Simulation Analysis of Fire Hydrant Usability Levels after Large Earthquake

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ABSTRACT

Since large earthquakes can disrupt water supply networks, it is essential to gain an understanding of the expected usability of fire hydrants in post-quake firefighting activities. In this study, data about water supply networks was collected and a water outage simulation model was constructed in order to predict the likelihood that individual fire hydrants would become unusable in the wake of a large earthquake. The water outage simulation model was integrated with a previously developed urban zone damage simulation and a fire department activity simulation in order to carry out a simulation-based analysis of the 23 wards of Tokyo, after which a quantitative analysis of the relation-ship between use of fire hydrants and the number of buildings lost to fire was performed. This analysis revealed the benefits of hardening water lines against earthquakes, fire hydrant usage variations depending on locality, and the benefits of using water pressure sensors to identify usable fire hydrants.

Keywords

large earthquake, hydrant, water outage, fire-spread, firefighter.

INTRODUCTION

Research background

When multiple fires break out simultaneously, it is vital to identify and quickly extinguish those that have the highest risk of spreading. However, in the immediate aftermath of a large earthquake, it can be expected that responding fire departments will be delayed by street blockages and further hampered by inadequate supplies of water due to water outages at fire hydrants and/or low supplies in fire cisterns. Therefore, it is essential to establish comprehensive strategies for firefighting that not only account for fire spread but also consider street blockages, water outages, and other obstacles. Such a comprehensive study has never been done before.

In this study, we have combined a large-scale fire spread simulation model and an urban zone damage simulation model developed by Hirokawa and Osaragi (2016a, 2016b, 2017) by incorporating a street blockage simulation model into a fire department activity simulation model, and have used an index of fire spread risk (fire spread potential) to demonstrate the potential for immediate deployment of firetrucks in order to greatly reduce the number of buildings lost to fire. These models employed the assumptions of earlier studies (Fujii and Itoigawa, 2017; Sasaki and Sekizawa, 2014) that showed water would only be available from sources other than fire hydrants (fire cisterns, rivers, etc.). More specifically, they did not sufficiently scrutinize the actual usage availability of fire hydrants. However, efforts have been made to harden fire hydrants against earthquakes in recent years, so an investigation of the usability of fire hydrants incorporating water outage considerations is needed in order to facilitate a more exhaustive examination of firefighting activities in the event of a large earthquake.

The Tokyo Fire Department (TFD) (2015) and Takada et al. (2005) have published studies regarding the use of fire hydrants after a large earthquake. The TFD analysis was based on an exhaustive simulation model incorporating activities initiated upon learning of a fire, activities in gathering of fire department personnel, time for preparing the hose, and other factors. However, that fire hydrant usage analysis focused on early fire extinguishing activities by residents rather than by TFD firefighting teams. Additionally, the modeling of water outage consequences went no further than a simple representation in which the number of fires expected to be extinguished was multiplied by the rate of ordinary water delivery conditions (1.0 – water outage rates). The analysis was based on the mean rate of water outages for each city, ward, town, or village according to damage estimate for Tokyo (Tokyo Metropolitan Government, 2012). Accordingly, as will be described later in this study, no details related to water line damage between water supply points and fire hydrants were considered.

Takada et al. (2005) examined records from the Great Hanshin Earthquake, in which numerous fire hydrants became unusable, and stated that personal suffering would have been significantly reduced if those fire hydrants had been operable. In their detailed analysis of the reasons for failures to prevent fires from spreading (insufficient water, etc.), in which they examined the times of fire breakouts and firetruck arrival times, among other factors, they provided much to consider in the drafting of this fire hydrant usability investigation. Nevertheless, prior to this study, the usability of fire hydrants to stop spreading fires in the immediate aftermath of a large earthquake has only been examined in a qualitative fashion.

Turning to studies with water outage simulations, post-quake Tokyo damage estimates (Tokyo Metropolitan Government, 2012) examined both the types and diameters of water lines, block-by-block, throughout Tokyo, along with ground velocities and potential of liquefaction indexes (*PL* values) in an effort to predict water outage rates. According to the Japan Water Research Center (2011), water outage rates can also be estimated using the characteristics of ground surface layers instead of the liquefaction index. In these studies, the damage occurring, in terms of the rate of water outages and other problems, was estimated using data about the lengths of buried pipes, information about the ground surface layers, and other data tabulated for each portion of the cell in the model. However, actual damage such as water outages does not occur in the cell units. Instead, they are considered as components of a networked structure (the water supply network) branching out from the water supply point. More specifically, this approach did not account for the downstream effects of damage to water mains at the network origin (i.e., near the water supply point), and could well have underestimated water outage rates at fire hydrants far downstream from the water supply point.

Research objectives

When there are no limits on the volume of available water and a high density of installed fire hydrants are available for use, we can expect firefighters to perform their duties efficiently, which will reduce the damage resulting from fires. However, a review of previous studies has turned up no investigations of the actual usability of individual fire hydrants in a water supply network structure that has suffered damage in the immediate aftermath of a large earthquake. The assumption that only fire cisterns, rivers, streams are available can be thought of as one possible assumption, when we consider an uncertain disaster situation after the occurrence of a huge earthquake. It can also be thought of as one reasonable assumption to lead the serious evaluation of disaster. Nevertheless, even any small resources that might be available after the disaster should be utilized to assist firefighting activities.

Therefore, in this study, we constructed a simulation model of fire hydrants in a water supply network suffering outages in the aftermath of a large earthquake. In order to analyze with consideration of the availability of each individual fire hydrant, it is necessary to construct a model that can describe the damage of each water pipe. The most unique viewpoint and the principal originality of this research is that we constructed the detailed simulation model which describes water outages by modeling the damage of individual water pipe, that has not been discussed yet in the previous research. Also in order to accomplish comprehensive and complex simulation analyses, we utilized some sophisticated models developed by Hirokawa and Osaragi (2016a, 2017, 2016b). They integrated previously proposed urban zone damage simulation models and a TFD activity simulation model, and used the result to observe ways in which the spread of fire could be halted in order to examine strategies for firefighting during a water outage. Since the installation of water pressure sensors was assumed to have been completed (Nikkei, 2016) by the TFD, it was also assumed that water outages at hydrants could be remotely detected. This novel analysis never done before is outcomes based on the detailed simulation model of water outages developed in this research. Using the analysis results, the reduction in the number of buildings lost to fire was demonstrated and the potential for retaining the usability of fire hydrants was examined.

