Cluster Analysis to Extract Municipal Road Recovery Features in the Tohoku Region Following the 2011 Tohoku Earthquake

Jieling Wu, Noriaki Endo, *Member, IAENG,* and Mitsugu Saito

***Abstract*—The Tohoku Earthquake of March 11, 2011, and tsunami triggered by it caused severe damage throughout the northeastern coast of Japan. The transport network in the Tohoku region was severely damaged by this disaster. A huge earthquake and tsunami are predicted to occur in the Nankai Trough in the future. Furthermore, the three prefectures (Fukushima, Miyagi, and Iwate prefectures) on the Pacific side of the Tohoku region, are relatively similar to the three prefectures (Shizuoka, Aichi, and Mie prefectures) in the Tokai region in terms of the topographical environment. We think that the recovery of regional roads in the three prefectures affected by the Tohoku Earthquake can be studied to help promote the rapid recovery of the three prefectures in the Tokai region after a possible Nankai Trough earthquake in the future. In this study, we applied cluster analysis to examine the driving data in the Tohoku region to classify the road recovery condition among municipalities in the first six months after the disaster. For the cluster results, we examined them using an analysis of variance (ANOVA) and visualized insights into road recovery characteristics through a geographic information system (GIS). Furthermore, our analysis of objective data reflecting regional characteristics showed that the road recovery conditions are similar from the viewpoints of topography, the importance of the road, snow, population density, damage, and geographical location.**

***Index Terms*—2011 Tohoku Earthquake; analysis of variance (ANOVA); big data analysis; cluster analysis; geographic information system (GIS); Pearson correlation analysis; probe-car telematics data; SPSS; the Nankai Trough earthquake; the Tohoku Region; vehicle-tracking map**

I. Introduction

THE Tohoku Earthquake of March 11, 2011 and the tsunami triggered by it had devastating effects throughout the northeastern coast of Japan [1]. The transport network in eastern Japan was severely damaged by this disaster. In the Tohoku region, main roads and railways ceased to function for a long period of time, and the lives of the people in these areas drastically altered.

From the day after the disaster, the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) carried out road clearance (Operation "Teeth of a Comb") [2] [Fig.1] to open up as many routes as possible for vehicles to pass. This operation involved road clearance to secure rescue and relief routes on many national highways, extending from inland areas toward the Pacific coastal area of Tohoku. The main routes in the Tohoku region were restored in the first week after the serious earthquake at a speed that surprised the whole world. Studying the road recovery in the Tohoku region will provide a reference for road recovery in the event of future earthquakes and tsunamis in other areas.

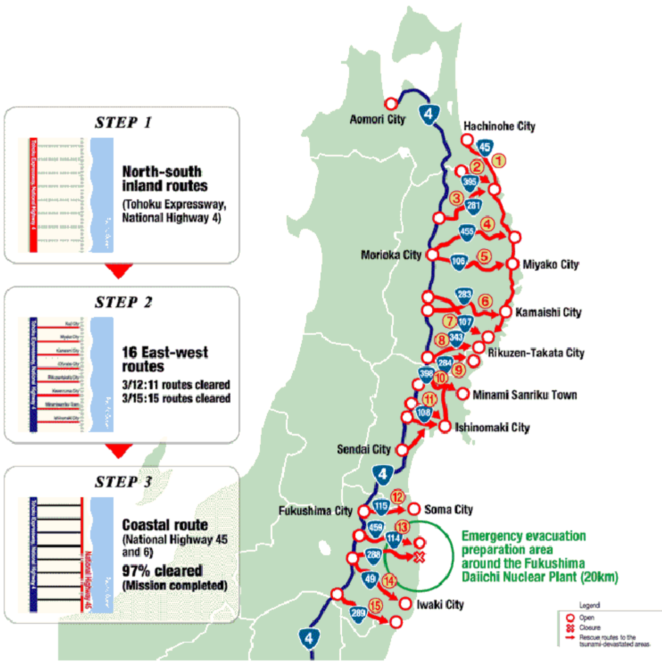

Fig. 1. The routes of "road clearance" (Operation "Teeth of a Comb")

A huge earthquake and tsunami are predicted to occur in the Nankai Trough in Japan by 2050 with a probability of 70%–80% [3]. This disaster is predicted to cause significant damage, and hence, it is essential that measures are taken in advance. The three prefectures (Fukushima, Miyagi, and Iwate prefectures) on the Pacific side of the Tohoku region are relatively similar to the three prefectures (Shizuoka, Aichi, and Mie prefectures) in the Tokai region in terms of their topographical environments (rias coast, sandy coast, plain and mountainous area, etc.). Hence, we think that the knowledge of the recovery of regional roads in the three prefectures affected by the Tohoku Earthquake can be used to help promote the rapid recovery of the three prefectures in the Tokai region in the event of a huge Nankai Trough earthquake in the future.

