A DEVELOPMENT OF DISASTER MANAGEMENT SUPPORTING SYSTEM FOR EATHQUAKE TAKING ROAD NETWORKS INTO ACCOUNT

Koichi MITSUNARI[1], Takeyuki EBI[2], Yuji TAKAHASHI[3], Reiko AMANO[4], Yasunori HIRAYAMA[5], Manabu AKOSHIMA[6], Toshihiko TAKAHASHI[7]

[1] *Chief Engineer, Civil Engineering Design Division, Kajima Corporation. JAPAN*
[2] *Chief Engineer, Engineering Management Division, Kajima Corporation. JAPAN*
[3] *Group Manager, Civil Engineering Design Division, Kajima Corporation. JAPAN*
[4] *Dr. of Eng., Group Manager, Engineering Management Division, Kajima Corporation. JAPAN*
[5] *Senior Manager, Planning System Gr., IT Solutions Department, Kajima Corporation. JAPAN*
[6] *Engineer, Planning System Gr., IT Solutions Department, Kajima Corporation. JAPAN*
[7] *Chief Research Engineer, Kajima Technical Research Institute, Kajima Corporation. JAPAN*

Email: mitsunari@kajima.com, ebi@kajima.com, takahashi-yuji@kajima.com, amanor@kajima.com, y-hirayama@kajima.com, m-akoshima@kajima.com, takahtko@kajima.com

ABSTRACT :

Preparing for the impact of anticipated earthquake disasters, many municipal governments in Japan are now drawing up their action plans. Private sectors are also forced to take a prompt action for establishing their own business continuity plans (BCPs) to protect and maintain their own businesses.
In a time of earthquake disaster, road networks are important as well as any other facilities for disaster mitigation. Once a severe earthquake occurs, road networks will be the most vital infrastructure to convey food, medicine, people, and all other supplies necessary for victims.
However, the evaluation of the stability of road networks against earthquake is not considered enough for disaster management supporting systems.
We have therefore developed a disaster management supporting system for earthquake taking road networks into account, targeted for evacuation routes and emergency transportation routes. Considering the damage of road networks by earthquake practically, we will have become able to support establishing efficient action plans of municipal governments for disaster mitigation or companies' BCPs.
The proposed system takes the following factors causing road blockade into account:

- Infrastructure damage
- Building collapse
- Ground liquefaction
- Flood by tsunami

In this paper, we introduce the outlines of this system first, then demonstrate some procedures we developed for reflecting the road blockade by the said factors, and finally present some examples of road network analysis for an assumed earthquake.

KEYWORDS: disaster management, road network, road blockade, infrastructure damage, building collapse, ground liquefaction, flood by tsunami

1. INTRODUCTION

Municipal action plans and private companies' BCPs in preparing for earthquakes and other natural disasters have become a vital management issue. In these plans, the road transportation networks are quite important as well as disaster shelters and other emergency facilities. When an area is struck by a major earthquake, roads are the most important facilities to ensure transportation of people and distribution of goods. Road damage caused by an earthquake therefore should be considered properly for accessibility evaluation.

The damage of road infrastructures such as bridges and slopes are very likely to form a bottleneck when an earthquake occurs. In order to secure transportation routes in case of earthquake disaster, accessibility should be evaluated considering road blockade due to the damage of earthquakes.

In this paper, we demonstrate the evaluation method of road blockade caused by infrastructure damage, building collapse, ground liquefaction, and flood by tsunami, then present some examples of the result of road network analysis reflecting road blockade for an assumed earthquake.

2. OVERVIEW OF THE SYSTEM

The disaster management supporting system that we developed consists of five components: (a) hazard estimation; (b) earthquake damage assessment; (c) road blockade evaluation; (d) road network analysis; and (e) disaster information display. (See Figure 2-1)

Considering anticipated influence on road traffic caused by an earthquake, we employed ground motion, liquefaction, and tsunami as for hazard estimation (a).

Earthquake damage such as infrastructure damage and building collapse is empirically assessed by the simplified diagnosis and statistical estimation (b).

Road blockade rates shall be evaluated by the earthquake damage assessment as well as surrounding events that can lead to road blockade, such as liquefaction of the ground, and flood by tsunami (c).