SIMULATION OF THE WATER SUPPLY NETWORK AND OF A WATER OUTAGE

Water outage simulation overview

Our simulation of a water outage at fire hydrants consisted of (1) the assumed water supply network, (2) the assumed damage to individual water lines, and (3) the hydrants assumed to have been cut off from the water supply. However, since actual data about the water supply networks are unavailable due to security considerations, street network data were used to deduce the water supply network layout. Next, the water lines assumed to have suffered damage were selected on the basis of the *PL* value, the peak ground velocity (*PGV*), and the physical properties of the pipes. Finally, the water supply network was reconstructed while treating the damaged water lines as unable to carry water, and the possibility of water supply from the purification plant to every fire hydrant was calculated to identify the unusable hydrants.

Method for deducing water supply network layout

Kobayashi et al. (2013) proposed a method for deducing the layout of water supply networks from street network data based on the fact that the supply lines for water, natural gas, and other utilities are generally buried beneath streets or roads. They showed that as long as grade separated intersections do not overlie the buried water lines and that the private roadways that are not included in district data are neglected, this method can provide highly precise data for densely inhabited districts (DID), which have pronounced needs for water lines.

Since most of Tokyo meets the DID definition, this study also employed the above procedure for deducing the water supply network locations (Fig. 1(1)). Next, the purification plants and fire hydrants were located on the street network data (Fig. 1(2)) and the directions of water supply through the networks were estimated from each network origin (purification plant) to the endpoint at each fire hydrant. It was assumed that water supply would be by the shortest route from a purification plant to a fire hydrant, and that route was found using Dijkstra's algorithm (Dijkstra, 1959) for searching for a path (Fig. 1(3)). Additionally, since there were multiple purification plants, calculations were carried out while assuming multiple independently operating water supply networks with origins at each purification plant.

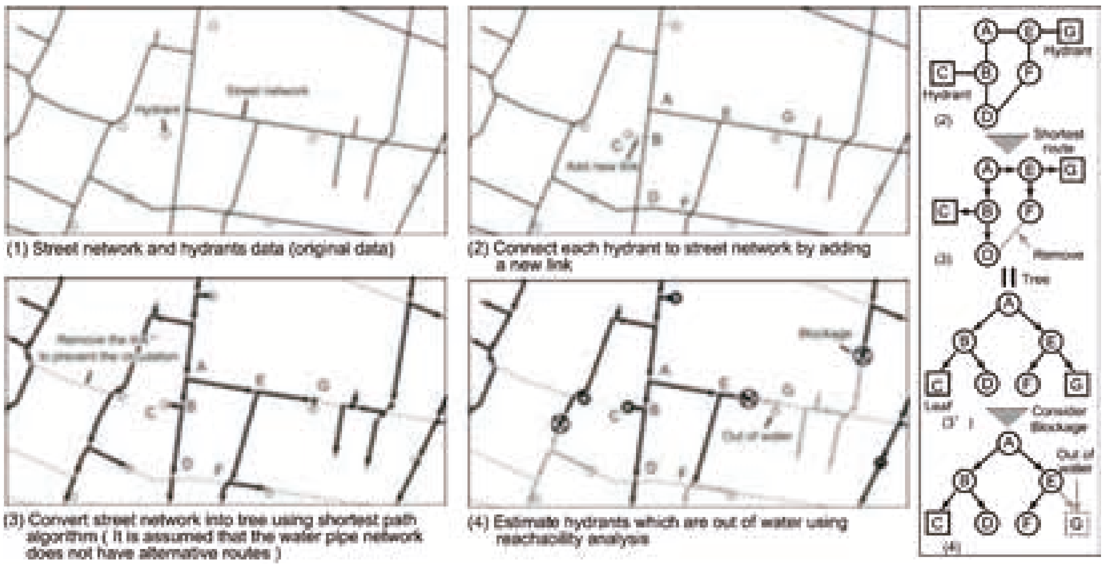

Figure 1. Construction of water pipe network and estimation of water outage

Damage prediction method for individual water lines

The occurrence of damage to any single water line is independent of the conditions of other lines. In this study, the damaged locations were predicted using the water line damage model contained in the damage estimate for Tokyo (Eq. (1)), which considered local *PL* values in order to provide exhaustive damage predictions (Tokyo Metropolitan Government, 2012).

$$E_D = 2.24 \times 10^{-3} \times C_{PL} \times C_D \times (PGV - 20)^{1.51} \times L \qquad (1)$$

where E_D is the number of damaged locations in a water line. *PGV* is the peak ground velocity (cm/sec), *L* is the length of each pipe section (m), and C_{PL} is a correction coefficient based on the *PL* value for the soil surrounding any given water line (Fig. 2). The *PL* values were estimated by converting the image data provided in the damage estimate for Tokyo into vector data. C_D is a correction coefficient that varies with pipe type and diameter. However, since these data were unavailable, it was assumed that the pipe type was ordinary ductile cast iron (without earthquake-resistant joints) and pipe diameters were estimated from street widths.

$$P_D(k) = \frac{(-E_D)^k \, exp(-E_D)}{k!} \qquad (2)$$

$$1 - P_D(0) = 1 - exp(-E_D) \quad (3)$$

Furthermore, assuming that the probability of breakage at each part in the water distribution pipe is uniform and independent for each part, the probability that the number of damaged parts is k at the length L (km) becomes Poisson distribution, and it can be expressed by Eq. (2) using the value of E_D. That is, the probability of occurrence of one or more breakages is expressed by Eq. (3).

