REPRODUCTION SIMULATION OF 1995 KOBE EARTHQUAKE BY EARTHQUAKE DAMAGE SIMULATIONS IN EXPRESSWAY NETWORK

M. Hattori [1], H. Ohishi [2], M. Shinohara[3], M. Nakamura[4] , K. Magoshi[5]

[1] *Hanshin Expressway Technology Center, hattori_m@tech-center.or.jp*
[2] *Hanshin Expressway Technology Center, oishi@tech-center.or.jp*
[3] *Hanshin Expressway Company Limited, masatsugu-shinohara@hanshin-exp.co.jp*
[4] *Earthquake Engineering Research Center Inc, nakamura@eerc.co.jp*
[5] *Earthquake Engineering Research Center Inc, magoshi@eerc.co.jp*

Abstract

Earthquake damage simulations in expressway network targeted major earthquakes in the future has been researched in Hanshin Expressway. This simulations target all Hanshin Expressway route. So, it can evaluate the bridge damage conditions in route units or span units. If damaged piers can be predicted by the earthquake damage simulation, it is possible to clarify the piers where we should conduct the seismic reinforcement. In addition, if amount of step displacement on the road surface can be predicted, it is possible to clarify the places where we should prepare equipment to eliminate the steps.

This earthquake damage simulation system is divided into three stages. Every earthquake simulation delivers the simulation results.

Step 1 : Deep ground response analysis (from epicenter to engineering foundation)

Step 2 : Shallow ground response analysis (from engineering foundation to pier foundation)

Step 3 : Structural response analysis

In this study, 1995 Kobe earthquake was tried to reproduce by using this earthquake damage simulation to verify this simulation accuracy. As a result, the damage dispersion of the actual structures at 1995 Kobe earthquake and this reproduction simulation were coincided. Therefore, this simulation was confirmed the accuracy.

In addition, earthquake damage simulations targeted various epicenter were conducted, such as Nankai Trough earthquake and Uemachi earthquake. It was clarified that this simulation system is possible to evaluate pier damages and the amount of step displacement before earthquakes.

Keywords: earthquake damage simulation, expressway network, 1995 Kobe earthquake

1. Introduction

On Hanshin Expressway, seismic retrofit projects have been conducted after 1995 Kobe earthquake, i.e. strengthening of bridge piers, ensuring adequate seating of girders and improving bridge restrainers. In addition, earthquake damage simulations in expressway network targeted major earthquakes in the future has been also researched as one of efforts for preventing and mitigating disasters. These simulations target all Hanshin Expressway route. Therefore, it can evaluate the bridge damage conditions in route units or section units. If damaged piers can be predicted by the earthquake damage simulation, it is possible to clarify the piers where we should conduct the seismic reinforcement. In addition, if amount of step displacement on the road surface can be predicted, it is possible to clarify the places where we should prepare equipment to eliminate the steps.

In this study, 1995 Kobe earthquake was tried to reproduce by using this earthquake damage simulation to verify this simulation accuracy. In addition, earthquake damage simulations targeted various epicenter were conducted, such as Nankai Trough earthquake and Uemachi earthquake. In this paper, these simulation results were reported at the current level.

2. Method of earthquake damage simulations in expressway network

As shown in Fig. 1, this earthquake damage simulation system is divided into 3 steps. Step 1 is "Deep ground response analysis" which evaluate transmission of earthquake ground motions from epicenter to base ground surface for seismic design. Step1 results (such as acceleration response values at base ground surface for seismic design) are passed to Step 2. Step 2 is "Shallow ground response analysis" which evaluate amplification of earthquake ground motions from base ground surface for seismic design to each of pier foundations. In Step 2, 1-dimensional non-linear dynamic analyses for shallow grounds below each of pier foundations are conducted. Step 2 results (such as accelerations response values just below pier foundations) are passed to Step 3. Step 3 is "Structural response analysis" which evaluate seismic behavior of bridges.

