A Systemic Approach for the Optimum Firefighting Operation against Multiple Fires Following a Big Earthquake

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ABSTRACT

The system for predicting the optimum firefighting operation against multiple fires following a big earthquake was developed. The computational calculation using this system provides how to dispatch fire engines in order to obtain the most effect such as the most number of suppressed fires and the least burned area in the initial stage of the firefighting operation. Additionally, this system, which is basically for the real time simulation, has other applications: the estimation of the firefighting force and the firefighting facilities, the evaluation of fire resistance of the urban configuration against fires following an earthquake, and the training of the commander for the firefighting operation. The model of this system and the results of case study for a certain ward in Tokyo Metropolis are presented.

INTRODUCTION

Against the problem of the simultaneous multiple fires following a big earthquake, it is greatly important to estimate how the firefighting force is able to achieve its proper functionality, that is, how fire engine companies are able to overcome various obstacles such as the damage to transportation facilities, communications systems, and water supply etc. and also how many fires can be suppressed in the early stage by fire engines. Therefore, the real time system, which is for predicting the optimum operation of the firefighting force, is eagerly desired as an useful supporting tool for the operation control of fire engines. In this field, although there are not so many papers yet, some contributive works have been introduced recently. (See, for example, ref. 1)

The operation of the firefighting force in case of a big earthquake is generally divided into following two stages.[2-6] The first operation is aimed to suppress fires as many as possible in the early stage of fire spread which is considered to be approximately within one hour after the shock of an earthquake. On the other hand, the second one is mainly aimed to defend the roads of refuge for the safety of evacuees in the later stage of fire spread where some fraction of initial fires develop to conflagrations which occur a few hours later from the occurrence of an earthquake. This paper intends to describe the systemic approach seeking for the most effective operation in the first stage of the firefighting at an earthquake.

THE MODELING OF THE OPTIMUM FIREFIGHTING OPERATION

The Basic Idea of the Model

The aim of the model is to predict how many fire engines from (m) sites of fire station and branch offices should be dispatched to suppress (n) spots of fires inside the jurisdiction in order to obtain the best achievement of the firefighting. Because the fire engine companies are principally in charge of the fires only in their jurisdiction in the first stage of firefighting operation. The number of suppressed fires and/or the burned area is evaluated for examining the effectiveness of the firefighting. The former one is used preferentially. The algorithm consists of the following two steps as illustrated in Fig. 1.

1st step: To determine how to dispatch the fire engines so as to minimize the burned area

2nd step: To determine how to remove fire engines so as to maximize the number of the suppressed fires and to minimize the burned area, starting from the result of the 1st step as an initial condition