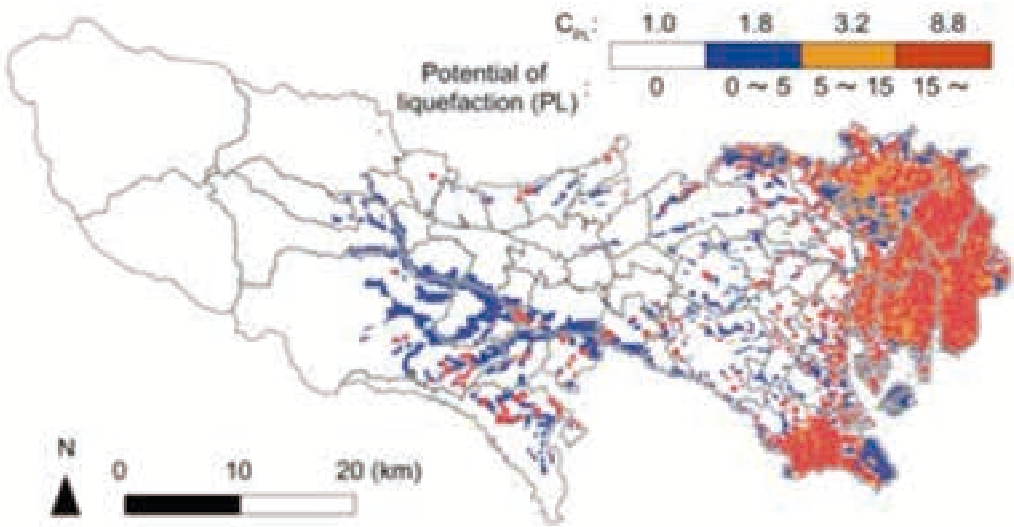

Figure 2. Potential of liquefaction (PL) in Tokyo Metropolitan area

Method for predicting outages at fire hydrants

Water outages were predicted based on the potential for damage along the water supply route from the purification plant to the fire hydrant and taking into consideration the possibility that damaged water lines in the network will no longer carry water (Fig. 1(4)). However, outages were specified only for fire hydrants that were determined to have become unable to receive water from any connected purification plant.

URBAN ZONE DAMAGE SIMULATION AND FIRE DEPARTMENT ACTIVITY SIMULATION

Overview of urban zone damage simulation

Using the urban zone damage simulation models and integrated a new model that allows users to predict physical damage due to collapsing buildings, street blockage, and spreading fires in urban zones, etc., at the level of individual buildings and streets. More specifically, the extent of destruction in the examined urban zone is estimated by the procedure shown in Fig. 3 using the ground surface response (Bureau of Waterworks Tokyo Metropolitan Government , 2016; Wakamatsu and Matsuoka, 2008; Fujimoto and Midorikawa, 2003; Matsuoka and Midorikawa, 1994; Si and Midorikawa, 1999), building collapse data (Midorikawa et al., 1994; Murao and Yamazaki, 1999), street blockage data (Murao and Yamazaki, 2000; Ministry of Land, Infrastructure and Transport, 2003), and the breakout and spread of fires (Ieda et al., 1998; Tokyo Fire Department, 1997, 2001).

First, the data about the ground surface layers, buildings, and earthquake source parameters were loaded into the ground surface response model on a 250-m cell. The seismic response at the ground surface (PGV, peak ground velocity) was then estimated at the level of individual buildings. Next, the number of buildings suffering complete collapse was predicted using the estimated PGV and the data for construction year (five classifications: prior to 1970, 1971-1980, 1981-1990, 1991-2000, 2001, and thereafter), and construction type (three classifications: wood, ferroconcrete/steel-framed reinforced concrete, and steel frame).

Based on these results, predictions were made as to which streets which would be blocked due to the complete collapse of adjacent buildings, which allowed us to envisage which streets would be rendered impassable for firefighters. This calculation was carried out for all the streets in the examined region. The outbreak or absence of building fires was calculated from the probability of an outbreak, which depended on the use of the building, the season, time of day, and the degree of structural damage. Outbreak times were distributed according to the TFD survey results. The fire spread in the urban zone was estimated using a model that incorporates factors including the fire resistance properties of a given building to combustion itself, heat radiation from neighboring buildings, and spacing between neighboring buildings.

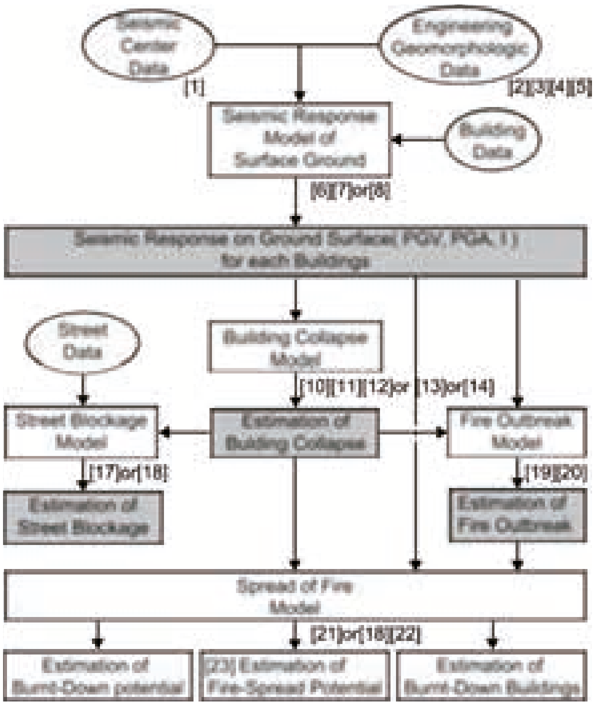

Figure 3. Outline of urban zone damage simulation model

Estimation of time limit for arrival of fire department to prevent fire spread

The time by which a fire department must arrive at a fire in order to prevent its spread (arrival time limit) is estimated based on the current fire spreading condition (fire circumference) in the fire spread simulation, whereas the maximum containable fire circumference is estimated by the number of responding firetrucks. In the simple method proposed by the TFD, a circle is drawn around the fire whose area equals the actual total floor area of the building on fire, and the circumference of this circle is used (Tokyo Fire Department, 2015). The TFD method is simpler but tends to underestimate the fire circumference as the fire spreads, which leads to overestimations of the arrival time limit. The method more closely represents the area to be sprayed with water under actual firefighting conditions (Fig. 4 left) should be used, however it requires very complicated calculation. In order to simplify analyses in this study, we only used more simple method by approximating the fire circumference with a convex envelope (Fig. 4 right). In the other, the fire circumference is represented by the length of the straight lines making up a convex envelope containing all the vertices of the polygon corresponding to the building on fire.