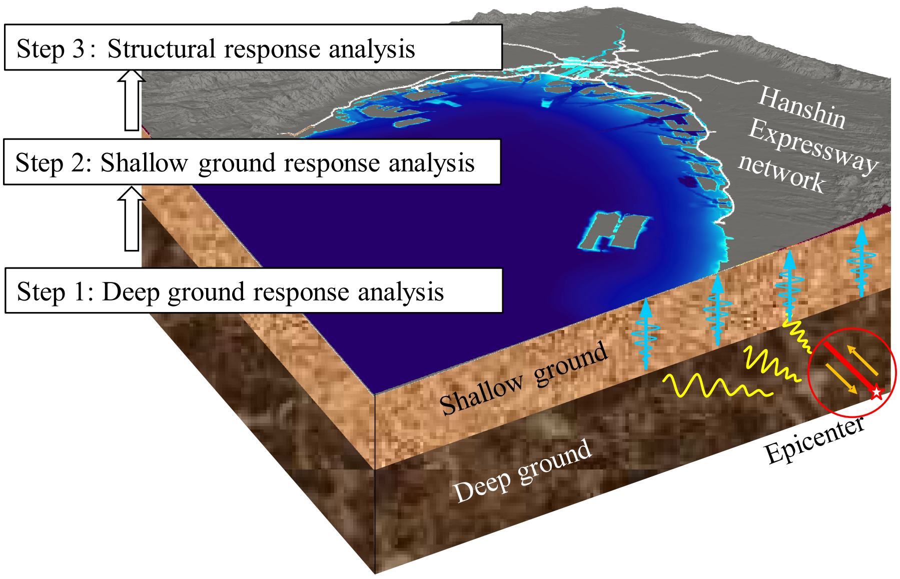


Fig. 1 – Method of the arthquake damage simulation in expressway network

Table 1 shows the current analysis methods and analysis models. There are some analytical methods and analytical models in each of the steps. We will improve the accuracy level of analytical methods and analytical models sequentially in the future.

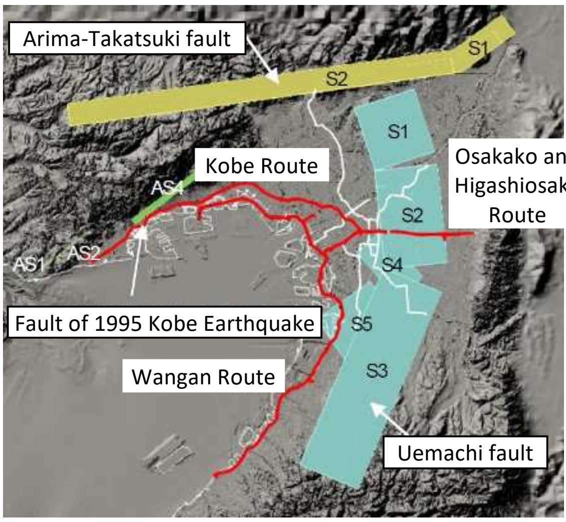
Table 1 – Current analytical methods and analytical models

Structural response analysis	earthquake response analysis which ground motions passed from Step2 were inputted at below each of pier foundations
Shallow ground response analysis	sequential nonlinear dynamic analysis (YUSAYUSA etc.) - available for large strain occurred - difficult to consider frequency characteristics
Deep ground response analysis	Statistical Green's function method - easy to calculate short period component of ground motions - impossible to calculate long period component of ground motions

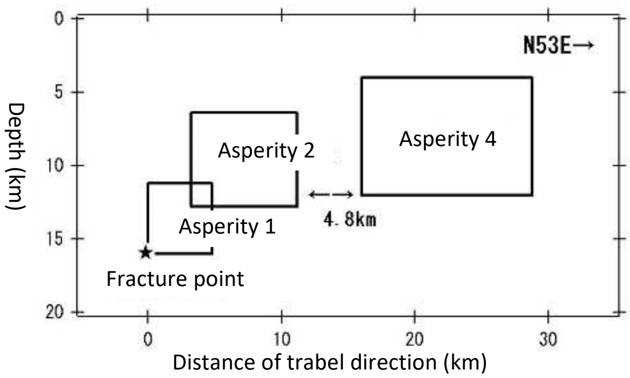
3. Construction of analytical models

3.1 Deep ground response analysis model (Step1)

Fig.2 shows the fault model for 1995 Kobe Earthquake. Nozu et al. used this model and almost reproduced 1995 Kobe earthquake ground motion [1]. Statistical Green's function method was used in this reproduction analysis. Analytical region was set at 400 km x 400 km centering on SMGA fracture point and was divided with a 100m mesh.



(a) fault distribution



(b) fracture point and asperities

([1] Fig.9 quoted)

Fig. 2 – Fault model for 1995 Kobe Earthquake

Table 2 shows the details of its parameters. Unpublished parameters were set based on "Strong ground motion prediction method for earthquakes with specified source faults" ("Recipe") published by the Headquarters for Earthquake Research Promotion [2].

