13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 658

GIS FOR ASSESSING EARTHQUAKE DISASTER OF TOKYO METROPOLIS

OGAWA Yoshimi[1] and SEKINE Atsushi[2]

SUMMARY

A computer simulation system has been developed to facilitate engineering decision-making concerning earthquake disaster. By simply setting the location, focal depth and magnitude of an assuming earthquake, the maximum value of seismic ground motion (acceleration / velocity) and liquefaction potential are automatically calculated. This system utilizes over thirty kinds of spatial information concerning geology, geography, affected area of the 1923 Kanto earthquake and estimated results for the setting of simulation conditions such as the amplification factor of subsurface ground and the distribution of liquefiable areas. The numbers of casualties and damaged buildings are evaluated by the Chocho-moku quarter on the bases of their tabular data inventories.

The present system provides an appropriate platform to examine the following topics of the Tokyo Metropolitan Government:

(1) Assessment of earthquake-resisting capacity and retrofit program of the water supply network (Bureau of Waterworks).

(2) Assessment of evacuation difficulty within congested areas of wooden houses (Bureau of Housing).

(3) Evaluation of transportation difficulty caused by damaged bridges and debris of collapsed buildings (Bureau of Construction).

The database with GIS can treat complicated network data easily, and it prepares good situations for engineers to comprehensively understand the evaluated results.

INTRODUCTION

Assessment of potential earthquake hazard is indispensable when the Metropolitan Government is introducing new measures to prevent and mitigate earthquake losses. Although these assessments are different in subjects such as waterworks, road transportation and evacuation within congested area, they are interrelated closely. Items of basic damage conditions to be estimated are the maximum ground motion, liquefaction possibility and the numbers of damaged buildings and casualties etc., and are common among these assessments. The computer simulation system is designed for providing an appropriate platform to carry out these assessments. The disaster simulation system with GIS for twenty-three wards of Tokyo Metropolis is originally developed that meet a variety of needs.

[1] Inst. of Civil Eng. of Tokyo Metropolitan Govt., Japan, Email: ogawa@doken.metro.tokyo.jp
[2] Road and Street Adm. Div., Tokyo Metropolitan Govt., Japan, Email: asekine@olive.ocn.ne.jp

DATABESE CONTENTS

Database of Thematic Maps

All the relevant information on printed maps is digitized and transformed to raster data by the auto-digitizer. Raster maps are corrected by normalized operation and unified scales by computer processing. The topographic information has vector graphics structure, is transformed to raster map. Then all raster maps are compiled according to the Standard Regional Grid and Mesh Code of the Geographical Survey Institute. The unified pixel size is 30"/190 (real length is about 4.86 m) for latitudinal direction and 45"/230 (about 4.92 m) for longitudinal direction. To standardize the regional grid and pixel size, composite maps are compiled easily by overlay operation.

Geological Information

1. Isobath of Alluvium Map: This map is prepared for the estimation of the maximum ground motion on the ground surface.
2. Thickness of Sand Layer Map: This map shows the thickness of Alluvial sandy layer as the critical layer for the probability of liquefaction.
3. Groundwater Table Map: The map shows approximate depth to groundwater that was compiled from over 11,000 boring records.
4. Distribution of Alluvial Gravel Layer Map: The map shows the distribution of Alluvial gravel layer existing less than 5m beneath the ground surface. This gravel layer is considered to reduce liquefaction likelihood.

Geographical Information

1. Land Condition Maps: There are the most detailed micro-topography maps in Tokyo and the original were edited and published by the Geographical Survey Institute in 1970 and in 1980.
2. Landform Classification Map: This map classifies the objective area into terrace, alluvial plane, the Tama river plane and valley plane with soft soil deposits.
3. Land-use Classification Maps in 1880 and in 1937: It is well known that the land-use of cultivation is closely related with the soil of surface layer. The maps show the land-use of cultivation when the urban area has not expanded widely.
4. Maps of the Past Waters in 1909, in 1925 and in 1937: To understand transitions of the waters during past several tens of years, these maps are prepared.
5. Map of the Drainage System and Coast Around 1460: This map illustrates the landform before land improvements have been made in Tokyo lowland. The mapping area is central part of Tokyo Metropolis.

Topographic Information

1. Distribution of Buildings Map: The locations and shapes of buildings are mapped out. Buildings are classified according to stories and the fire defense structure type. The original map is edited and distributed by the Bureau of Planning.

Information about Past Earthquake Disaster

1. Liquefaction Distribution Map During the 1923 Kanto Earthquake: The original maps was edited and published by the Inst. of Civil Eng. of Tokyo Metropolitan Govt. in 1987.
2. Distribution Map of Damaged Wooden Buildings During the 1923 Kanto Earthquake: The original map is in the observation of the Geological Survey published in 1925.

Information about Liquefaction Potential

1. Liquefaction Potential Maps: Five types of liquefaction potential maps and two types of lateral flow potential maps based on different types of the simplified liquefaction analysis formulae are prepared.

