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Statistical Data Analyses for Investigating Recent Major Earthquakes and Mitigating their Damages in Japan

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Abstract

Japan has experienced many large-scale natural disasters such as earthquakes, typhoons with heavy rain and landslides, tornadoes and so on. Every time we have such serious damages due to major natural disasters, public utilities such as electricity, gas, and water have been cut off and stopped. In this paper we take four major earthquakes, which occurred very recently with serious damages. Using data such as deaths and missing people, refugees, and refugee camps, water supply suspension and its recovery and applying various statistical data analyses techniques and mathematical models, we show our findings and policy suggestions obtained from those analyses. In addition, we propose a mathematical modeling technique for quantitatively measuring the robustness of the water supply network system. Our approach is based upon the network flow optimization model and Monte Carlo random generation technique. We illustrate numerical results obtained from our numerical experiments.

Key words. : Statistical data analysis, earthquakes, mathematical model, water supply network, network flow optimization model

1 Introduction

Japan has experienced many serious natural disasters including earthquakes, typhoon, floods, landslides, and so on. Hanshin-Awaji earthquake in January, 1995 has caused 6,400 deaths and missing people. Then in March, 2011 the Great East Japan Earthquake has caused 16,000 deaths and 2,800 missing people. Still more than 320,000 refugees remain at refugees camps even now, living far from their home areas where they lived before the incident. East South Sea earthquake, which is said to occur in the near future, may bring the worst case of 25,000 deaths and missing people, 960,000 broken houses, and even 50 trillion economic loss. Every time we have such serious damages due to major natural disaster earthquake, public utilities such as electricity, gas, and water have been cut off and stopped. Then a lot of refugees are brought to the refugee camps such as public schools and public halls, then they have to stay there for a certain or long period. We have investigated the damages and the recovery processes for the Great East Japan Earthquake (refer to Parwanto and Oyama [3], [4], [6]], Parwanto, et al. [5].

In this paper we take four major earthquakes Hanshin-Awaji, Niigata-Chubu, Great East Japan and Kumamoto, which occurred recently with serious damages. Using data such as deaths and missing people, refugees, and refugee camps, water supply suspension and its recovery, and so on, we apply statistical data analysis techniques to investigate those four major earthquakes in detail with various corresponding mathematical models to derive more desirable and efficient mitigation policies for preparing natural disasters in Japan.

In the following Section 2 we show the trend of refugees for recent major earthquakes in Japan. In Section 3 we describe the suspension and recovery processes of social infrastructures such as electricity, gas, water and communication line. In Section 4 we explain how to measure the robustness of the water supply system Finally, in Section 5 we give summary and conclusion of our paper.

2 Trend on refugees for recent major earthquakes in Japan

We take four major earthquakes, which occurred recently in Japan with serious damages including a lot of deaths and missing people: Hanshin-Awaji earthquake (1995/01/17) denoted by HNSA, Niigata-Chubu earthquake (2004/10/23) denoted by NGTC, Great East Japan earthquake (2011/03/11) denoted by GEJE, and Kumamoto earthquake denoted by KMMT, Tables A1 and A2 in the Appendix show the trend of the number refugee camps and refugees for recent major earthquakes in Japan, respectively. In those Tables “period” indicate the number of days (D), weeks (W), and months (M), respectively.

Figure 1 indicates the number of refugees for the GEJE, NGTC and HNSA, respectively while Figure 2 shows the number of refugees camp sites for those major earthquakes. In Figure 1 GEJE(Whole) indicates the data for the whole area affected by the GEJE, while GEJE(3 Pref.) shows the data for the three prefectures Iwate, Miyagi and Fukushima. In these Figures number of refugees and number of refugee camps are shown daily until 1M (1 month), then monthly up to 4M (4 months). We see from Figure 1 that number of refugees increases in the first 3 days after the incident, then drastically decreases in a few weeks, then slowly decreases in a few months. Almost similarly, number of refugee camps increases in the first 5 days, then declining slowly while only GEJE(Whole) shows rather constant or increasing trend exceptionally in 2 months, thereafter decreases, but still we see around 1,500 refugee camps after 3 months.

Figure 3 indicates the relationship between the number of refugee camps and the number of refugees for recent major earthquakes mentioned above. In Figure 3 we find that most earthquakes show similar declining trend for both number of refugees and number of refugees camps. In Figure 3 we find that the GEJE only shows a different move from others regarding the decreasing trend of the relationship between the number of refugees camp sites and the number of refugees until three to four months after the incident. Excluding the GEJE data in Figure 3 we obtain Figure 4, showing the relationship between those two factors for three recent major earthquakes HNSA, NGTC and KMMT in Japan. From Figure 4 we see that the relationship between those two factors can be expressed by some mathematical model expressed by using a polynomial function. This implies that the declining trend of those two factors, i.e. number of refugees camps and number of refugees can be more commonly and more generally expressed by the mathematical model.