Using the road blockade rates, the road network system seeks out the most appropriate road for evacuation and emergency transportation (d).

The disaster information display system visually displays the results of (a), (b), (c) and (d) on a map. Its visual display function of disaster information allows quick understanding of a disaster situation (e). The system then contributes effectively to supporting municipalities' disaster management plans and companies' BCPs.

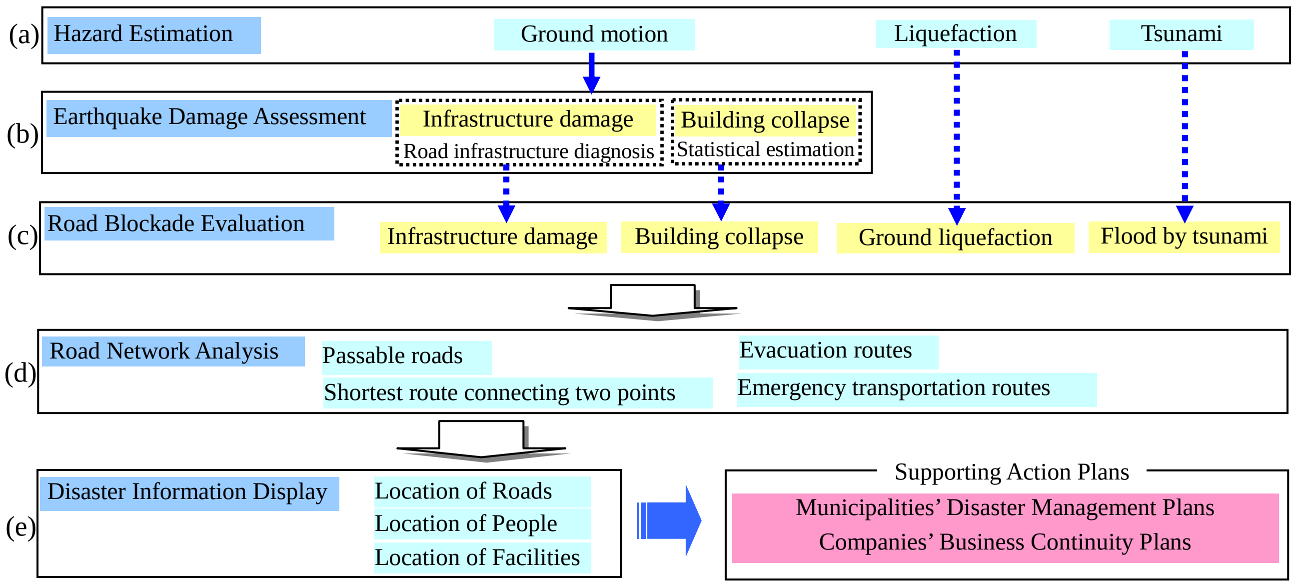

Figure 2-1 Overview of the system

3. ANALYSIS OF HAZARD CAUSED BY EARTHQUAKES

3.1. Estimation of Ground Motion during Earthquakes

Ground motion can be estimated based on the information of anticipated earthquakes announced by public agencies and research institutions, the record of major earthquakes occurred in the past, and the result of stochastic earthquakes calculated by probabilistic approach. In order to apply the result of hazard analysis to network analysis, ground motion shall be evaluated by seismic intensity allocated to every 1km grid cell. We employed the following sources for ground motion estimation.

3.1.1 Source 1:Seismic information by the Japanese Meteorological Agency

Seismic intensity data is updated in the website of the Japanese Meteorological Agency when an earthquake occurs. Seismic intensity data of major earthquakes in the past has been downloaded from this website as a database for the system. The downloaded seismic intensity data is converted to seismic intensities with 1km grid cells, reflecting the difference in characteristics of subsurface layers of each location.

3.1.2 Source 2: Scenario earthquakes

Seismic intensity distributions of scenario earthquakes with 1km grid cells prepared by the Japanese Central Disaster Prevention Council and the Headquarters for Earthquake Research Promotion have been open to the public.

3.1.3 Source 3: Major earthquakes in the past

Seismic fault models are proposed for several major earthquakes in the past. Seismic intensities are evaluated by the attenuation equation proposed by Si and Midorikawa[1], adopting equivalent hypocentral distance of the fault.