Table 2 – the details of 1995 Kobe Earthquake fault model parameters

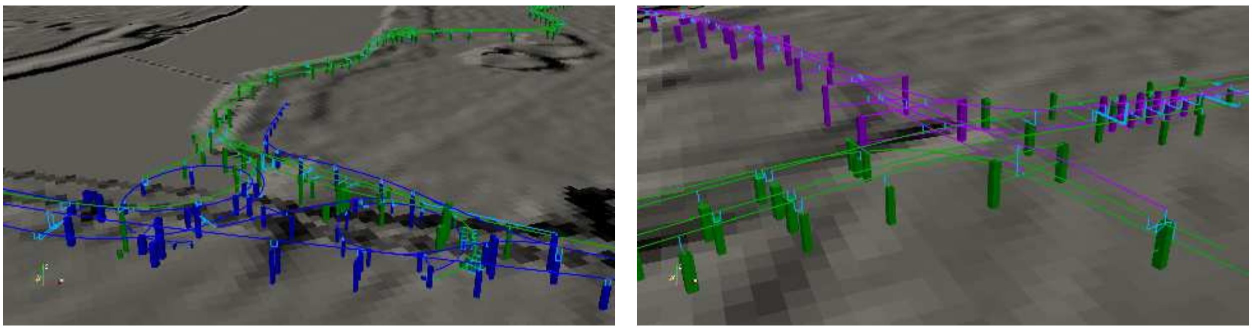
Name of fault	Asperity1	Asperity2	Asperity4
Position at southwest tip of fault	34.616700	34.635673	34.688183
	135.02940	135.05923	135.18803
Average angle of fault travel direction θ (°)	N53	N53E	N233E
Average angle of fault inclination direction δ (°)	90	90	85
Average angle of fault slip λ (°)	0	0	0
Fault length L (km)	4.8	8	12.8
Fault width W (km)	4.8	6.4	8
Fault section S (km2)	23	51	102
Head depth of fault Z0 (km)	3.0	3.0	3.0
Moment of Earthquake (N・m)	3.40E+17	1.30E+18	2.30E+18
Magnitude of Earthquake Mw	5.6	6.0	6.2
Average amount of slip (m)	0.4	0.7	0.7

3.2 Shallow ground response analysis model (Step2)

In the shallow ground response analysis, analytical models reproduced the ground structures at immediately below each pier foundation. Ground constants of analytical models were set based on boring data in the Kansai Geo-informatics database [3]. When the analytical models were built, the nearest boring data from each of pier foundations were used because boring data was limited [4]. In this study, shallow ground was divided into 4 geological groups, alluvial sand (As), alluvial clay (Ac), diluvial sand (Ds) and diluvial clay (Dc). Hyperbolic curve models were applied to each of groups and were set based on the triaxial test results in the Kansai Geo-informatics database.

3.3 Structural response analysis model (Step3)

Fig. 3 shows examples of the structural response analysis model by SeanFEM[5,6]. At this stage, structural response analysis models of Kobe Route, Wangan Route, Kita-Kobe Route, Higashiosaka Route and Osakako Route were constructed. All route analytical models in Hanshin Expressway will be constructed in 2020.



(a) near Awaza Curve (b) near Tenpozan Junction

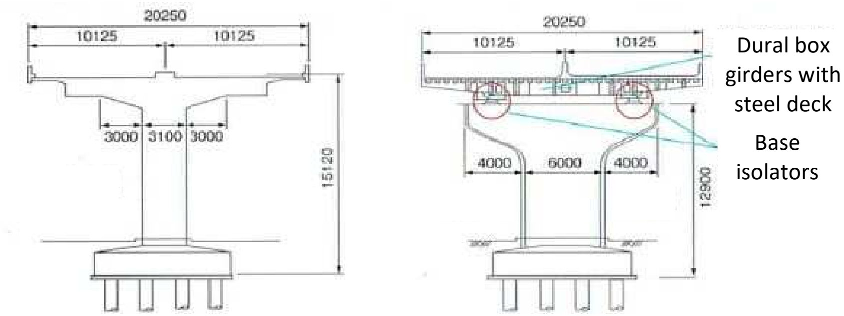
Fig. 3 – Examples of the structural response analysis model

Table 3 shows elements of the structural response analysis models. Super structurers were modeled by linear elements. Steel bearings were reproduced the support conditions and rubber bearings were modeled by spring elements with equivalent rigidity. Piers were modeled by nonlinear elements. Pier foundations were modeled by spring elements.

Table 3 – Elements of structural response analysis models

Superstructures	linear beam element
Bearings	Steel bearings : fixed or movable Rubber bearings : spring element (with goruping equivalent rigidity)
Pier	nonlinear beam element (groping)
Pier foundation	spring element (S-R model)

In this study, all piers in Hanshin Expressway were divided into 13 groups according to structural configuration and diameter of the cross section, and the representative piers were selected from each of the groups. The representative pier's cross section was applied to that of piers divided into same group. Seismic reinforcement has been conducted after 1995 Kobe Earthquake in Hanshin Expressway, i.e. steel piers were filled with concrete or RC piers were wrapped by steel plates. The analysis models had unreinforcement cross sections to reproduce structural condition at the time of the earthquake. In addition, as shown in Fig. 4, Pilz piers collapsed at the earthquake were modeled based on the drawing at the time.