Applying a mathematical model to approximate the relationship between number of refugees

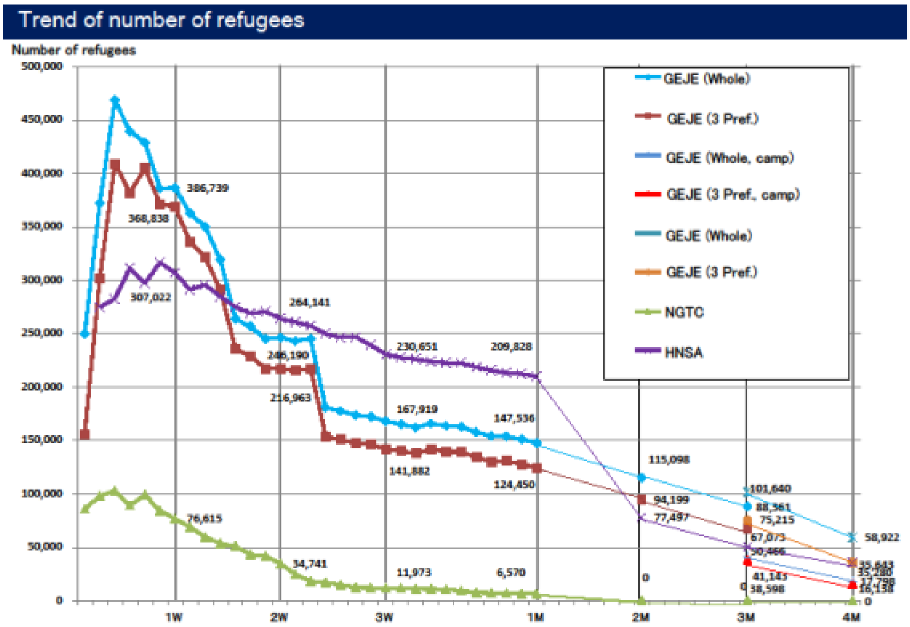

Figure 1: Number of refugees for the GEJE, NGTC and HNSA,

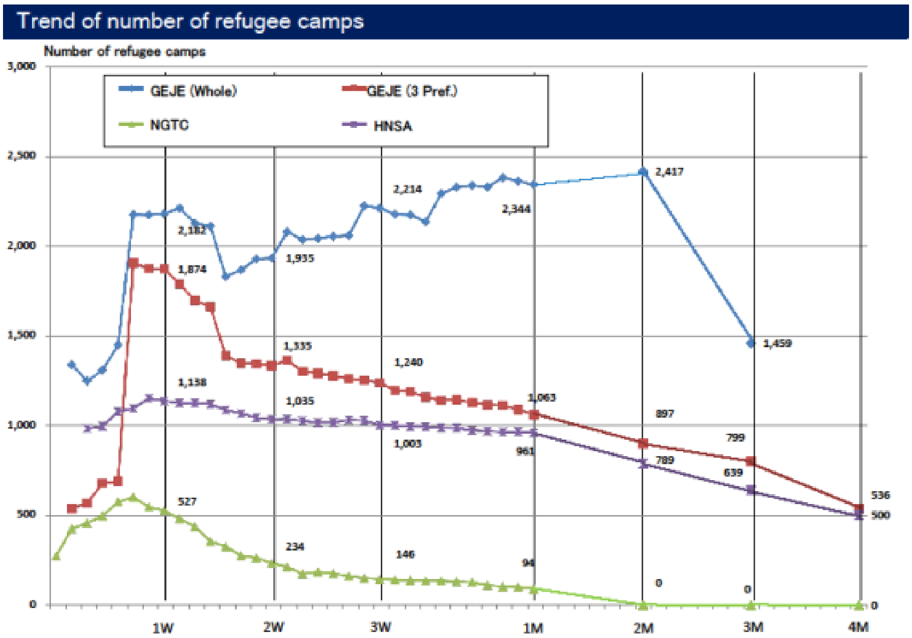

Figure 2: Number of refugees camp sites for the GEJE, NGTC and HNSA,

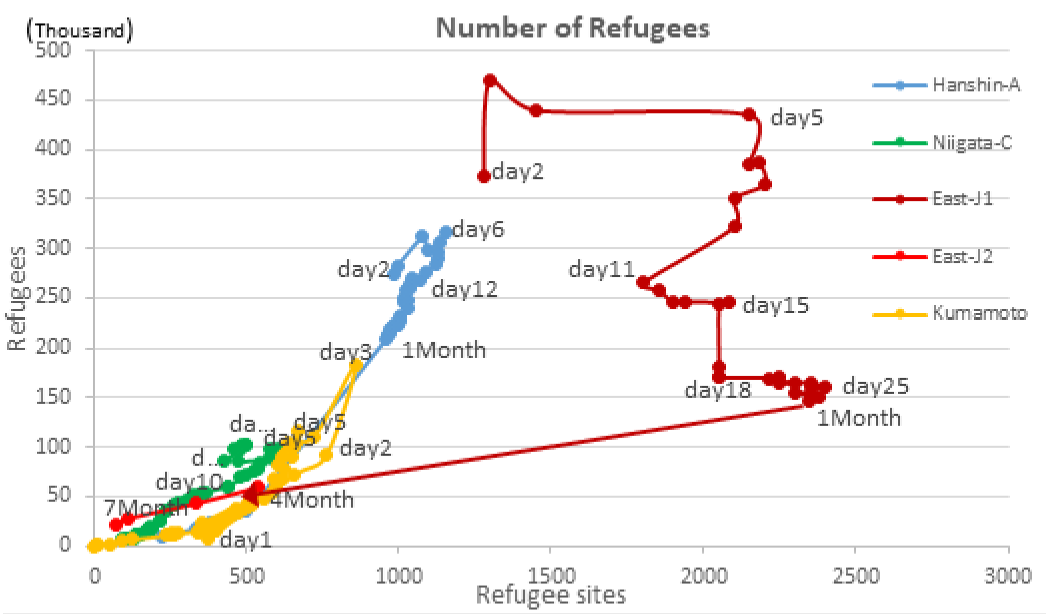

Figure 3: Relationship between refugees camp sites and refugees,

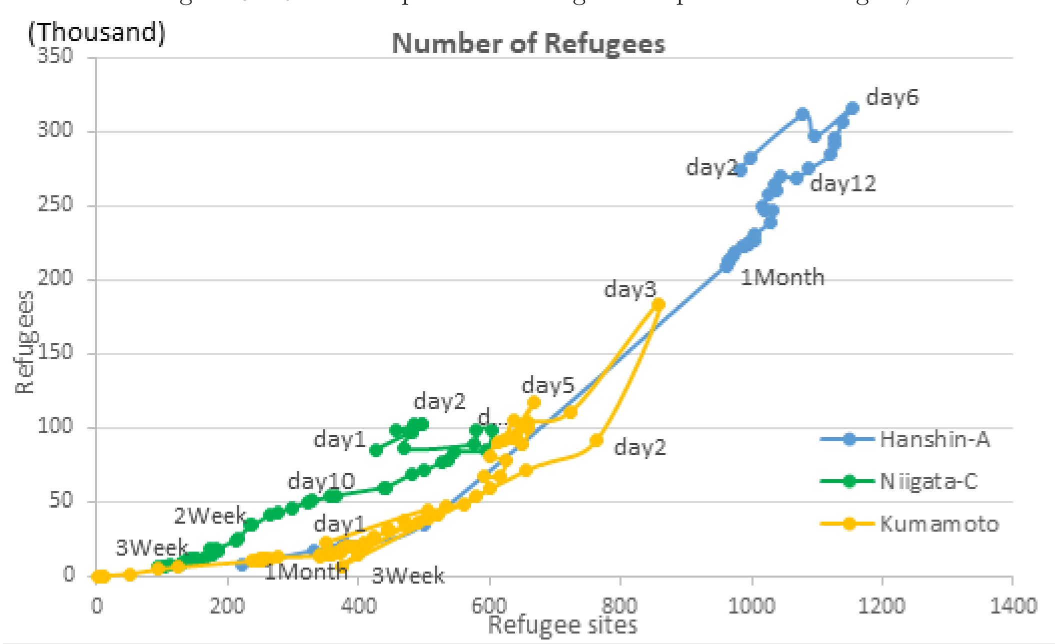

Figure 4: Relationship between refugees camp sites and refugees (HNSA, NGTC and KMMT)

camp sites and number of refugees for HNSA, NGTC and KMMT shown in Figure 3, we find that a quadratic function fits best as shown in Figure 5 below, whose mathematical formula is given as follows.

$$y = 1.989x^2 \tag{1}$$

where y : number of refugees, x : number of refugee camps.

From the above result we find that the number of refugees increases following a quadratic function with respect to the number of number of refugee camp sites, not linearly. More concretely, we can say that the number of refugees increases following the relation

$$\frac{dy}{dx} = 3.978x \tag{2}$$

Namely, almost 4 times with respect to the number of refugee camps. Thus, we can conclude that the more refugee camps, the more refugees increases following four times the number of refugee camp sites.

