A METHOD TO DETERMINE SEISMIC PERFORMANCE OF HIGHWAY NETWORK SYSTEM

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SUMMARY

Highway networks play an important roll immediately after an earthquake as transportation backbone. To secure the earthquake standing highways, it has been intended to improve individual facilities in the networks through aseismic design and retrofit. However, the functionality of the highway must be improved as a network system which is constructed from many facilities having effects to the overall network performance [1].

This paper aims to propose a method and indexes to evaluate the seismic performance of the highway network for emergency disaster prevention activities immediately after an earthquake. The index introduced here is *SP*, seismic performance of the network system, which is calculated based on supposed damage patterns of the network. By referring *SP*, planners can quantitatively understand the functionality of highway network for emergency activities such as rescue and fire fighting. In addition, importance level of each link and the efficiency of earthquake countermeasures including the retrofit patterns and the traffic control patterns can be evaluated quantitatively by using *SP*. The method here is distinct from preceding researches as it is taking the effect of background traffic to the disaster prevention activities into account [2]. Thus the index do not only represent the topological performance of the highway network but also include the effect of the traffic congestion.

To investigate the adequacy of the proposed indexes, they are calculated for a simple model network. By assuming the damage of the links and the traffic control pattern, *SP*s are calculated. Through the test, it was concluded that they do not have conflicts with the intuitive consequence, and it can be applied to more complicated actual networks. Also, it was clarified that they are useful to plan the structural/ nonstructural earthquake countermeasure for the highway networks.

INTRODUCTION

To secure the functionality of highway networks, two types of countermeasures are considered, that is, the pre-earthquake structural measures such as retrofitting and the post-earthquake nonstructural measures such as traffic control. Usually, those earthquake countermeasures are performed individually: e.g., the improvement of the facilities on the portions of the network. However, planners and decision makers are required to compare, select and combine those programs efficiently so that the highway systems provide sufficient functionality immediately after the earthquake. To do so, they must evaluate the performance and the risk of the highway system against the earthquake quantitatively [4].

This paper introduces the method to calculate the seismic performance index of highway network: *SP*. It is calculated based on the topological network data, supposed link damage patterns and other data regarding the traffic source. By referring *SP*, the planners and the decision makers can evaluate the seismic risk and performance of the highway network system and examine the alternative counter-earthquake programs quantitatively.

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To be utilized at the actual highway administrative occasions, the method consists of general techniques including traffic assignments. The models and the procedure are described in the section two. The simple case study to check the validity of the method is shown in the section three. To illustrate the utility of the method to actual planning, quantitative comparison of structural and non-structural aseismic countermeasure by using *SP* is explained in the section four.

SEISMIC PERFORMANCE INDEX OF HIGHWAY NETWORK

Fundamentals:

Instead of several preceding researches in which the economic loss is calculated caused by the damage on highway network [2][3], the effect to the emergency activities such as rescue and fire fighting immediately after the earthquake is considered in this research. The seismic performance index, *SP*, is determined based on the travel time of emergency traffic from origin zones to destination zones and on the ‘unit degree of efficiency’ defined for respective emergency activity.

$$SP^k = \frac{E_{EM-TOT}{}^k}{T_{EM-TOT}{}^k} = \frac{\int_0^\infty E^k(t) T_{EM}{}^k(t)dt}{\int_0^\infty T_{EM}{}^k(t)dt} \tag{1}$$

Where, SP^k: network seismic performance in terms of emergency objective *k*, $E_{EM-TOT}{}^k$: total efficiency of emergency objective *k*, $T_{EM-TOT}{}^k$: total emergency traffic volume of objective *k*, $T_{EM}{}^k(t)$: emergency traffic volume with the travel time *t*, $E^k(t)$: unit efficiency function in terms of travel time *t*. The image is shown on Figure 1.