Database of Choropleth

An adequate zonal system is convenient to compile spatially distributed objects. As choropleth zones, the Chocho-moku quarters are employed in the assessment system. The Chocho-moku quarter is the minimum census tract and the second smallest zone of address in Tokyo. The twenty-three wards of Tokyo Metropolis contain about 3,120 Chocho-moku quarters.

The choropleth database contains the number of buildings by the story group, by the structure type and by the constructed age group, and the daytime and nighttime population by the age group. The building inventory, whose sources are property tax ledger, has been composed by the Chocho-moku quarters. Using the Chocho-moku quarters, population and building data become easily renewable.

Database of Networks

This database contains water supply, street and highway networks. Each network is decomposed into nodes and links. Information about locations, attributes and topology of nodes and links is stored in tabular database.

Attributes of networks are as follows:

Water supply network; diameter and material of pipe, buried age, hydrant, valve,

Street network; width of street,

Highway; lanes, width of roadway, sidewalk and median, overpass, underpass, viaduct, traffic capacity, observed traffic flow, number of pedestrian bridges and crossings.

STRUCTURE OF DISASTER SIMULATION SYSTEM

System Components and Simulation Flow

The main flame of simulation system is composed of seven layers as shown in Fig. 1. The evaluation flows upward from earthquake source setting of the bottom layer.

The Maximum Earthquake Motion on the Engineering Seismic Bedrock

The maximum earthquake motion is calculated on the bases of an earthquake source fault or a hypocenter. These sources can be set arbitrarily. The location of fault and epicenter are able to input by crick and drag on the location map of display. Dip and strike angles, depth and Magnitude are tabular input.

The maximum acceleration (PGA) and the maximum velocity (PGV) are calculated by some attenuation formulae. As an example of the fault source formula, equations proposed by Molas and Yamazaki [1] are:

$$\log_{10} PGA = 0.206 + 0.477 M_J - \log_{10} r - 0.00144 r + 0.00311 h + c_i^a$$
$$\log_{10} PGV = -1.769 + 0.628 M_J - \log_{10} r - 0.00130 r + 0.00222 h + c_i^v \qquad \cdots(1)$$

where PGA (cm/sec^2) and PGV (cm/sec) are the largest of the peak acceleration and velocities from two horizontal components, M_J is the JMA magnitude, r is the closest distance to the fault rupture, h is the depth, and c_i is the station coefficient of the recorded station.

The Maximum Earthquake Motion on the Ground Surface

The maximum motion on the engineering seismic bedrock is converted to the maximum motion on the ground surface by multiplying by the ground amplification factor. In another words, the maximum surface motion is given by Equation (1) with the adequate station coefficient c_i.
Local differences of the ground amplification factors are assumed to be the same as the distribution of ground types, and represented by the digitized micro-zoning map. Fig. 2 shows an example of digitized one. This composite map is compiled from the Land Condition Map, the Isobath of Alluvium Map and the Landform Classification Map as explained earlier by overlay operation.
The values of ground amplification factors corresponding to the classifications (legend) of the micro-zoning map are set as a tabular data. Linear or non-linear amplification factor can be set, alternatively.