(a) before the earthquake (Pilz pier) (b) after the earthquake

Fig. 4 – Cross-section before and after the earthquake

4. REPRODUCTION SIMULATION OF 1995 KOBE EARTHQUAKE

The reproduction simulation results of 1995 Kobe Earthquake are shown below. Further, this study on earthquake damage simulations in expressway network is in a research and development stage. The accuracy of the analysis results will be verified in the future.

4.1 Deep ground response analysis

Fig. 5 shows the maximum acceleration values distribution at the base ground surface for seismic design. It is confirmed that maximum acceleration values calculated on Kobe Route because the point was near the epicenter of 1995 Kobe Earthquake.

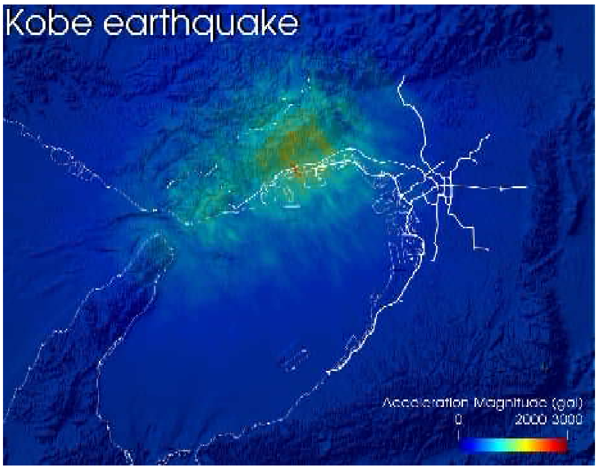
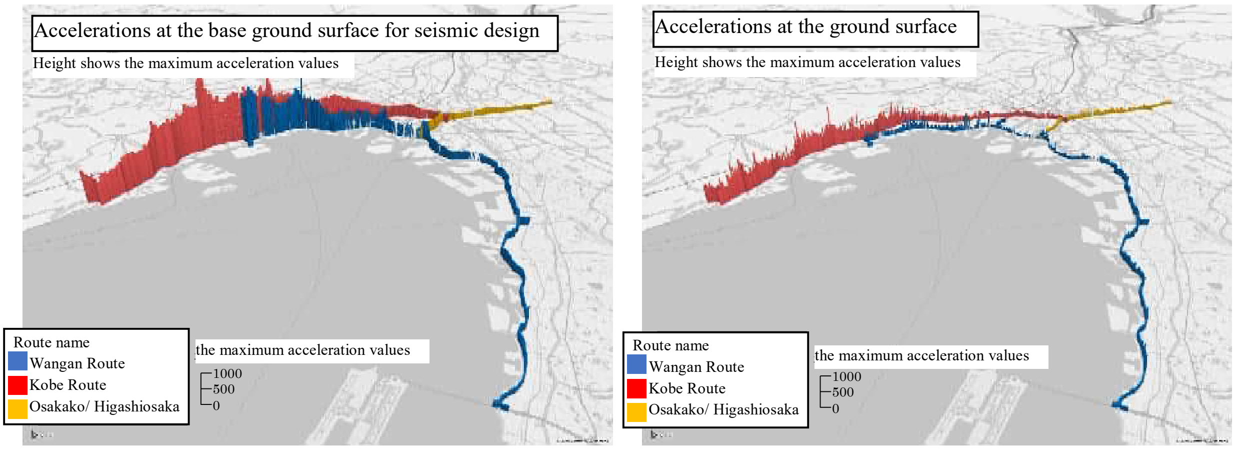


Fig. 5 – the maximum acceleration values distribution at the base ground surface for seismic design

4.2 Shallow ground response analysis

Fig. 6 shows the maximum acceleration values distribution at the base ground surface for seismic design and the ground surface below each of pier foundations. Although large accelerations at ground surface were calculated on Kobe Route, the acceleration values at the ground surface were lower than at the base ground surface for seismic design.