3.1.4 Source 4: Stochastic earthquakes

Using "New SEIRA(Newly developed SEIsmic Risk Analysis system) [2]," the expected seismic intensity of each location can be evaluated by statistical analysis of seismic data in the past. (See Figure 3-1)

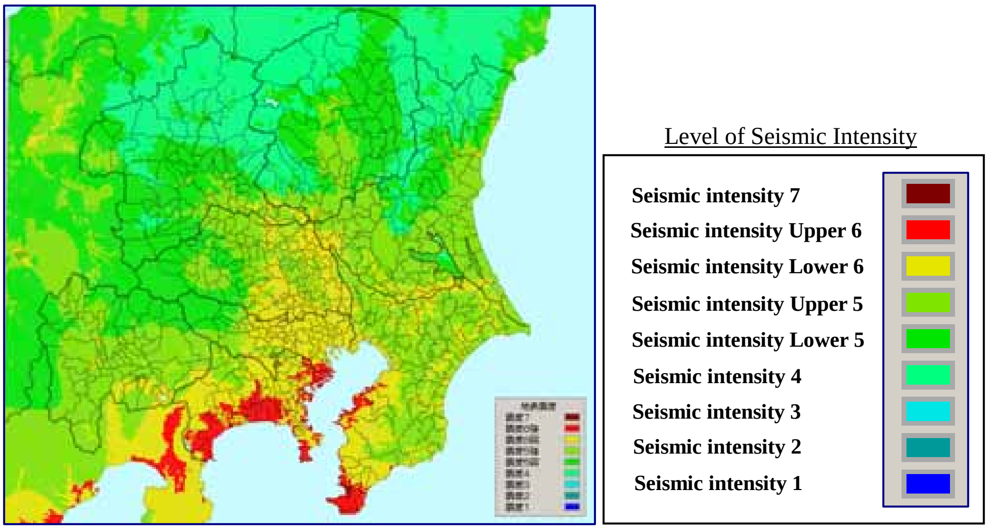

Figure 3-1 Surface seismic intensity of stochastic earthquake in Kanto area (50 year period, excess probability:10%)

3.1.5 Source 5: Hypothetical earthquake

The system also enables us to assume hypothetical earthquakes. By allocating any point hypocenter with a certain magnitude, surface seismic intensities with 1km grid cell can be evaluated by the system. This function is especially targeted for an earthquake whose hypocenter is directory below a populated area.

3.2. Liquefaction of the Ground

The simplified liquefaction prediction method proposed by Wakamatsu et. al.[3] is employed in this system. Liquefaction of the ground will be evaluated by geomorphologic classification as shown in Table 3-1.

Critical surface seismic motion velocity causing liquefaction (PGVC) is calibrated to each liquefaction classification as shown in Table 3-2. Ground motion velocities corresponding to the assumed earthquake (PGV) can be calculated from seismic intensities obtained from section 3.1. Then PL values, which represent the possibilities of liquefaction, shall be converted by the value of PGV/ PGVC as shown in Table 3-3.

Figure 3-2 shows an example of liquefaction hazard in Kanto area assuming the North Tokyo bay earthquake.

Table 3-1 Liquefaction levels by geomorphologic class

Geomorphologic class	Liquefaction level
Valley-bottom plains	2
Alluvial fan	3
Natural levees	1
Marshy area	2
Former river channels	1
Delta/ Coastal lowland	2
Bar / Pebble bank	3
Sand dune	1
Reclaimed land	1
Filling land	1

Table 3-2 Critical surface seismic motion velocity of liquefaction for each liquefaction level

Liquefaction level	Critical surface seismic motion velocity of liquefaction (PGVC (cm/s))
1	15
2	25
3	30

(Data source: Wakamatsu et.al. ; Japan Engineering Geomorphologic Classification Map, 2005.)