Concerning post-earthquake road recovery research, many research reports on the recovery of motorways and gen-

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eral national roads after the 2011 Tohoku Earthquake are available [4], [5]. However, few studies examined the road recovery of prefectural and municipal roads that play an important role in the daily lives of residents. In this study, we focused on the local road network, which is one of the most important factors in rescuing victims and supplying them with daily commodities, and surveyed the situation of roads accessible to motor vehicles in the first six months after the disaster and their recovery process in the municipalities of the Tohoku region. The purpose of this study was to understand the situation of local road use from objective data, to find the shared characteristics of local road recovery, and to support disaster mitigation measures according to the recovery conditions.

II. Previous Relevant Studies

In the event of a disaster, the collection and consolidation of road information is a time-consuming process for a various emergency, rescue, and recovery operations. To quickly understand the road conditions after the disaster, a vehicle-tracking map was built by Honda Motor Company, Ltd. after the 2007 Niigata-ken Chuetsu-Oki Earthquake [6]. This system can be used as reference information to support evacuation and rescue operations in disaster areas as based on actual vehicle traffic data, it shows the traffic routes that are accessible to a large number of people after a major disaster. In addition, the G-BOOK telematics data of Toyota Motor Corporation was used to survey roads after the Tohoku Earthquake [7].

In previous studies [8], [9], [10], [11], [12], [13], [14], [15], the vehicle driving data were used to divide a prefecture of the Tohoku region according to local consensus. In addition, studies [14] and [15] compared regions in different prefectures, either coastal or inland, that had reached 90% recovery rates. They had similar recovery dates which illustrate similar rates of recovery between regions. Although these studies have shown that there are differences in road recovery between regions, the number of municipalities varies from region to region, and some have more roads than others. Hence, it is inappropriate to make such comparisons. The broad classification was considered to have affected the result, and the road recovery speed was not the same for municipalities in the same region. Moreover, the similarity of road restoration between regions cannot be seen in terms of similarity at one time alone but should be considered in terms of similarity of the entire restoration process. Therefore, we conceived a study [16], [17], using municipalities with consistent units and finding the road recovery characteristics of fragmented municipalities through cluster analysis.

In our previous study [16], we analyzed the data of vehicles driving in Fukushima and Miyagi prefectures to classify the road recovery conditions among municipalities in the first six months after the disaster. The results of the study are divided into 7 clusters to show that the road recovery conditions are similar according to the geographical location and topographical structure.

In another one of our previous studies [17], the same cluster analysis was performed to analyze the road recovery conditions in Iwate Prefecture, which has a rias coast unlike the coastal conditions of the other studied prefectures. The results of this study are divided into five clusters to show that the road recovery conditions are similar according to damage, recovery policy, the importance of the road, and population density.

The visual results of our previous studies as shown on the map showed that similar road recovery areas in the two studies [16], [17], have different influencing factors; however, we think that road recovery after earthquakes can be expected to differ based on regional characteristics and this can be verified by objective data. The two previous studies did not illustrate how cluster analysis selects the optimal classification. In this study, we hope to analyze the methodology in detail. Furthermore, studying the three prefectures together will help identify regional commonalities, which will be important for regional resource deployment after the disaster. Therefore, it is necessary to study the three prefectures in the Tohoku region following the Tohoku Earthquake to provide a reference for future road recovery in the Tokai region in the event of a Nankai Trough earthquake.

III. Methodology

A. Research area

The research area comprises 152 municipalities in three prefectures (Fukushima, Miyagi, and Iwate prefectures) of the Tohoku region (excluding the municipalities located in the no-go zone in the aftermath of the Fukushima Daiichi Nuclear Power Plant accident).