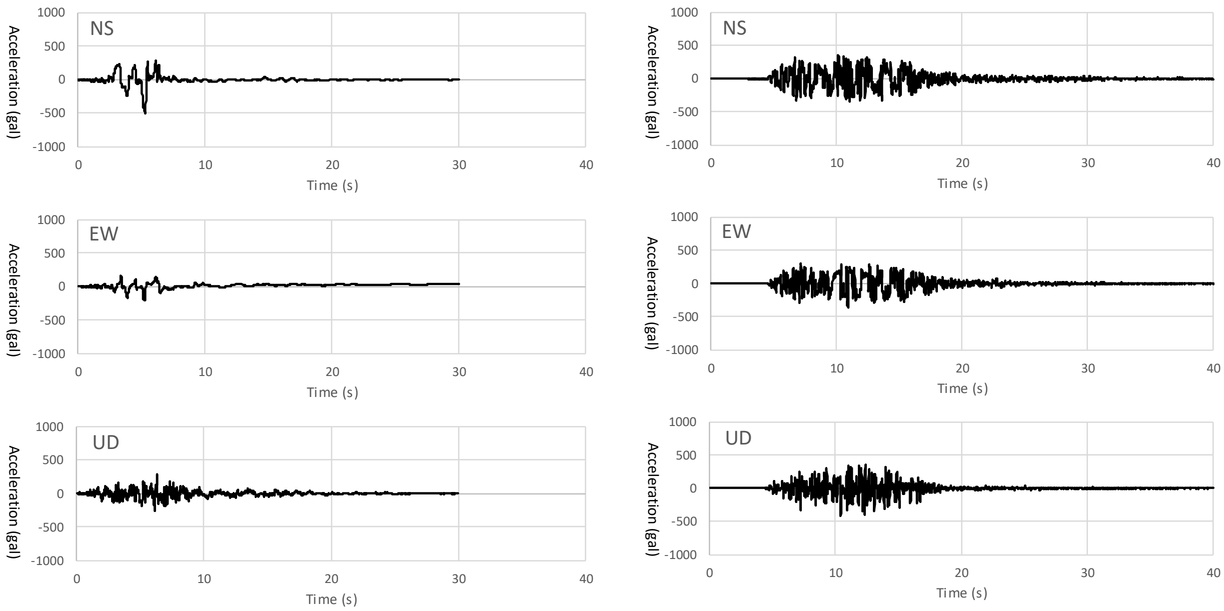


(a) at the base ground surface for seismic design (b) at the ground surface

Fig. 6 – the maximum acceleration values distribution

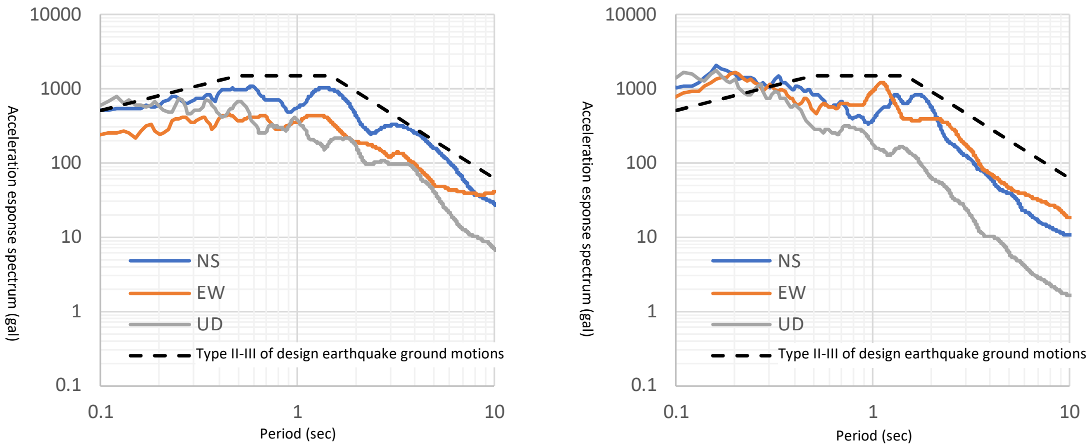
Fig.7 shows the time history accelerations at the ground surface of the actual observation record and the reproduction analysis. Here, the observation record was recorded at Kobe-S observation station by the Strong Motion Earthquake observation in Japanese Ports [7]. This record was selected because it was thought that the station was the nearest of all stations recorded at the earthquake ground motions. The analysis results were picked up at the pier position close to Kobe-S observation station. The distance from Kobe-S observation station to the objective point in reproduction analysis is about 330 m.

Fig.8 shows the acceleration response spectrum at the ground surface of the actual observation record and the reproduction analysis. The NS and EW components of the observation record are dominant at a period of about 1.5 seconds. All components of the reproducibility analysis are dominant at a period of around 0.2 seconds and 1.5 seconds. General piers have eigen period over 0.2 seconds in Hanshin Expressway, the simulation results were similar to the observation record in period band of structural response. However, in the NS and EW components of the observation record, the main motion continued for about 5 seconds after the seismic motion reached the observation point, but in the reproduction analysis, the main motion continued for about 15 seconds. Therefore, the reproducible analysis evaluated the duration of the ground motion longer than the observation record. It was thought that the parameter of the epicenter model in the deep ground response analysis effect on the duration of the ground motion. Therefore, deep ground response analysis with different parameters will be conducted to improve the accuracy of the ground motion.