Table 3-3 PL values corresponding to PGV/ PGVC

PGV / PGVC	PL value
1.25～	15＜PL
1.0～1.25	5＜PL≦15
0.75～1.0	0＜PL≦5
～0.75	PL≦0

PGV: Surface seismic motion velocities corresponding to the assumed earthquake (cm/s)

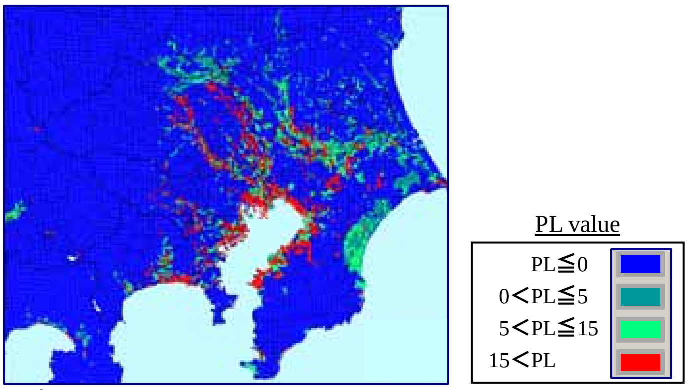

Figure 3-2　Liquefaction hazard in Kanto area assuming the North Tokyo bay earthquake

3.3. Flood by Tsunami

Numerical simulations of tsunami propagation are conducted with a program code called TUNAMI, which was originally developed by Tohoku University and have been modified by Kajima Corporation. This program employs a leapfrog finite difference scheme with staggered grids and is written in FORTRAN.

There were several difficulties to complete the numerical simulations, because some input data, such as topographical features and roughness coefficients in selected areas, are lacking and initial deformation data have to be carefully generated by assuming an appropriate fault model. Several years ago, the Central Disaster Prevention Council conducted integrated numerical simulations of tsunami propagation for representative hypothetical earthquakes to create and promote the implementation of the Basic Disaster Management Plans. Recently, these data generated and developed by the Central Disaster Prevention Council have been open to the public, which enables us to conduct the numerical simulations readily without the above-mentioned difficulties.

From the viewpoint of computational time and accuracy, a nesting scheme was applied, which is common in conducting numerical simulations of tsunami propagation. Similar to the Central Disaster Prevention Council's, four levels of the grid size, 1350m, 450m, 150m, and 50m, were employed. Figure 3-3 shows an example of the topographical features.

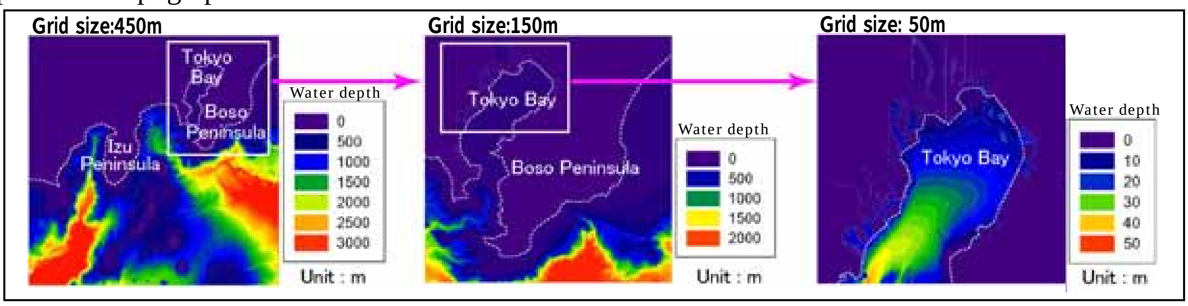

Figure 3-3 Nesting scheme for topographical features

4. EARTHQUAKE DAMAGE ASSESSMENT AND EVALUATION OF ROAD BLOCKADE

4.1. Road Infrastructures

Based on the "Guidelines for roads affected by earthquake disaster[4)]" published by the Japan Road Association, other relevant manuals and research papers by official agencies, we have developed the simplified quake-resistant capacity diagnosis methods for road infrastructures such as bridges and slopes. Essentially common data open to the public can be applicable to this diagnosis method.

4.1.1 Diagnosis method for Bridges

According to the report on damage due to the Kobe earthquake (1995), almost all damaged bridges that obstructed traffic were limited to those conforming to the design standard established before 1971[5)]. Furthermore, the damage of bridges obstructing traffic is limited to areas whose seismic intensity is 6 or more. We therefore evaluated the possibility of obstructing traffic for each bridge considering these factors.