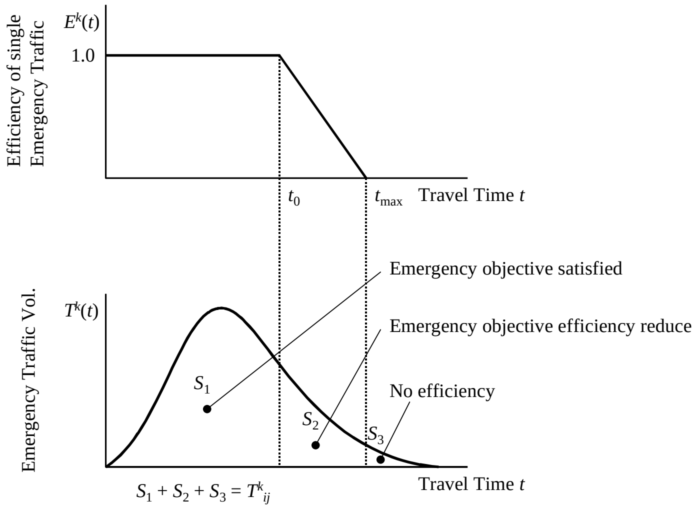


Figure 1: Efficiency Function

Eq. (1) also can be expressed as eq. (2) for the OD (origin-destination) matrix data.

$$SP^k = \frac{\sum_{i,j,r} E^k(t_r) T_{EMijr}{}^k}{\sum_{i,j,r} T_{EMijr}{}^k} \tag{2}$$

Where, *i*, *j*: indicators of origin zone (*i*) and destination zone (*j*), *r*: indicator of route from zone *i* to *j*, t_r: travel time along route *r*, $T_{EMijr}{}^k$: emergency traffic volume (objective *k*) along route *r* from zone *i* to *j*.

Procedure:

The procedure to obtain *SP* given a network damage pattern is shown on Figure 2. Topic is that the travel time (thus *SP*) is effected by the background traffic condition of each link. Therefore this method is capable of taking the traffic congestion caused by such non-emergency activities such as returning to home and evacuation.

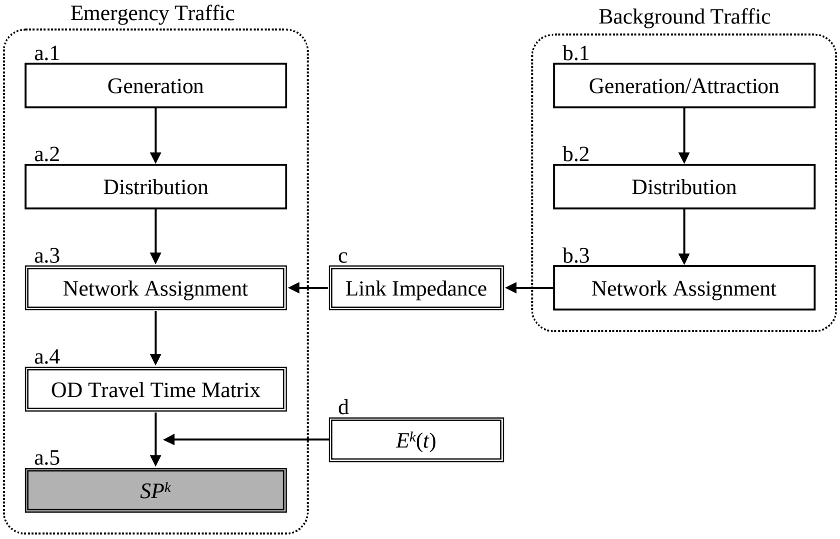


Figure 2: Procedure to Calculate SP

Here, the emergency traffic is assigned to each link in the network by referring the link impedance: i.e., travel time for each link (a.3, c). The link impedance is set by the background traffic assignment (b.1~b.3, c), however, the impedance is not effected by the emergency traffic condition once it is set. Thus the emergency traffic is assigned by simple all-or-nothing method searching the shortest paths under given link inpedance. SP^k is determined by using the travel time OD matrix of the emergency traffic and the efficiency function (d).

Procedures of step a.1 and a.2 require the demand relation matrix exemplified in Table 1. In the table, disaster prevention bases and damaged areas between which the transportation is required are marked as ‘X’. However, its detail varies depending on the emergency activity objective *k*. For the procedures regarding background traffic estimation (b.1~b.3), any traffic analysis methods ranging from general ones to much sophisticated ones can be utilized. Detailed procedures for the case studies are described in the sections three and four.