(a) observation record (b) reproduction analysis

Fig. 7 – The time history accelerations at the ground surface

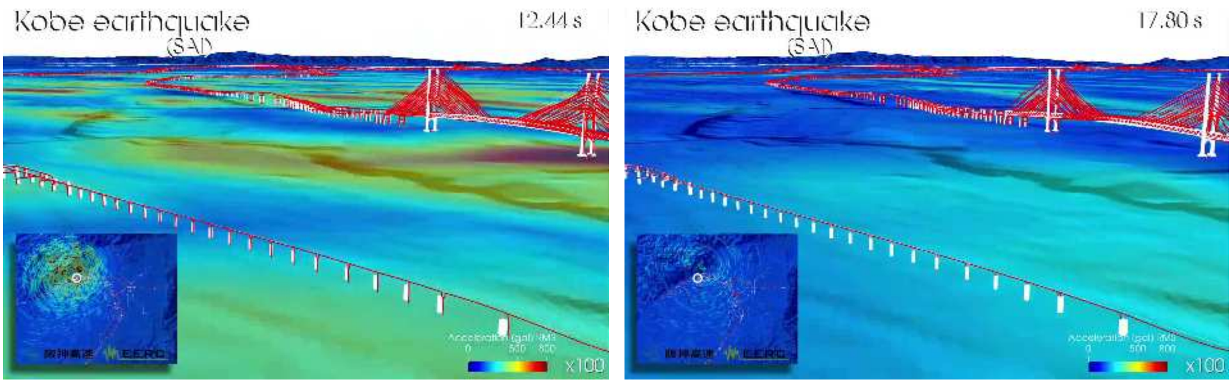


(a) observation record (b) reproduction analysis

Fig. 8 – The acceleration response spectrum at the ground surface

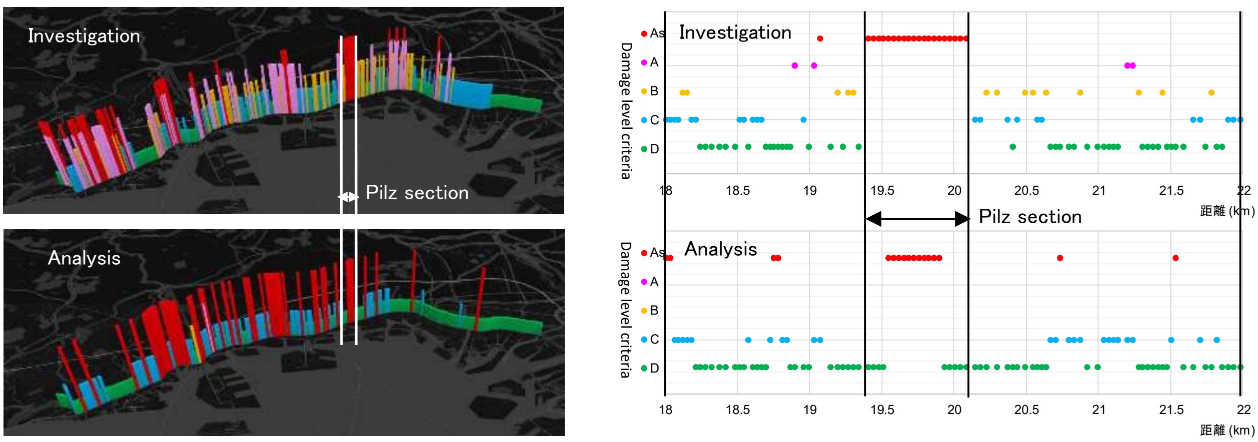
4.3 Structural response analysis

Fig.9 shows the deformation modes near Higashi-Kobe Bridge at about 12 second and 18 second from occurring the earthquake. Fig.10 shows damage level criteria of piers along Kobe Route. Here, 5 ranks from As to D were set for the damage level criteria of pier capacity. The investigation results at the time were classified based on the actual external damage after 1995 the earthquake. The damage level criteria of them was determined by the policies as shown in Table-4. In reproduction analysis, it was determined according to the maximum strains of longitudinal rebars, those of concrete and the maximum shear capacity. Thresholds to class the damage level criteria were set based on prevent examinations and the latest design specification [8-10]. Focusing on Pilz piers along Kobe Route collapsed by 1995 Kobe Earthquake, it was classified as "As" in the investigation result. In the reproduction analysis results, it was classified as "As" although not all spans. Therefore, it was confirmed that there was a certain accuracy to class damage level criteria of piers under large earthquakes.