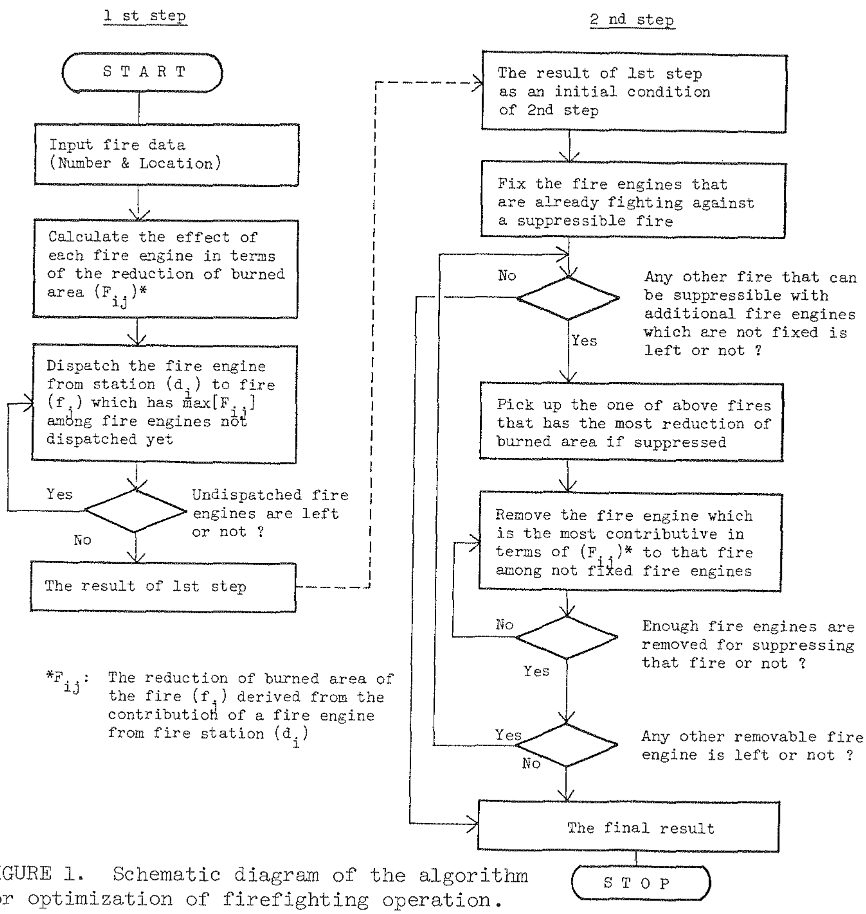


FIGURE 1. Schematic diagram of the algorithm for optimization of firefighting operation.

The Model of Fire Spread

The burned area $S(t)$ and its circumferential length $L(t)$ at the lapse of time "t" from the outbreak are expressed as follows.

$$S(t)=\frac{1}{4}A(R_F,R_{SL})+\frac{1}{4}A(R_F,R_{SR})+\frac{1}{4}A(R_{SL},R_B)+\frac{1}{4}A(R_{SR},R_B) \quad (1)$$

$$L(t)=\frac{1}{4}C(R_F,R_{SL})+\frac{1}{4}C(R_F,R_{SR})+\frac{1}{4}C(R_{SL},R_B)+\frac{1}{4}C(R_{SR},R_B) \quad (2)$$

where $A(a,b)$ indicates the area of an ellipse with a long axis of "a" and short axis of "b", and $C(a,b)$ is its circumferential length. And R_F, R_{SL}, R_{SR}, R_B are burned lengths in the leeward, in the left sideward direction, in the right sideward direction and in the windward direction respectively as shown in Fig. 2. The fire spread velocity inside a block is calculated by using Dr. Hamada's formula.[7] On the other hand, the fire spread velocity between neighboring blocks is estimated differently with the following idea. A fire is assumed to take the time "t_B" to spread over a road between neighboring blocks. "t_B" is expressed as;

$$t_B=t_0(d/D(y))^2 \quad (3)$$

where "t_0" is assumed to be 120 minutes at present, since there is very few data available[8] for identifying the time needed for fire spread beyond a road. "d" is the width of the road and $D(y)$ is the marginal distance of the fire spread where the width of the fire front is "y".

The Model of Fire Fighting

The time "t_{ij}", which is needed for the fire engine to reach the fire spot "f_j" from the fire station "d_i" and to begin water discharge, is given as;

$$t_{ij} = t^D + t^P + t^R_{ij} + t^H_j \quad (4)$$

where "t^D" : The time needed for the control center to catch the fire occurrence after its outbreak

"t^P" : The time needed for preparation of dispatching

"t^R_{ij}" : The time needed for a fire engine to reach the fire spot "f_j" from the fire station "d_i" using minimum path on the designated road network

"t^H_j" : Time needed for the hose coupling and extension

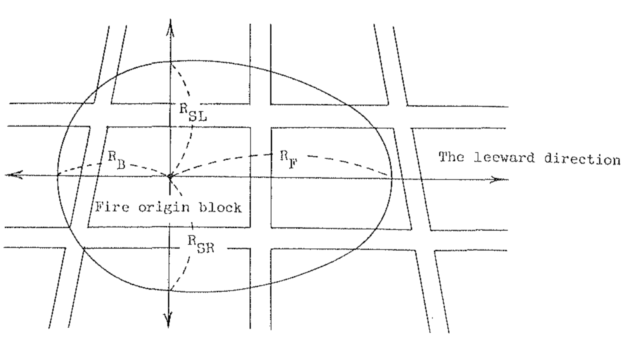


FIGURE 2. The model of the fire spread in an urban area.

The Model of the Effect of Fire Fighting

If p of fire engines discharge water to fire "f_j", the circumferential length H(p) of the fire that can be charged by p of fire engines is shown as;

$$H(p)=2hp \tag{5}$$

where "h" is the circumferential length which can be charged with one nozzle and each fire engine has two nozzles. The effectiveness of water discharge can be expressed by the reduction of fire spread velocity. The reduction rate $\alpha(t,p)$ is defined herein as;

$$\alpha(t,p)=(L_j(t)-H(p))/L_j(t) \tag{6}$$

where L_j is the circumferential length of the fire "f_j" itself. If $\alpha \leqq 0$, then the fire "f_j" is considered to be suppressible.