Table 1: Example of Demand Relation Matrix

	.....	Regional Hospitals	Large Hospitals	Public Health Office	Police Office	Fire Station	.....	Evacuation Area	Damaged Area
⋮				⋮				⋮	
Regional Hospitals	.....	X	X	X		X	.....	X	X
Large Hospitals			X	X		X		X	X
Public Health Office				X		X		X	X
Police Office					X				X
Fire Station						X			X
⋮				⋮				⋮	
Evacuation Area	.....						.....	X	X
Damaged Area									X

SIMPLE CASE STUDY

Model Network Settings:

To verify the validity of the method, a case study was performed for a simple model network of web shape shown as Figure 3. All the zone have equal population as the centroids. Also, each zone has certain number of disaster prevention bases regarding the emergency activity. The total area is assumed as that of average regional core cities. For simplicity, only one kind of emergency objective, the suffers-based type such as first aid activity is considered. Population is distributed equally for each node; thus the population is denser in the central area than the outer area. Disaster prevention bases are distributed in two patterns: namely, concentrated pattern and dispersed pattern (Figure 4). The population pattern is used both for the estimation of the background traffic and the emergency traffic, and the disaster prevention pattern is used for the emergency traffic estimation.

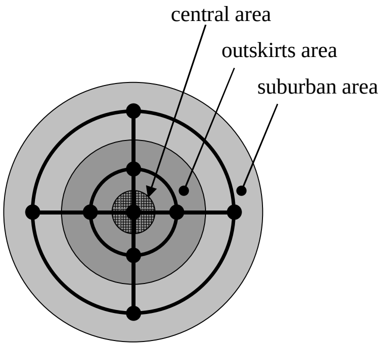


Figure 3: Simple Model Network

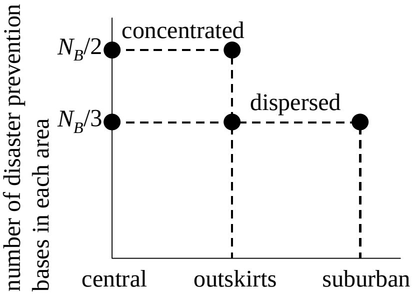


Figure 4: Disaster Prevention Base Distribution Pattern

Background Traffic Assignment

Background traffic assignment is necessary to determine the impedance of each link. In the case study, the control total of the background traffic is determined from the total traffic generation of the certain region. They are distributed in terms of the ratio based on the population in each zone(eq. (3)).

$$T_{BKij} = \frac{\hat{T}_{BKij}}{\sum_{i,j} \hat{T}_{BKij}} \quad , \quad \hat{T}_{BKij} = (N_{Pi})^{\alpha} (N_{Pj})^{\beta} (d_{ij})^{\gamma} \tag{3}$$

Where, T_{BKij}: background traffic volume between zone i and j, N_{pi}: population of zone i, d_{ij}: distance along the shortest route between zone i and j. The background traffic volume is assigned on the network by the heuristic method by assuming user equilibrium. After the background traffic is assigned, the travel time of each link is determined to be used for the emergency traffic assignment.

Emergency Traffic Assignment

The emergency traffic generation is calculated by the unit ratio in terms of population of each zone as eq. (4).

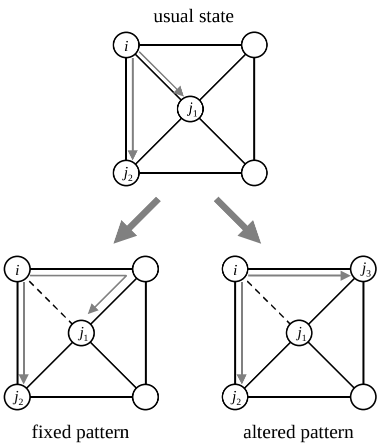
$$G_{EMi} = g_{EM} N_{POPi} \tag{4}$$

Where, G_{EMi}: emergency traffic generation from zone i, g_{EM}: unit coefficient, N_{POPi}: population of zone i. g_{EM} is assumed based on the casualties and the population of Hyogo-ken in the Hyogo-ken Nanbu Earthquake.