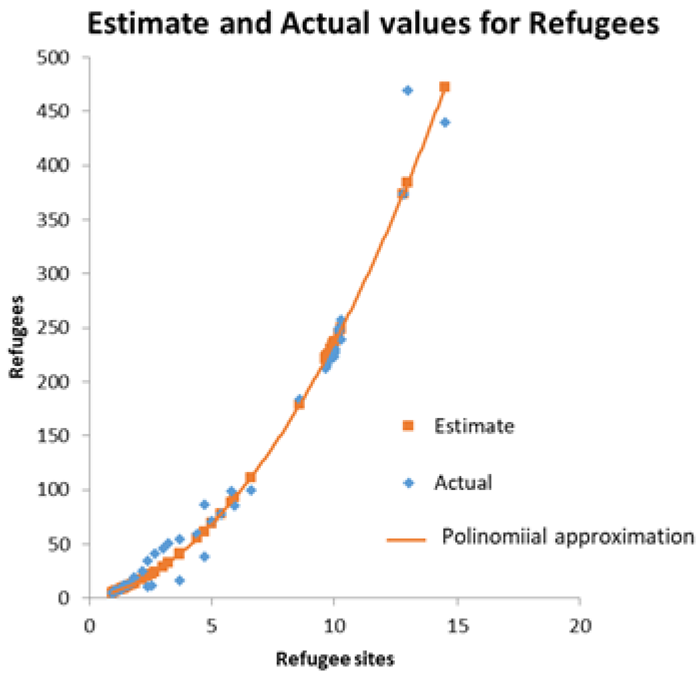

Figure 5: Approximate quadratic function for the relationship between number of refugees camps and number of refugees

3 Suspension and recovery of social infrastructures

Table 1 indicates the suspended households for various public utilities such as electricity, gas, water supply and communication lines, and necessary days for recovery for those public utilities in Kobe city for the HNSA earthquake which occurred in 1995. We find that electricity recovers quickest in only 6 days while gas and water supply take almost 3 months, and communication line in 2 weeks. These trends hold almost similarly to any natural disasters cases. This means it will be more effective if we could shorten the recovering period for gas and water supply even a few weeks. In addition we also know that their recovering trend curves are different by public utilities. Namely, cases for electricity and water supply show convex form while gas and communication lines show rather concave form, among these gas sometimes shows convex-to-concave (first convex, then concave afterwards). This means we need to think about these properties when we try to develop certain natural disaster mitigation policy.

Table 1: Suspended households for various public utilities, and necessary days for recovery for public utilities

Public utility	Suspension	Days for recovery
Electricity	2,600 HH	6
Gas	855.9 HH	84
Water supply	495.3 HH	90
Communication line	101.66 LN	14

HH : Households (Unit : 1,000), LN : (Unit : Lines)

Table A3 indicates the recovering trend for public utilities in the HNSA. In this Table A3 Cities and Towns mean number of those in which the water supply was disrupted. Figure 6 indicate the curve for the recovering trend of electricity corresponding to the data shown in Table A3. Approximating the actual data shown by the red points, we obtain the function form as follows, whose approximating curve is given by dotted line in Figure 6.

$$y = 2.589x^{(-2.726)} \tag{3}$$

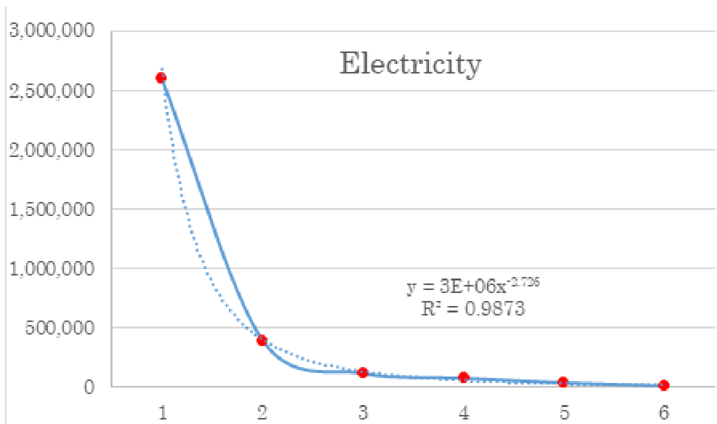

Figure 6: Recovering trend of electricity in the HNSA with its approximation curve

Figure 7 shows the trend of the number of households with disrupted water supply for the HNSA in which almost 1.3 million households were disrupted their water supply. From

Figure 7 we find that during the first one month recovering speed was very fast while it took almost two to three months after the incident until all households could get the water supply.