THE CASE STUDY

The Conditions of the Case Study

A certain ward in Tokyo was selected for the case study. This area covers about 10 km x 10 km as shown in Fig. 3, which is divided into 3 areas of jurisdictions. In each area of jurisdiction, there are one fire station and some branch offices. Table 1 shows the number of fire engines at each fire station or branch office. The calculation conditions for the case study are shown in Table 2.

Among the calculation conditions, one of very important factors which affect firefighting activity is the speed of a fire engine. Since there should be road damage and/or traffic jam after an earthquake, a fire engine has probably less speed than usual. Therefore, we adopted 15 km/h as an expected average speed on the road network according to the value presumed by Tokyo Fire Department in their report.[11]

TABLE 1. Fire stations/branch offices and the number of fire engines

Area of jurisdiction	Fire station & branch office	Number of fire engines
1	1 (Fire station)	4
	2	2
	3	2
	4	2
	5	2
	6	2
2	1 (Fire station)	4
	2	2
	3	2
	4	2
3	1 (Fire station)	4
	2	2
	3	2

The Results of the Case Study

24 fires, that is a certain estimated number[11] of post-earthquake fires in the winter evening in this district, were randomly input. Two cases of wind velocity as 5 m/s and 10 m/s were selected. The numerical effectiveness of the operation of firefighting is shown in Table 3 and Table 4. We see that in case of 5 m/s of wind velocity, 10 of given 24 fires will be able to be suppressed under the optimum operation of firefighting force, and 6 of 24 given fires are suppressible in case of 10 m/s of wind velocity. Fig. 4 shows the example of the optimum initial dispatching of fire engines in case of 10 m/s of wind velocity.

TABLE 2. The calculation conditions for case study

Items	Numerical values
Time of the estimate	60 minutes after the outbreak
Time for the recognition of the fires	4 minutes
Time for the preparation of dispatching	1 minute
Speed of each fire engine on the road network	15 km/h
Speed of each fire engine outside the road network	10 km/h
Maximum number of hoses that can be coupled	20
Length of one fire hose	20 m
Available water supply for each fire engine	40 m
Time for the coupling of N hoses	0.15N + 1.22 (minutes)
Width of the fire front charged by each fire engine	30 m
Time for the fire spread over the marginal distance	120 minutes
Maximum width of the fire front	50 m

TABLE 3. Effectiveness of the firefighting at 5 m/s of wind velocity (The estimate at 1 hour after the outbreak)

Area of jurisdiction	No. of fires	Burned area (m^2)		Number of dispatched fire engines	Suppressive or not
		Without firefighting	With firefighting		
1	1	6338	231	2	o
	2	8947	4800	1	x
	3	9199	(9199)		
	4	7814	(7814)		
	5	8483	(8483)		
	6	9872	277	2	o
	7	8164	(8164)		
	8	10086	6321	1	x
	9	11872	(11872)		
	10	9088	6116	1	x
	11	8389	425	3	o
	12	10193	5858	1	x
	13	8132	613	3	o
2	14	9977	7237	1	x
	15	4661	216	2	o
	16	10344	736	4	o
	17	8773	3241	1	x
	18	8525	238	2	o
3	19	1257	573	3	o
	20	9800	(9800)		
	21	7535	264	2	o
	22	8580	(8580)		
	23	5608	275	2	o
	24	13435	11513	1	x

TABLE 4. Effectiveness of the firefighting at 10 m/s of wind velocity (The estimate at 1 hour after the outbreak)

Area of jurisdiction	No. of fires	Burned area (m^2)		Number of dispatched fire engines	Suppressive or not
		Without firefighting	With firefighting		
1	1	13411	986	4	o
	2	20134	(20134)		
	3	20745	(20745)		
	4	18807	(18807)		
	5	19364	(19364)		
	6	21899	(21899)		
	7	18352	(18352)		
	8	21287	(21287)		
	9	22778	(22778)		
	10	16509	2196	6	o
	11	12552	987	4	o
	12	22619	(22619)		
	13	11181	(11181)		
2	14	21717	(21717)		
	15	10236	547	3	o
	16	23504	15606	1	x
	17	18043	737	4	o
	18	19763	3734	2	x
3	19	3193	(3193)		
	20	21159	20313	1	x
	21	23504	(23504)		
	22	16976	13189	3	x
	23	13628	809	4	o
	24	31212	(31212)		