The generated traffic is distributed to the limited destination zones. In this case study, the traffic starting from a zone is assumed to choose the nearest and the second nearest zones as the destinations (Figure 5). Here, the two patterns for destination choice are assumed. One is fixed pattern in which the destination choice does not change from the usual network state instead of the link damages. The other is altered pattern in which the destination zone can be changed given the damaged network condition. Those patterns correspond to the situation whether the emergency traffic drivers are given the network state information or not. After the destination zone of each origin zone is determined, the emergency traffic generation is distributed based on the number of the disaster prevention bases at the destination zones and the distance between origin/ destination zones (eq. (5), Figure 6).

$$\begin{gathered} T_{EMij_1} = G_{EMi} \frac{\hat{T}_{EMij_1}}{\hat{T}_{EMij_1} + \hat{T}_{EMij_2}} \quad , \quad T_{EMij_2} = G_{EMi} \frac{\hat{T}_{EMij_2}}{\hat{T}_{EMij_1} + \hat{T}_{EMij_2}} \\ \hat{T}_{EMij_1} = (N_{DPBj_1})^{\beta} (\hat{d}_{ij_1})^{\gamma} \quad , \quad \hat{T}_{EMij_2} = (N_{DPBj_2})^{\beta} (\hat{d}_{ij_2})^{\gamma} \end{gathered} \tag{5}$$

Where, N_{DPBj}: number of disaster prevention base in zone j, d_{ij}: distance along the shortest route between zone i and j. In other words, an emergency traffic is assumed to choose one from the nearest two zones (j_1, j_2), and the ratio between the zones are estimated based on the number of the disaster prevention.



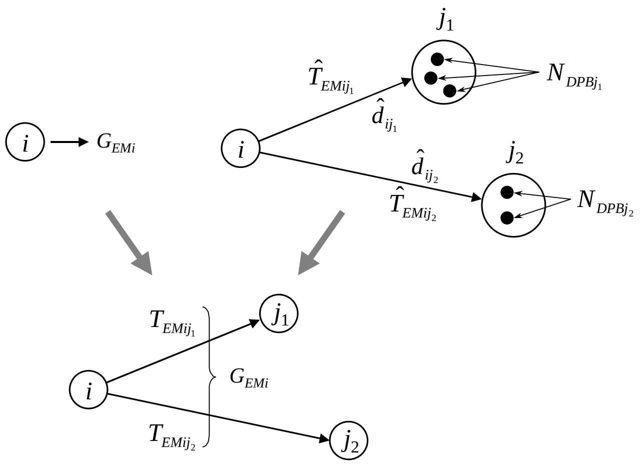


Figure 5: Destination Choice Pattern **Figure 6: Emergency Traffic Distribution**

Once the emergency traffic is distributed for each zone pair, it is assigned on the network by all-or-nothing method in which all the emergency traffic is assigned on the shortest path with the fixed link impedance. Here, the emergency traffic is assumed not to affect the link impedance because it is less in volume than the background traffic.

Seismic Performance and Link Importance

In this case study, *SP*s are calculated and compared for the cases with different combinations of damaged links, destination choice patterns and disaster prevention base distribution patterns. In addition, quantitative importance degree of links are evaluated for several cases. The link importance (*LI*) is defined as the difference of *SP*s, one for the network with damaged links and the other for the same pattern in which one of the damaged link is reconnected supposing it is retrofitted before the earthquake.

$$LI_l = SP - SP_l \tag{6}$$

Where, LI_l: link importance of link l, SP: seismic performance of network with initially supposed damage, SP_l: seismic performance of network in which the state of a damaged link l is changed to not-damaged. Therefore LI_l represents the effect of the link l to SP; that is link importance.

Cases and Results

Variations of the study cases are shown on Table 2 and 3. For the cases regarding *SP*, four links are cut to represent the damage, and damage pattern, disaster prevention distribution pattern and destination choice are altered. For the damage pattern, three types are defined, namely, 'Radial Only', 'Loop Only' and 'Radial & Loop'. By considering the symmetry, there are fourteen patterns of damage for Radial Only case and Loop Only case, and 41 patterns for Radial & Loop case. Variation of disaster prevention base distribution pattern is 'Concentrated' and 'Dispersed', and destination choice patterns are 'Fixed' and 'Altered' as described in 3.1. For the cases regarding *LI*, typical six damage pattern are considered, and each link of damaged four links are reconnected to express the retrofit before the earthquake.