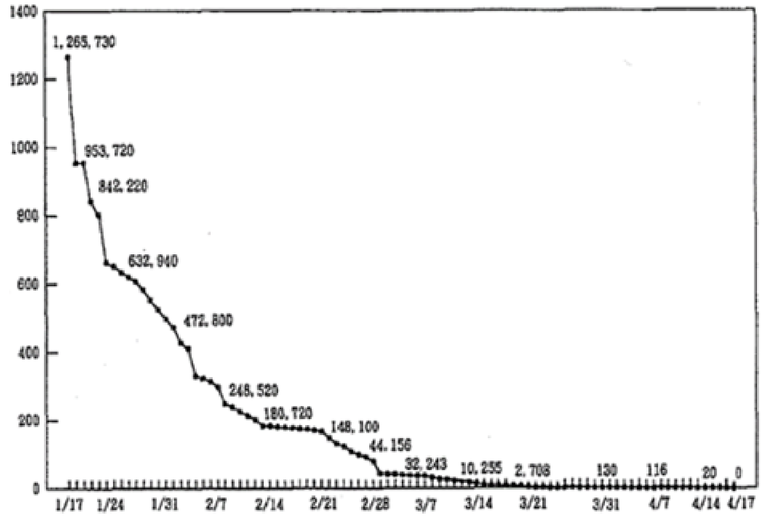

Figure 7: Trend of the number of households with disrupted water supply for the HNSA

In HNSA earthquake number of households for which water supply was cut off just after the incident amounted to 1.265,730 in 10 cities and 7 towns. This corresponds to almost 90% of the total number of households in those areas, moreover in 5 cities and 4 towns. However, their recovery has been very quick: 1 town had the water supply on the day of incident; 1 city and 1 town next day; 2 cities and 4 towns in a week. After a week, percentage of households with suspended water supply became 45.1%, almost half of the total on the first incident day. Furthermore, after two weeks, it became 3.2%, which means almost all households were provided with water supply. In the whole Hyogo prefecture the percentage of households with suspended water supply was 33.7%. Using those statistical data for households with suspended water supply, we show various types of mathematical models expressing their data, relationships and proceeding processes.

4 Measuring robustness of the water supply system

We aim at measuring the robustness of the water supply network system by applying network flow optimization techniques, investigating the emergent situations, and obtaining efficient countermeasures strategy for the risk management of the water supply system in Tokyo. We have applied our approach to measure the robustness of the water supply network system in Tokyo (refer to Ashida, et al. [1], Fithriyah, et al. [2]).

The network flow optimization approach used in this study is mathematically called multi-source multi-sink maximum flow model, wherein sources correspond to water intake sites, while sinks are demand sites. We formulate the network flow optimization problem maximizing the total flow, under the conditions that each source node corresponding to water intake site has upper bound, each edge corresponding to the water pipeline has capacity, and each sink node has an upper bound of its each water demand. We solve the network flow optimization problem for each case such that several edges are "broken" randomly, thus arbitrary number of edges are "disrupted", thus try to measure quantitatively, indicating how much of the total demand can be met.

Given an undirected network $G = (V, E)$ consisting of the node set V and edge set E with $|V| =$ n and $|E| =$ m, respectively, we assume each edge $(i, j) \in E$, $i, j \in V$, has its capacity u_{ij}. We partitioned the node set V into three subsets, denoted by source (S), intermediate (R), and sink set (T) sets, respectively, thus $V = S \cup R \cup T$. The network $G = (V, E)$ is illustrated in Figure 8.

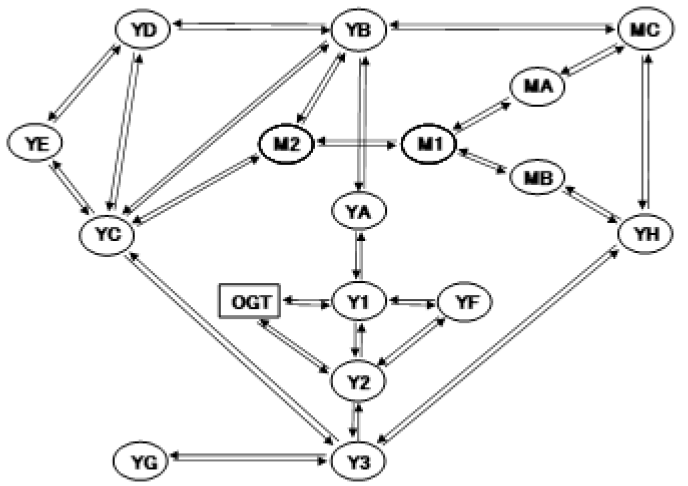

Figure 8: Water supply network

The mathematical formulation of this network flow optimization model can be given as follows.