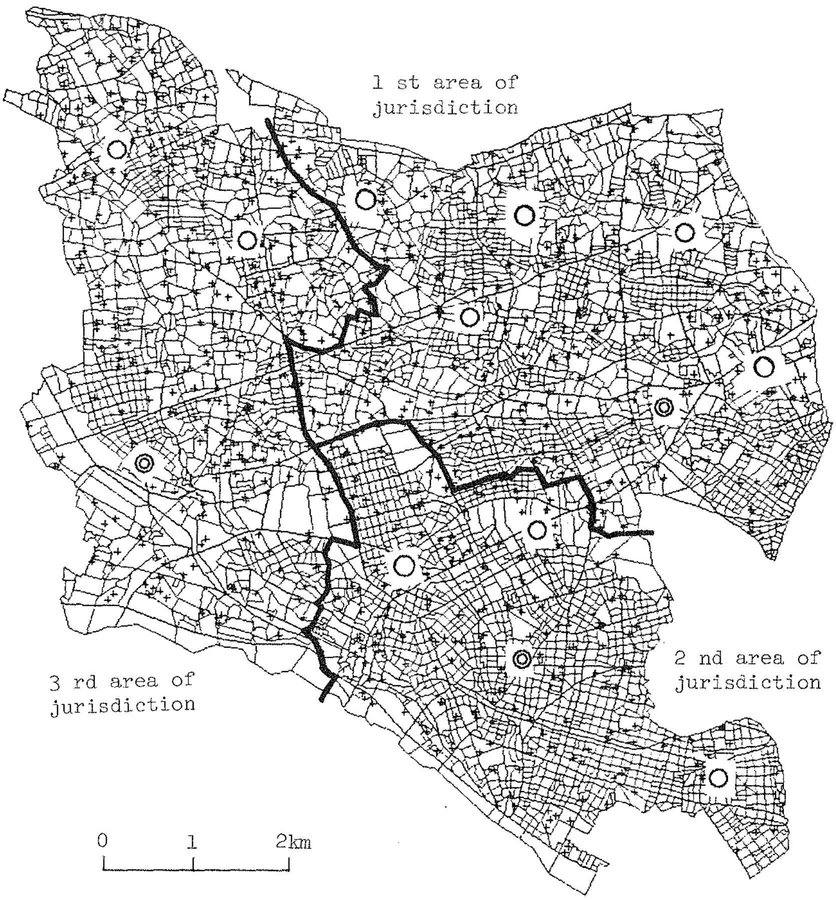
CONCLUDING REMARKS

The result of the case study for a certain ward in Tokyo shows that 10 of given 24 post-earthquake fires (at 5 m/s of wind velocity) and 6 of them (at 10 m/s of wind velocity) could be suppressed, if the optimum firefighting operation is taken place in the early stage of fire spread. The estimate of this result is close to the statistical estimate of the study in the "Report on the Estimation of the Damage derived from a Big Earthquake in Tokyo Metropolis Area[11]", which shows that 10 of 24 fires in the same ward district are supposed to be suppressible by professional firefighting at 6 m/s of wind velocity. Consequently, this work indicates the possibility that we will be able to have the practical real time system for the operation control of fire engines under the situation of multiple post-earthquake fires.

By the way, the model introduced in this paper can provide only the optimum operation for the initial dispatch of fire engines. Therefore, it is needed to develop the model for the optimum operation in the second stage of firefighting against the fires which are left unsuppressed.

DISCUSSION

The system for the optimum firefighting operation serves as a tool for the control of fire engines as well as the prediction of the damage by fires following a big earthquake. However, for the practical use, this system contains some limitations due to the use of presumed values