B. Research materials

In our current study, we used the vehicle-tracking maps built from the G-BOOK telematics data available on the Internet on March 18, 2011, following the 2011 Tohoku Earthquake [18]. The data used in this study were collected between March 18 and September 30, 2011 (i.e., approximately six months following the 2011 Tohoku Earthquake).

C. System

1) Hardware: The computations were performed on a standard PC laptop with a Core i7-6700U CPU (2.6 GHz) and 16 GB memory (Hasee Z7M-SL7D2).

2) Software: The software QGIS version 2.18.20, IBM SPSS Statistics 23, and Microsoft Excel 2019 running on a Windows 10 Professional operating system were used in this study.

D. Data Processing

1) The vehicle-tracking maps constructed from the G-BOOK telematics data were provided in the Google Map KMZ format in a geographical coordinate system. For our analysis, we first converted the KMZ files to SHP files in a rectangular coordinate system.

2) After merging daily data into weekly data and removing duplicate data, we calculated the exact usable road distance available for a given week. In this context, a usable road is one on which at least one vehicle was tracked during the observation period. The daily data were converted to weekly data to smoothen the daily fluctuations in the traffic flows.

3) Next, we calculated the proportion of the cumulative distance up to the specified date. Note that the cumulative distance up to September 30, 2011, was considered 100%.

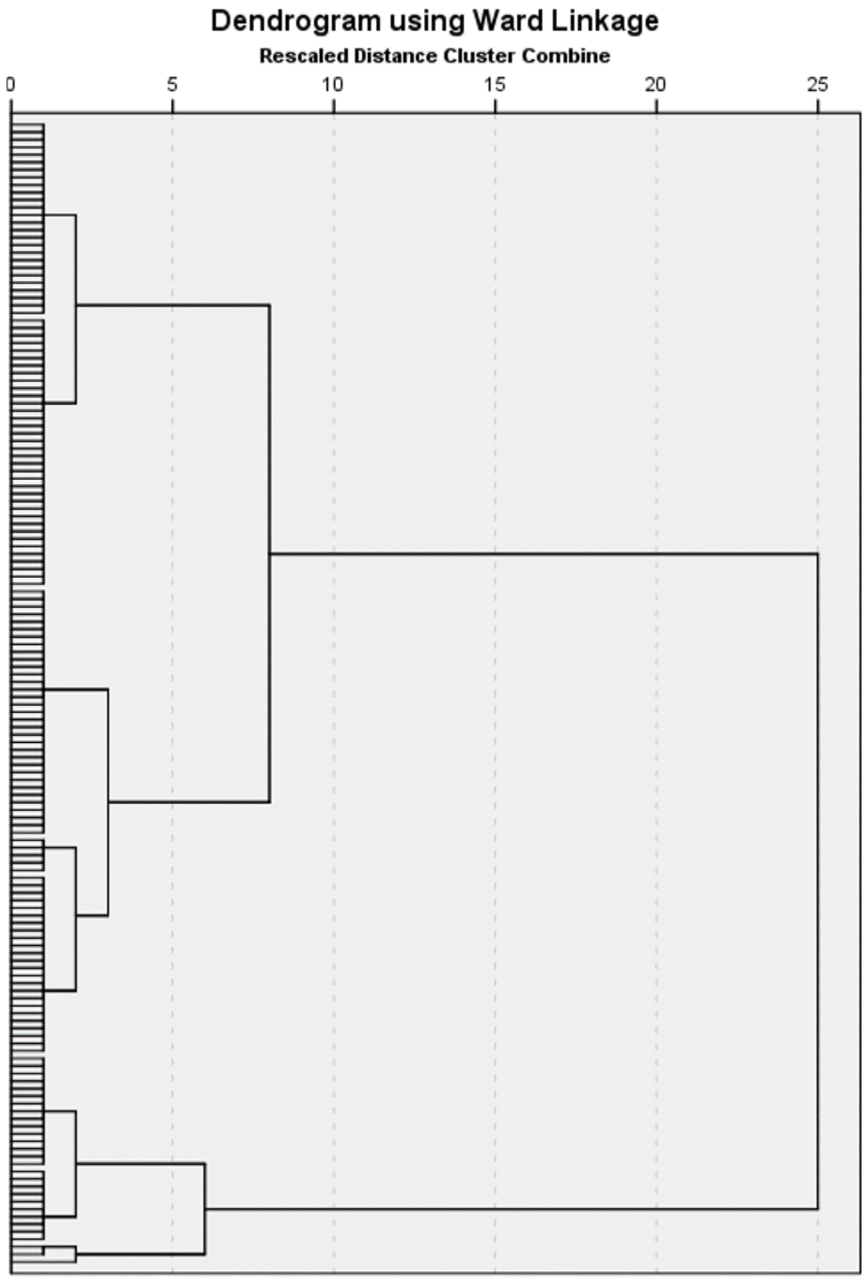

Fig. 2. Classification dendrogram.