(a) about 12 sec.　　(b) about 18 sec.

Fig. 9 – The acceleration response spectrum at the ground surface



(a) along Kobe Route　　(b) around Pilz section

Fig. 10 – damage level criteria of piers along

Table 4 – The policies for the damage level criteria

Rank	damage level
As	Collapse or toppling, or equivalent damage
A	Damage affecting the load carrying capacity significantly and causing risk of potential life-threatening secondary disasters
B	amage affecting the load carrying capacity but allowing for temporary use as long as it does not worsen any further during aftershocks or under live load
C	Damage with no adverse effects on the short-term load carrying capacity
D	Damage with no specific effects on the load carrying capacity

5. Damage evaluation by earthquake response simulations for various hypocenter

5.1 Assumed ground motion

Table 5 shows a list of ground motions assumed in this study. In this study, 4 inland active fault type earthquake and 1 trench type earthquake were assumed. Uemachi Earthquake (South collapsed case and North collapsed case), Arima-Takatsuki Earthquake and 1995 Kobe Earthquake were targeted as inland active fault type earthquake. Nankai Trough Earthquake was targeted as trench type earthquake.

Fig.2 shows the fault distribution of Uemachi Earthquake, Arima-Takatsuki Earthquake and 1995 Kobe Earthquake. The seismic center distribution and the fault parameters of the target earthquakes are based on the Osaka Prefectural Natural Disaster Prevention Measures for Uemachi Earthquake and Arima-Takatsuki Earthquake [11]. Analytical region for Uemachi Earthquake and Arima-Takatsuki Earthquake were set at 400 km x 400 km centering on SMGA fracture point and was divided with a 100m mesh.

Fig.11 shows the fault distribution of Nankai Trough Earthquake. The seismic center distribution and the fault parameters of Nankai Trough was based on published data (land side case) by the Cabinet Office Nankai Trough Great Earthquake Model Study Group [12]. Parameters that are not shown in the public documents were set based on “Recipe”. The deep ground response analysis model was built based on J-SHIS information (ver. 2017) [13]. Analytical region for Nankai Trough Earthquake was set at 500 km x 500 km centering on SMGA fracture point and was divided with a 100m mesh.

Table 5 – Analysis case

Case	Earthquake ground motions
1	1995 Kobe earthquake
2	Uemachi fault earthquake (north fault case)
3	Uemachi fault earthquake (south fault case)
4	Arima-Takatsuki fault earthquake
5	Nankai Trough earthquake

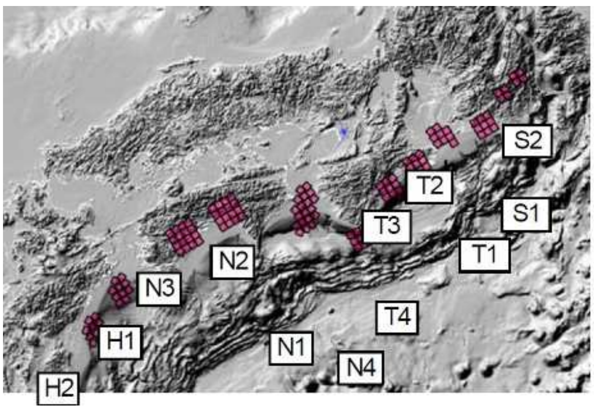


Fig.11 – Fault model for Nankai Trough Earthquake

5.2 Earthquake damage simulation results

Fig.12 shows the damage degree maps of pier capacity at each pier based on earthquake response simulations. It was calculated that some piers along Wangan Route or Kobe Route were greatly damaged under 1995 Kobe Earthquake and Arima-Takatsuki Earthquake. It was also calculated that some piers along the entire route were greatly damaged under Uemachi Earthquake (north failure case and south failure case). The number of damaged piers under Nankai Trough earthquake was lower than other earthquakes.

Fig.12 also shows those of car runnability based on earthquake response simulations. As a result, it was clarified that this simulation system is possible to evaluate pier damages and the amount of step displacement before earthquakes.