Table 2: Cases for *SP*

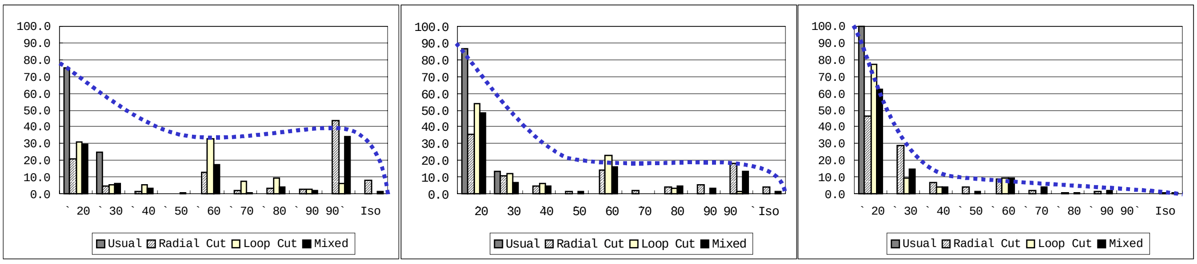
	Concentrated		Dispersed		Total
	Fixed	Altered	Fixed	Altered	
Radial Only	14	14	14	14	56
Loop Only	14	14	14	14	56
Radial & Loop	41	41	41	41	164

Table 3: Cases for *LI*

	Number of Damaged Links			
	Outer Radial	Inner Radial	Outer Loop	Inner Loop
Outer Radial +Inner Radial	2	2		
Outer Loop +Inner Loop			2	2
Outer Radial +Outer Loop	2		2	
Inner Radial +Inner Loop		2		2
Outer Radial +Inner Loop	2			2
Inner Radial +Outer Loop		2	2	

Results

The distribution of the emergency traffic volume by their travel time is shown on Figure 7 for three cases. It can be noted that the travel time is comparatively low for the altered destination case and the dispersed base case.



Fixed Destination/ Concentrated Bases	Altered Destination/ Concentrated Bases	Altered Destination/ Dispersed Bases

Figure 7: Results of Simple Case Study

SP for all the initial simple cases are shown on Figure 8. In contrast to Figure 7, the quantitative comparison between the cases is possible. It is natural that the seismic performance is better for the altered destination than fixed because the emergency traffic can change the destination depending on the damaged network situation. Also, the *SP* is greater for the dispersed base cases than the concentrated cases, and the results do not have conflict with inferred consequences.

As for *LI*, one can investigate the importance of each link under the given damage patterns from the Table 4. For example, *LI* of the outer radial road is 11.97 with the damage on outer loop while it reduces to 6.82 with the damage on inner loop. Thus, the importance of the highway portion changes depending on the damage pattern. Also, the table depicts overall tendency that radial roads are more important than loop roads.

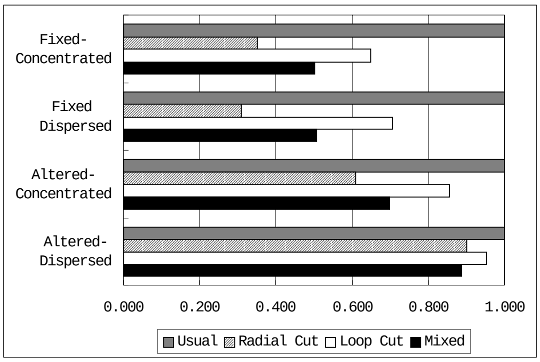


Figure 8: Results of SP

Table 4: Results of *LI*

		Fixed		Altered	
Damage	Retrofitted	Concentrated	Dispersed	Concentrated	Dispersed
Outer Radial + Inner Radial	Outer Radial	9.79	12.01	18.95	4.64
	Inner Radial	28.77	26.32	3.78	4.05
Outer Loop + Inner Loop	Outer Loop	0.62	0.62	0.55	0.00
	Inner Loop	0.00	0.00	0.23	0.00
Outer Radial + Outer Loop	Outer Radial	11.97	13.53	11.89	16.18
	Outer Loop	28.42	32.94	17.50	13.92
Inner Radial + Inner Loop	Inner Radial	13.33	9.67	20.00	4.44
	Inner Loop	22.14	19.34	19.57	4.44
Outer Radial + Inner Loop	Outer Radial	6.82	12.55	18.17	1.05
	Inner Loop	7.64	5.54	2.88	1.09
Inner Radial + Outer Loop	Inner Radial	1.40	0.39	0.97	1.05
	Outer Loop	14.74	8.69	4.02	1.05
Average for Categories	for Radial	12.01	12.41	12.29	5.24
	for Loop	12.26	11.19	7.46	3.42
	for Outer	12.06	13.39	11.85	6.14
	for Inner	12.22	10.21	7.91	2.51
	for All	12.14	11.80	9.88	4.33

