Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 130

FIRE-FIGHTING PERFORMANCE IN A CONGESTED URBAN AREA UNDER SEISMIC RISK

K. Nomura[1], T. Imai[2] and T. Koike[3]

ABSTRACT

Methods of preventing fire when a major earthquake strikes a congested area of a modern big city are discussed. This study investigates the fire-fighting capability of professional staff and volunteer teams following an earthquake and proposes preventive measures. The time to arrival of fire engines is simulated under road blockage conditions, and the possibility of volunteer teams extinguishing fires is evaluated based on the availability of the water delivered from the cisterns. Finally, an appropriate fire protection measure is proposed for each subdivision of the site.

1. Introduction

The damage caused by seismic disasters largely depends on the extent of modernization of a city. In Japan, fires caused by large earthquakes in densely populated cities have caused terrible damage. Since highly modernized cities attract large numbers of people to central business zones and neighboring residential areas, damage caused by an earthquake is concentrated at these densely populated areas because ruptured wooden houses can easily ignite.

Fires are initiated by collapsed houses, and simultaneously break out at many points. The speed with which the fire spreads depends on the wind velocity, spatial distribution of fireproof structures and open space boundaries including streets and roads of fire-protecting width. Other factors in Japan that hinder fire-fighting activities immediately after an earthquake include roads in residential areas that are too narrow for a fire engine, as well as blockage of many streets due to collapsed old houses, un-reinforced block walls, fallen

[1]Graduate student, Dept. of Civil Engineering, Tokyo City University, 1-28-1 Tamazutsumi, Setagaya, Tokyo, Japan
[2]Technical Chief Manager, Water Pipeline Dept., JFE Engineering Corp., 2-1 Suehiro, Tsurumi, Yokohama, Japan
[3]Professor, Dept. of Civil Engineering, Tokyo City University, 1-28-1 Tamazutsumi, Setagaya, Tokyo, Japan

vending machines and advertising signboards.

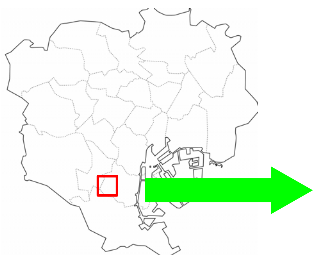
This study investigates the fire-fighting performance for a congested area with many wooden houses in an urban area during a fire following an earthquake, and proposes measures to prevent fire disasters. The vulnerability of the water supply for fire hydrants is also discussed as earthquakes may damage the water distribution network. The arrival time of fire engines, and the possibility and effectiveness of volunteers pumping up water from cisterns for fire extinguishing are also discussed.

A numerical simulation is used to estimate the probability of fire engine arrival at the fire front under many uncertain road-closing conditions. Ways of deciding an effective fireproof housing ratio and of preventing fire initiation are discussed, as well as disaster prevention strategies for the optimal allocation of movable water-pumping equipment.

2. Seismic Hazards

2.1 Site

The Tokyo metropolitan area has not only highly modernized zones crowded with ultra-high-rise buildings, but also old residential areas in which there are many narrow streets and old wooden houses. Figure 1 shows the area used in this study: a typical old congested area which is classified into one of the highest seismic risk zone[1)] in the Tokyo Metropolitan area.



(1) Central area of Tokyo Metropolitan District

(2) Congested urban area

Figure 1 Model area.

2.2 Fire-Fighting Conditions

The site is composed of several layers which include the street layer, important building layer, residential housing layer, open space layer, several lifeline layer and other structural layers as shown in Figure 2. Once an earthquake occurs, each layer exhibits its own damage mode. For instance, the water pipeline layer will cause water leakage and pipe breaks, and many fallen houses and other structures may prevent traffic from entering the streets, while the housing layer may produce a fire ignition from an old wooden house. These simultaneous and multiple damages at each layer cause the blockage of streets, water shortages from hydrants, and difficulties for fire engines trying to reach the burning point.

Therefore, it is important to consider the mutual effect of multiple damages for the fire following an earthquake. For this purpose, a GIS technique is useful to simulate the temporal and spatial development of the fire disaster.

Figure 3 shows the spatial distribution of fireproof housing in the model site, where the red mesh is a lower percent and the blue mesh is a higher percent of fireproof housing.