4) Using these cumulative distance data, we obtained the percentage of road use recovery in each municipality. We introduced the percentages into SPSS Statistics software and used Ward's method with the Squared Euclidean distance as the measurement interval in hierarchical cluster analysis to produce a classification dendrogram [Fig.2].

IV. Results of the Cluster Analysis

According to the results of the cluster analysis [Fig.2], municipalities with similar road recoveries were divided into 2 to 9 clusters [Table I]. To test the validity of these clusters, we used the Means and analysis of variance (ANOVA) methods to test the differences between the clusters in terms of road recovery. It is well-known that ANOVA is one of the most popular statistical methods to test the differences between groups. If the differences are significant, the classification results can be considered reliable.

First, we used the Means method in the analysis function of SPSS to calculate the mean of each cluster classification. An example of 5-cluster classification is provided in [Table II]. Second, we used the One-Way ANOVA of SPSS to examine the significance of the differences between eight classification results. For example, in the case of 5 clusters [Table III], the difference between groups in each recovery period was less than 0.05. The significance of the differences between groups for eight classifications is summarized in Table IV.

The column of significance shows that all the indicators are significant, except for one, which is greater than 0.05, in 9, 4, and 2 clusters [Table IV]. This table indicates that this classification is relatively valid. No significant differences in this indicator were seen in August. As the date of 100% recovery in the data is set as September 30, the differences between regions become less consequential as

TABLE I
NUMBER OF MUNICIPALITIES IN 2-9 CLUSTERS AFTER CLUSTER ANALYSIS

Cluster	9 clusters	8 clusters	7 clusters	6 clusters	5 clusters	4 clusters	3 clusters	2 clusters
1	36	36	36	62	62	62	62	124
2	33	33	33	33	33	62	62	28
3	26	26	26	25	25	25	28	
4	10	25	25	29	29	3		
5	24	24	29	2	3			
6	15	5	2	1				
7	5	2	1					
8	2	1						
9	1							
Total	152	152	152	152	152	152	152	152

TABLE II
MEAN OF THE CLUSTERS WHEN DIVIDED INTO 5 CLUSTERS

Cluster	N		Mar-3w	Mar-4w	Apr-1w	Apr-2w	Apr-3w	Apr-4w	May	Jun	July	Aug	Sep
1	62	Mean	63.81	82.40	88.53	92.15	94.40	95.99	97.03	98.07	98.76	99.38	100.00
		Std. Deviation	10.36	5.67	4.26	3.37	2.71	2.43	2.17	1.66	1.53	1.10	0.00
2	33	Mean	53.93	68.20	75.41	79.82	83.41	87.54	91.17	94.17	96.46	98.06	100.00
		Std. Deviation	7.51	5.09	5.25	4.78	4.97	4.99	4.24	4.14	3.77	2.99	0.00
3	25	Mean	30.66	49.33	60.92	65.85	72.23	78.38	87.22	92.56	95.13	98.73	100.00
		Std. Deviation	13.26	7.76	8.94	8.83	7.87	8.68	7.50	6.16	6.44	1.27	0.00
4	29	Mean	34.44	68.80	81.88	87.71	90.18	92.02	95.11	97.45	98.56	99.21	100.00
		Std. Deviation	12.86	10.80	7.25	4.03	3.70	3.75	3.19	2.20	1.56	0.99	0.00
5	3	Mean	1.42	5.78	29.22	32.81	39.10	49.96	68.01	95.54	97.96	98.29	100.00
		Std. Deviation	2.46	6.60	30.39	30.63	34.30	17.42	8.88	5.21	3.54	2.96	0.00
Total	152	Mean	49.38	69.77	78.70	83.13	86.47	89.59	93.21	96.15	97.61	98.93	100.00
		Std. Deviation	18.72	16.34	13.89	13.30	12.04	9.86	6.61	4.11	3.63	1.79	0.00