$$\text{minimize} \quad Z = \textstyle\sum_{i \in T} (\sum_j x_{ji} - \sum_j x_{ij})$$

$$\text{subject to} \quad \geq -s_i \quad i \in S$$

$$\textstyle\sum_j x_{ji} - \sum_j x_{ij} = 0 \quad i \in R, \tag{4}$$

$$\leq t_i \quad i \in T$$

$$0 \leq x_{ij} x_{ji} \leq A_{ij} u_{ij}, \quad (i, j) \in E$$

Each x_{ij} is the decision variable designating the flow passing through each edge (i, j) from node i to j. The volume t_j indicates the "demand of water" at each sink node j, whilst the flow from each source node indicated by s_i, respectively. The objective function of this model is to maximize the amount of total flow running into sink nodes. Assuming that each edge in the network may be broken with equal probability, we measure the reliability of the network system by computing the maximum flow of this network. In the formulation, we include random variables $A_{ij} : (i, j) \in E$, with each takes the value of 0 or 1, corresponding to the case that each edge (i, j) is "broken" or "unbroken" (alive). The capital letter Z is used here to denote the stochastic maximum flow value, since the realized maximum value of (1) naturally becomes a random variable, because it depends on the random capacity $A_{ij}u_{ij}$. Moreover, since we assume each edge is "broken" independently, and the maximum flow of (4) including the mean value of Z under the condition that the random variables A_{ij} is satisfying $\sum A_{ij}$ = m − k, corresponding as the condition that k edges out of m edges are randomly broken, then the conditional distribution function can be defined by

$$F_k(z) = P\{Z \leq z | \sum A_{ij} = m\text{–}k\}. \tag{5}$$

which provides the ratios of the networks which maximum flow value is less than or equal to z to all the $\binom{m}{k}$ networks obtained by deleting k edges randomly from the original network. Thus, the conditional expected maximum flow of this network can be defined as:

$$z_k = E\big[Z | \sum A_{ij} = m\text{–}k\big] \tag{6}$$

As a result, the coverage rate or reliability of this network can be computed as the degree of satisfying the total demand as follows:

$$r_k = \frac{z_k}{\sum_{i\in T} t_i} \tag{7}$$

Therefore, the maximum and minimum of coverage rate (CR) are:

$$max \quad r_k = \frac{max \quad z_k}{\sum_{i\in T} t_i} \tag{8}$$

$$min \quad r_k = \frac{min \quad z_k}{\sum_{i\in T} t_i}, \tag{9}$$

respectively. It is practically impossible to find r_k by computing Z for all $\binom{m}{k}$ cases; instead we consider estimating z_k approximately. Therefore, in order to estimate the approximation of the coverage rate r_k iteratively with respect to k (ranging from 0 to m), we apply Monte Carlo method. Given the conditional distribution function defined by: $F_k(z) = PZ \leq z | \sum A_{ij} = m\text{–}k$, the conditional expected maximum flow of this network defined as: $z_k = E[Z | \sum A_{ij} = m\text{–}k]$, and the reliability of this network computed by: $r_k = \frac{z_k}{\sum_{i\in T} t_i}$, thus this research is conducted in three steps (iterating the following steps 10,000 times):

Step 1. Determining the set of k "broken" edges out of m edges obtaining a network

$G_k = (V_k, E_k)$.

Step 2. Solving the network flow optimization problem for the $G_k = (V_k, E_k)$.

Step 3. Calculating the coverage rate (r_k).

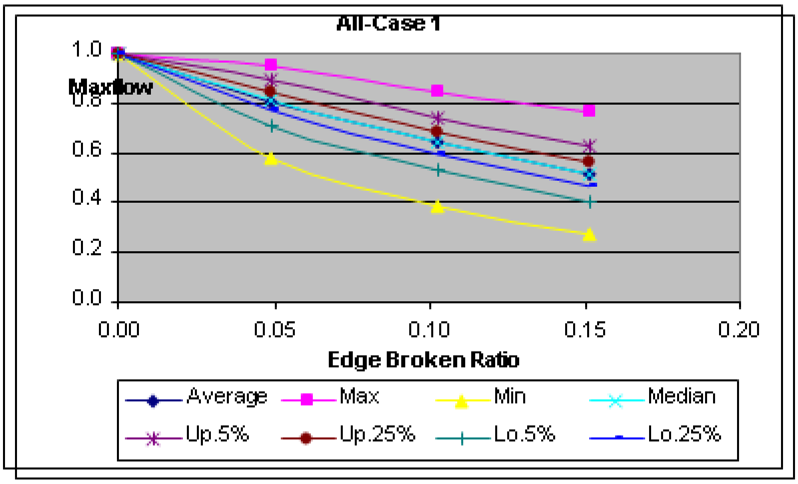

Figure 9: Illustration for the numerical results.

We solve the above network flow optimization problem for each k, ranging from 0 to m, thus obtain the estimation of r_k . Figure 9 below illustrate the numerical results following the computational procedure described above. In Figure 9 horizontal coordinate indicates the edge deletion ratio given by the percentage of the broken edges in the network while the vertical coordinate shows the maximum flow ratio given by the ratio to the maximum flow value corresponding to the original network in which no edge is broken yet. Figure 9 also includes more flow value data such as maximum, minimum, average, median, 5% and 25%, respectively, upper and lower from the average.