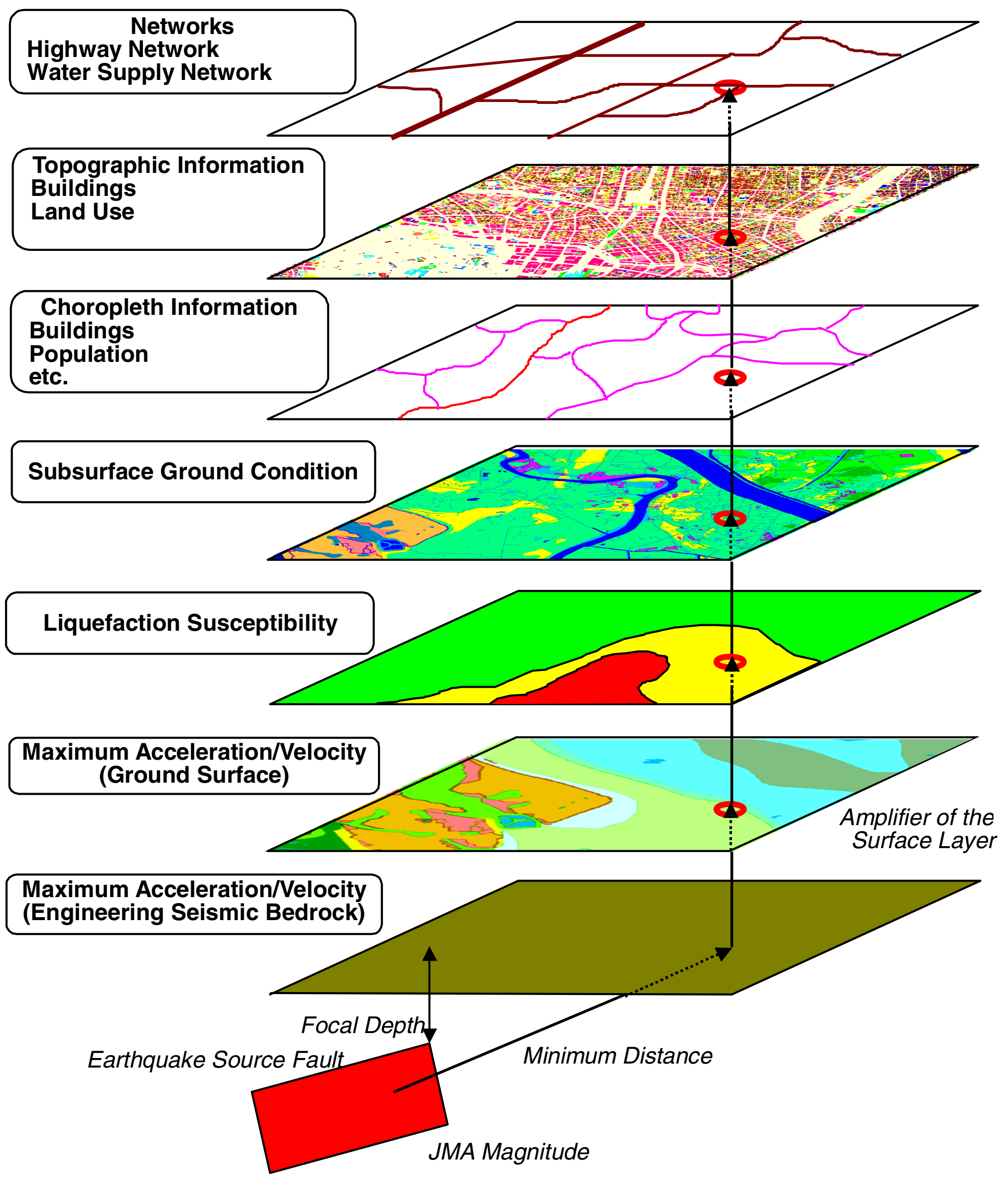

Fig1 Structure of the Disaster Assessment Platform

Liquefaction Susceptibility

Liquefaction susceptibility is estimated based on the maximum ground motion at each pixel. The liquefaction susceptibility base map is compiled from the Liquefaction Potential Map, the Land Condition Map, the Thickness of Sand Layer Map and the Land Classification Map by overlay operation. The Liquefaction Potential Map whose liquefaction likelihood is evaluated on the basis of the same maximum acceleration on the seismic bedrock provides distribution of ordinary liquefaction potential. It has been determined statistically that there is a close relation between thickness of sand layer and past liquefaction occurrence (Inst. of Civil Eng. of Tokyo Metropolitan Govt. [2]). The information of sand layer thickness is introduced to distinguish high liquefaction potential areas. The Land Condition Map and the Land Classification Map are employed to separate the terrace plane area into slightly liquefiable valley plane zones and no liquefiable terrace plane zones.

The tabular threshold values corresponding to the categories of the liquefaction susceptibility base map are set to determine the criteria of the maximum ground motions for liquefaction occurrence. In evaluation processing, the criterion of the maximum ground motion derived from the tabular threshold and the calculated one is compared at each pixel, then the liquefaction susceptibility of the pixel is determined.

To support the setting of the criteria, an aiding subsystem has been developed. This subsystem composed of over 11,000 boring records displayed on the subjected area, the tool of simplified liquefaction analysis based on a boring record and the statistical arrangement tool for calculated results of the simplified liquefaction analysis. The tool of liquefaction analysis is available to calculate on the bases of arbitrary acceleration input. The statistical arrangement tool assembles and correlates calculated results according to the categories of the liquefaction susceptibility base map.

Reference of Subsurface Ground Condition

Some earthquake assessments employ the information of subsurface ground condition together with the estimated seismic ground motion and the liquefaction susceptibility. A concrete example is mentioned later in this article.