TABLE III
ANALYSIS OF VARIANCE (ANOVA) OF 5 CLUSTERS

		Sum of Squares	df	Mean Square	F	**Sig.**
Mar-3w	Between Groups	35729.165	4	8932.291	76.286	**.000**
	Within Groups	17212.211	147	117.090		
	Total	52941.377	151			
Mar-4w	Between Groups	32726.416	4	8181.604	158.484	**.000**
	Within Groups	7588.747	147	51.624		
	Total	40315.163	151			
Apr-1w	Between Groups	21883.872	4	5470.968	111.261	**.000**
	Within Groups	7228.355	147	49.172		
	Total	29112.227	151			
Apr-2w	Between Groups	21079.779	4	5269.945	137.712	**.000**
	Within Groups	5625.369	147	38.268		
	Total	26705.148	151			
Apr-3w	Between Groups	16415.318	4	4103.830	110.446	**.000**
	Within Groups	5462.050	147	37.157		
	Total	21877.368	151			
Apr-4w	Between Groups	10706.468	4	2676.617	99.218	**.000**
	Within Groups	3965.640	147	26.977		
	Total	14672.108	151			
May	Between Groups	3950.316	4	987.579	54.683	**.000**
	Within Groups	2654.833	147	18.060		
	Total	6605.149	151			
Jun	Between Groups	730.879	4	182.720	14.779	**.000**
	Within Groups	1817.442	147	12.364		
	Total	2548.321	151			
July	Between Groups	306.103	4	76.526	6.682	**.000**
	Within Groups	1683.479	147	11.452		
	Total	1989.582	151			
Aug	Between Groups	41.597	4	10.399	3.445	**.010**
	Within Groups	443.741	147	3.019		
	Total	485.338	151			
Sep	Between Groups	0.000	4	0.000		
	Within Groups	0.000	147	0.000		
	Total	0.000	151			

the road recovery is prolonged. Nevertheless, compared to 9, 4, and 2 clusters, more significant differences are seen in the case of 8, 7, 6, 5, and 3 clusters. Further, according to the agglomeration coefficient line shown in Fig. 3, there is a large drop in the aggregation coefficient between 1 and 4 clusters, and then, the coefficient starts to plateau at 4 to 5 clusters. When there are 4 or 5 clusters, the distance between the clusters becomes manageable; hence, the most useful number of classifications can be set as 4 or 5 clusters. Between these, the most statistically significant information can be obtained using 5 clusters. Therefore 5 clusters were chosen in this study.

V. Discussion

A. Cluster visualization from GIS

According to the results of the cluster analysis, municipalities with similar road recoveries were divided into 5 clusters. The cluster for each municipality is shown on the map [Fig.4].

The order of the recovery reaching 90%, averaged for each cluster, is $1 > 4 > 2 > 3 > 5$ [Table V, Fig.5].

Consider the order and characteristics of recovery of each cluster:

Cluster 1: The fastest recovery occurred in the major cities in the plains, where there are more main roads, followed by municipalities with fewer roads, which benefited from the ”Teeth of a Comb” recovery policy.

Cluster 4: The second-fastest recovery is mainly concentrated in the coastal lowlands affected by the tsunami and in inland mountains affected by snow; roads recovered gradually after the road closures necessitated by the disaster were lifted.

Cluster 2: The speed of road recovery was intermediate compared to other clusters, and the distribution was similar to that of Cluster 4 but was mainly concentrated on the northern rias coast, which was more severely affected than the region in Cluster 4. In the inland areas, this cluster included municipalities in the plains with many routes that had suffered extensive earthquake damage; the road recovery was slow in municipalities in the mountains were due to snow.

Cluster 3: The slowest recovery was observed for this cluster, mainly in the mountains, minor routes with relatively low population density. The recovery of road use was delayed possibly because of the restriction of traffic until the road closures in urban areas of the prefecture were lifted.

Cluster 5: The slowest recovery was observed in locations with heavy snowfall areas and mountainous locations. Note that in inland Tohoku region, especially in the mountainous areas, roads are closed from the previous winter until June this year because of snow [19].