The result of damage assessment related to impassableness based on a reference year of the design standard and a seismic intensity of the bridge location is sorted out in Table 4-1. The road blockade rates can be obtained by the result of relative risk as shown in the Note 1 of Table 4-1.

Table 4-1 Damage assessment for bridges

		Reference year of the design standard		
Seismic intensity	Max. acceleration	1971 or before <I>	1980 <II>	1996,2002 <III>
Seismic intensity 6 or more	800 Gal or more	Relative risk "a"	Relative risk "b"	Relative risk "c"
Seismic intensity 5-6	250-800 Gal	Relative risk "b"	Relative risk "c"	Relative risk "c"
Seismic intensity 5 or less	Less than 250 Gal	Relative risk "c"	Relative risk "c"	Relative risk "c"

Note 1: Relative risk "a": Impassable (blockade rate=100%) ⇒ Close down (automobile velocity=0)
Relative risk "b": Traffic difficulty (blockade rate=50%) ⇒ Reduction in traffic capacity (ex. 50% reduction in velocity)
Relative risk "c": Passable (blockade rate=0%) ⇒ Same as normal state

Note 2: The relationship between the measured seismic intensity and maximum acceleration is obtained by the estimation formula of measured seismic intensity based on the maximum velocity by Tong and Yamazaki [6)].)
$I = 0.59+1.89 \cdot \log10(PGA)$

4.1.2 Diagnosis method for slopes

We proposed a simple diagnosis method for assessing slope stability based on an elevation data alone, applying the discriminant function formula established by the National Institute for Land and Infrastructure Management[7)].

Taking slope inclination, mean curvature, and maximum acceleration of an earthquake into account, this method enables us to assess the relative risk of slope failure by an earthquake practically even if there is no record regarding slope failures in the past earthquakes.

The discriminant function formula (4.1) shown below, assesses the relative frequency of slope failure by discriminant analysis using occurrence and not-occurrence of failure as an objective variable based on the slope failure distribution after the Kobe earthquake (1995).

$$FR = 0.0075 \cdot \text{inclination } (^\circ) - 8.9 \cdot \text{mean curvature} + 0.0056 \cdot \text{max. acceleration } (cm/s^2) - 3.2 \qquad (4.1)$$

The slope failure area ratio corresponding to the discrimination score (FR) of a certain grid cell is considered to imply the possibility of slope failure in the grid cell. We therefore assigned the slope failure risk corresponding to the slope failure area ratio as shown in Table 4-2. The road blockade rate can be obtained by the result of relative risk as shown in the Note 1 of Table 4-2, in the same way as the bridge damage assessment.

Table 4-2 Damage assessment for slopes

Relative risk	Relative risk of slope failure	Discrimination score (FR)	Slope failure area ratio	Slope failure risk
High	Collapse occurs easily.	3.0 or more	30%	Relative Risk “a”
	Collapse occurs rather easily.	2.0-3.0	10%	Relative Risk “b”
	Collapse does not occur easily.	–1.5-2.0	3%	Relative Risk “c”
Low	Collapse can hardly occur.	Less than –1.5	1%	

Note 1: Relative risk “a”: Impassable (blockade rate=100%) ⇒ Close down (automobile velocity=0)
Relative risk “b”: Traffic difficulty (blockade rate=50%) ⇒ Reduction in traffic capacity (ex. 50% reduction in velocity)
Relative risk “c”: Passable (blockade rate=0%) ⇒ Same as normal state

4.2. Building Collapse

Building collapse is forecasted by estimating population density and wood-frame building density from the officially announced population distribution in the affected area. Then, the roads to be blocked due to building collapse are estimated by reflecting the actual road blockade rates due to building collapse and neighboring street width in the past earthquakes such as the Kobe Earthquake (1995). In order to harvest the statistics of actual blockade rates due to building collapse, we adopted the method proposed by the Tokyo Metropolitan Government[8].