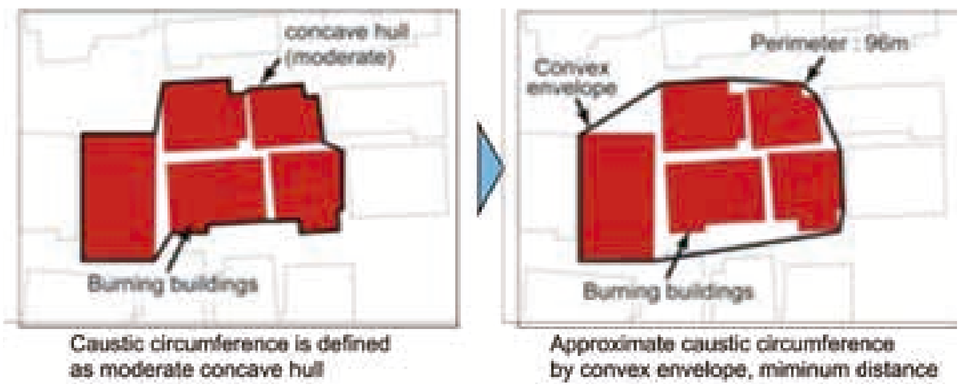

Figure 4. Approximate caustic circumference based on fire-spread simulation

Figure 5 shows the relationship between the elapsed time t since the fire breakout and the fire circumference $L(t)$ based on the mean values found in fire spread simulations incorporating all the buildings in Tokyo. D is the containable fire perimeter, the total actual portion of $L(t)$ that can be covered by the firefighters on site. D is determined by the number of responding firetrucks and the length of the sector assigned to each firefighting team. Then, Eqs. (4) and (5) determine the arrival time limits T_{lm}:

$$D = n \times d_a + m \times d_b \quad (4)$$

$$T_{lm} = L^{-1}(D) \quad (5)$$

where d_a represents the length of the sector assigned to a single fire department hose team and d_b represents the length of the sector assigned to a volunteer firefighter team. n and m indicate the respective numbers of hoses. In this study, it was assumed that a hose team was assigned two hoses and a fire front of 15 m (d_a = 15, n = 2), whereas a volunteer firefighter team was assigned one hose and a fire front of 10 m (d_b = 10, m = 1), and D was 40 m.

It should also be noted that even when the firetrucks arrived later than the arrival time limit (specifically, when [the sum of the time elapsed from the occurrence of the disaster to dispatch + travel time] was greater than [the sum of time elapsed from the occurrence of the disaster to fire breakout + arrival time limit]), by spraying selected portions of the fire, it is still possible to reduce the number of buildings lost to fire. However, that consideration was neglected in this study to avoid complications in calculating the number of losses.

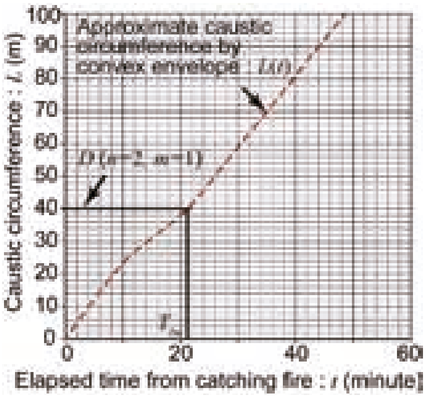

Figure 5. Average ratio of water outage and location of water purifying plant

Definition of fire spread potential inside a single building

The fire spread potential (Hirokawa and Osaragi, 2017), which is an index of the fire spread risk inside a single building, was defined using the results of fire spread simulations. The fire spread potential P_{Fi} of building B_i is defined using Eq. (6), and represents the final, total number of buildings that could be totally lost to fire if building B_i continued to burn freely.

$$P_{Fi} = \sum_{j \in BS} \delta_{ij}, \quad (6)$$

where variable δ_{ij} takes the value 1 if fire spreads from building B_i to building B_j and the value 0 otherwise, and BS is the set of all the buildings to be of concern.

Strategies for selecting dispatch destinations using fire spread potential

Because there is a fire which occurs after the time lag, we have to wait for a while and gather the information to judge fires with a relatively high fire spreading risk. In such a strategy based on standby, there is a danger of failing to prevent spreading fire. Therefore, using the fire spread potential and fire-outbreak probability for each building, we predict the ranking of the danger degree of a fire among all the fires that may occur as the result. Specifically, we calculate the expected value of the number of fires and its standard deviation by applying Eqs. (8) - (10) to the set of buildings whose fire spread potential within the jurisdiction k represented by the expression (7) is EP or more (Fig. 6). Thus, we can obtain the value of the fire spread potential, EP_k^*, that minimizes the value of Eq. (11).

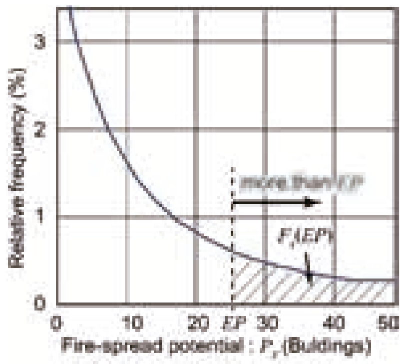

Figure 6. Relative frequency of Fire-spread potential

$$Bs_k = \{ (ep_{ki}, use_{ki}, I_{ki}) \mid ep_{ki} \geqq EP \} \quad (7)$$

$$E(X_k) = \sum_{b_{ki} \in B_{sk}} P(b_{ki}) \quad (8)$$

$$V(X_k) = \sum_{b_{ki} \in B_{sk}} P(b_{ki})(1 - P(b_{ki})) \quad (9)$$

$$P(b_{ki}) = P(use_{ki}, I_{ki}, S) \quad (10)$$

$$EP_{k*} = argmin_{EP} (|E(X_k) + \gamma_k \sqrt{V(X_k)} - Np_k|) \quad (11)$$

where, Bs_k is a set of buildings whose fire spread potential is EP or more within the jurisdiction k. ep_{ki}, use_{ki}, I_{ki} are the fire spread potential of the building B_{ki}, use and seismic intensity, respectively. X_k is a stochastic variable representing the number of fire in jurisdiction k, and its expected value and variance are denoted by $E(X_k)$ and $V(X_k)$, respectively. $P(b_{ki})$ is the probability of fire outbreak of the building B_{ki}, and S is a variable common to all buildings such as season and time. Np_k is the number of firetrucks in jurisdiction k, and γ_k is a parameter to be set according to characteristics of the urban area in order to cope with the fluctuation of stochastic event.

