
Water supply	Water outage or decompression water supply in Takatsuki, Suita, and Minoo City, Osaka Prefecture. Approximately 90,000 households	The water outage was resolved before dawn on the following day
Gas	Osaka Gas service suspension of supply of approximately 110,000 units	Restored on June 24.
NTT	15,000 lines	Restored after one and a half hours on the day
Shinkansen	Temporary suspension / suspension of operation on the Shinkansen Sanyo / Tokaido Line	
Other railways	Vehicles stopped between other railway stations Temporary suspension of operation at JR and private railway companies	Resumed operation of some private railways from the afternoon of the day Operation resumed on some lines from the following 19th Osaka Monorail resumed 23rd
Express ways	NEXCO West Japan, Hanshin Expressway closed	at 13:00 on the day except for some
Airplane	Japan Airlines / All Nippon Airways cancels a total of 74 flights scheduled to arrive and depart on the 18th	

Water cutoff also occurred over a wide area owing to damage of a large water pipeline. This functional damage of lifeline resources had a strong societal impact. **Table 3** summarizes the service functional damage and restoration of the main lifeline facilities.

(2) Damage to water supply system

One factor that caused many water cutoffs in the Hokusetsu region of Osaka Prefecture during this earthquake was the damage to the Osaka Water Supply Authority (OWSA) pipelines, which supply water to the cities in the Hokusetsu region. In this section, we report on this damage and OWSA's restoration of the water supply system and the provision of end supplies by Takatsuki City and Ibaraki City.

OWSA is the successor of the Osaka Prefectural Water Department and has been independent from the prefecture as a special district authority since 2011. The OWSA currently supplies water to 32 prefectural cities, 9 towns, and 1 village in the prefecture. The total length of the water conveyance and transmission pipes is approximately 570 km. The ratio of the amount of water received from the OWSA to that of the local governments' supply in the daily water supply volume varied among the water receiving municipalities. However, municipalities in Osaka Prefecture do not have stable water sources, thus they rely on the OWSA for an average of approximately 70%–80%. The OWSA supplies 60%–80% of the daily water supply in Takatsuki City, Ibaraki City, Settsu City, Suita City, Mino City, and Toyonaka City around the earthquake epicenter.

The OWSA reported no remarkable damage to facilities, including water purification plants and pump stations, but damage occurred in the valves, water meters, and main body of the pipeline, as shown in **Table 4**. Damage occurred in two locations along 113 km of drinking-water transmission pipes controlled by the Northern Water Supply Office (0.02 points/km). Three locations were damaged in 102 km of industrial transmission pipe (0.03 points/km).

Table 4 Number of damaged pipes of the Osaka Water Supply Authority

	Numbers	Remarks
Valves	15 (Drinking 9/ Industrial 6)	
Pipes	8 (Drinking 3/ Industrial 5)	Leakage point on the day of June 18 5 (Drinking 2/ Industrial 3) Both are DIP

The most affected damage to the surrounding municipalities was the ductile cast iron pipe DIP (A) of the drinking water with the diameter of φ900 in Shimotanabe-cho, Takatsuki City (**Fig.17**). Water began spurting from the road surface immediately after the earthquake. Closing valves started by workers at approximately 10:30 on the same day and were completely closed by 11:00. Pipe breakage was confirmed at 15:00. The breakage was approximately 0.3 × 1.5 m in the 1–2 o'clock direction in the section against the water flow direction and its point was the body part of a 6-m straight pipe. The burial depth was 1.6 m from the ground surface to the top of the pipe. The construction year was 1963. The pipe was a ductile cast iron pipe with mortar lining. Extensive corrosion unevenness was confirmed on the damaged pipe body. Several pipes were buried in parallel under the road where the damaged water transmission pipe in the fourth extension line was buried, including the transmission pipe in the fifth extension line (φ1600), the industrial water transmission pipe (φ900), and the main distribution pipe of Takatsuki City (φ500). However, damage to the adjacent pipes owing to water leakage was not reported. The amount of water that leaked from the damaged transmission pipe reached 16,000 m^3 (50 times an elementary school's pool with 25 m in length) and flowed out to the idle land of the factory on the west side of the road. The pipeline was restored overnight; this work was completed by 9:45 on the day following the earthquake, at which point the road was reopened.

The second instance of damage to drinking water was a ductile cast iron pipe DIP (B) in Suita City (φ 800) (**Fig.18**). The construction year of this pipe was 1965, and this pipe was in the same fourth extension line as that mentioned above. A crack approximately 1.6 m in length occurred in the pipe axis direction at the top of the pipe buried beneath the sidewalk. The damaged pipeline was a transmission line to Suita City and Toyonaka City. Until the restoration, the workers attempted to send water in the opposite flow direction from the Senri purification plant, but the valve did not move and the water could not be redirected. It took 54.5 hours to restore this pipeline.

Three instances of damage to industrial water pipes where water leakages were found immediately after the earthquake are as follows. In DIP (A) (φ400) in Suita City, a hole was found on the side of the pipe. The construction year of the pipe was 1966. Overall, 22 hours were required to reopen the road. Another hole was found on the side of DIP (A) (φ200) in Suita City. The construction year of the pipe was 1967. Here, 35.5 hours were required to reopen the road. At DIP (AII) (φ400) in Toyonaka City, another hole formed on the upper half of the pipe. The construction year of the pipe was 1967. Here, 32 hours were required to reopen the road. These types of damage are similar as well as the size of each hole (several cm). The pipeline construction years are also within the same period.

Much of the water leakage valve damage was caused by contaminant clogging. There is also the case of the Hirakata Water Pipe Bridge, which was completed in 1964 on the downstream side of the Hirakata Bridge over the Yodo River, the boundary between Takatsuki City and Hirakata City. Two air valves attached to the pipe on this water pipe bridge were damaged. This bridge is a Langer truss bridge with 10 spans and two pipelines of φ1200 each. The pipeline on the river's downstream side, which is part of the fourth extension line, was under suspension because of the renewal construction of buried pipes at the downstream side of the lines at the time of the earthquake (**Fig.19**).

Fig.17 Damage of water transmission pipe DIP (A) (φ900) in Takatsuki City (from OWSA)

In the pipe on the upstream side, which is a part of the fifth expansion lines, two of the five air valves were damaged on the water pipe bridge. The grey cast iron air valve boxes showed brittle failures at both points (**Fig.20**). After the earthquake, the air valves were closed. Three other air valves were renewed before the earthquake and there was no earthquake damage at this time.