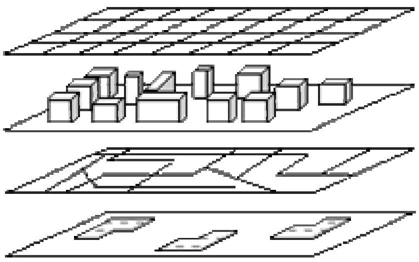


Figure 2 Various layers affecting fire ignition following an earthquake.

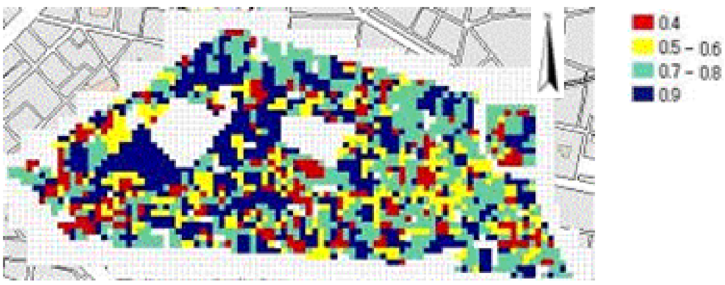


Figure 3 Spatial distribution of fireproof housing in the mesh-based zoning classification.

The fire-fighting performance just after an earthquake depends on the following site assumptions:

1) Immediately after a very large earthquake, the damaged water distribution network cannot always deliver a stable supply of water for fire hydrants, because shut-off valves in front of the water storage tank will be automatically closed, and the valves and pumping equipment in the main line will be controlled by the operation center in emergency conditions.
2) In such a situation, this local site may have only a single fire engine available.
3) Available cisterns are allocated at 150m intervals, but not all ponds have an uplifting pump.
4) Volunteer teams will be expected to support the fire-fighting activities immediately after the earthquake, yet there may be no uplift pump and equipment for carrying it near the ignition area.

Figure 4 shows the allocation of fire hydrants and cisterns for emergency use; they are usually located at 150m intervals. When a fire occurs at any point in this site, volunteer teams will pick up the pump from the storage yard and then rush to the fire. However, the availability of multiple pumps might restrict the fire-fighting activities of these volunteer teams. Furthermore, when a large earthquake occurs, the fire hydrants may not work, because the water supply authority might have ordered the water supply to be stopped if the seismic damage is serious.

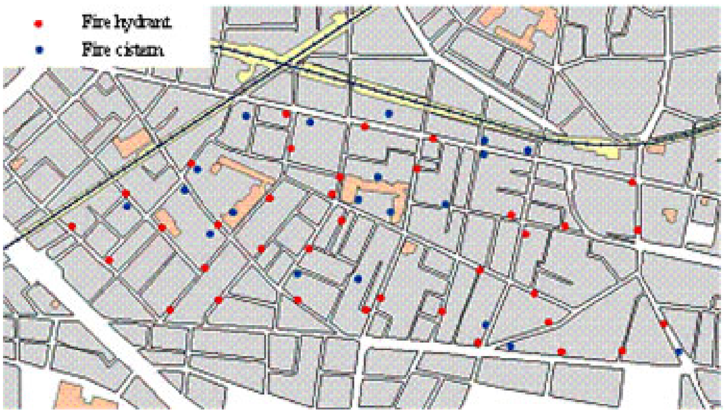


Figure 4 Spatial allocations of fire hydrants and cisterns.

3. Prediction of Spread of Fire

3.1 Spread of Fire

The Tokyo Fire Department[2)] developed the so-called TOSHO model in 1997. This model determines the speed with which a fire spreads as a function of time. Originally, the TOSHO model assumes that the area over which the fire spreads is spatially homogeneous in terms of conditions that affect the fire, such as density of bare wood houses, fireproof structures, spaces between neighboring houses and road width. All these local characteristics are built into the estimation of the fire-spreading speed in the model. In order to reflect these spatial variations, several layers are introduced so that each mesh has its own fire-sensitive conditions.

The fire-spreading speed, *V(t, x)*, at any time point *t* and spatial point *x* after the initial ignition, is given by

$$V(t,x)=\frac{V_f(x)}{1+\left(1.3-0.3e^{-0.3t}\right)\left(\frac{V_f(x)}{V_0(x)}-1\right)\exp\left[-\frac{0.5V_f(x)}{V_f(x)-V_0(x)}t\right]} \qquad (1)$$

where,

$V(t,x)$: spreading speed at t and x (*m/h*)
V_0 : initial spreading speed (*m/h*)
V_f : final spreading speed (*m/h*)
t : elapsed time (*h*)

Figure 5 Simulated result of fire spreading from an ignited point.