CASE STUDY FOR STRUCTURAL/ NON-STRUCTURAL COUNTERMEASURES

Model Network and Traffic Control Pattern

The network seismic performance index *SP* does not only give the performance of a given network, but also helps planners to determine the retrofit priority through the link importance *LI*. This idea can be extended to the comparison of alternatives including structural/ non-structural countermeasures. This section describes an example of such application of this method. The model network for this case study is slightly more complex than that of simple case study, and has external centroids to consider the background traffic as shown in Figure 9. Three traffic control methods considered in this research is shown in Figure 10. In the ‘uncontrolled’ pattern both the emergency traffic and the background traffic use the same lanes. In the ‘directional control’ pattern, all the lanes of a specified direction are open only to the emergency traffic while other lanes are used by both kinds of traffic. ‘Exclusive lane’ is limited for emergency traffic as is named. Other settings such as cover area are similar to the simple case study. The population is distributed uniformly to each zone, and the disaster prevention bases distribution is dispersed pattern.

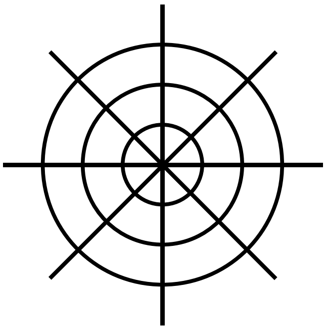
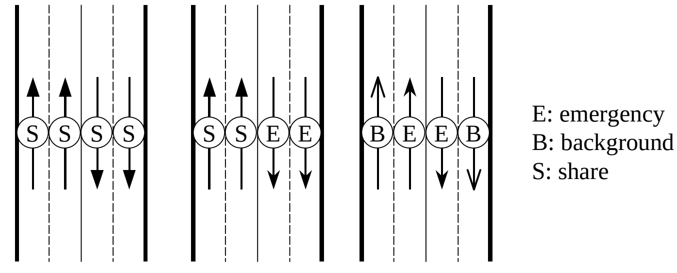