Fig.18 Water transmission pipe in Suita City DIP (B) (φ800) S40 (from OWSA)

Fig.19 State of Hirakata Water Bridge. Front 5 expansion line and rear side 4 expansion line. One of the leaked air valves is indicated by an arrow

The damage owing to the destruction of the ductile cast iron pipes is similar to that in the grey cast iron pipes observed in the Hyogo-ken Nanbu earthquake in 1995 and previous earthquakes. Considering that only the fourth expansion line (1960–1965) of the OWSA was damaged, even though numerous major water transmission pipes of the fourth and fifth extension lines (1965–1972) are laid in parallel under the same road, it is assumed that the pipe material used during the construction period is responsible for the damage, not the local conditions (e.g., soil, topography, water pressure, geometric pipe shape). The damaged pipelines were all constructed in the mid-1960s, which was the transition period from cast iron pipes to ductile cast iron pipes owing to improved pipe materials. These were so-called early ductile cast iron pipes. The Japan Ductile Iron Pipe Association specified in 1959 that the elongation rate of the pipe be at least 3%. This was later modified by the JIS standard in 1974 to state that the ductile (spheroidal graphite) cast iron pipe should have an elongation rate of at least 5%, and the JIS standard in 1982 stipulated that the ductile cast iron pipe should have an elongation rate of at least 10%. Therefore, the specifications of ductile cast iron pipes currently on the market differ from those of earthquake-damaged pipes. Considering that damage (e.g., joint leakage) was scarcely reported in this earthquake, it is unlikely that the damage was caused by ground deformation from the earthquake. It is also conceivable that at the time of the earthquake, water in the pipe had an inertial force and that temporary water column separation occurred (i.e., a vacuum state formed in the pipe) owing to the shaking of the seismic motion or some action, and when water was pulled back to the vacuum, a water shock pressure occurred. It is considered that the pipes deteriorated by age were likely to be damaged at the bottom by the stationary load, but that all of the damage was in the upper half of the pipes in this earthquake. Considering that pipe material quality is crucial, it is also necessary to examine the damage mechanism in detail.

Fig.20 Air valve of the Hirakata Water Bridge showing brittle failure of the air valve box

Takatsuki City mainly distributes the water received from the OWSA to four water distribution zones. Ohkanmuri water purification plant system with 138,000 inhabitants (approximately one-third of the city users) blends water received from the OWSA with self-water from deep wells and supplies. Because the water supply from the OWSA was suspended, the water supply was restricted after 20:00 on June 18. Furthermore, even in the Shimizu receiving reservoir system, which supplies water by pressing to the Shiroyama No. 1 Distribution Reservoir and Hiyoshidai Distribution Reservoir, the water in the distributing reservoirs was exhausted and affected by the water cut-off because the water supply from the OWSA stopped at approximately 18:00 on June 18. However, in the early hours of June 19, the water supply pipe of the OWSA in Takatsuki City was restored, water transmission was resumed, and the city water distribution was restored on the morning of June 20. However, turbid water remained for approximately three days after the earthquake.

Takatsuki City has an approximately-1,000 km water distribution pipe. According to the preliminary damage report two days after the earthquake, there was damage to the water distribution pipe. One case at the water pipe bridge (φ300), six cases at the air valve (φ400–1100; including three cases on the pipe and three cases on water pipe bridge), and seven instances of damage in the water distribution pipe were reported.

Takatsuki City requested water supply support from the Osaka branch of the Japan Water Work Association at 10:00 on the day of the earthquake. It received 17 water tank trucks on June 18 from 11 municipalities in the prefecture and 27 water tank trucks on June 19 as well. The water shuttle transportation was achieved between the Ohkanmuri water purification plant and elementary schools or parks.

Ibaraki City has an approximately-800-km water distribution pipe. According to the damage report a week after the earthquake, there were four instances of damage in the water distribution pipe and nine at the air valve. Much of the damage occurred in small-diameter pipes, but steel pipes (SP) with large diameters of φ600 were also damaged. On the route crossing the main road, water leakage was found at the bent part of the pipe, which was constructed under the jacking method 4 m underground. However, because there are other buried pipes in the upper part of the damaged pipe, restoration was impossible. The valves were thus closed, the pipe was replaced after the water leakage point, and the water was redistributed to other distribution pipes. Leakage damage occurred to the air valve in the old plate packing.

Ibaraki City is downstream of the damaged area in Takatsuki City. Therefore, because the OWSA stopped water transmission, the distribution reservoir nearly completely emptied. Thanks to the OWSA's Nasahara reservoir tank and the earthquake occurrence time (~8:00), the water reservoir was nearly full and could still supply If the earthquake occurrence time had been different, the water cut-off area would have likely been larger.

(3) Damage and restoration of city gas

Osaka Gas supplies city gas to customers while reducing the pressure from the city gas production facility through high-pressure, medium-pressure-A, medium-pressure-B, and low-pressure pipelines via a governor (i.e., pressure regulator). No particular damage was reported in the Senboku or Himeji plants, which are the city gas production plants. To prevent secondary damage owing to leakage from the gas pipe during the earthquake, not only was the SI sensor installed in the governor automatic shutdown system but also a remote shutdown system was established, as described below, when earthquake ground motion exceeds a certain level. The remote and automatic shutdowns of city gas stopped a total gas supply for 111,951 households (64,254 in Ibaraki City, 45,745 in Takatsuki City, 1,208 in Settsu City, and 744 in Suita City). Because the seismometer placed in a small block that divides the low-pressure network into approximately 50,000 households exceeded the SI value of more than 60 cm/s, the gas supply was stopped by remote control at two places of the small block with the seismometer.[14)]

When the city gas supply stops, the gas company first closes the gas meter of each customer. Next, to investigate the leakage of the gas pipe within the shutdown area, the company divides the small block into smaller blocks. The company then investigates and checks gas leakages, and in the of case gas leaks, the company digs the pipe and repairs it. After repairing the pipe, the company then restarts the governor. The opening operation of the meter was performed in the presence of the customer. A considerable number of workers are required to follow this protocol. A total of 5,100 people worked to restore the gas supply, including 2,400 Osaka Gas officials, workers of new entrants, such as electric power companies that retail gas within the Osaka Gas providing area, and 2,700 support workers from other gas companies. Among those supporters, the electric power companies that entered the gas business through the liberalization of energy were also included. Immediately after the earthquake, the prospect of restoration was slated to occur between June 26 and 30. However, because the damage of the low-pressure pipes on the site was minor, restoration of the pipeline was completed on June 22 and the opening work to the customer ended on June 24. **Fig.21** shows the process of restoring the city gas.