Fire department activity simulation accounting for water outage

The series of activities of a fire department responding to a fire were modeled as follows: The firetruck moves to an optimal water source for fire extinguishing activities, and the firefighting team carries a hose from the water source to the burning building (Fig. 7). The firetruck and the firefighting team speeds were set to different values ($speed_{Ve}$ and $speed_{Ff}$, respectively), and the passable streets (streets at least 4 m in width, all streets) were differentiated between for the firetruck and firefighting team. The optimal water sources were determined using Eq. (12).

$$WS_* = argmin_{ws \in WS} \left(\frac{D_n(ff, ws)}{speed_{Ve}} + \frac{D_e(ws, fire)}{speed_{Ff}} \right) \quad (12)$$

where WS_* represents the optimal water source, WS is the set of all water sources, $D_n(A, B)$ represents the distance from A to B in the network, $D_e(A, B)$ represents the straight-line distance from A to B, and ff, ws and $fire$ represent the locations of a firefighting team, a water source, and a burning building, respectively. Four cases can be anticipated when selecting a water source: (1) No fire hydrant usage (use only of fire cisterns, rivers, streams, etc.); (2) fire hydrant use (no water outages); (3) fire hydrant use (possibility of water outages); and (4) use of fire hydrants (known water outages). When anticipating the use of fire hydrants (Cases (2), (3) and (4)), fire cisterns, rivers and streams are used in addition to fire hydrants. In Case (3), if the fire hydrants at the destination have no water pressure, fire hydrant use must be abandoned and other sources must be sought. Case (4) assumes that individual fire hydrants have been installed with water pressure sensors (Nikkei, 2016) and that water outages at hydrants can be remotely detected.

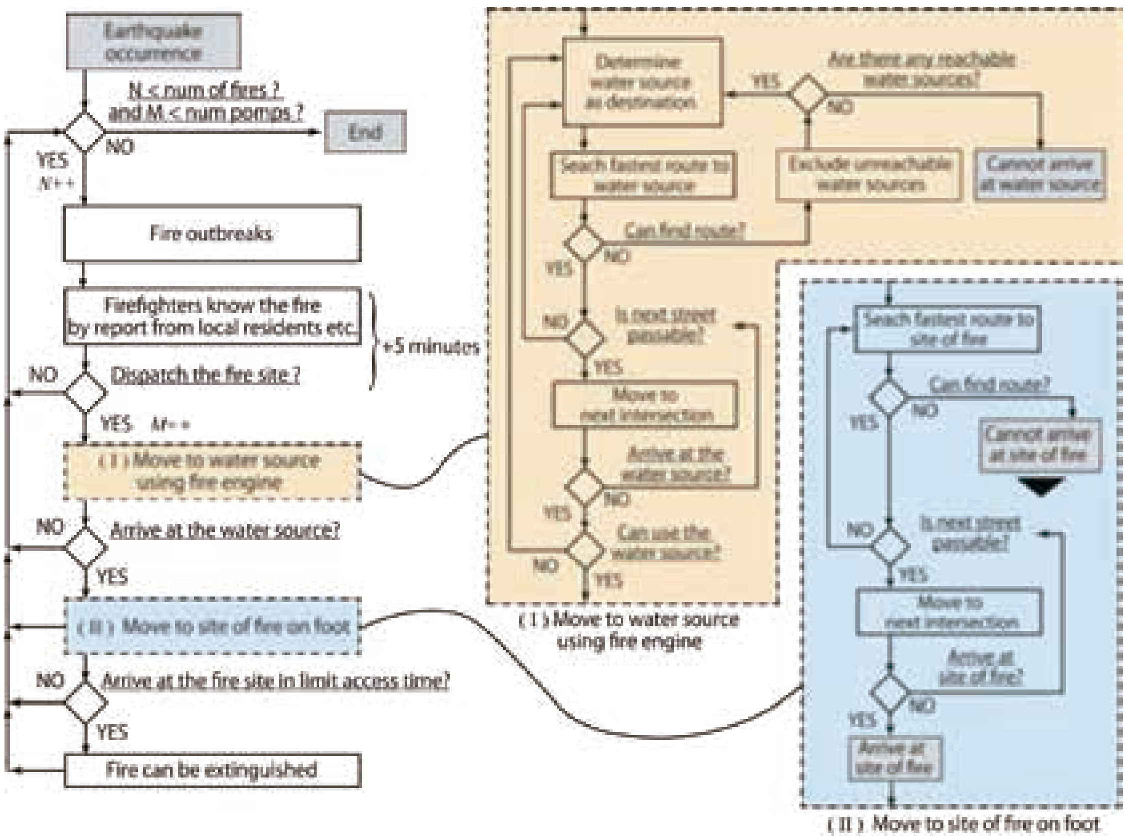

Figure 7. Outline of firefighter simulation model

In the urban zone damage simulation, it is also assumed that some streets will be blocked when calculating the time necessary to arrive at a burning building. Specifically, the simulation uses the following process. First, a path to the optimal firefighting water source is identified while assuming that all streets are passable. If blockage makes a street along the way impassable, a new path is then plotted from that location to the optimal firefighting water source. This process is assumed to take 30 seconds for the path search, course revision, etc. All the impassable streets found along the way are stored in memory and avoided when conducting new path searches. Additionally, when the firetruck has arrived at the firefighting water source and it turns out to be an unusable fire hydrant, the firetruck proceeds to another firefighting water source.

It is assumed that a combined team or number of teams, each consisting of a single fire station team and a volunteer firefighter team, are dispatched. The number of teams is the number of firetrucks held by the responding station and the branch fire stations. Considering the distribution of the clock times of fire breakouts in past damage data (Tokyo Fire Department, 2015) and the time needed for spraying, it was assumed that firetrucks are not deployed to other burning buildings after a fire has been controlled and that sufficient water is available for spraying the burning building being serviced. Note that half of the total number of fires that ultimately break out after a disaster do so within about 15 minutes after its occurrence, and 80% do so within the first 60 minutes.