5 Summary and conclusion

In the last four decades, based on the International Disaster Database (EM-DAT), between 1970-1979 and 2000-2012, the number of natural disaster events reported globally increased significantly from 837 to 4,939 or increased almost six times. Over the whole period of 1970-2012, 40.8% of these natural disasters occurred in Asia. Japan has been experiencing many serious natural disasters causing huge damages. Based upon the statistical data analyses regarding those four major earthquakes recently occurred in Japan, we have applied mathematical modeling techniques to investigate disaster damages and recovery processes. Refugees and refugee camps analyses would be useful to review and evaluate the declining trend of refugees and refugee camps. Also public utilities recovering trend could be checked and also improved by investigating more details comparing with their mathematical models recovering process we have proposed.

We have proposed a mathematical modeling technique for quantitatively measuring the robustness of the water supply network system. Our approach is based upon the network flow optimization model and Monte Carlo random generation technique. We have illustrated numerical results obtained from our numerical experiments.

Finally, we believe these approaches would contribute for us to derive effective mitigation policies for preparing natural disasters in Japan.

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Appendix

Table A1. Number of refugee camp sites

Period	HNSA	NGTC	GEJE	KMMT
	1995/1/17	2004/10/23	2011/3/11	2016/4/14
0 D				352
1 D		427		505
				399
				375
2 D	984	482	1,280	655
		481		763
		458		
3 D	998	486	1,300	859
		497		723
		498		
4 D	1,079	470	1,450	638
		576		632
5 D	1,097	579	2,150	667
		603		641
6 D	1,153	594	2,150	660
		547		623
1 W	1,138	536	2,182	658
		527		650
8 D	1,127	501	2,200	614
		482		602
9 D	1,127	442	2,100	625
		439		615
10 D	1,120	367	2,100	591
		356		600
11 D	1,088	324	1,800	581
		328		561
12 D	1,068	299	1,850	534
		277		521
13 D	1,045	265	1,900	506
				492
2 W	1,035	239	1,935	469
		234		474
15 D	1,037	217	2,080	444
		214		444
16 D	1,027	184	2,050	424

Period	HNSA	NGTC	GEJE	KMMT
		175		423
17 D	1,018	187	2,050	409
		186		412
18 D	1,019	176	2,050	396
		176		391
19 D	1,033	163	2,050	383
		163		380
20 D	1,029	153	2,250	376
		152		375
3 W	1,003	146	2,214	369
				371
22 D	1,003	142	2,300	359
				360
23 D	996	140	2,250	356
				355
24 D	995	136	2,350	342
				342
25 D	989	136	2,400	276
				265
26 D	987	132	2,350	258
				257
27 D	975	128	2,350	251
				252
28 D	970	112	2,300	253
				251
29 D	964	104	2,380	244
				244
30 D	966	102	2,350	243
1 M	961	94	2,344	238
2 M	789	0	2,417	124
3 M	639		1,459	93
4 M	500		536	50
5 M	379		334	13
6 M	332		112	9
7 M	222		73	1

Table A2. Number of refugees

Period	HNSA	NGTC	GEJE	KMMT
	1995/1/17	2004/10/23	2011/3/11	2016/4/14
0 D			20.499	23.233
1 D		85.667	250	44.449
				15.176
				7.262
2 D	274.78	97.798	374	70.911
		97.71		91.763
		98.087		
3 D	282.756	101.958	470	183.882
		103.172		110.816
		103.178		
4 D	311.476	86.182	440	104.9
		89.244		93.874
5 D	297.313	98.345	435	116.861
		99.111		95.052
6 D	316.678	85.067	385	103.38
		84.063		92.314
1 W	307.022	77.662	386.739	99.868
		76.615		89.513
8 D	291.147	71.407	365	90.97
		68.847		81.006
9 D	295.696	59.668	350	78.228
		59.634		67.136
10 D	284.575	54.427	322	67.788
		53.458		59.912
11 D	274.999	50.351	265	53.457
		50.819		48.238
12 D	268.874	46.37	258	47.032
		43.193		41.119
13 D	270.686	41.68	245	39.702
				36.866
2 W	264.141	34.75	246.19	38.196
		34.741		33.6
15 D	260.698	25.51	245	31.735
		24.56		30.629
16 D	257.512	18.919	243	26.567
		18.292		25.894
17 D	250.067	17.401	180	23.246

Period	HNSA	NGTC	GEJE	KMMT
		17.101		22.078
18 D	246.557	14.873	170	20.557
		14.873		20.002
19 D	246.871	12.551	170	19.81
		12.551		19.509
20 D	239.271	12.147	170	18.762
		12.143		18.017
3 W	230.651	11.973	167.919	16.699
				16.357
22 D	227.56	11.833	165	15.693
				15.158
23 D	226.122	11.188	165	14.775
				14.33
24 D	223.919	11.071	165	14.77
				13.883
25 D	222.564	10.663	160	12.836
				11.99
26 D	222.528	9.31	160	12.523
				12.009
27 D	218.724	7.903	155	11.886
				11.676
28 D	215.745	7.313	155	11.239
				10.703
29 D	213.379	7.1	150	10.843
				10.477
30 D	212.515	6.849	150	10.606
1 M	209.828	6.57	147.536	10.312
2 M				6.211
3 M				4.592
4 M	35.28		58.922	1.714
5 M	22.937		42.744	0.471
6 M	17.569		27.531	0.164
7 M	8.491		21.899	0.003