Basic concept of this method is as follows;

- Roads whose widths are 13m and above would not be blocked,
- Blockade rates for roads whose widths are less than 13m would be calculated by the following formulas, proposed based on the investigation data of the Kobe earthquake(1995);

$$\begin{aligned} &\text{Road width} < 3.5\text{m}: && \text{Blockade rate (\%)} = 0.9009 \cdot \text{damaged building rate} + 19.845 \\ &3.5\text{m} =< \text{Road width} < 5.5\text{m}: && \text{Blockade rate (\%)} = 0.3514 \cdot \text{damaged building rate} + 13.189 \\ &5.0\text{m} =< \text{Road width} < 13.0\text{m}: && \text{Blockade rate (\%)} = 0.2229 \cdot \text{damaged building rate} - 1.5026 \end{aligned} \tag{4.2}$$

A damaged building rate by seismic intensity is estimated by the statistics of damage caused by the recent earthquakes such as the Kobe earthquake (1995), the West Tottori earthquake (2000), and the Geiyo earthquake (2001).

Employing these formula, blockade rates are allocated for individual 1km grid cells thus enabling us to reflect building collapse damage to road network analysis.

4.3. Liquefaction Hazard

Passableness of roads under liquefaction hazard is assumed based on the result of comprehensive traffic impact assessment by local governments[9]. According to this traffic impact assessment method, even though a road section is ranked in the top hazard grade of liquefaction, it could be subject to a minor level of difficulty in passing or could rarely be subject to difficulty in passing.

As for road blockade rates by liquefaction, we assumed the maximum blockade rate to be 50%, taking the characteristics of damage of liquefaction. Road blockade rates corresponding to PL values (obtained in 3.2) are set as shown in Table 4-3.

Table 4-3 Road blockade rate PL values

PL value	Road blockade rate
$15 < PL$	50% passable
$PL \leqq 15$	100% passable

4.4. Tsunami Hazard

Whether roads flooded by tsunami are passable or not is decided based on maximum tsunami run-up heights computed by the above-mentioned numerical simulations of tsunami propagation. For instance, a critical water level, with which people have difficulty in walking, is considered around 30cm to 70cm[10]. Figure 4-1 shows an example of maximum tsunami heights computed for hypothetical Tokai Earthquake Tsunami.

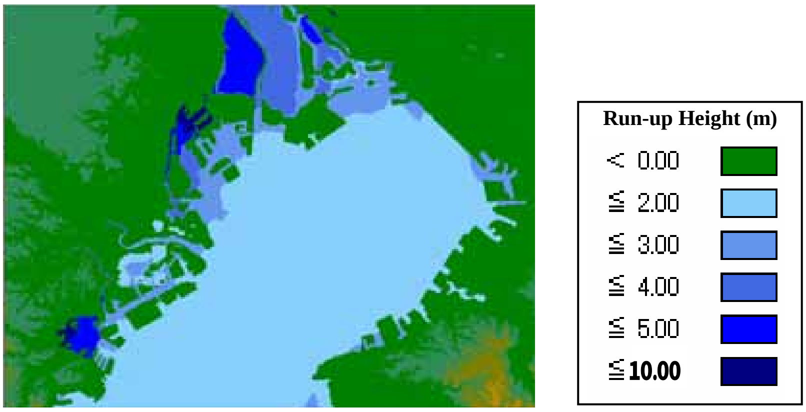

Figure 4-1 Estimated maximum tsunami height of Tokyo bay caused by the Tokai earthquake

5. EXAMPLES OF ROAD NETWORK ANALYSIS

When a disaster occurs, roads are vitally important means in every aspect as they are indispensable for evacuation, transportation, rescue activities, call of public service personnel, emergency medical care, emergency repairs and restoration, and so on.