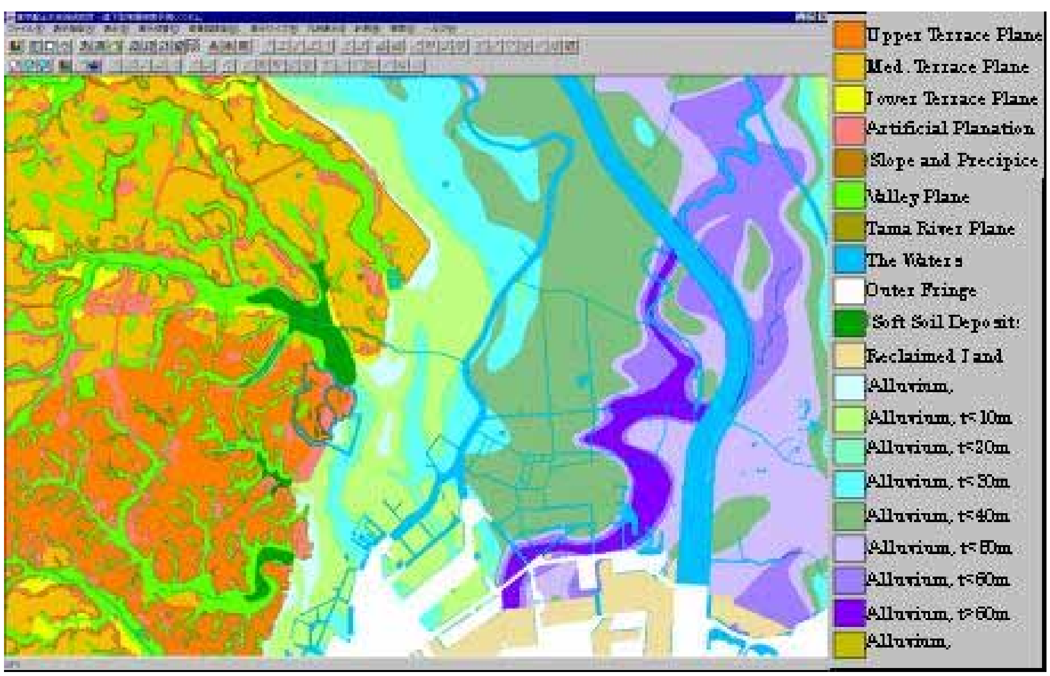

Fig. 2 Composite Map Corresponding to the Amplification Factor of Surface Ground

Damage Estimations on the subject of Choropleth Database

Damages of buildings and victims are estimated in this layer. The sampling points are arranged at regular intervals within the choropleth zone to obtain the variation of the maximum ground motions and the liquefaction conditions. The damage of buildings is evaluated based on the fragility function with the average of various outcomes by the story group, by the structure type and by the constructed age group. The number of victims at each choropleth is estimated on the bases of daytime/nighttime population and the rate of damaged buildings.

Reference of Topographic Information

Some assessments require neighborhood information to determine the objective malfunctions. For example, transportation difficulty of highway and street-blockage are caused by collapse of roadside buildings. To evaluate these malfunctions exactly, precise information on locations of buildings is needed. The Topographic Information is used in these cases.

Damage Estimations of Networks

To introduce the maximum ground motion and liquefaction condition to the link of the investigating network from lower layers, the sampling points are set along the location vectors of the link. If subsurface ground condition is required, this information is also referred at the same point.

To evaluate the neighborhood information, the contributing area of specified width is located on the both sides of the link.

ASSESSMENT OF EARTHQUAKE-RESISTING CAPACITY AND RETROFIT PROGRAM OF WATER SUPPLY NETWORK

Structure of Water Supply Network

The water supply network is composed of three categories as the distribution mains (diameter of pipes is more than 400 mm), the distribution minors (it is less than 400 mm) and the water service pipes. The distribution mains have been classified into the primary group and the secondary one according to the consequence of maintenance and retrofit. The distribution mains and minors have been digitized with GIS including their attributes, but the information of water service pipes is not prepared.

The damage estimation process is classified into two stages because the links of the distribution minors are too many to deal within a short time. The first stage is the estimation to the distribution mains, and it is calculated on the top layer for networks in Fig.1. The second stage includes the distribution minors and the service pipes is estimated on the choropleth layer. The number of links of the distribution minors within each Chocho-moku quarter is counted according to the boundary of the quarter and locations of pipes by their attributes. The number of water service customers by the Chocho-moku quarter, which is assumed to be the same as the number of the water service pipes in the quarter, is added to the choropleth database.

Damage Estimation of Water Supply Network

The vulnerability of pipes is estimated on the bases of the maximum acceleration and velocity by the formulae of the Japan Waterworks Association [3] as follows:

$$R_m(PGA) = C_p \cdot C_d \cdot C_g \cdot C_l \cdot R(PGA)$$
$$R_m(PGV) = C_p \cdot C_d \cdot C_g \cdot C_l \cdot R(PGV) \qquad \cdots (2)$$

where $R_m(PGA)$ and $R_m(PGV)$ are the damage rate of pipe (point/km), $R(PGV)$ and $R(PGV)$ are the standard damage rate of them, C_p, C_d, C_g and C_l are the corrective coefficients of pipe type, of pipe diameter, of ground type and of liquefaction, respectively.
These formulae are applied in both the estimation on the network layer and that on the choropleth layer. The sampling of the maximum ground motion, liquefaction susceptibility and subsurface ground