Osaka Gas established front-line bases at eight locations, including parking lots and parks adjacent to the shutdown area to make restoration activities more efficient, and adjusted the number of support vehicles and workers. **Fig.22** shows the state of the front base using the parking lot in Expo Memorial Park. The candidate sites of these frontline bases were preliminarily listed in advance. Facilities in other prefectures, such as Shiga Prefecture, were used to accommodate the support workers.

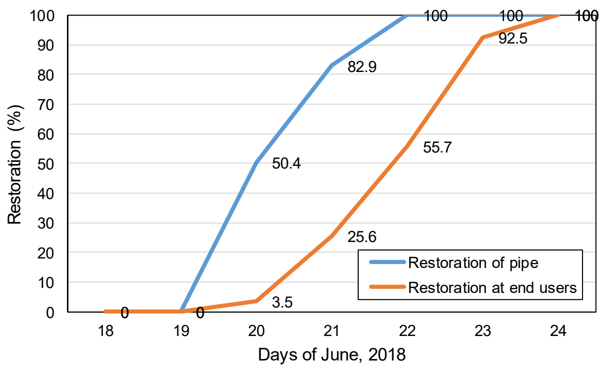

Fig.21 Osaka Gas restoration process (restoration number 111,951 households)

Fig.22 State of the front base of Osaka Gas (Expo Park parking lot)

In many areas other than those in which the supply stopped, the microcomputer meter detected shaking of approximately 250 cm/s^2 and automatically shut down. Osaka Gas cooperated with the Chubu Kinki Industrial Safety and Inspection Department, Takatsuki City, and Ibaraki City and attached links to each homepage and made efforts to inform users how to reset the gas meter operation. The "Recovery Visualization System", which began operation in April 2018, functioned effectively during the earthquake. This system comprises two types of retrieval systems, listing the progress of gas recovery on a regional basis and drawing a color-coded map (**Fig.23**) for each gas recovery progress, which can be browsed from the homepage. Within this system, information was updated twice a day at the time of the recovery. Osaka Gas had prepared multiple communication lines to handle extensive access, but because there was substantial access from both affected and non-affected areas, the number of lines was increased during recovery.

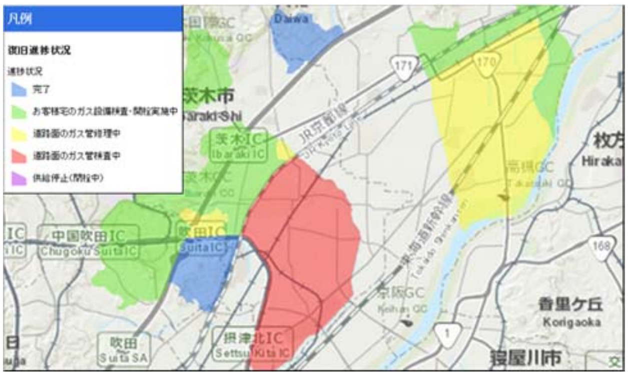

Fig.23 Recovery visualization system

Since the 1995 Hyogo-ken Nanbu earthquake, Osaka Gas has promoted numerous earthquake countermeasures. The total length of polyethylene pipes for low-pressure pipelines increased from 1,200 km in 1995 to 15,800 km in 2018, and the adoption rate of microcomputer meters increased from 75% in 1995 to 99% and to 100% for home use in 2018. The earthquake resistance rate of the pipe also improved from 68% in 1995 to 87% in 2018. Furthermore, the above-mentioned small block that was 55 blocks in 1995 is now divided into 164 blocks for localizing the gas shutdown area even when an earthquake occurs. The number of seismometers was also increased from 34 to 258, and at least 1–2 seismometers were installed within each small block. In this way, both the earthquake resistance and blocking progressed compared with the situation in 1995. After the Hyogo-ken Nanbu earthquake, the standard of automatic shutdown was set to 60 cm/s in accordance with national guidelines.

According to Osaka Gas, the number of damage instances to the low-pressure pipeline in the shut-off area was seven for the main pipe, three for the service pipe, and 53 for the inner pipe, whereas those in the continuous supply area were 12 for the main pipe, three for the service pipe, and 15 for the inner pipes. No damage was reported to the other facilities or to the high- or medium-pressure gas pipelines. The damage rate of the main branch of the low-pressure pipeline was 19 cases, which is 0.04 cases/km, compared with previous earthquake damage of 14 cases/km of the Hyogo-ken Nanbu earthquake, 0.9 cases/km of the 2011 Tohoku earthquake, and 0.6 cases/km of the Kumamoto earthquake. The comparison shows that the damage was substantially less than that associated with these previous earthquakes.

From the 2007 Niigata Chuetsu-oki earthquake, small- and medium-sized enterprises that can promptly check the damage situation of a supply area were able to decide whether to continue supplying or shut down by themselves. In one case, Furukawa Gas in Osaki, Miyagi Prefecture continued to supply gas although the ground motion exceeded 60 cm/s in the 2011 earthquake because there was no road damage. Further consideration regarding the standard for automatic shutoff is also underway in Japan.

(4) Damage and restoration of electric power

Kansai Electric Power Company (KEPCO) reported that there was no trouble in nuclear, thermal, and hydropower power generation facilities due to the earthquake. A total of 173,060 customer power outages occurred in Osaka Prefecture including Toyonaka City (~95,000 customers), Minoh City (~41,000 customers), Suita City (~25,000 customers), Ikeda City, Settsu City, Takatsuki City, and Ibaraki City and in Hyogo Prefecture including Nishinomiya City and Itami City. However, the number of outages decreased to 2,062 customers 10 minutes after the earthquake occurred. The restoration was then completed at 10:43 on the same day. **Fig.24** shows the KEPCO restoration process.[15]

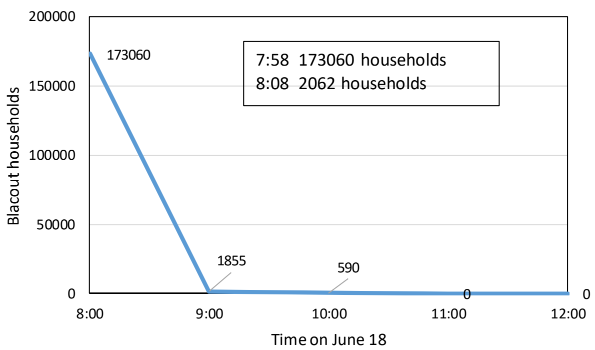

Fig.24 Electric power recovery process (maximum blackout number = 173,060 households) (from Kansai Electric Power Co.)