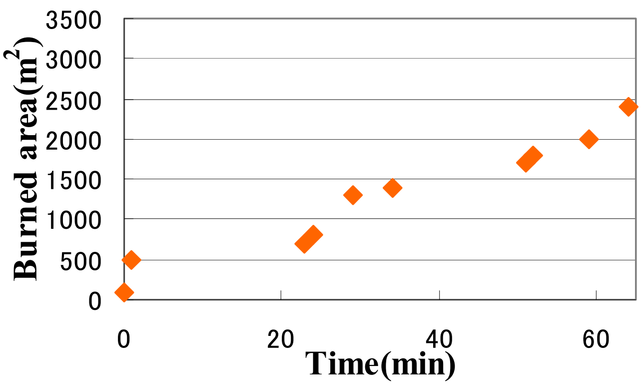


Figure 6 Spread of burned area for each time step after an earthquake.

Figure 5 shows a simulated result of a fire disaster after an earthquake in the congested area assuming a wind speed of 5 m/s to the east. Since this burned area has many low-fireproof houses, the fire spreads in all directions. Figure 6 shows the burned area for each time step obtained by the simulation

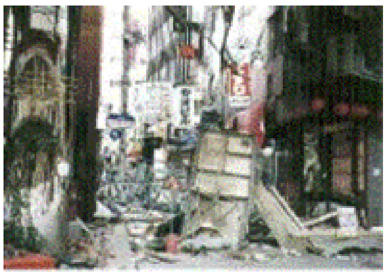
4. Road Blockage by Fallen Structures

4.1 Formulation

Along roadsides, not only old houses but also other structures such as electric poles, advertising signboards, vending machines and concrete block walls may be located. When an earthquake occurs, these structures may fall into the street side as shown in Figure 7 and cause obstruction.

(1) Houses

(2) Electric pole



(3) Advertising obstacles

(4) Vending machine

(5) Concrete block wall

Figure 7 Photos of fallen structures along streets after an earthquake.

Each street has its own probability of a road blockage occurring which can be estimated by taking into account the structural conditions of cross-section and longitudinal section along the roadside.

The occurrence probability[3)] of the i-th road blockage $DC_i(EQ)$ due to an earthquake EQ is given by:

$$P[DC_i(EQ)] = P[K(R_i)] \cdot P[DC_i(EQ) | K(R_i)] \tag{2}$$

where $\{K(R_i)\}$ is a damage event in the cross-section of the i-th road, R_i, which includes the widths of the roadway and the sidewalk as well as roadside trees, while the conditional event $\{DC_i(EQ) | K(R_i)\}$ shows the damage in the longitudinal direction along the roadside.

Since there are many obstacles along the roadside such as old houses, concrete block walls, electric poles, vending machines and other structures, the probability of $\{DC_i(EQ) | K(R_i)\}$ is evaluated as follows:

$$\begin{aligned} P[DC_i(EQ) | K(R_i)] = 1 - (1 - P[H_i(EQ)]) \cdot (1 - P[E_i(EQ)]) \\ \times (1 - P[C_i(EQ)]) \cdot (1 - P[D_i(EQ)]) \cdot (1 - P[W_i(EQ)]) \end{aligned} \tag{3}$$

where the damage events of the house, electric pole, advertising signboard, vending machine and wall are denoted as H_i, E_i, C_i, D_i, W_i, respectively.

4.2 Fragility Curves of Fallen Structures

There are many data on the fallen old houses and concrete block walls as well as the electric poles, but there is little data available for fallen vending machines and other street structures for earthquakes in the past.

In this study, a vending machine is assumed to behave as a rigid block. Therefore, structural failure occurs when the horizontal acceleration exceeds the critical acceleration which is simply estimated from the geometrical condition of vending machines.

A simplified probability of occurrence of fallen vending machines for various seismic intensities can be estimated in terms of a fragility curve as:

$$p_X(a) = 1 - \frac{1}{1 + \alpha_X \left(\frac{a}{A_{cr}^X} \right)^{\beta_X}} \tag{4}$$

where a is a horizontal ground acceleration (cm/s^2), and α_X and β_X are parameters to control the fragility curve for the critical acceleration A_{cr}^X of the structure denoted by X.