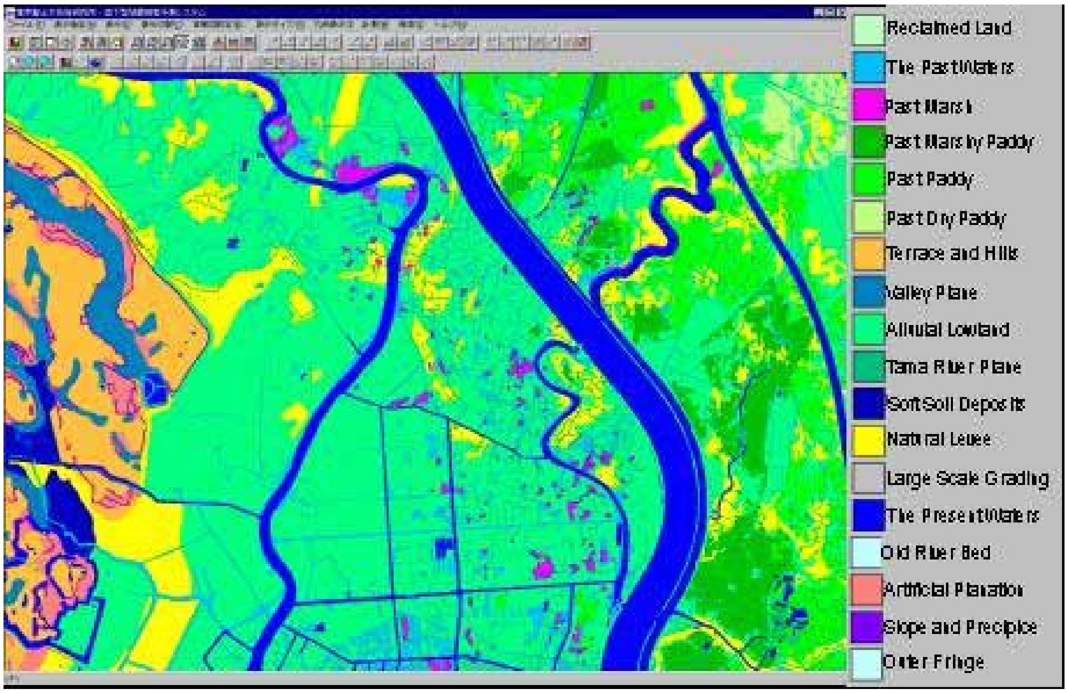

Fig. 3 Distribution of Ground Types (Composite Map)

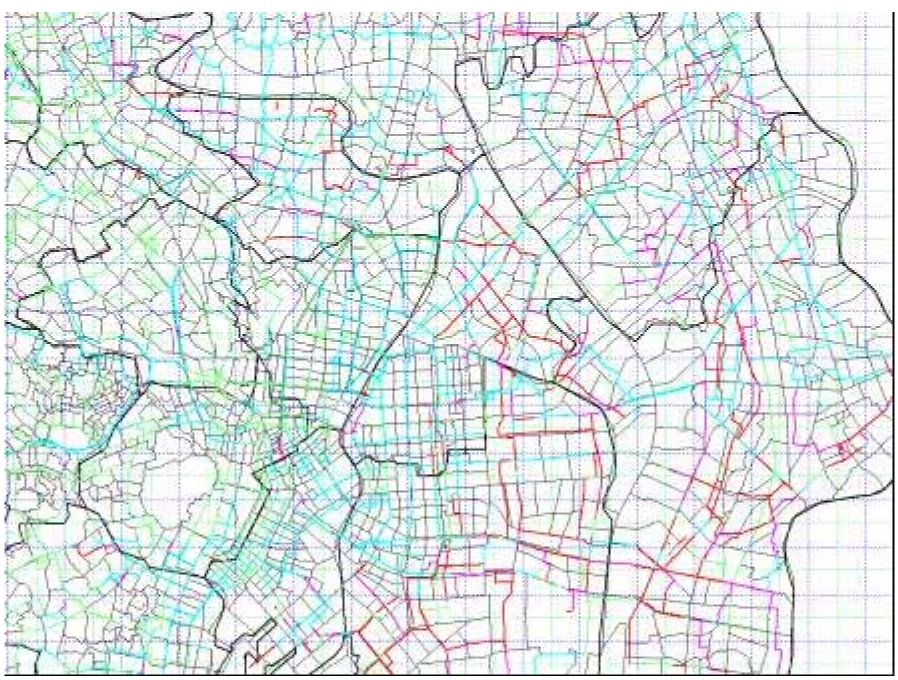

Fig. 4 Estimated Damage of Distributed Mains

condition are according to the manner of the network layer and that of choropleth layer, respectively. The distribution of ground types corresponding to the corrective coefficient of ground type is shown in Fig. 3. This map is complied from the Land Condition map in 1980, the Land Classification map, the Land-use classification map in 1937 and the Map of the Past Waters.

Fig. 4 shows estimation results of the distribution mains. In this figure, red lines and purple lines indicate more than 0.25 and more than 0.15 point/km of the damage rate, respectively.

The reference subprogram is applied to evaluate the retrofit necessity ranking of pipes on the bases of the estimated vulnerability, attributes, building damages estimated at the choropleth and the street-blockage probability mentioned in the next chapter. The ranking of pipes is tabulated to refer the location of the pipe on the graphic map of GIS.