(5) Damage and restoration of telecommunication

According to NTT West Japan, the service of 15,000 lines (12,800 fixed line telephone lines, 2,200 INS net lines) were troubled in some areas of Osaka Prefecture. Service was recovered at approximately 9:28 on the same day, 1.5 hours after the earthquake. Previous restricted call times for fixed line telephone service included 6 hours following the Niigata Prefecture Chuetsu Earthquake in 2004 and 3.5 hours following the Niigata-ken Chuetsu-Oki Earthquake in 2007. The quick recovery was considered possible because the ground motion was rather small and catastrophic damage was limited, even though it was an urban earthquake.

The disaster message line (171) and disaster message board (web 171) started operation at 8:10 on June 18; the former had approximately 47,000 accesses (recording: ~18,700, playback: ~28,300), the latter had about 53,900 users (registration: ~10,100 cases, viewing: ~43,800 cases). The NTT InfraNet conducted an emergency infrastructure inspection from the day of the earthquake and inspected the bridging facilities (479 bridges), manhole surroundings (4,957), and duct facilities (28.6 km) in the areas with intensities of 5^+. No effects on the facilities were reported.[16]

6. Railway and road

(1) Summary of damage

High seismic intensity was recorded in the Kansai region owing to the M_J6.1 earthquake on June 18, 2018. The Japanese seismic intensity was 6^- in northern Osaka Prefecture and the intensity was 5^+ in southern Kyoto Prefecture. From that day, surveys were conducted to assess the earthquake response and civil engineering structural damage. The main research subjects were the Osaka Monorail, Tokaido Shinkansen (bullet train), Sanyo Shinkansen, JR Local Line, Meishin Expressway, and Hanshin Expressway.

Although the seismic intensity of the earthquake near the epicenter was 6^-, there was no serious damage to the civil infrastructure. It is therefore necessary to evaluate whether this was because of seismic reinforcement and countermeasures, which have steadily proceeded until present. Meanwhile, although there was no damage to the civil infrastructures, some transportation facilities required time to completely recover. In this chapter, we summarize the situation of civil structures, including the damage of accompanying facilities.

(2) Osaka Monorail

Facilities constituting the Osaka monorail are roughly classified into an infrastructure section and a transport section (**Fig.25**). The road administrator (Osaka Prefecture) constructed and maintained the infrastructure section as subsidiary facilities for traffic, piers, and girders of the overhead bridge and basic structure of stations as road structure. In addition, the outside of the infrastructure included facilities necessary for operations, such as trains and a signal system. These are operated and managed by a third sector (Osaka Monorail Co., Ltd.), established by Osaka Prefecture and private companies.

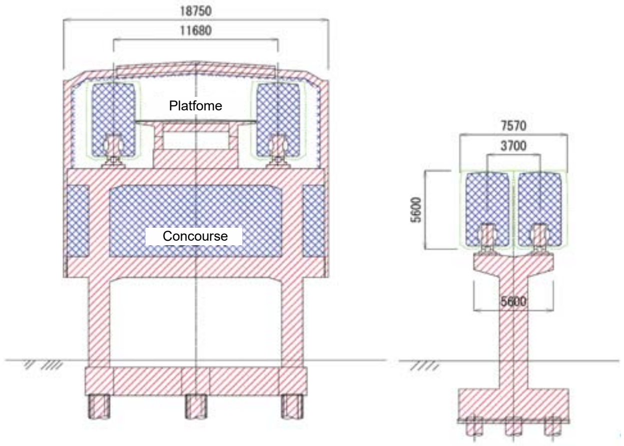

Fig.25 Infrastructure (red) and transport section (blue) on Osaka Monorail

Between 1997 and 2007, the bridge piers were reinforced and measures were taken to prevent the steel rail girder from falling near the infrastructure section. Measures were taken to prevent the PC rail girder and station girder from falling from 2006 to 2014. Following this earthquake, damage was not observed in the infrastructure sections in which these measures were taken.

Concrete peeling at the end of the PC rail girder (**Fig.26**) and loosening of the bearing anchor bolt were observed in the affected part of the infrastructure section (**Fig.27**), but were determined to be minor. There was also damage to the locking devices and limit switches, insulators that support the electric lines, and some parts of the trains.

Although the damage to the civil structure remained minimal, the failure of the monorail switches hindered the resumption of operations (**Fig.28**). Because the switches were used not only for the turnout of the main line/branch line but also for exchanging the upper and lower lines (U turn) in the station building and exits of the repair train used for checking the rail girder, it became impossible to make them work.

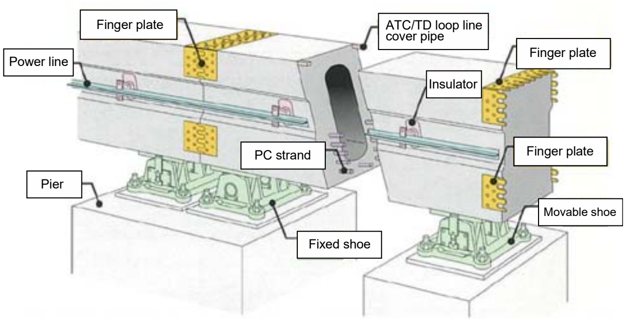

Fig.26 Configuration of the PC rail girder (from Osaka Monorail)

Fig.27 Concrete failure at the joint of the PC rail girder (from Osaka Monorail)

Fig.28 Repair situation of the PC orbit girder branch taken on June 19, 2018

Additionally, because the monorail had low redundancy, the stopped monorail trains became obstacles. The inspection was time-consuming because the repair train (Diesel train) and the monorail trains couldn't run simultaneously. After the electricity turned off, the repair train checked the rail girders up to the point at which the monorail train stopped. If it was found that the girders had no problem, the repair train must return to the garage in order that the electricity turned on for the monorail trains. Furthermore, because a road runs beneath the monorail route, there was a fear that a train might cause objects to fall onto the congested road. In situations which the repair train cannot run, it is necessary to conduct a visual inspection, but this can be delayed if the road is congested.