On the other hand, the fragility curves for old houses, concrete block walls and electric poles are taken from existing investigations on these structures for earthquakes in the past.

Figure 8 shows the fragility curves for several kinds of fallen structures commonly located along streets. Figure 9 is the simulated results for several ground accelerations in terms of the probability of road blockage occurring

.

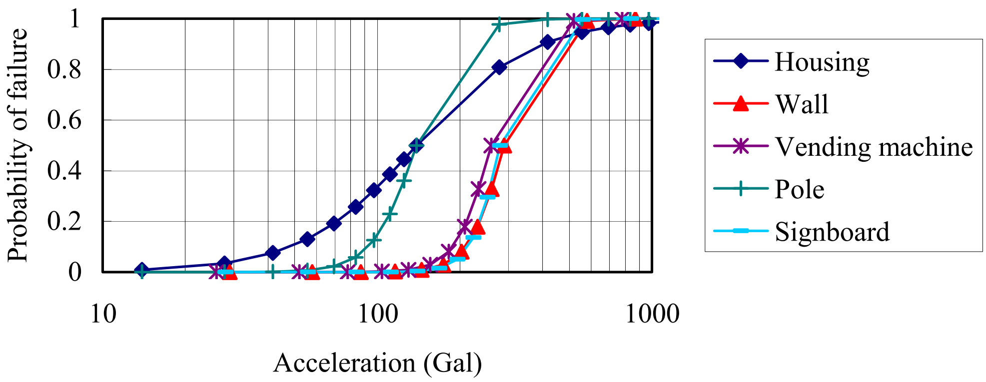


Figure 8 Fragility curves for fallen structures.

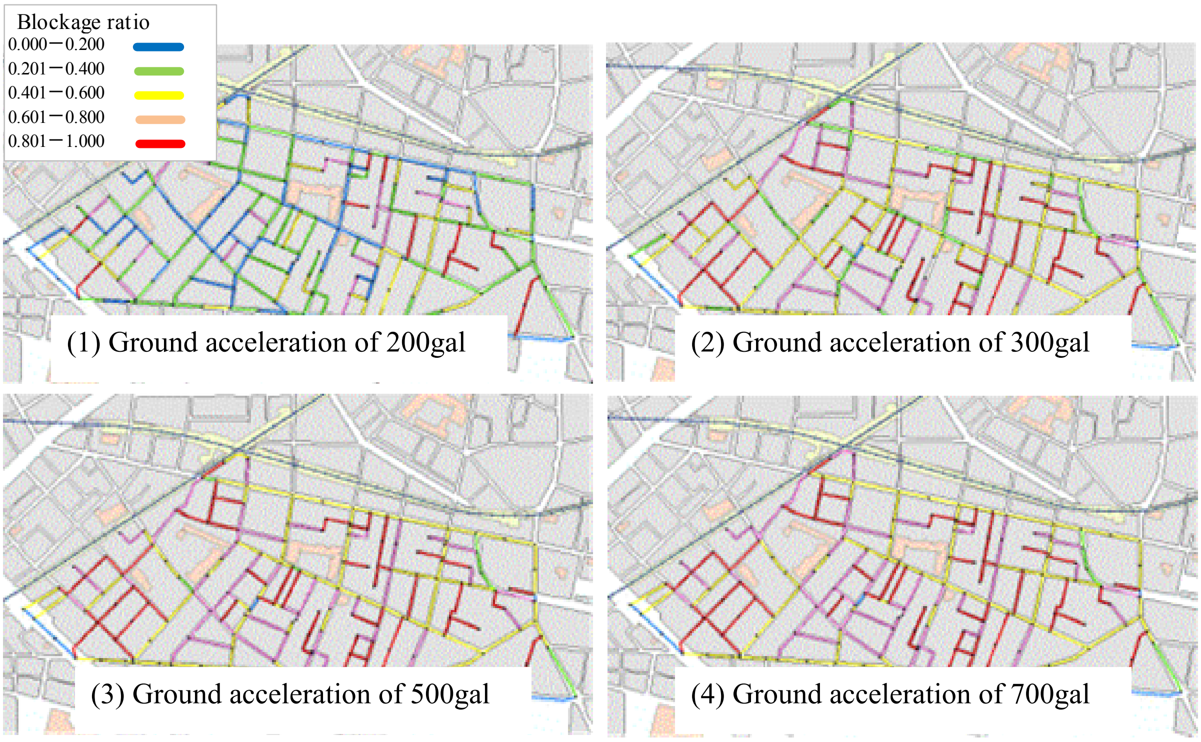


Figure 9 Simulated results of road blockage for various ground accelerations.