—— : Roads whose widths are 8 m or more

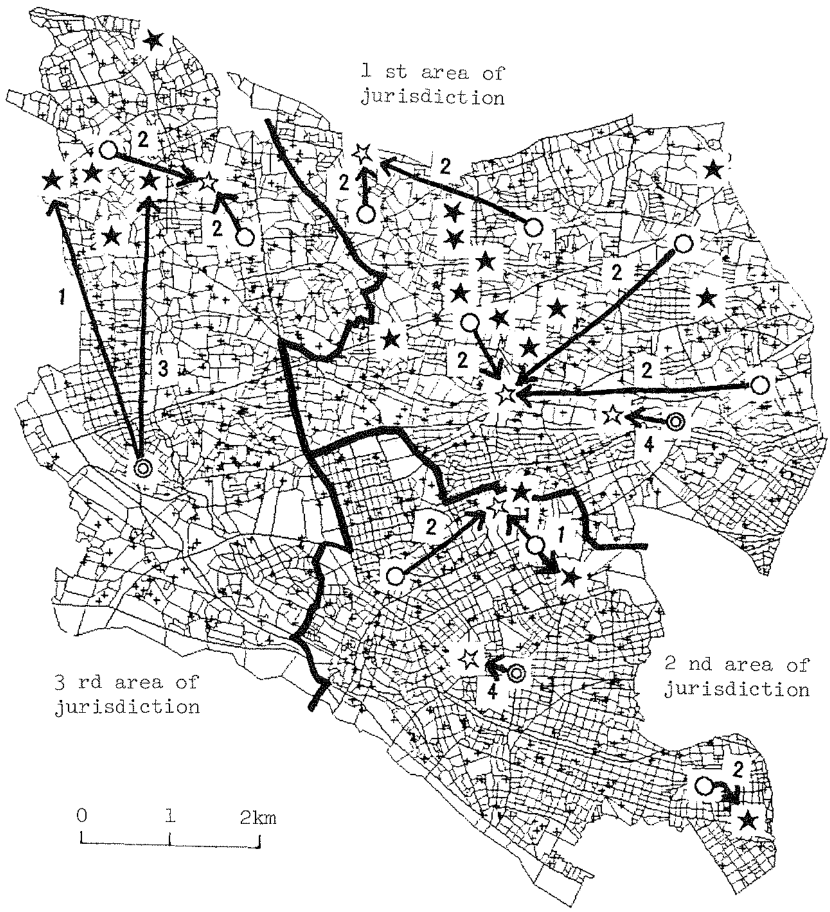
▬ : Boundary of jurisdiction

+ : Water tanks and pools

◎ : Fire station

○ : Fire station (Branch office)

FIGURE 3. District as the object of the case study



★ : Fire spots

☆ : Suppressed fires

→ N : Dispatch way & number of fire engines (N)

FIGURE 4. The example of the optimum initial dispatching of fire engines

and assumptions in its calculation conditions. Also, the algorithm of this system is somewhat simplified for shortening the calculation time. So, if saying strictly, the result of the calculation is not always assured to be literally optimum, although it is close to the optimum answer. Therefore, there are some issues to discuss for improvement of this method as follows.

Expressions and Numerical Values for the Calculation

Assumed expressions and values were used for the time needed for fire spread over a road between blocks and also for the reduction effect of the fire spread velocity by firefighting. Further, Dr. HAMADA's formula, which is the basis of fire spread velocity in this study, is now being refined by Tokyo Fire Department and etc. So then, these expressions and values are to be replaced with those which will be obtained in new advanced studies.

Algorithm for the Optimum Operation

The strict accuracy of the optimum operation can be obtained just after taking various combinations of many factors into consideration. However, since a real time simulation is essentially required to produce a quick response and output, the strictness of the result must harmonize with the restriction of the calculation time.

Modeling of Simultaneous Outbreak of Post-Earthquake Fires

Literally simultaneous outbreak of many fires is presumed in this system. However, at the 1923 Kanto Earthquake, 80 % of all fires occurred in 60 (min.) after the shock of the earthquake, and the left of them occurred later. Also, at the 1964 Niigata Earthquake and the 1968 Tokachi-Oki Earthquake, only 60 % of all fires broke out in 5 (min.) after the earthquake. So, the system should be elaborated in this point for the future.

Obstacles to the Firefighting Operation

The performance of firefighting force under a strong earthquake largely depends on the quality and quantity of the obstacles caused by an earthquake. Especially, the transportation obstacles such as road damage and traffic jam, and the damage to communications systems[13] and water supplies are the main causes of weakening the firefighting force. The methodology for the estimate of the influence of these obstacles is still insufficient at present. So, some presumptions for the obstacles to the firefighting operation are inevitable for the time being.

Other Issues for the Practical Use

In order to put the system for the practical use, an assured communications system among a headquarter, fire stations, and fire sites is very important as well as the improvement of this system for practical application.

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