(3) JR local line facilities

There was no serious damage to the civil structures in the JR West local line facilities, but there was a partial settlement of the track and rail irregularity in some parts (**Fig.29**).

One section required substantial time to be returned to normal operations. Additionally, various sections between Takatsuki and Ibaraki on the Kyoto Line, including a truss girder, iron girder of a brick

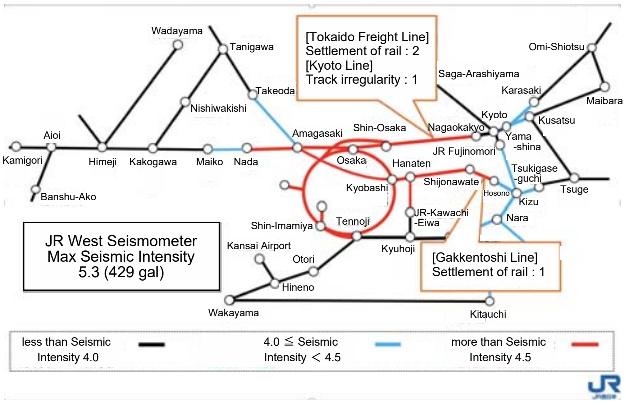

Fig.29 Damage to the JR West local line facilities (from JR West)

arch bridge, H-shape steel girder, and filled land, required repair. The connections of these various sections received different shake magnitudes. Track deformation was recognized around Kakegusi immediately after the earthquake. The repairs were performed and the absence of abnormality was confirmed by visual inspection, therefore the operation was restarted. After the start of operations, because a larger sway was confirmed than usual, it was decided to repair this part and to run slow operations in that section. The part was compacted using the improved backhoe (**Fig.30**) and the slow operation was terminated on July 17.

Fig.30 Situation of compacting use of the improved backhoe (from JR West)

(4) Shinkansen facilities

A report was published about the bridges over National Highway No. 176 west of Shin-Osaka station. The stopper at the mount part of one girder was damaged and the concrete piece was in danger of falling. This bridge is a box girder with a large skew angle (**Fig.31**). The 1995 Hyogo-ken Nanbu Earthquake damaged the stopper of the bearing, after which stoppers were added to the side surface of the girder. In this 2018 earthquake, the attached part of the added stopper was damaged. The damage is thought to have been caused because the distance from the edge at the mount could not be sufficiently secured because of the shortage of space on the side part. After the earthquake, a new stopper was installed and restored.

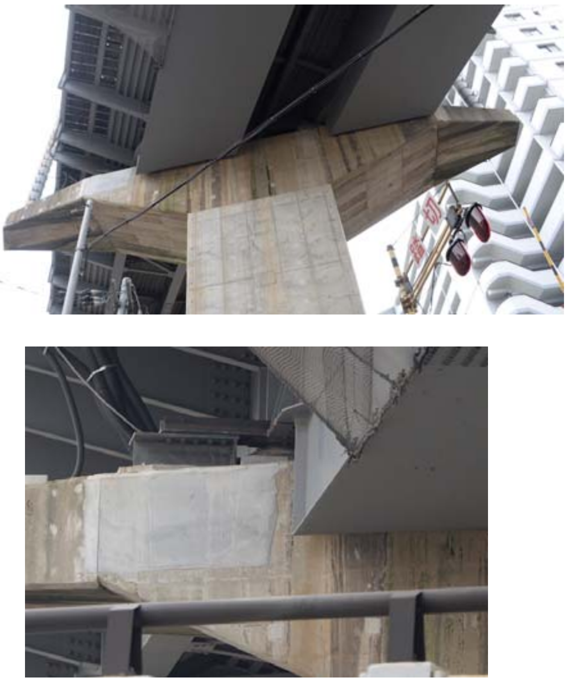

Fig.31 Damaged bridge (repaired left side)

Surveys were also conducted along the Tokaido Shinkansen viaduct running between Ibaraki and Takatsuki, where many houses were damaged. However, because various kinds of seismic retrofitting measures (**Fig.32**) had been made, no damage was observed.

Fig.32 Situation of Tokaido Shinkansen Seismic Retrofitting (taken on June 19, 2018)

(5) Meishin Expressway

The Meishin Expressway runs near K-NET Takatsuki, which observed the seismic intensity to be 6, and is considered to be in the strong motion region (**Fig.33**). Most sections of the expressway between Ibaraki and Takatsuki are filled land, but there are some viaducts. An oblique crack was found in one viaduct.

During construction of the Meishin Expressway, a multi-span continuous bridge with rocker piers was considered a reasonable viaduct structure.

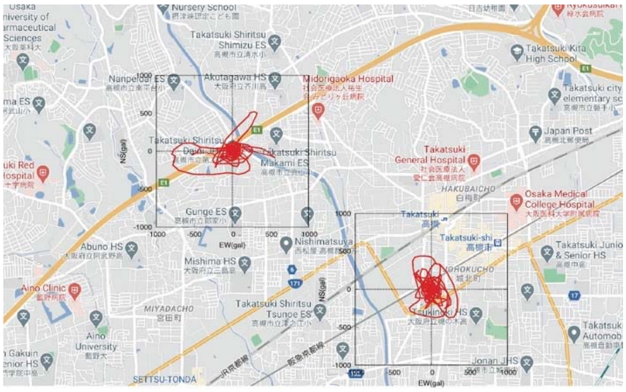

Fig.33 Acceleration trajectory of the strong motion record near Meishin expressway (from Google Maps)

The rocker pier supports only the vertical force and the horizontal force is supported by the rigid frame pier and the abutment at both ends of the girder. Between Ibaraki and Takatsuki, piers were added during widening construction in several sections (**Fig.34**). When the girder was widened after opening, rocker piers were added to both sides of the original bridge piers, in addition to the bridge piers at the time of opening in the intermediate piers. In the 1995 Hyogo-ken Nanbu earthquake, severe damage occurred in the rigid frame pier in the viaduct with the rocker bridge piers. Thus, a seismic reinforcement, namely, a rubber bearing and damper, were installed at the bearing of the viaduct end. The stopper was installed in the transversal direction of the bridge (**Fig.35**).

