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Resilient Restoration Scheduling on Road Network

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ABSTRACT: The purpose of this study is to enhance the resilience of restoration scheduling for road networks. Optimal scheduling for resource allocation plays an important role on early restoration. However, circumstances in the post-seismic period are more likely to change due to various factors such as secondary disaster. Furthermore, it is necessary to prepare for unexpected damages. This study examines a method to reduce changes of restoration plan with keeping the adaptability against uncertainties in the post-seismic period. Specifically, an attempt is made to clarify factors strongly related to the delay of restoration in the flexible scheduling which is based on allocation priorities of restoration groups proposed by the existing studies. In this study, numerical simulations are presented to investigate the influence of the change of schedule on early restoration. And then, this paper discussed a method to keep initial restoration plan and to enhance adaptability to circumstances' changes.

1. INTRUDUCTION

In the area of countermeasures against natural disaster such as earthquake and tsunami, the concept called "resilience" has been paid attention since the Great East Japan Earthquake at March 2011. Resilience is a concept that includes continuity and recovery capacity. In other words, a resilient countermeasure contains the capacity to maintain usual state of system and to restore to its former state in addition to disaster prevention and damage reduction. The definition of resilience has been discussed by Holling (1973), Birkmann (2006) and Norris et al. (2008). The common definition of resilience in these researches is a capacity to recover to former state even if damaged from disasters.

Applying the concept of resilience to restoration scheduling, this study attempts to development a plan that adopts to various situations with keeping its function under uncertain environments. Existing studies on restoration scheduling have developed scheduling method for damage reduction. Furuta et al. (2008) developed a method to program a robust schedule against uncertain circumstances like secondary disaster. However, a schedule developed by this method was difficult to accomplish early restoration due to the improvement of robustness against uncertainties. In order to overcome this problem, Xu et al. (2007) has indicated that optimization of priority on work assignment in consideration of uncertainties enabled us to achieve early recovery and improvement of robustness by changing schedule in response to circumstances. Furthermore, Nakatsu et al. (2010 and 2011) proposed a method to develop a schedule in feasible computational time in the aftermath of disaster. However, accidental situations difficult to address in the aftermath of disaster were caused by recent seismic disasters such as the Great East Japan Earthquake and Kumamoto Earthquake. The former caused tsunami, the latter caused multiple large earthquakes in the short term. Therefore, Takahashi et al. (2015) has studied the application of restoration scheduling system to previous consensus formation and discussion about unexpected circumstances as a tool for simulation. That studies deeply relates to resilience of countermeasures against disasters. It is necessary to address the definition, evaluation and improvement of resilience for restoration activities and schedule development in that studies. This study is to address restoration scheduling to develop a plan for discussion of countermeasures against disasters as well as Takahashi et al. (2015).

This study discusses about resilient restoration scheduling focusing on flexible scheduling based on priority on work assignment proposed by Nakatsu et al. (2010), and an attempt is made to clarify the influence of change of assignment on schedule. The flexible scheduling has elements related to 4R of resilience (robustness, redundancy, resourcefulness and rapidity) proposed by Bruneau et al. (2003). However, change of assignment oppose a keeping state on resilience. In actual work, frequent changes of allocation of restoration group have possibilities to cause unexpected circumstances. Therefore, this study analyzes the influence of change of schedule from obtained results of simulation using a solution of flexible scheduling. Specifically, this study calculates allocations of restoration group with low priority as the variation of allocation priorities. And then, the correlation between the variation of allocation priorities and index related to simulation results such as evaluation value is investigated. Furthermore, this study clarifies factors of variation of allocation priorities related to worsening of indexes through the application of decision tree analysis. These investigations are presented to indicate guideline for improvement of resilience of restoration scheduling.

2. INFLUENCE OF CHANGE OF WORK ASSIGNMENT ON SCHEDULE

This study investigates an influence of change of work assignment on early restoration focusing on flexible scheduling using assignment priorities of restoration group.

2.1. Problem settings

In this study, simulation is performed relying on the settings of road network, damage situation, restoration group and uncertainties (increase of damage and delay of work) used in Nakatsu et al. (2010).

Firstly, restoration of damaged area is accomplished through both (1) removal of interrupted things (removal work) and (2) repair of road (repair work). Here, the repair work must be started after completion of removal work at an area. Predicted damage amount is set to each damaged area, and uncertainties probabilistically increase its damage. Restoration works are classified into 3 damage levels (small, middle and large) relying on Furuta et al. (2008). In addition, each damaged area is set importance represented by 3 levels (low, middle and high) based on the role on usual road network system. Tables 1 and 2 show the number of damaged area corresponding to predicted damage level and importance in the settings of this study.