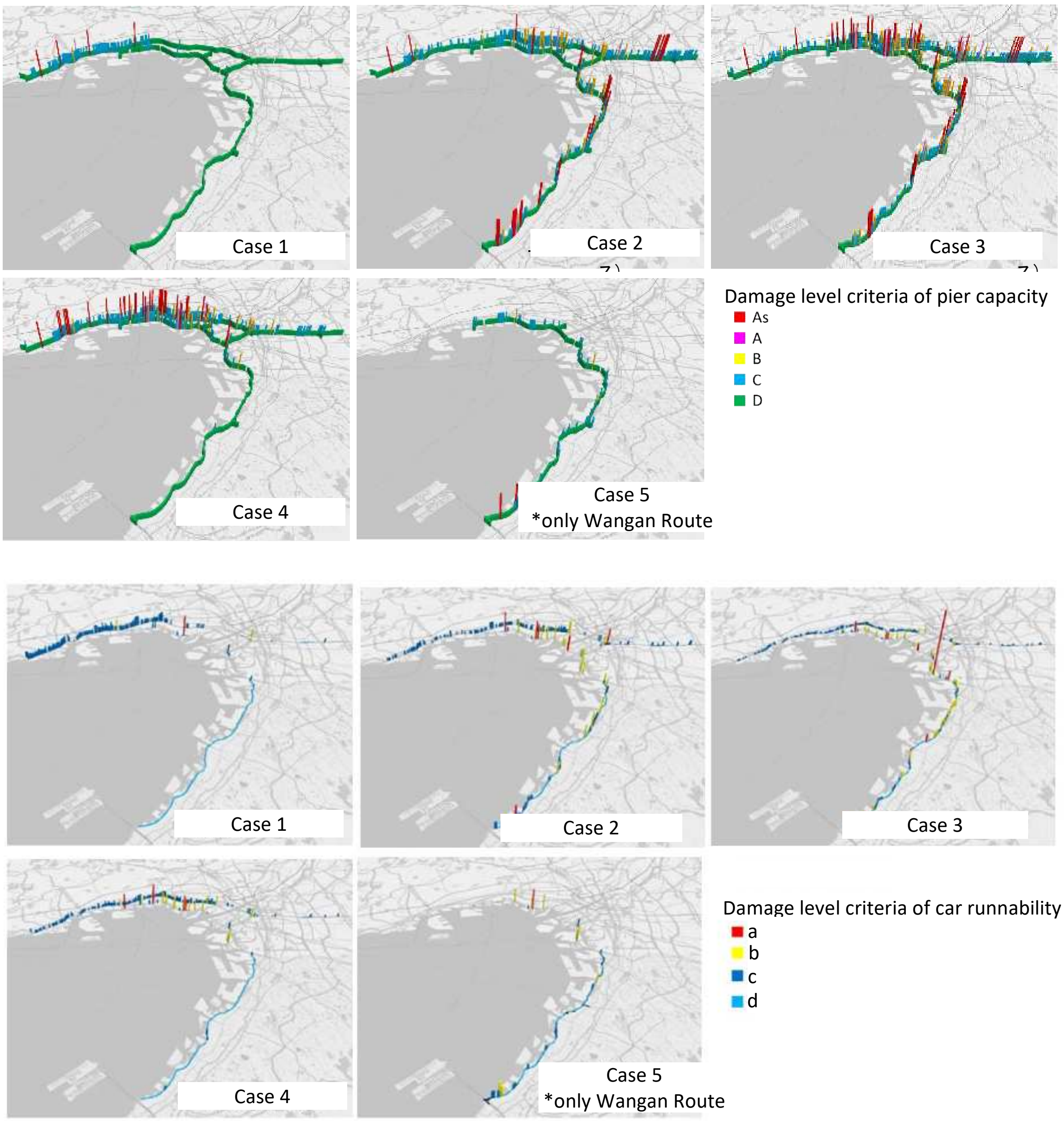


Fig. 12 – damage level criteria of pier capacity and car runnability

6. Conclusion

In this study, 1995 Kobe earthquake was tried to reproduce by using this earthquake damage simulation to verify this simulation accuracy. As a result, the damage dispersion of the actual structures at 1995 Kobe earthquake and this reproduction simulation were coincided. Therefore, this simulation was confirmed the accuracy.

In addition, earthquake damage simulations targeted various epicenter were conducted, such as Nankai Trough earthquake and Uemachi earthquake. It was clarified that this simulation system is possible to evaluate pier damages and the amount of step displacement before earthquakes.

In this paper, we showed the simulation results in a research and development stage. In order to improve prediction accuracy of this simulation system in the future, it is necessary to improve the level of analysis model for structural response analysis. It is also necessary to reevaluate the parameters using ground motion analysis and thresholds determining the degree of damage.

7. Acknowledgments

This research is part of the joint research between Hanshin Expressway Co., Ltd. and the Earthquake Engineering Research and Development Center Co., Ltd. on “joint research on earthquake response simulation for Hanshin Expressway network under large earthquake. We thank all the parties concerned here.

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