Shear cracks due to the earthquake were found in the initial constructed piers (**Fig.36**). In terms of the seismic reinforcement part of the rigid frame pier, a steel bracket on the stopper in the transversal direction hit the pier head (**Fig.37**). It is therefore understood that it moved in the transversal direction of the bridge within the allowable displacement. Although no damage was found on the rocker piers of the widened part, and no girder settlement was found even at the pier part where the oblique crack occurred, a vent for vertical support of the girder was set up when the site was revisited on July 11.

Fig.34 Rocker pier added to both sides of the original intermediate piers at the widened part (taken on June 21, 2018)

Fig.35 Seismic retrofitting of rigid frame pier (taken on June 19, 2018)

Fig.36 Damaged rocker pier (taken on June 21, 2018)

Fig.37 Collision of stopper in transversal direction (taken on June 21, 2018)

Surrounding viaducts with the same structure were assessed, but no other damage was found. It can be concluded that the influence of the shear was large and cracking occurred in this section because the height of the pier was lower than the others (**Fig.38**).

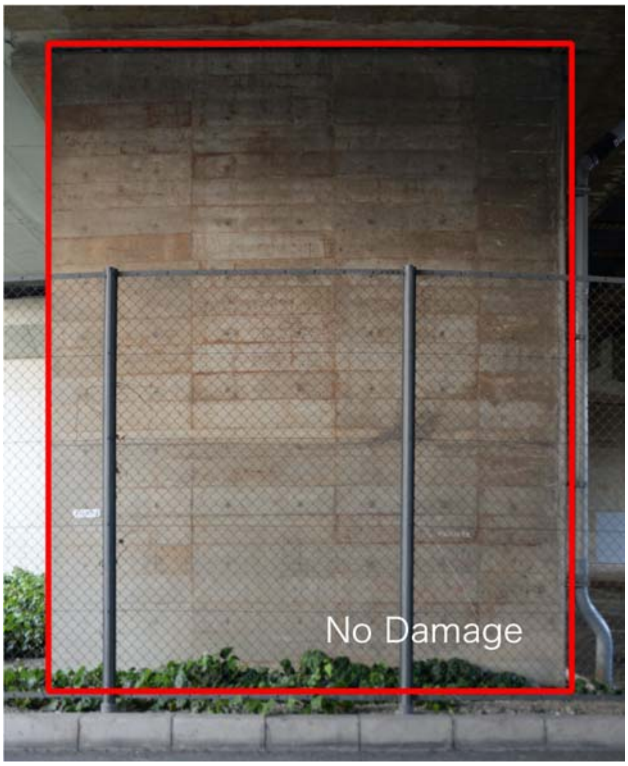

Fig.38 Comparison of damaged and undamaged rocker bridge piers

(6) Hanshin Expressway

No particular damage was reported on the Hanshin Expressway where earthquake observations[17)] (**Fig.39**) were conducted on 22 bridges. Acceleration response of approximately 0.3 s dominated at the Toyonaka (**Fig.40**) and Moriguchi observation points, which recorded a seismic intensity of at least 5; thus, the influence on the civil structure was limited. It was confirmed that installing a seismograph on the bridge allowed for a rapid understanding of the situation.

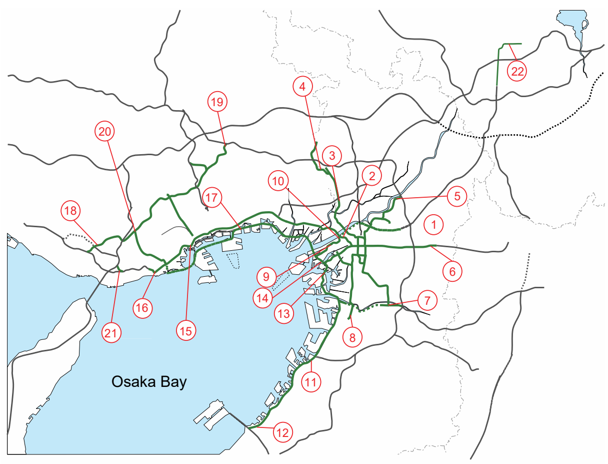

Fig.39 Earthquake observation network on Hanshin Expressway

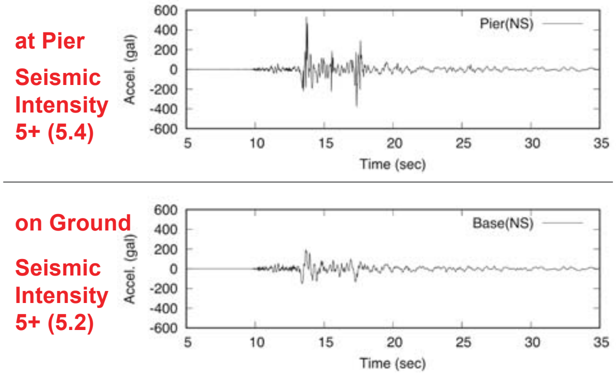

Fig.40 Observation record at Toyonaka (Point 3 in **Fig.39**) (provided by Hanshin Expressway)

7. DISASTER RESPONSE

(1) Life issue

The characteristics of the Osaka-Fu Hokubu earthquake are described below, focusing on human life issues.

a) Possibility that many dangers remain

One person was killed by falling furniture, and two people were killed by falling objects such as books. A seismic intensity of 5^+ indicates that unfixed furniture may topple. Stronger shaking than an intensity of 5^+ was observed in 23 municipalities in Osaka and Kyoto prefectures. In these areas, there is the possibility that many items of furniture had fallen. In a field survey conducted the day after the earthquake, some people related stories such as “The dresser in the bedroom turned over, but I was unharmed because I was in the living room.”

There were also two deaths owing to the collapse of a block wall. Takatsuki City decided to remove all block walls in public facilities in the city. Removal of block walls at schools also spread outside the afflicted area.

This was the first time that ground motion of a seismic intensity 6 class was observed in Osaka Prefecture since the JMA began observations in 1923. Many residents must have therefore seen for the first time how familiar objects can become hazards during an earthquake, even though many objects may remain unmoved without change. The block fence and furniture caused the deaths in this earthquake, but those were not the only objects that could have been hazards.