5. Fire-Fighting Strategy

5.1 Fire-Fighting Capability by Fire Engine

In an ordinary situation, a fire engine travels to the burning point as soon as possible. When an earthquake occurs, however, fire engines will be sent to the key areas. The flow chart of Figure 10 determines the probability of arrival at fire-fighting nodes by a single fire engine under road blockage conditions by the Monte Carlo Simulation method in which the cycle of successful arrivals is counted in terms of m.

In the fire-fighting activity, the water is supplied along the fire front which has the stretching length S around the burning area A. One hose can cover a width W of approximately 15 m across the fire front as shown in Fig.11.

A fire engine has four hoses, so the maximum stretching length S_{max} for a single fire engine is $S_{\max} = 4W$. From the data of the 1995 Kobe Earthquake[4)], the stretching area is related to the burned area A as follows:

$$S = 1.11A^{0.655} \quad (5)$$

Therefore, the maximum burning area covered by a single fire engine is given by:

$$A_{\max} = \left(\frac{4W}{1.11}\right)^{1/0.655} \quad (6)$$

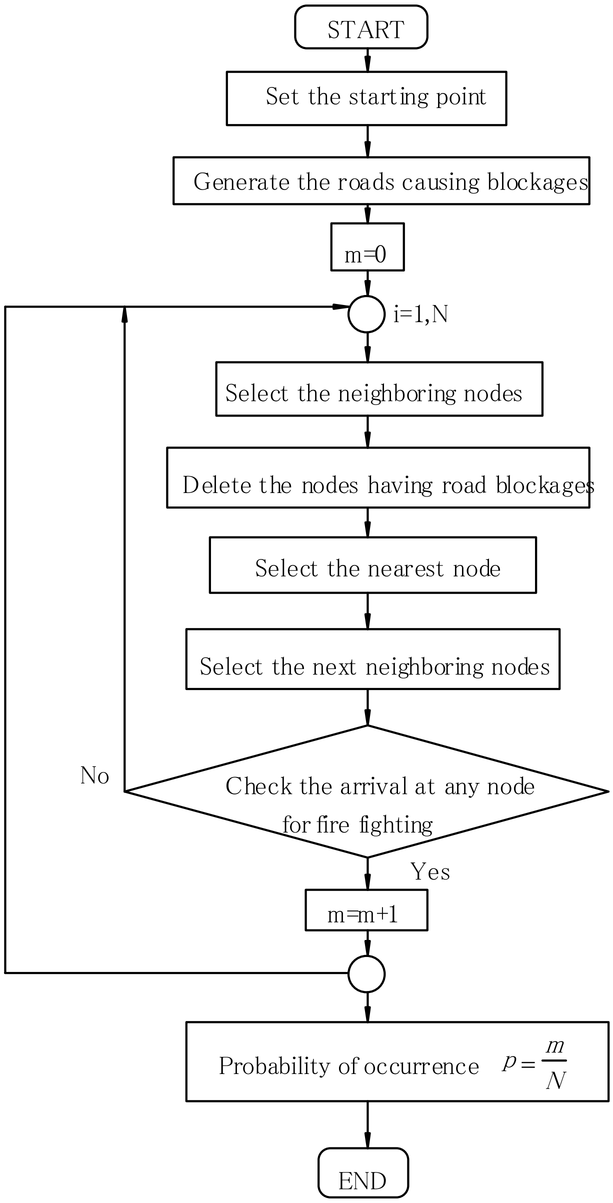


Figure 10 Monte Carlo Simulation to obtain the probability of arrival by a fire engine.

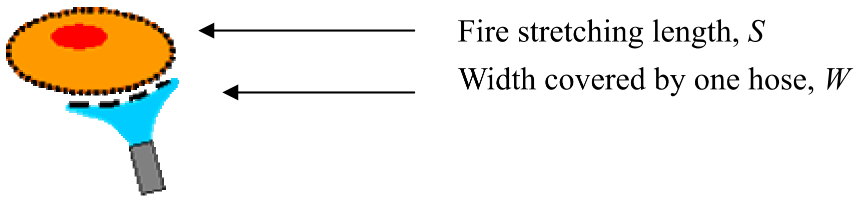


Figure 11 Stretch length surrounding burning areas and possible width for fire-fighting.