ASSESSMENT OF EVACUATION DIFFICULTY WITHIN CONGESTED AREAS OF WOODEN HOUSES

Compilation of Street Database

To assess the evacuation within congested areas, information about narrow lanes as a few meter width is required. As such detailed information is not prepared, the street database is compiled from the digitized topographic map on a scale of 1:2,500 distributed by the Bureau of Planning. Although this map has a layer of road polygons in the vector graphics structure, width of road could not read automatically.

To determine the centerline and width of a road element as link, the following operation is applied. All polygons of road are filled with the pixel in size of 50 cm. Then pixels are eliminated in line on the both sides of the zones filled with pixels. To iterate the elimination, the pixels corresponding to the centerline remain, and the number of iteration gives the width of road. Automatically processed result are checked and corrected manually. The compiled network data has vector graphics structure, and number of total rink is about 380,000. Nodes of the network data indicate crossings, and a changing point of road width is also recognized as a node.

Estimation of Street-Blockage caused by Collapsed Buildings

The street-blockage is estimated on the bases of the formula of Street-Blockage Probability proposed by Ieda et al. [4,5], is as follows:

$$
\begin{aligned}
&F = 1 - b \cdot \exp\left(-\frac{1}{a} y_0\right) \\
&a = 4.24 X_1^{0.404} + 0.356 X_2^{2.15} + 11.9 X_3^{18.4} - 2.18 \qquad \cdots(3) \\
&b = 1.23 \big/ \left(1.0 - 0.160 \cdot \ln X_4 - 0.323 \cdot \ln X_5\right)^{1.37} \\
&y_0 = \left(W_R - W_U\right)/1.39 \cdot \exp(0.00061 \cdot l)
\end{aligned}
$$

where F is the probability of blockade, W_R is the width of present road, W_U is the assumed width to be required for passing, X_1 is the percentage of total collapse, X_2 is the average stories of buildings, X_3 is the density of buildings, X_4 is the percentage of wooden buildings, X_5 is the percentage of buildings constructed before 1950.

This formula is analytically determined on the basis of aerial photographs during the aftermath of Hanshin-Awaji Earthquake Disaster. The parameters of the neighborhood conditions, X_1 to X_5, are based on the cholopleth data in the original papers. The Distribution of Buildings Map compiled from the Topographic Information is introduced to realize the environmental situation of congested areas of wooden buildings in this assessment. To examine the neighborhood information in more detail, the Distribution of Buildings Map is remade. The new pixel size is 30"/760 (real length is about 1.22 m) for latitudinal direction and 45"/920 (about 1.23 m) for longitudinal direction. The attributes of pixel are stories of building and the fire defense structure type, and a blank pixel indicates no building.

The width of the contributing area to evaluate the neighborhood information is set to 5 m from the roadside. This width is decided based on the experience of the Hanshin-Awaji Earthquake Disaster. To introduce the conception of the contributing area, adequate resolution could be given in the area where distribution of buildings is not equable such as roads alongside a river and a park.

The average story of buildings X_2, the density of buildings X_3 and the percentage of wooden buildings X_4 are calculated based on the attributes of pixels within the contributing area. The percentage of building collapse by the structure group is calculated at each choropleth because the attributes of pixel lack information on construction age. Then the percentage of each structure type is corrected by the rate of the contributing area to the choropleth in pixel volume. The percentage of total collapse X_1 is calculated from these corrected percentage. The percentage of buildings constructed before 1950 X_5 is set to be equal to the percentage of the choropleth.

Fig. 5 shows the estimation result of street-blockage probability where the assumed width to be required for passing, W_U , is 3.5 m. This width is decided to suppose the passage of fire engines and ambulances through congested areas. In this figure, reddish lines indicate high probability of street-blockage, and the bottom of right corner is the area of Nishi-Shinjyuku high rises.

Assessment of Evacuation Difficulty

The evacuation difficulty is estimated from the probability of passage between a crossing within the congested areas and wide streets around it. Crossings within congested areas are indicated of origin nodes of the network database. The wide street is supposed not to be blockaded by debris, and the threshold of width is defined as 12 m on the bases of the reports of the Hanshin-Awaji Earthquake Disaster. The nodes connected to the links of the wide streets are set as the destination nodes of the network database.