To prepare for the active fault type earthquake such as the Arima-Takatsuki fault zone and the Nankai Trough massive earthquake, which have been pointed out conventionally, we must proceed to quantify and remove the remaining danger.

b) Emergency response and permanent measures against danger

On the fourth day after the earthquake, all public elementary schools and junior high schools canceled school holidays in Osaka Prefecture, (Osaka Prefecture “The 7th Disaster Countermeasure Headquarters Conference Material”). However, dangerous materials such as block walls had not yet been removed. It is impossible to keep school closed until dangers are permanently removed. Therefore, emergency measures were taken to ensure safety, such as reconsidering school roads and arranging teachers and volunteers during the commuting time, after which schools were able to restart in an early stage.

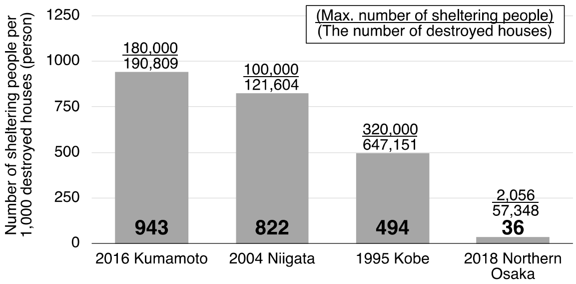

Fig.41 Number of sheltering people per 1000 destroyed buildings

In this earthquake, it became apparent that not only furniture, home appliances, and block walls, but also numerous dangerous goods exist both indoors and outdoors. Bearing in mind that securing permanent safety and returning to daily life as soon as possible is a major goal of a catastrophe-stricken society, coping with both emergency measures and permanent measures is needed.

c) Problems that tend to be overlooked become apparent in disasters

In the Hanshin-Awaji earthquake, approximately 10% of the direct death and 70% of the injuries occurred because of falling furniture and home appliances. However, in an earthquake disaster with strong ground motions of a seismic intensity exceeding 6, house collapse becomes more likely and the dangers posed by furniture or home appliances become less relevant.

In this earthquake, there were no deaths due to house collapse. Therefore, attention was paid to issues that were likely to be overlooked in the past large earthquake disasters. This must serve as an opportunity to solve such problems.

d) Safety and quick dilemma resolution in secondary disaster countermeasures

In this earthquake, there were 21 completely destroyed houses, 454 half destroyed houses, and 56,873 partially destroyed houses as of February 12, 2019. Because the earthquake occurred during the rainy season, prompt measures were required to avoid leaking in houses with damaged tile roofs. For example, Takatsuki City began distributing blue sheets the day following the earthquake. However, human support was delayed compared with the support of goods.

It was necessary to put blue sheets on the damaged tile roofs to prevent the houses from suffering more rain damage. However, owing to the lack of specialists, many residents were forced to do the dangerous work by themselves in the rain. Unfamiliar and dangerous work on a roof with the risk of earthquake ground motion (e.g., aftershocks) can cause potential secondary damage.

e) Attention to subsequent earthquake ground motion

In the Osaka-Fu Hokubu earthquake, caution was required regarding the subsequent ground motions based on the experience of the 2016 Kumamoto earthquake. The main shock of the Kumamoto earthquake occurred 28 hours after the foreshock. Emergency risk assessment was not available in time.

However, there were few residents going to shelters for damage to buildings considered to be vulnerable to subsequent ground motion. **Fig.41** shows the number of refugees per 1,000 damaged buildings for this earthquake, the 2016 Kumamoto earthquake, 2004 Niigata Earthquake, and 1995 Kobe Earthquake. In the Kumamoto earthquake, 943 residents went to shelters per 1,000 damaged buildings. Conversely, this number was smaller by a factor of 20 following the Osaka-Fu Hokubu earthquake, when only 39 people per 1000 damaged buildings sought shelter. This is because (1) there were few houses that entirely or partially collapsed and (2) there was no aftershock with a seismic intensity higher than 5 that caused most people to be evacuate.

It is necessary to understand the actual condition in terms of the response taken by residents and whether they took measures to prevent falls of indoor furniture and home appliances, or whether they changed bedrooms or took measures such as moving dangerous furniture and appliances in the bedroom to other rooms after the earthquake.

(2) Problems related to civic life

Here we describe the characteristics of the northern Osaka Prefecture earthquake, focusing on issues related to civic life.

a) Impact of service outage for safety confirmation

Railways, gas, elevators, and other services stop when a certain amount of shaking is detected because the service cannot continue until safety is confirmed, even though no damage actually occurred.

Regarding elevators, 339 confinement cases occurred[18]. This number exceeded 210 cases of the Great East Japan Earthquake and 54 cases of the Kumamoto earthquake. In addition, tens of thousands of elevators could not be used until they underwent a safety inspection. It is considered that the P-wave sensing type earthquake control apparatus, a device that makes an elevator stop emergently at the nearest floor after detecting P-waves, would not work in time. This could be because the S-wave arrived in only a short time after detecting the P-wave, caused by the epicenter being close.

For railways, 245 stops between stations occurred[18]. As a result, 140,000 people were trapped on JR trains. Owing to safety checks, operations resumed between 21:00 and 22:00 on the June 18.

Although there was no major actual damage, service was suspended for safety confirmation, which largely influenced the citizens' lives. The criteria for stopping services for safety confirmation should be discussed for review to minimize the impact to citizens' lives.

b) Roles and tasks of smartphones for confined and stranded commuters

In addition to elevator and railway confinements, as mentioned above, many other people were left stranded. Motoyoshi noted that many people gathered information using smartphones and acted relatively calmly in the actual situation survey (preliminary report) conducted for people who were commuting on the train and those who were in the station.[19] After the earthquake, cell phones were left without a signal for a long time, but residents could still access the Internet. People were therefore able to collect and send information using smartphones. It is possible that people could use smartphones to improve their mood and avoid distress. This role of smartphones could have increased the calmness of confined and stranded commuters.

However, smartphone batteries run out rapidly. College students volunteered to charge cell phones at JR Takatsuki station. Smartphones were confirmed to effectively reduce confusion among stranded commuters and those trapped in elevators and trains. However, a volunteer-based emergency power supply is unusual, uncertain, and unsustainable. Thus, it is necessary to increase power supply spots to cell phones which are useful even in an emergency.

c) Support for partly damaged households

The number of houses partly damaged by this earthquake stood at 56,873 buildings as of February 12, 2019. Partially damaged houses were not subject to emergency repair assistance by the Disaster Relief Act or support from the Act Concerning Support for Reconstructing Livelihoods of Disaster Victims. Therefore, there was no choice for affected people but to rely on donation and local government's original support measures.