Next, 8 restoration groups are allocated to restoration activities per work type. 8 restoration groups have different restoration capacity each other due to the number of members and allocated equipment for restoration. Relying on Furuta et al. (2008), each restoration group is classified into 3 levels (low, middle and high) corresponding to its capacity. The days required for accomplishment of work are decided by combination of restoration capacity and damage level described above as the same way as Furuta et al. (2008). And, a restoration group with low capacity cannot complete a work with large damage level. Table 3 shows the number of restoration group per capacity in the problem settings.

Evaluation value in the simulation of restoration is calculated by using the restoration rate proposed by Furuta et al. (2008). The restoration rate is defined to be improve the evaluation value as an important area is repaired early. When the days spent for accomplishment of restoration works is x-axis and the restoration rate

Table 1: The number of areas per expected damage level

Work type	Small	Middle	Large	Total
Removal	2	20	16	38
Repair	10	25	15	50
Total	12	45	31	88

Table 2: The number of areas per importance on road network

Work type	Low	Middle	High	Total
Removal	14	13	11	38
Repair	15	19	16	50
Total	29	32	27	88

Table 3: The number of restoration group per work capacity

Work type	Low	Middle	High	Total
Removal	1	3	4	8
Repair	1	3	4	8
Total	2	6	8	16

is y-axis, the evaluation value is represented as the area of not restored (the summation of the non-restored rate per day). The area is represented as colored portion in Figure 1. In other words, early restoration of important road reduces the non-restored rate per day, and then the evaluation value is optimized (minimized).

2.2. Flexible scheduling and resilience

Flexible scheduling (Nakatsu et al. 2010) is a method to establish a restoration plan based on priority of restoration group for each work. In the aftermath of disaster, circumstances are very uncertain due to the difficulty to grasp damage states and the secondary disaster. Delay of works is likely to be caused by these uncertainties. Flexible scheduling can minimize the delay of works under the uncertain environments because it decides assignment of restoration group to a work in response to change of circumstances. Nakatsu et al. (2010) decides assignment priority of restoration group to all works. In addition, this method can improve the robustness of plan by determining whether or not to follow the priority per work if assignment change of certain work causes long delay on schedule (Nakatsu et al. 2011).

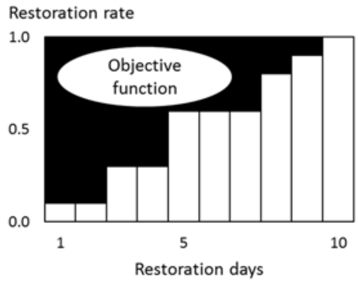

Figure 1: Objective function

This study investigates influence of change of work assignment on the schedule in flexible restoration scheduling. Features of flexible scheduling are corresponding to 4 elements related to resilience on countermeasure of earthquake proposed by Bruneau et al. (2003). Those are followings: Firstly, priority of work assignment improves schedule’s (1) robustness and (2) redundancy. Allocation of appropriate group to a work prevents a restoration schedule from collapsing under uncertain environments and minimizes the influence of secondary disaster like aftershock. Next, change of allocating group can improve (3) resourcefulness of restoration activity because it is done in consideration of resource such as restoration equipment and manpower. Finally, (4) rapidity of restoration is accomplished by following the priority of work assignment even if influence of uncertainties is small, as shown in Nakatsu et al. (2010). These features of flexible scheduling are expected to improve the resilience of restoration plan.

Flexible scheduling has advantages of improvement of resilience but has some opposite characteristics. The concept of resilience contains the system stabilization and the maintain of its state. Change of work assignment, however, causes modification of schedule, and then restoration operation may become rough. In other word, it is necessary for improvement of resilience of restoration schedule to consider influence of uncertainties and change of work assignment simultaneously. In fact, scheduling method proposed by Nakatsu et al. (2011), which inhibits several works from changing work allocation, has indicated that change of work