SIMULATION CONDITIONS FOR THE COMPLETE TOKYO AREA AND WATER OUTAGE RATE PREDICTIONS

Target region for analysis and conditions for simulation

Urban zone damage simulations incorporating all of the buildings (2,784,101) and streets in Tokyo were carried out. The total of 1,000 simulations predicted varying physical damage situations (building collapse, street blockage, fire breakout/spread, and water outages) were conducted. A large earthquake with a magnitude of 7.3, centered in the north portion of Tokyo Bay on a winter evening (when the number of fire breakouts is likely to be the highest) was assumed. Other assumptions include a north wind of 8 m/sec and a humidity level of 50%.

The mean number of buildings lost to fire was estimated using the predicted physical damage, destinations for the fire stations (burning buildings) and arrival times in a Monte Carlo simulation (1,000 runs). The final numbers of buildings lost to fire were classified into those to which no firefighters were dispatched (free-burning fires) and those to which firefighters were dispatched but were unable to prevent fires from spreading. However, a very consistent number of buildings succumbed to free-burning fires in these simulations. More specifically, the final numbers of buildings lost to fire depended solely on the number of burning buildings tackled by fire stations. Therefore, this discussion focuses solely on the number of buildings lost to fire due to failure to prevent fires from spreading.

Estimates of rate of water outages in water outage simulation

Figure 8 shows the figures for each ward in Tokyo for the fraction of the total number of unusable fire hydrants (rate of water outages) estimated by the water outage simulation. These rates were found to be high in the east and south parts of Tokyo, where liquefaction damage is expected to occur (Fig. 2) and in the west part of Tokyo, which has no nearby purification plants, while they were low in the north part of Tokyo, which has a number of local purification plants. The damage estimate for Tokyo predicted a water outage rate of 46.7% in wards with dense networks of water pipes and relatively numerous water supply points, while the authors' water outage simulation predicted a rate of 50.3% for the same locations. The discrepancy between these predictions is well within 10%. This consistency suggests that the outage estimates by our simulation were plausible.

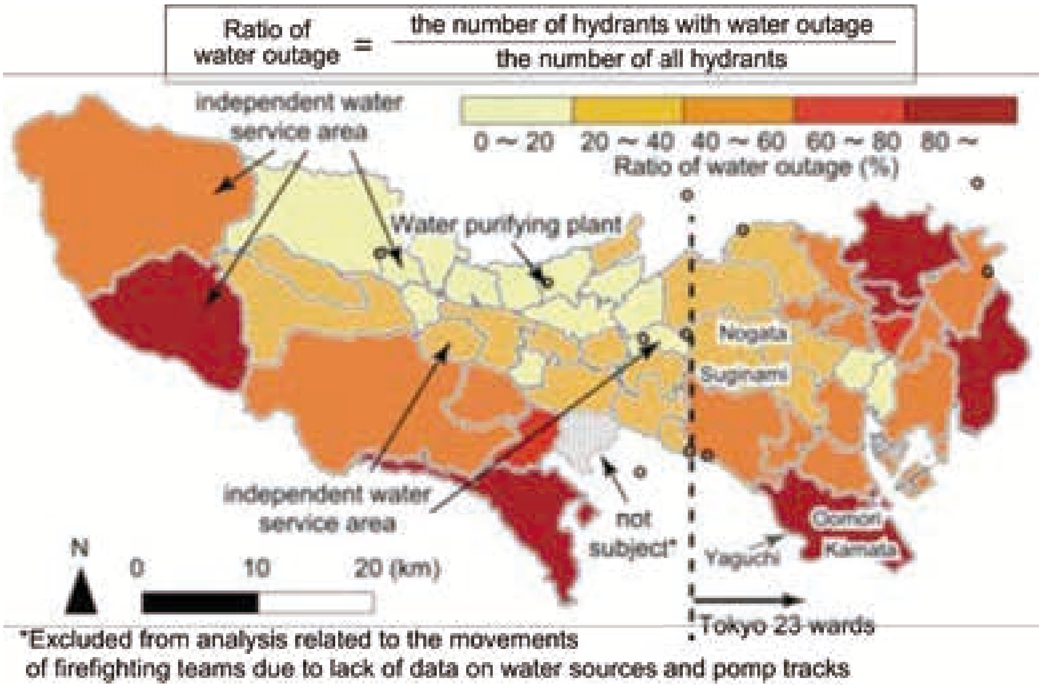

Figure 8. Average ratio of water outage and location of water purifying plant

INVESTIGATION OF USABILITY OF FIRE HYDRANTS IN FIREFIGHTING ACTIVITIES

Investigative method overview

In order to validate the effectiveness of utilizing fire hydrants for reducing the maximum number of buildings lost to fire, we examined that number while comparing the cases defined in 3.5 above. Comparing between Case (1) no usage of fire hydrants and Case (2) use of fire hydrants and no water outages, Case (2) corresponds to a situation in which individual water lines have been hardened against earthquakes (with earthquake-resistant joints, etc.) and will continue to function. Next, in order to examine the usability of fire hydrants during a water outage, we compare Case (1) no fire hydrant usage with Case (3) fire hydrant use and possible water outages. Finally, we observe the benefit of using fire hydrants by comparing Case (4) fire hydrant use (known water outages), which assumes that water outages at hydrants can be remotely detected with water pressure sensors that have been installed by the TFD, with Case (1) in which no fire hydrants are usable.

Effectiveness of fire hydrant used in reducing building losses

As an analysis reference of the effectiveness in reducing the number of buildings lost to fire, Fig. 9(1) provides the spatial distribution of buildings lost due to the failure to prevent fire from spreading under Case (1). Here, it can be seen that the areas in which these losses were high form a wide ring within the 23 wards of Tokyo. Examination of the position densities of firefighting water sources other than fire hydrants (cisterns, etc.) in Fig. 10(1) show that many of the jurisdictions are underequipped with such sources. Comparing Case (1) with Case (2), it can be seen that the number of buildings lost to fire could be reduced in virtually all the jurisdictions (Fig. 9(2)). Figure 11 shows how the reduction in the number of buildings lost to fire varies with the water outage rates. Specifically, some jurisdictions could see reductions by about 100 buildings, and the jurisdiction with the maximum reduction in losses would see about 400 buildings saved (Fig. 11(1)). On the other hand, some of the jurisdictions with high fire hydrant densities showed little benefit in terms of the reduction in the number of buildings lost to fire (Figs. 9(2), 10(2)). This was ascribed to the small number of buildings lost to fire caused by the failure to prevent fire spread in the central portions of Tokyo and neighboring cities and to the fairly efficient positioning of firefighting water sources other than fire hydrants (firefighting water cisterns, etc.) (Fig. 9(1)).