The probability of passage is evaluated by reachability from the objective origin node to the destination

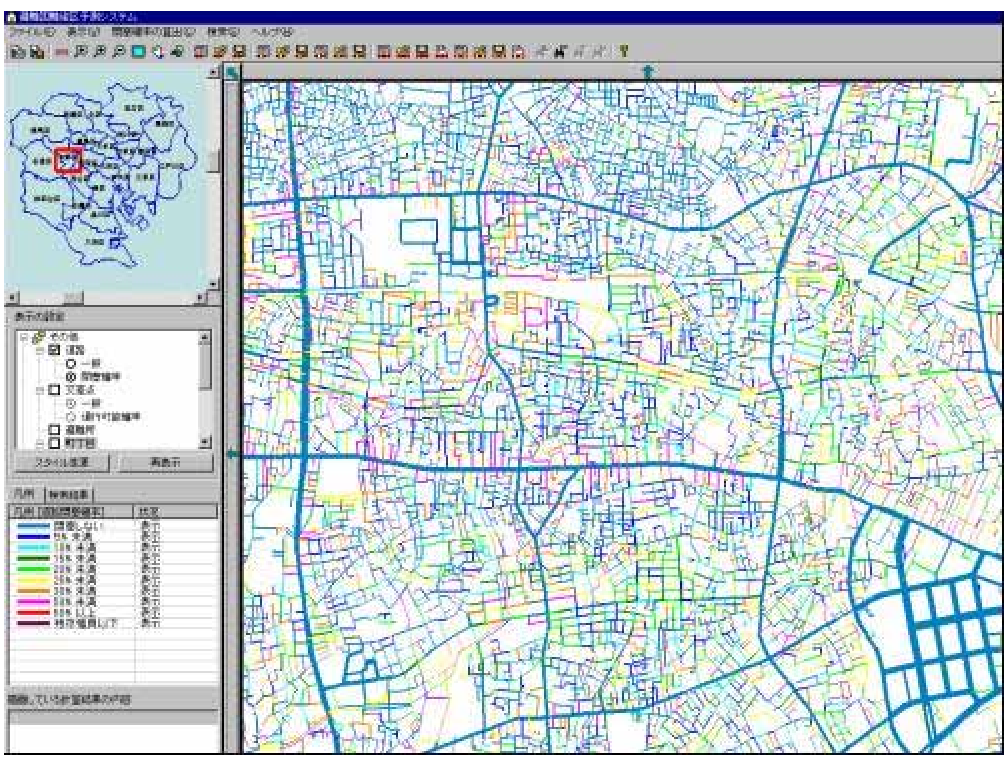

Fig. 5 Estimation of Street-Blockage Probability (W_U , = 3.5 m)

nodes. Two ways of evacuation route search are provided, one is the most reachable route and another is the shortest route.

The calculation result of evacuation difficulty is shown in Fig. 6. In this case, the assumed width to be required for passing, W_U , is 3.5 m and the probability of the shortest evacuation route is selected. In the figure, reddish dots indicate high evacuation difficulty.

To understand the evacuation difficulty over the Metropolis, the system is designed to collected the result at each node according to the boundaries of the choropleth.

EVALUATION OF TRANSPORTATION DIFFICULTY CAUSED BY DAMAGED BRIDGES AND DEBRIS OF COLLAPSED BUILDINGS

Outline of Evaluation Subsystem for Transportation Difficulty

The subsystem is developed to aid the opening road works in point of information during the future earthquake disasters. This information supposed here includes not only the evaluation of transportation difficulty but also the collected dispatches during the aftermath of the earthquake.

The highway network treated in the subsystem is composed of national highways, metropolitan roads and main roads administered by wards. The transportation malfunction of highways is mainly caused by damages of bridges and debris of collapsed buildings. The damage of bridges particularly brings highway networks into the long time malfunction. Information on brides with functional relations between highways is introduced to the subsystem to recognize highway occlusions caused by damaged bridges. The bridge inventory of the Construction Bureau is added to the database.

The urgent manual of the Construction Bureau provides that debris displayed on the highways should be removed to roadsides and not to be transferred other places during a few days after the earthquake because these carriage accelerate traffic confusions. The information about width of roadways and sidewalks is important for the opening road works. As the information on width of roadway and number of lanes is also