A numerical simulation of fire-fighting activities assuming road blockage is carried out under the conditions of Table 1. In this simulation, one fire engine is assumed to start at the point STA in 30 minutes after the earthquake, because of various difficulties during the seismic emergency, while the assumed fire ignition point is shown by the red mark in Figure 12.

This simulation, as shown in Figure 13, reveals that under many road blockage conditions, a fire engine must select any possible nodes that connect to the target nodes surrounding the burning area. This simulation shows that the fire engine can arrive at the fire-fighting points in just over 30 minutes by avoiding many road blockages, and can then stop the fire. If this fire engine cannot arrive at the target point within just over 30 minutes, the burning area expands and exceeds the water supply capacity of the single fire engine. If this happens, other additional fire-fighting approaches are required.

Table 1 Conditions for a fire disaster.

Wind speed	Wind direction	Road blockage ratio	Traffic direction	Driving speed of a fire engine
5m/sec	West	over 50%	one way	15km/hour

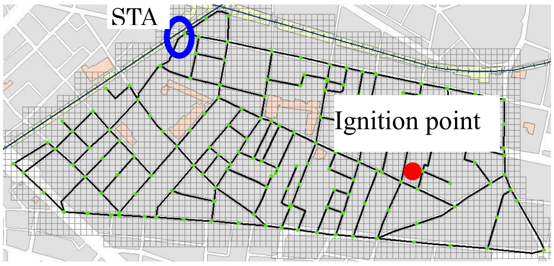


Figure 12 Assumed ignition point after an earthquake and the starting point (STA) of a fire engine.

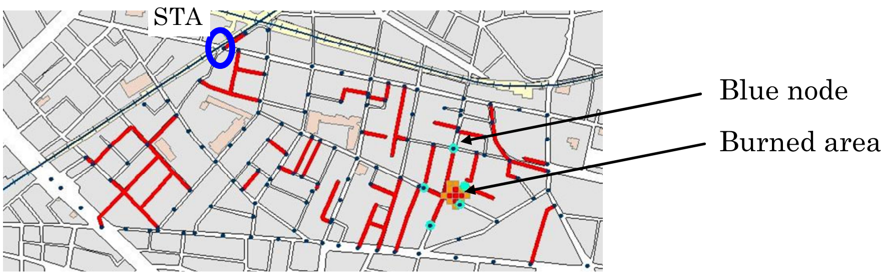


Figure 13 Possible points (green nodes) near the fire disaster area that a fire engine can reach.

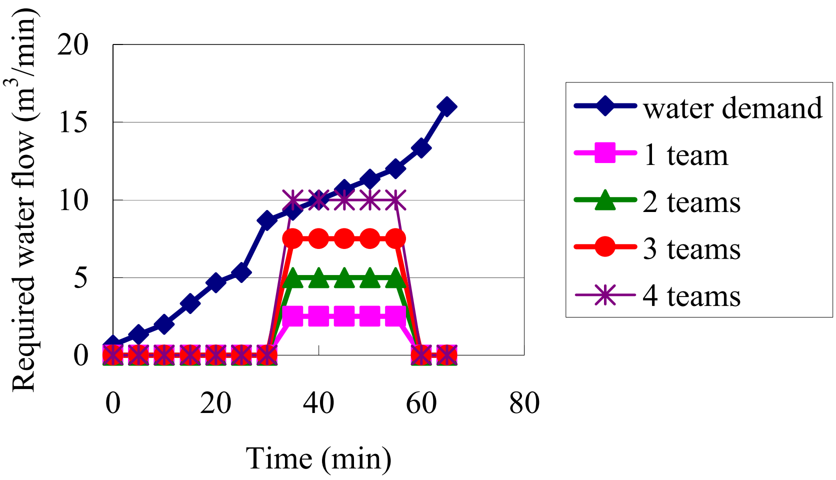


Figure 14 Capability of fire-fighting activity by volunteer teams.