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				257
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1 M	961	94	2,344	238
2 M	789	0	2,417	124
3 M	639		1,459	93
4 M	500		536	50
5 M	379		334	13
6 M	332		112	9
7 M	222		73	1

Table A3. Recovering trend for public utilities in the HNSA

Date	Day No.	Cities & Towns	Gas (1000)	Electricity	Telephone line	Date	Day No.	Cities Towns	Gas
1995/1/17				2,600,000	101,660	1995/3/20	61	3,520	
1995/1/18				400,000	101,660	1995/3/21	62	2,600	
1995/1/19	1	495,300		120,000	101,660	1995/3/22	63	1,300	
1995/1/20	2	456,300	849.5	80,000	101,660	1995/3/23	64	650	
1995/1/21	3	393,250		40,000	101,660	1995/3/24	65	650	40.95
1995/1/22	4	384,800		15,000	101,660	1995/3/25	66	650	
1995/1/23	5	373,100	855.9	0	92,160	1995/3/26	67	650	
1995/1/24	6	367,250			92,160	1995/3/27	68	650	
1995/1/25	7	359,450			81,160	1995/3/28	69	650	
1995/1/26	8	347,100			81,160	1995/3/29	70	130	
1995/1/27	9	338,650	834.1		61,660	1995/3/30	71	130	
1995/1/28	10	321,100			48,660	1995/3/31	72	130	20.25
1995/1/29	11	302,900			31,660	1995/4/1	73	130	
1995/1/30	12	286,650			15,660	1995/4/2	74	130	
1995/1/31	13	267,800			0	1995/4/3	75	130	
1995/2/1	14	253,500				1995/4/4	76	130	
1995/2/2	15	245,700				1995/4/5	77	130	
1995/2/3	16	239,200	737.8			1995/4/6	78	130	
1995/2/4	17	232,700				1995/4/7	79		
1995/2/5	18	216,450				1995/4/8	80		
1995/2/6	19	200,850				1995/4/9	81		
1995/2/7	20	193,050				1995/4/10	82		
1995/2/8	21	182,000				1995/4/11	83		
1995/2/9	22	168,350	644.8			1995/4/12	84		
1995/2/10	23	157,300				1995/4/13	85		
1995/2/11	24	141,500				1995/4/14	86		
1995/2/12	25	141,500				1995/4/15	87		
1995/2/13	26	141,400				1995/4/16	88		
1995/2/14	27	139,100				1995/4/17	89		
1995/2/15	28	139,100				1995/4/18	90		
1995/2/16	29	139,100				1995/4/19	91		

Date	Day No.	Cities & Towns	Gas (1000)	Electricity	Telephone line	Date	Day No.	Cities Towns	Gas
1995/2/17	30	138,450	529.9			1995/4/20	92		
1995/2/18	31	135,850				1995/4/21	93		
1995/2/19	32	132,600				1995/4/22	94		
1995/2/20	33	122,850				1995/4/23	95		
1995/2/21	34	106,600				1995/4/24	96		
1995/2/22	35	98,150				1995/4/25	97		
1995/2/23	36	92,300				1995/4/26	98		
1995/2/24	37	83,200	415.1			1995/4/27	99		
1995/2/25	38	77,350				1995/4/28	100		
1995/2/26	39	70,200				1995/4/29	101		
1995/2/27	40	55,250				1995/4/30	102		
1995/2/28	41	55,250				1995/5/1	103		
1995/3/1	42	55,250				1995/5/2	104		
1995/3/2	43	55,250				1995/5/3	105		
1995/3/3	44	55,250	203.1			1995/5/4	106		
1995/3/4	45	55,250				1995/5/5	107		
1995/3/5	46	55,250				1995/5/6	108		
1995/3/6	47	35,750				1995/5/7	109		
1995/3/7	48	35,750				1995/5/8			
1995/3/8	49	35,750				1995/5/9			
1995/3/9	50	23,350				1995/5/10			
1995/3/10	51	21,450				1995/5/11			
1995/3/11	52	20,800				1995/5/12			
1995/3/12	53	18,550				1995/5/13			
1995/3/13	54	13,000				1995/5/14			
1995/3/14	55	10,400				1995/5/15			
1995/3/15	56	8,450				1995/5/16			
1995/3/16	57	7,800				1995/5/17			
1995/3/17	58	7,800	73.359			1995/5/18			