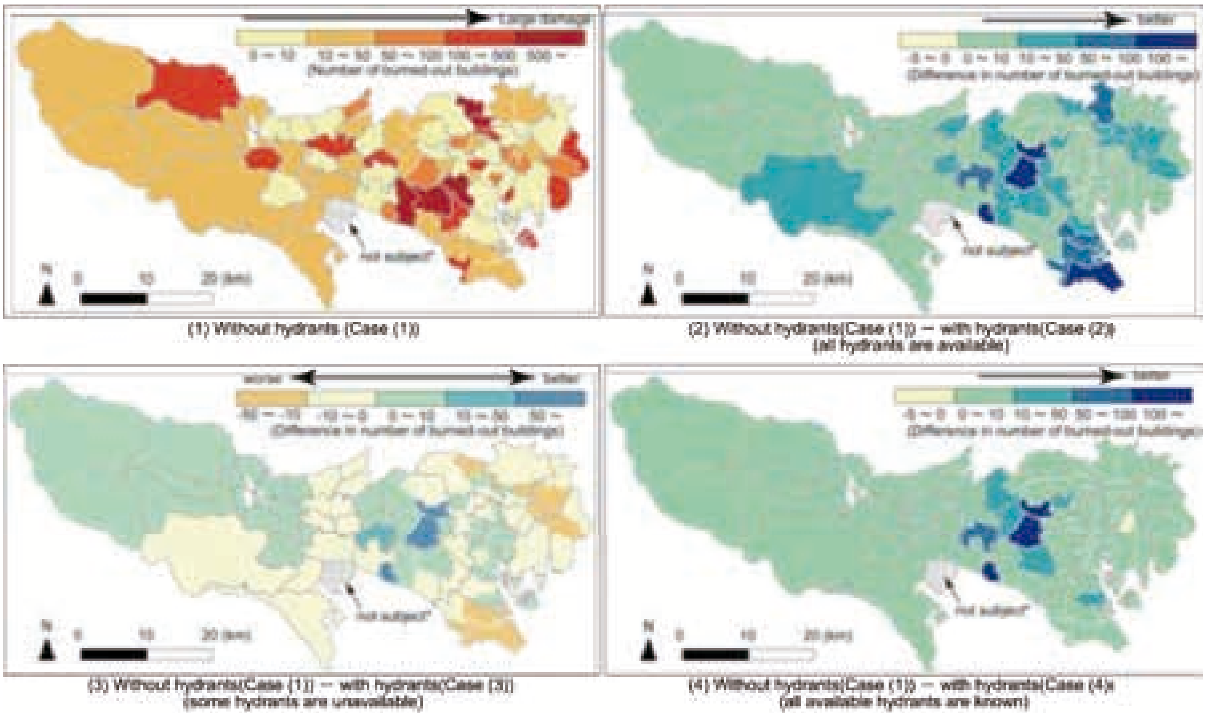

Figure 9. Difference in the number of burned-down buildings in each condition

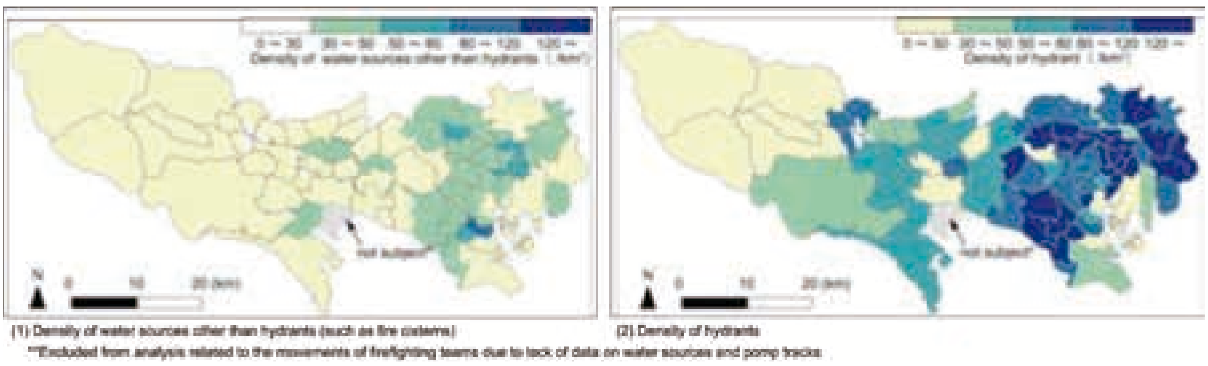

Figure 10. Density of water sources

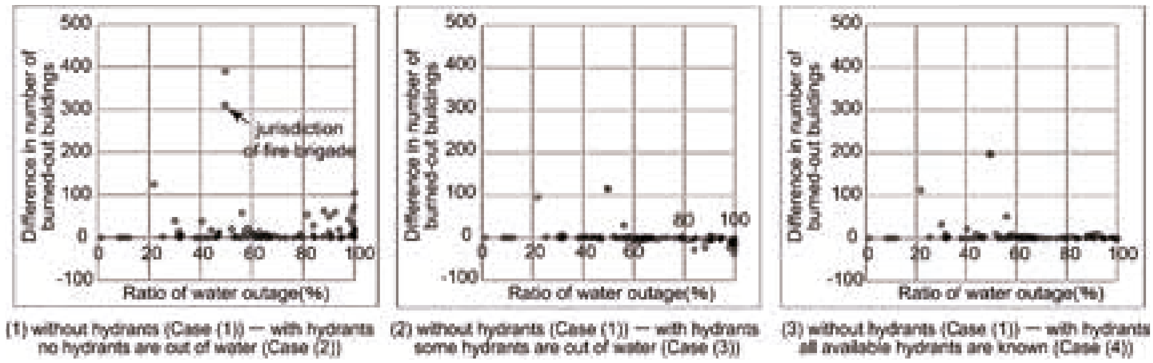

Figure 11. Relationship between difference in the number of burned-down buildings and the ratio of water outage

Influence of fire hydrants suffering water outages on number of buildings lost to fire

In Case (3), the use fire hydrants during potential water outages was attempted, but the number of buildings lost to fire increased in a total of 46 (56.1%) jurisdictions (Fig. 9(3)). However, the increase only exceeded 10 buildings in eight jurisdictions (9.76%), and was about 37 buildings at most (Fig. 11(2)). Additionally, some jurisdictions suffering water outage rates of around 50% were still able to save over 100 buildings, thus showing an advantage of using fire hydrants.