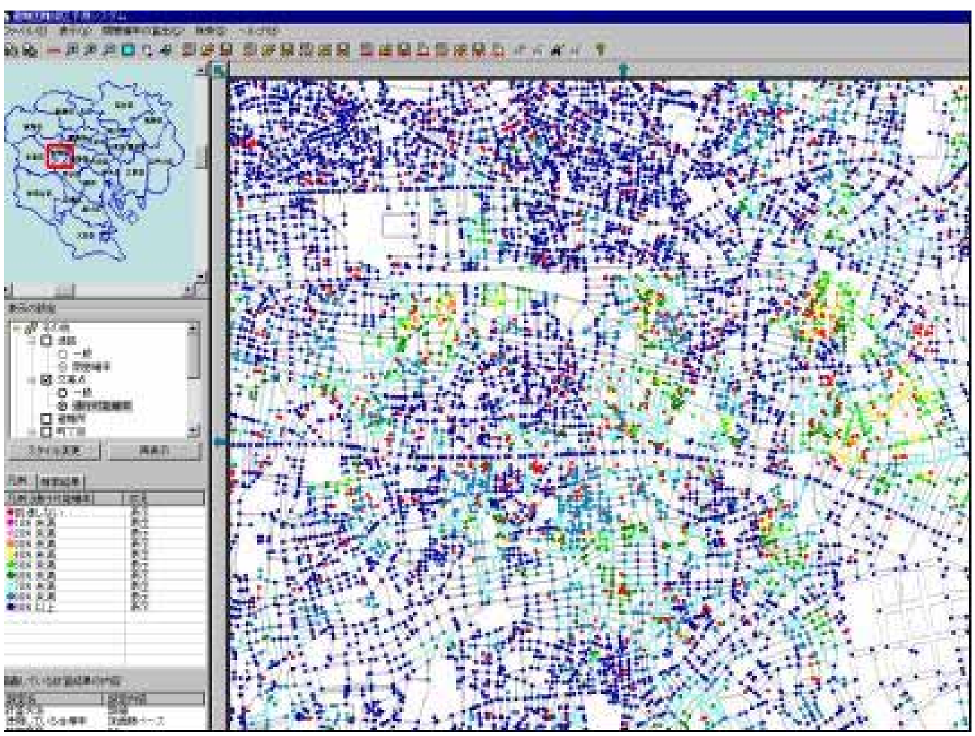

Fig. 6 Assessment of Evacuation Difficulty (W_U , = 3.5 m, The shortest evacuation route)

indispensable for the management of transportation control during the aftermath of the earthquake, these kinds of information of road inventories are stored in the database.
The subsystems have been distributed to the main and branch offices of the Construction Bureau.

Contents of Evaluation Subsystem

Menu of the subsystem
This subsystem is designed to support the users may be not familiar with GIS. To input the hypocenter, magnitude and focal depth on the display, the following estimations are automatically executed. To select the menu on the display, the users could recognize these evaluated results visually. The flow of estimations and analytical methods are almost same as the flow in Fig. 1 and described in former chapters.
The menu of estimations is as follows:
1) Seismic intensity, the maximum acceleration and velocity on the ground surface
2) Liquefaction susceptibility
3) Number of damaged buildings by choropleth
4) Number of casualties by choropleth
5) Total volume and weight of debris by choropleth
6) Number of collapsed tall buildings in the contributing area of each link of highway
7) Percentage of blocked width of roadway by debris

Alteration of Damage Information
The subsystem is designed the users replace the estimation results with observed damages easily. The locations of highway and bridge are easily selected by crick on the map of display and replaced by tabular input. It is afraid that the sufficient collection of damage information needs a long periods, therefore the online information communication system by cellular phone with GPS is now planned (Sekine et al. [6]).

Search for Substitute Route
The substitute route of blockaded highway is calculated between two crossings and a evacuation site to a crossing. This function provides useful information for the management of transportation control.

CONCLUSIONS

The disaster simulation system with GIS is originally developed. The system is applied to the assessment of the water supply network, the estimation of evacuation difficulty within congested areas and the evaluation of transportation difficulty caused by damaged bridges and debris of collapsed buildings.
Through these studies, it is certified that the disaster simulation system with GIS is the powerful tool to accomplish the assessment of earthquake disasters.

ACKNOWRADGEMENTS

The assessments described in the preceding pages were performed as part of joint researches with the Bureau of Waterworks and with the Bureau of Housing of Tokyo Metropolitan Government. The writers are most grateful for good cooperation of MIYAMOTO Yasuhiko, OKUMURA Kazuo, YODA Hideyo and OGURA Yuki. The writers are also grateful for the support of OYANAGI Hitoshi and MASUBUCHI Kiyotaka, Intage Co., in making the system programs required in the assessments.

REFERENCES

1. Molas, Gilbert L. and Yamazaki, Fumio, "Attenuation of Earthquake Ground Motion in Japan Including Deep Focus Events", Bulletin of Seismological Society of America, Vol. 85, No. 5, pp. 1343-1358, 1995.
2. Inst. of Civil Eng. of Tokyo Metropolitan Govt., Liquefaction Potential Map in Tokyo Lowland, Japanese Society of Soil Mechanics and Foundation Engineering, 1987, (*in Japanese*).
3. Japan Waterworks Association, Damage Evaluation of Water Supply System During Earthquakes, pp. 54-67, 1998, (*in Japanese*).
4. IEDA, Hitoshi, MOCHIZUKI, Takuro and KAMINISHI Shuko, "Street-Blockades Analysis and Its Application on Assessment of Vulnerability in Urban Areas", Proceedings of Study on the Hanshin-Awaji Earthquake Disaster, JSCE, 1997, (*in Japanese*).
5. International Association of Traffic and Safety Sciences, Study on Road Transportation Management During Earthquakes Based on the Research of the Hanshin-Awaji Disaster, pp. 272-293,1998, (*in Japanese*).
6. Sekine, Atsushi and Ogawa, Yoshimi, "Highway Damage Information Communication System by GPS-aided Handset under Earthquake Disaster, The 58th Annual Conference of JSCE, I-343,pp. 685-686,2003.