Figure 9: Model Network

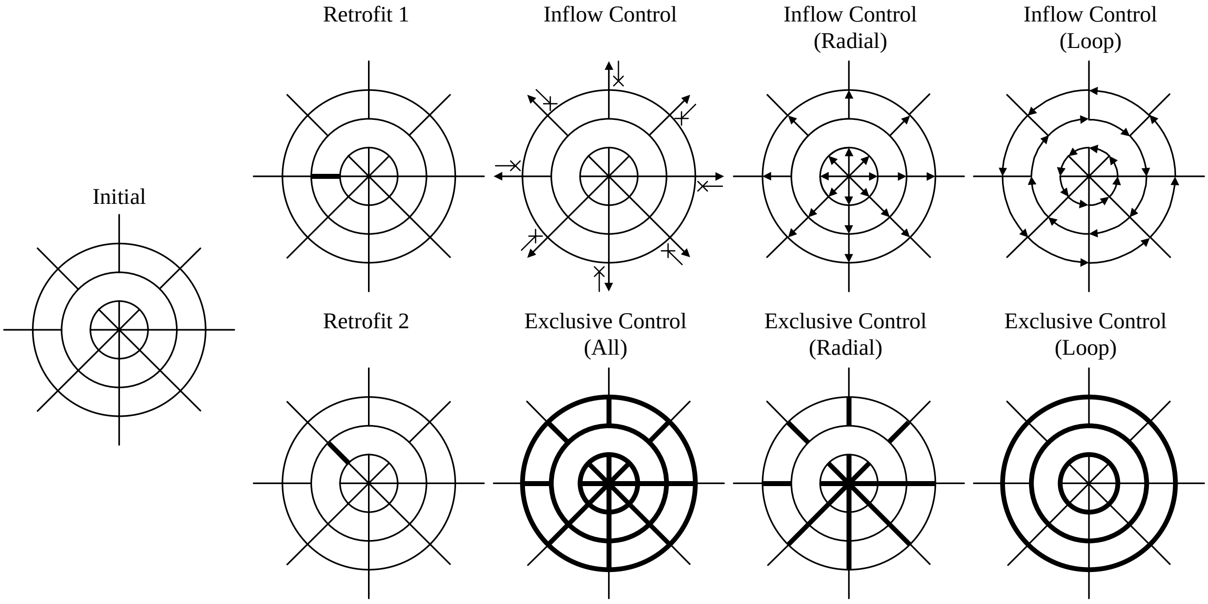


(a) uncontrolled (b) directional control (c) exclusive lane

Figure 10: Traffic Control Pattern

Structural/ Non-structural Countermeasures Settings

Figure 11 shows the examples of structural and non-structural countermeasures. Number of damaged links is four, and eight patterns of countermeasures including structural retrofit are set up. Among them, 'Inflow Control' pattern is to restrict the background traffic coming into the damaged area while those going out are fully permitted.



Initial

Retrofit 1

Inflow Control

Inflow Control (Radial)

Inflow Control (Loop)

Retrofit 2

Exclusive Control (All)

Exclusive Control (Radial)

Exclusive Control (Loop)

Figure 11: Countermeasure Pattern

Results

SP for the patterns are displayed on Figure 11. The new index *TTPV* is shown additionally. *TTPV* means the travel time per vehicle which is calculated by eq. (7).

$$TTPV = \frac{TSTT}{\sum_{i,j} T_{ij}} = \frac{\sum_{i,j,r} T_{ijr} t_{ijr}}{\sum_{i,j} T_{ij}} \tag{7}$$

Where, *TSTT*: total system travel time, T_{ij}: valid background traffic volume between zone i and j, T_{ijr}: valid background traffic volume on route r between zone i and j. Here the valid traffic exclude the isolated traffic demand. By referring *TTPV*, one can quantitatively know the effect of the countermeasure to the background traffic as well as the effect to the emergency traffic. The results of *SP*s and *TTPV* for the cases above are shown on Figure 12.

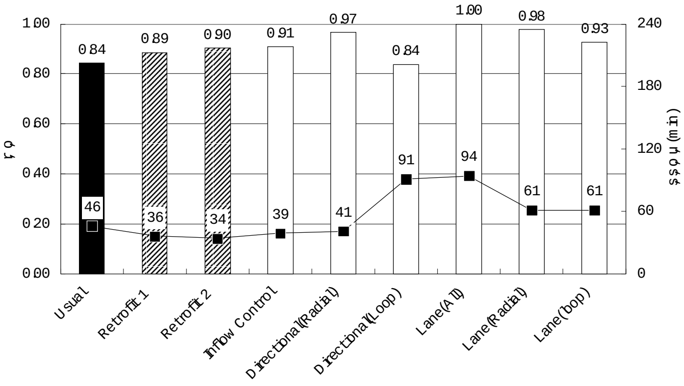


Figure 12: Results of Case Study

First, it is clear that the structural retrofit countermeasures satisfy both conditions, the improvement of *SP* in terms of the emergency traffic and the reduction *TTPV* regarding the background traffic. Second, the non-structural traffic control countermeasures usually improve *SP* more than the retrofit countermeasures. However, they may affect the background traffic seriously as seen in exclusive lane pattern. On the other hand, some non-structural countermeasures improve both performances for the emergency traffic and the background traffic (directional control for radial roads).

Thus, the structural and non-structural countermeasure for the earthquake standing highway network must be compared taking their effects and costs into account by quantitative assessment method like as the method introduced here.

CONCLUSIONS

1. A method to calculate the index to assess the quantitative seismic performance of a highway network (*SP*) is introduced.
2. The indexes for a simple model network with several damage patterns do not have conflict with inferred consequences. Thus, the method is thought to be able to be applied to more complex practical cases.
3. Several structural/ non-structural earthquake countermeasures are compared by using the method. The method is capable of showing the quantitative comparison between many types of countermeasures such as retrofit and traffic control.
4. The traffic control countermeasures immediately after the earthquake show better result than the structural retrofit, however, trade-off between the efficiency for the emergency traffic and the effect to the background traffic must be considered.

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