5.2 Fire-Fighting by Volunteer Teams Using Cisterns

Volunteer teams will perform fire-fighting if fires break out following an earthquake. Since they know the fire-fighting procedures in such an emergency situation, they will arrive at the burning area as soon as possible. First, they have to pick up pumping equipment to lift up the water in the cisterns. The maximum water supply for fire-fighting is approximately 50–100 m^3 for each cistern, so several teams can stop the fire from spreading if they can arrive at the burning area within 30 minutes as shown in Figure 14 with movable pumping equipment having a water flow rate of 2.5 m^3/minute.

5.3 Proposal for Fire Protection Measures

In order to identify detailed fire protection measures for each local site, the target area is subdivided into 20 zones as shown in Figure 15, then the simulation is repeated assuming that a fire starts in each zone. Table 2 shows the simulation results. This table suggests that zones No. 5, 6, 8, 11, 12, 16, 18 and 19 exceed the critical burned area of 1000 m^2 which is the maximum area for a fire engine to stop the fire expanding, while zones 1 to 5, 7 to 8, 10 to 11, 14, 16 and 18 cannot easily be reached by a fire engine because of road blockages. These results suggest that:

(1) For a zone in which the burned area is more than 1000 m^2, existing old wooden houses should be improved and made fireproof.

(2) For zones in which a fire engine cannot reach the target nodes because of road blockage or narrow road conditions, volunteer teams are needed to perform fire-fighting activities.

Figure 15 Subdivision of the site.

Table 2 Simulated result for each zone

Zone	Burned	Arrival ratio	Zone	Burned	Arrival ratio
1	800	0	11	1200	33
2	900	0	12	1100	100
3	800	0	13	800	100
4	500	0	14	1000	0
5	1200	40	15	900	100
6	1500	50	16	1100	0
7	700	0	17	800	100
8	1200	0	18	1600	0
9	500	50	19	1200	66
10	1000	0	20	700	50

Based on the numerical results, the fire protection measures for each zone are classified into three types as shown in Figure 16, in which (1) in blue zones, old wooden houses should be improved by retrofitting to make them fireproof, (2) in red zones, more pumping equipment should be installed, and (3) combined red and blue zones should be improved by both approaches.

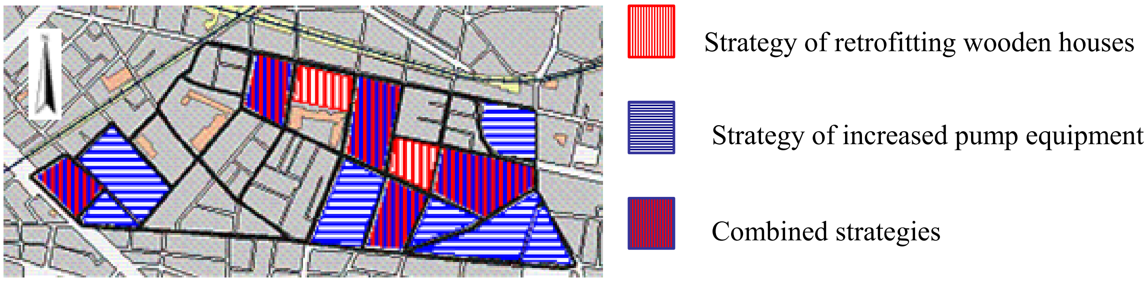


Figure 16 Proposal for disaster prevention strategies.

6. Conclusion

In order to assess the vulnerability of water supply for fire-fighting, the arrival time of fire engines and the possibility and effect of fire extinguishing by volunteers who can pump up water for fire-fighting from cisterns immediately after an earthquake, were discussed.

Based on a numerical simulation of fire engines reaching the fire front under many uncertain road-closing conditions, ways of deciding an effective fireproof housing ratio and of preventing fire initiation were discussed, as well as disaster prevention strategies for the optimal allocation of movable water pumping equipment.

References

1) Central Disaster Management Council: On countermeasures for the Tokyo Inland earthquake (2003-2005). Report of Central Disaster Management Council, 2005.

2) Scawthorn, C., Eidinger, J.M. and Schiff, A.J.: Fire following earthquake, Technical Council on Lifeline Earthquake Engineering, Monograph No. 26, ASCE, 2005.

3) Tokoi, T. et al.: Reliability of road network in a disaster situation, OR Annual Meeting, Japan, pp. 78–79, 1997

4) Yasuno, K. et al.: Required fire-fighting performance and fire stretching length in daily and seismic situations, Journal of Fire Disaster Science, Vol. 47, No. 2, 1997.