B. Analysis of factors affecting road recovery

To confirm our hypothesis, we collected data reflecting geographic location, topography, damage, recovery policy, the importance of roads, population density, and snow to examine their relationship with road recovery [Table VI]. A total of 152 municipalities exists, 15 of which are shown here for reference.

The individual factors are described as follows.

Type of municipality: In terms of geographic location, roads in major municipalities were generally prioritized for rehabilitation over other municipalities as seen in Cluster 1. Major municipalities are generally the principal cities and surrounding municipalities, denoted by 1 in the dataset, and other cities are denoted by 2.

Type of terrain: For topography, we classified the type of terrain to which the municipality belongs into four categories, with 1 in the database indicating that more than three-quarters of the terrain is plains, 2 indicating that it is half plains and half mountainous, 3 indicating that three quarters is mountainous, and 4 indicating that it is entirely mountainous.

Measuring seismic intensity: For damage, earthquake seismicity is often used as a criterion for predicting damage [20]. We collected measured seismic intensities from the Japan Meteorological Agency for each municipality in the Tohoku region for the 2011 Tohoku Earthquake [21].

Priority road restoration occupancy: For recovery policy, the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) implemented a road opening policy called ”Teeth of a Comb” [2] on the second day after the Tohoku earthquake, as the Tohoku coast was severely hit by the tsunami. The main roads were National Routes 4 and 45 in the vertical direction and National Routes 395, 281, 455, 106, 283, 107, 343, 284, 398, 108, 115, 459, 114, 288, 49, and 289 in the horizontal direction. We calculated the ratio of road distances to total road distances for each municipality participating in the recovery policy via GIS.

Proportion of important roads: For the importance of roads, we calculated the distances of highways and national roads that were given priority for restoration after the disaster as a percentage of the total distance of roads in the municipality.

Population density: For population density, it can be obtained using census data [22]. Here we used data from 2010, the year before the Tohoku earthquake as a reference.

Roads closed due to snow: For the snow factor, we calculated the closed roads in each municipality from the information on winter closure routes in the Tohoku region [19].

We imported Table VI into SPSS Statistics software and used Pearson correlation analysis to see how these seven factors specifically influenced the recovery of each cluster. From Table VII, all factors are significantly correlated with clusters, except for priority road restoration occupancy whose significance is greater than 0.05. In terms of the absolute value of Pearson’s correlation coefficient, the order of correlation for each factor and cluster is type of terrain, proportion of important roads, roads closed due to snow, population density, seismic intensity, and type of municipality. This shows the relationship between the influences of these six factors on road recovery patterns.

VI. Conclusion

In this study, cluster analysis was applied to find the similarities in road recovery after the earthquake in the municipalities in the Tohoku region. In the research methodology, the classification results obtained after cluster analysis were examined to select the best classification cluster. Moreover, we examined the recovery clusters on a map taking

TABLE IV
SIGNIFICANT DIFFERENCES BETWEEN GROUPS IN THE RECOVERY PERIOD FOR EACH CLASSIFICATION

	9 clusters	8 clusters	7 clusters	6 clusters	5 clusters	4 clusters	3 clusters	2 clusters
Mar-3w	.000	.000	.000	.000	.000	.000	.000	.000
Mar-4w	.000	.000	.000	.000	.000	.000	.000	.000
Apr-1w	.000	.000	.000	.000	.000	.000	.000	.000
Apr-2w	.000	.000	.000	.000	.000	.000	.000	.000
Apr-3w	.000	.000	.000	.000	.000	.000	.000	.000
Apr-4w	.000	.000	.000	.000	.000	.000	.000	.000
May	.000	.000	.000	.000	.000	.000	.000	.000
Jun	.000	.000	.000	.000	.000	.000	.000	.000
July	.001	.001	.000	.000	.000	.000	.000	.000
Aug	.054	**.033**	**.018**	**.012**	**.010**	.082	**.038**	.413
Sep								

Fig. 3. Agglomeration coefficient with the number of clusters.