Benefit of reducing number of buildings lost by tracking unusable fire hydrants

Thanks to the introduction of water pressure sensors (Japan Water Research Center, 2011), in cases in which fire departments can verify which fire hydrants remain functional before they arrive at a fire (Case (4)), nearly all the jurisdictions were able to reduce building losses (Fig. 9(4)). Jurisdictions where water outages were less severe were able to reduce losses by nearly 200 buildings (Fig. 11(3)). However, since the jurisdictions that were able to cut losses by nearly 100 buildings under Case (2) were those suffering more severe water outages, we infer that there would be no benefit in terms of reducing building losses conferred by this technology under Case (4) (Fig. 9(4), Fig. 11(1), (3)). In such regions, i.e., regions with insufficient fire cisterns (Fig. 10(1)), the severe water outages mean fire stations cannot count on being able to use fire hydrants. Therefore, it is imperative to take other measures such as hardening water lines against earthquakes, constructing more fire cisterns, and so on.

Potential for use of fire hydrants during water outages

Here, while considering the above observations, we investigate the utility of fire hydrants in firefighting activities in spite of a water outage. If fire hydrants remain usable, some jurisdictions will be able to reduce the number of buildings lost by more than 400 units. However, the central portions of Tokyo and neighboring cities have fairly efficiently distributed firefighting water sources other than fire hydrants (fire cisterns, etc.), so many of those jurisdictions are in a position to carry out sufficiently effective firefighting activities in the event of a water outage without depending completely on fire hydrants. Nevertheless, assuming that water outages can be remotely detected, it is highly probable that the number of buildings lost to fire could be reduced in nearly all the jurisdictions, even after a large earthquake, which means that the introduction of water pressure sensors will be extremely beneficial.

Additionally, since jurisdictions that are less vulnerable to water outages were also able to save nearly 200 buildings, there needs to be more investigation of the use of fire hydrants in such areas. Figure 12 shows the numbers of buildings that posed difficulties for firefighting activities when no fire hydrants were available, as estimated from the locations of firefighting water sources other than fire hydrants and firefighter hose lengths. There are approximately 20,000 buildings in the complete area of Tokyo which will be difficult to access by firetrucks if no fire hydrants are available. Thus, fire hydrants are crucial. In contrast, regions that have sufficient numbers of fire hydrants but are prone to water outages will benefit less from information about local water outages, so in those areas it is important to harden water lines and construct more fire cisterns.

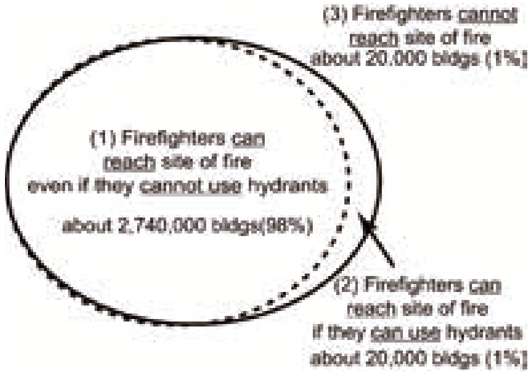

Figure 12. The number of burned-out buildings and difference in firefighters' reachability be-tween with/without hydrant

SUMMARY AND CONCLUSIONS

A simulation model was constructed in order to investigate the usability of fire hydrants during water outages following a large earthquake and to predict the occurrence of water outages at individual fire hydrants in a water supply network after such an earthquake. The authors also combined previously proposed simulation models of urban damage and fire department activities to quantitatively analyze the effects and benefits of fire hydrant usage in terms of reducing the number of buildings lost to fire.

From the results of the water outage simulation, it was determined that water outage rates will be higher in the east and south parts of Tokyo, where serious damage is expected due to soil liquefaction and in the west part of Tokyo, which is far from water purification plants. One of the most important results of this study has been the simulation model describing the phenomena of water outages occurring in water supply networks, which was used in place of the cell model previously employed for such simulations.

The simulation noted fire department jurisdictions in which more than 400 buildings were saved from complete fire destruction after a large earthquake because of the hardening of water lines that had been performed in those areas, which helped prevent water outages. A few jurisdictions saw a slightly greater damage rate when attempting to use fire hydrants during water outages, but jurisdictions that had low rates of water outage were able to reduce the number of buildings lost to fire by over 100. It was also determined that the central portions of Tokyo and neighboring cities are somewhat better equipped with firefighting water sources other than fire hydrants (fire cisterns, etc.) than the Tokyo suburbs.

Once Tokyo has completed its ongoing installation of water pressure sensors and water outages can be remotely detected as soon as they occur, nearly all jurisdictions will be able to save many more buildings from destruction by fire. Jurisdictions with lower rates of water outages (around 50%) will be able to save approximately 200 buildings. Additionally, there are about 20,000 buildings that fire departments would be unable to service without fire hydrants. Jurisdictions that are underequipped with fire cisterns and other backup sources of water should prepare to track water outages and plan to rely on fire hydrants.

In order to simplify water outage predictions, the water outage simulation in this study did not account for pressure losses due to leaks or the potential to continue some supply of water downstream of a breakage. Furthermore, it was assumed that the water supply network has a tree format when it actually has an interlinked format. Future research must include construction of a more exhaustive simulation model as the urban zone damage simulation mode used in this study did not account for effects such as street blockages or delays due to fleeing population, abandoned automobiles, or traffic jams. For that model, an approach using a physical model must also be examined.

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