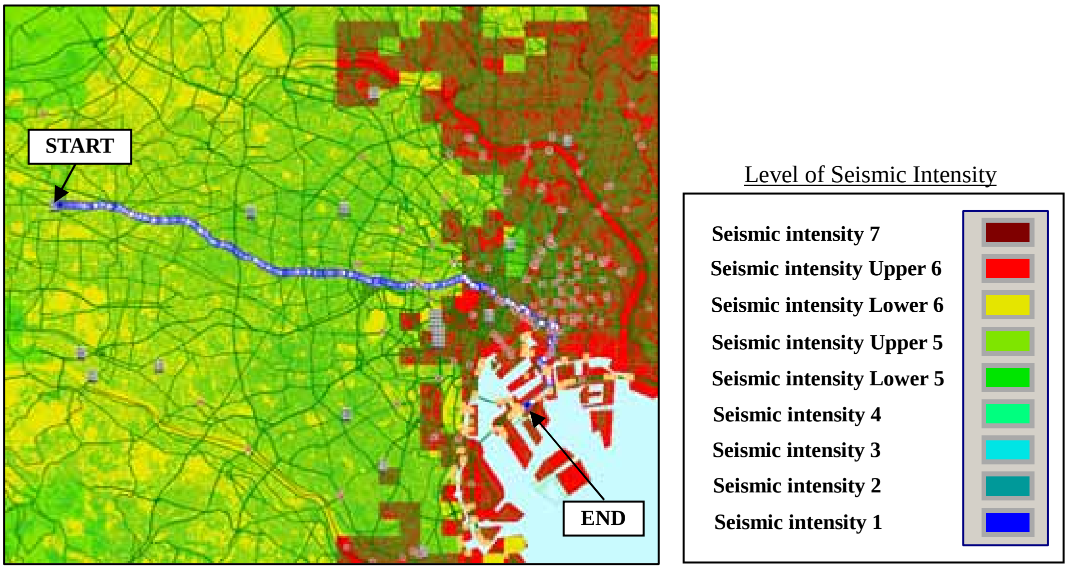

Figure 5-1 An example of the shortest route estimation in earthquake

* The example above shows the results of searching the most appropriate route between the start point (a company's office) and the end point (a customer's site requiring restoration) at the time of a disaster.
* The background map shows the estimated seismic intensity distribution.

Passable and the shortest route from the start point to the end point when disaster occurs are obtained by road network analysis in which a traffic load due to blockades is evaluated by reduction in traveling velocity.
Figure 5-1 shows an example of the shortest route estimated by the system, assuming the North Tokyo bay earthquake. Red zones on the background indicate areas with high level seismic intensity. By laying the locations of important facilities and the result of road network analysis on the top of the hazard information such as seismic intensity and liquefaction hazard, this system allows a user to visualize easily and quickly impassable roads and the shortest passable routes for simulated disasters.
The system thus effectively supports disaster management plans prepared by public sectors as well as companies' BCPs. Furthermore, this system can also be applicable for real time decision making against damage for which instantaneous judgment is required immediately after disasters.
Other examples of the utilization of the system are shown in Figure 5-2 and Figure 5-3.

Figure 5-2 An example of accessibility estimation
(Shaded circles show the areas within 60min by
walk from the designated points)

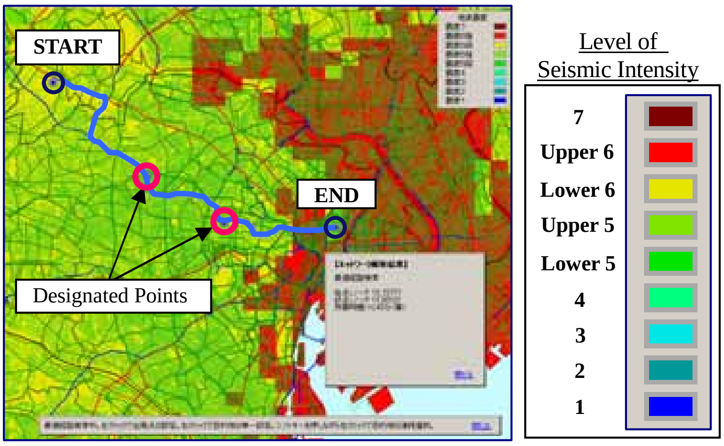

Figure 5-3 An example of the shortest route
relaying two designated points

6. CONCLUSION

Applying assessment for road infrastructure damage, building collapse, ground liquefaction and tsunami, we developed the disaster management supporting system considering the risk of road blockade caused by earthquakes and demonstrated its applicability. The utility of the system has been verified taking the Tokyo metropolitan area as a model area.

Since disclosure of fundamental data for this system is limited, it is necessary to promote data accumulation while conducting related studies and using the system in practical cases.

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