TABLE V
ROAD RECOVERY PERCENTAGES IN 5 CLUSTERS OF TOHOKU REGION

Cluster	Mar-3w	Mar-4w	Apr-1w	Apr-2w	Apr-3w	Apr-4w	May	Jun	July	Aug	Sep
1	64	82	89	**92**	94	96	97	98	99	99	100
2	54	68	75	80	83	88	**91**	94	96	98	100
3	31	49	61	66	72	78	87	**93**	95	99	100
4	34	69	82	88	**90**	92	95	97	99	99	100
5	1	6	29	33	39	50	68	**96**	98	98	100

TABLE VI
COLLECTION OF ACTUAL DATA AFFECTING ROAD RECOVERY FACTORS

Cluster	Municipality	Type of municipality	Type of terrain	Measuring seismic intensity	Priority road restoration occupancy	Proportion of important roads	Population density	Roads closed due to snow
1	Takizawa-mura	1	1	5.6	0.02	0.04	295	0
1	Sumita-cho	2	3	5.1	0.03	0.08	18	2
2	Ishinomaki-shi	2	2	5.3	0.02	0.03	289	0
2	Osaki-shi	2	3	5.3	0.01	0.04	170	2
3	Iwaizumi-cho	1	4	4.2	0.04	0.06	11	2
3	Iwate-machi	2	3	4.7	0.02	0.02	42	0
3	Noda-mura	2	3	4.9	0.02	0.02	57	1
3	Tono-shi	2	3	5.3	0.02	0.04	37	4
4	Kawasaki-machi	1	2	6.2	0.00	0.09	37	1
4	Kurihara-shi	2	2	5.38	0.02	0.04	93	3
4	Onagawa-cho	2	3	5.38	0.06	0.06	153	0
4	Ichinoseki-shi	2	2	5.8	0.02	0.05	127	1
5	Kaneyama-machi	2	3	3.3	0.00	0.10	8	4
5	Hinoemata-mura	2	3	3.5	0.00	0.13	2	4
5	Tadami-machi	2	3	3.8	0.00	0.13	7	4