However, owing to heavy rains on July 30, donation collections were switched to focus on people affected by the rain. Meanwhile, some local government systems supported households with partially damaged houses. Osaka Prefecture has an "Afflicted Housing Non-interest Loan System," which allows residents to borrow up to 2 million yen, and Takatsuki City and Ibaraki City have subsidy systems for partially damaged houses.

8. SUMMARY

This reconnaissance report summarizes the results of the survey teams organized in the Kansai branch of the Japan Society of Civil Engineers mainly with regard to the earthquake ground motion, ground vibration, lifeline damage including railways and roads, and disaster response. This survey was conducted in cooperation with the Kansai branch of the Japanese Geotechnical Society and the Japan Association for Earthquake Engineering. The conclusions are as follows.

(1) Because trench earthquakes and inland earthquakes can take place at any time in the Kansai area, we must learn valuable insights from this earthquake to add to the knowledge gained from previous earthquakes, including the Hyogo-ken Nanbu earthquake. It is also necessary to consider all aspects of earthquakes, tsunamis, and short- and long-period ground motions, which will undoubtedly occur again.

(2) The earthquake in Osaka-fu Hokubu was caused by the motion of at least two faults: a reverse fault and a right-lateral strike-slip fault. The observed earthquake ground motion was a pulse shape with a short duration, and the maximum velocity was approximately 40 cm/s near the epicenter. The predominant period of the velocity response was approximately 0.4 s in Takatsuki City and 0.6–0.8 s in Ibaraki City. An investigation of fallen tombstones showed that the tombstone falling rate was higher in the central part of Ibaraki City than just above the hypocentral fault. The distribution of observed seismic ground motion and tombstone falling rate are difficult to understand using only the seismic distance and cannot be explained by the ground amplification factor alone. The influence of rupture directivity can therefore not be ignored.

(3) Effective stress analysis was conducted for the Yodogawa riverbed, and the reason for the small liquefaction scale at the time of the earthquake was examined. Five strong motion records observed in recent large earthquakes, including this earthquake, were used as the input seismic motion, and the time history of the ground surface acceleration, Fourier amplitude spectra, and effective stress reduction ratio were compared. The liquefaction strength of the target layer was set by fitting to the strength curve of Toyoura sand with a relative density of 50%. This relative density is smaller than that estimated from the N-value of the original position. According to the analysis results, the maximum value of the effective stress reduction ratio was close to 1.0 for the four earthquake motions but only approximately 0.8 in the seismic motion in north Osaka. It can therefore be inferred that in this earthquake, the excess pore water pressure increased to a certain extent in the sandy ground of the Yodogawa riverbed, but did not reach a sufficiently liquefied state to lose supportive power.

(4) In terms of lifeline damage, several water leaks occurred in the large water pipes of the Osaka Water Supply Authority, but there was no other large structural damage in the other lifelines. Water pipe damage was concentrated in the old ductile cast-iron pipes manufactured during the transition from the cast-iron pipe to the ductile cast-iron pipe. The damage was not from water leakage of joints, which is the typical earthquake damage type of underground pipes, but rather destruction such as cracks and punctures in the pipe body. This damage was not caused by ground distortion owing to earthquake ground motion or ground deformity but is considered to be material or hydraulic damage. Detailed investigation of this is required. Damage also occurred in part of the city's water distribution pipe and gas low-pressure conduit, but the scope of this damage was small. Osaka Gas's supply to approximately 110,000 houses ceased because the SI sensor and seismograph in the low-pressure block shook with an SI value more than 60 cm/s. In addition to Osaka Gas, other gas companies provided restructuring support; thus, service was restored six days after the earthquake. However, as the seismic resistance of conduits improves and the restoration unit becomes sufficient only within the Osaka gas providing area, it is thus necessary to raise the standards for automatic and remote blocking systems.

(5) There was no major damage to the civil engineering structures on the railways or roads, except for one viaduct on the Meishin Expressway.

However, in the Osaka monorail, facilities associated with non-civil engineering structures and machinery were substantially damaged. In the JR West conventional (i.e., non Shinkansen) lines, it was difficult to conclusively find damage; thus, time was required to completely restore operations. To make use of these lessons, sufficient verification is considered necessary. Oblique cracks on rocker piers on the viaducts on the Meishin Expressway could lead to fatal damage. It is therefore important to verify the effect of earthquake reinforcement and widening. Records obtained from seismographs installed on Hanshin Expressway bridges enabled an understanding of the situation soon after the earthquake. This enabled the actual earthquake response of bridges to be observed, and it is desirable to use this information by verifying the design model using observation records.

(6) In this earthquake, problems were noticed that tend to be overlooked in other major disasters, such as the number of deaths caused by residential damage. These included furniture falls and block fence collapses, which were the causes of death in this instance. However, many other objects can transform into hazards. It is therefore necessary to assess and cope with any potential dangers around us. This also poses a major impact to civic life in which services are disrupted to check for damage of railways, gas, and elevators, amongst others. Although communication technologies such as smartphones, which were not available at the time of the Great Hanshin-Awaji earthquake, contributed to reducing the disorder, these have the problem of limited battery capacity. We should continue efforts for short-term safety confirmation, and we should keep discussion for review criteria for stopping services for safety confirmation, to minimize human damage and impact to citizens' lives.

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APPENDIX

The members of the disaster investigation team against the 2018 Osaka-Fu Hokubu earthquake and their main role sharing are described below.

Research team head: Junji Kiyono, Graduate School of Engineering, Kyoto University (outline and summary of earthquake and damage). Team members: Yoshikazu Takahashi, Graduate School of Engineering, Kyoto University (road and rail); Tetsuo Tobita, Graduate School of Science and Engineering, Kansai University (ground vibration and liquefaction); Yasuko Kuwata, Graduate School of Engineering, Kobe University (lifelines); Hiroyuki Goto, Disaster Prevention Research Institute, Kyoto University (seismic ground motion); Yoshihiro Okumura, Graduate School of Societal Safety Sciences, Kansai University (disaster response).

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