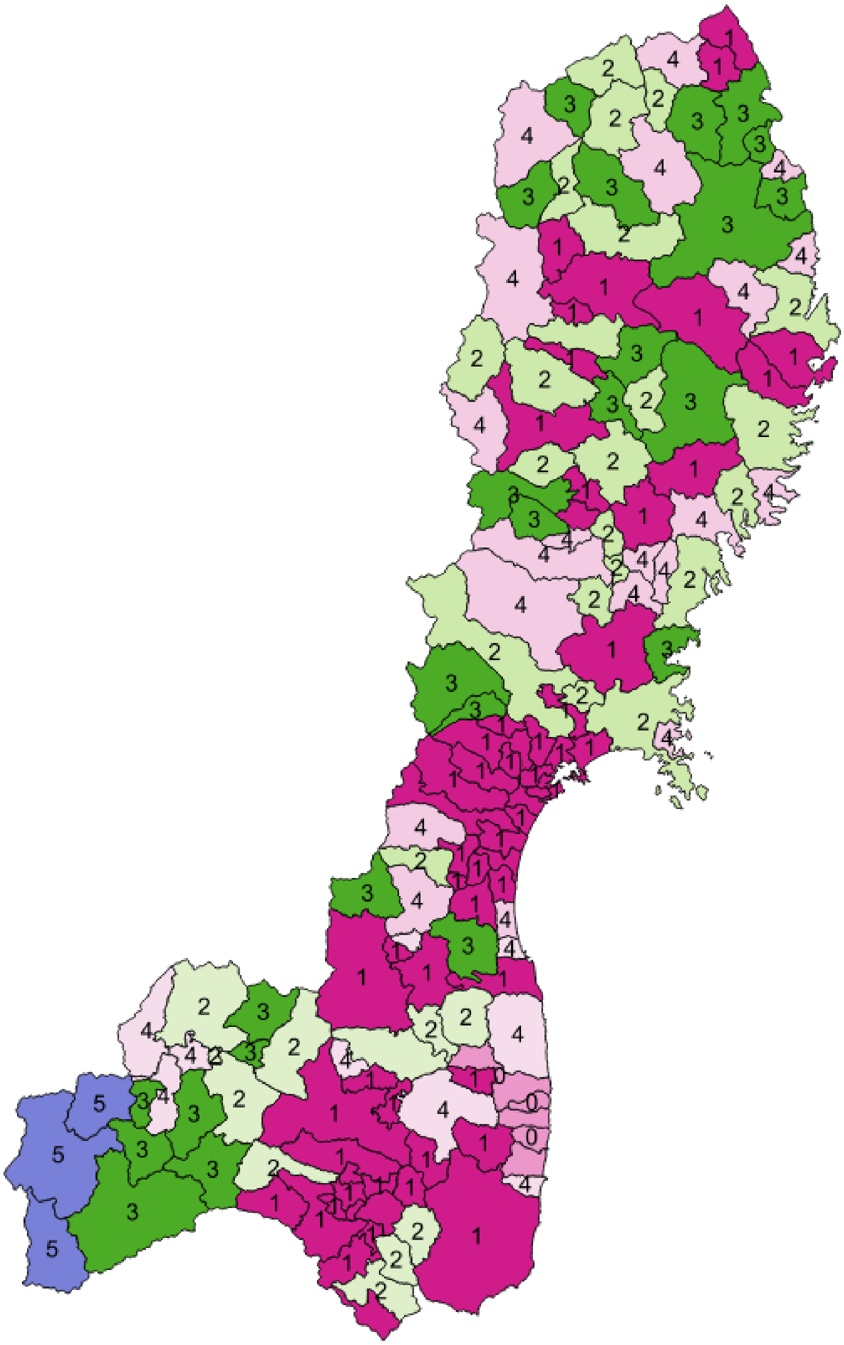

Fig. 4. Each municipality in the Tohoku region belongs to a cluster.

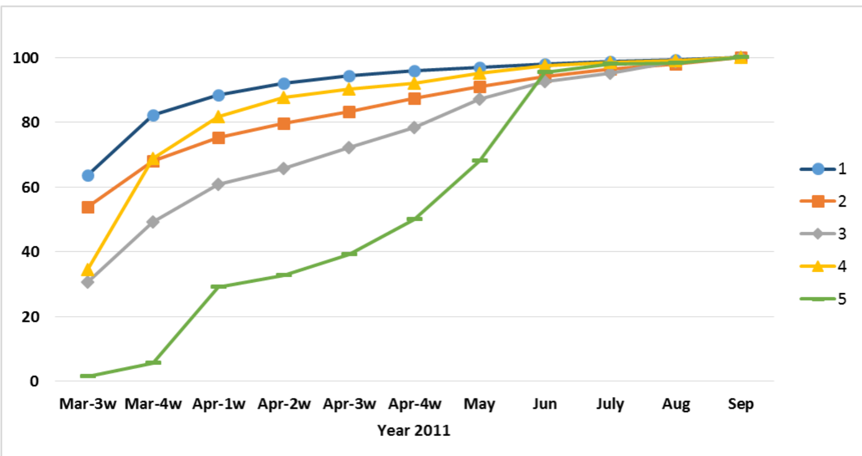

Fig. 5. Road recovery conditions of the five clusters in the Tohoku region.

TABLE VII
CORRELATIONS

		Type of municipality	Type of terrain	Measuring seismic intensity	Priority road restoration occupancy	Proportion of important roads	Population density	Roads closed due to snow
Cluster	Pearson Correlation	.264**	.520**	-.328**	.080	.419**	-.344**	.405**
	Sig.	**.001**	**.000**	**.000**	.326	**.000**	**.000**	**.000**
	N	152	152	152	152	152	152	152

into account their regional characteristics and validating them with objective data. In the Tohoku region, the road recovery conditions were found to be similar depending on topography, the importance of the road, snow, population density, damage, and geographical location.

Analysis of vehicle travel data for the six months following the 2011 Tohoku Earthquake was used to identify regional characteristics and factors affecting road recovery. We observed that six of the seven impact factors thought of by the clusters represented on the map were significantly correlated with the recovery clusters. Surprisingly, we found that the government's recovery policy of prioritization of certain roads did not show a significant correlation with all of the recovery clusters. Some municipalities in Cluster 1 have less road density and no detours that were passable after the earthquake. The only roads in these municipalities that were prioritized for restoration were the roads in municipalities passing through National Route 106. In a future study, we will analyze and quantify various influencing factors for each pattern of road recovery in more detail. By using the database, we will develop a new forecasting model that can be applied to other regions via a geographic information system-based mapping of the regional characteristics and road recovery in the Tokai region (Shizuoka, Aichi, and Mie prefectures) where a future Nankai Trough earthquake and resulting tsunami are expected to cause significant damage. We hope that this model can be applied to other regions.

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