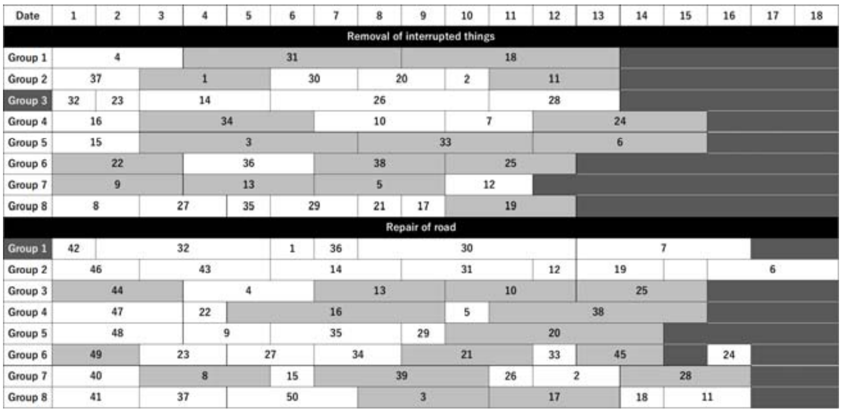

Figure 2: Example of restoration schedule obtained by flexible scheduling method

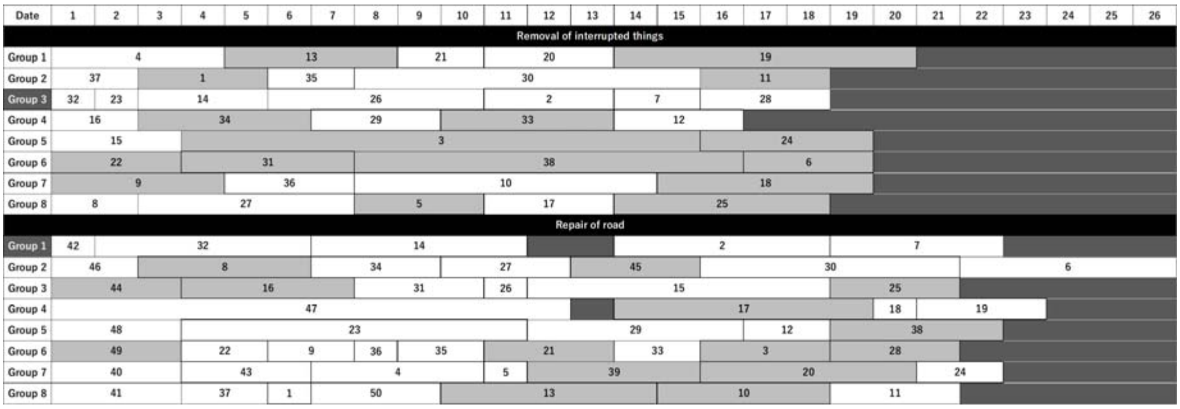

Figure 3: Example of restoration schedule under uncertain environments

assignment is not useful always. Moreover, frequent changes of work assignment in actual restoration activity may not only cause accidental situation but also collapse the schedule because it is difficult to grasp enough information and to share it in aftermath of disaster. Therefore, this study investigates influence of change of work assignment on the flexible restoration plan in order to improve resilience of schedule.

2.3. Analysis of simulation results

This study focuses on the results of existing study (Nakatsu et al. 2010) to investigate influence of change of work assignment. Schedules established from a solution of existing study are shown in Figure 2 and Figure 3. These schedules are developed in response to change of circumstances. Dark gray-colored portions in the figure represent waiting period of corresponding restoration group. Colored groups have low restoration capacity (Group 3 in removal work and Group 1 in repair work). Works for large-scale damaged location are presented by being colored light gray. Furthermore, works with bold frame in Figure 3 means its assigned group is changed from previous plan due to uncertainties.

This study uses "variation of allocation priorities" as an index that represents the extent of changes. In the definition, variation of allocation priorities enlarges when a group with low priority is assigned to the work. Specifically, variation of allocation priorities for a work is calculated by subtracting 1 from priority rank of assigned group. In the analysis, 1,000 times simulations using a solution obtained by Nakatsu et al. (2010) are run in order to investigate the relationship between variation of allocation priorities and indexes on restoration schedule. This study uses evaluation which is objective function value shown in Figure 1, days required for restoration, total movement distance, increase of damage due to uncertainties and delay of schedule which is compared with a situation without influence of uncertainties as indexes of simulation results. Table 4 shows correlation coefficient value between the summation of variations of allocation priorities on all works and each index.

From Table 4, it was found that there was a weak correlation between the variation of allocation priorities and evaluation (correlation coefficient value was more than 0.2). This indicates that frequent allocations of restoration group with low priority is more likely to interrupt rapid repair of important roads. Therefore, it is necessary to consider the variation of allocation priorities in order to improve resilience of restoration schedule.

Table 4: Coefficient of correlation between criteria

Indexes	Variation of allocation priorities
Evaluation	0.248
Days required for restoration	-0.040
Total movement distance	0.152
Increase of damage	0.060
Delay of works	0.119

3. CHANGE OF WORK ASSIGNMENT RELATED TO DELAY OF SCHEDULE

The necessity of reducing variation of allocation priorities on flexible scheduling was shown in section 2.3. However, change of schedule is important for achieving early restoration and for improving robustness and redundancy of plan. Therefore, this study attempts to clarify factors of variation of allocation priorities related to evaluation worsening through analyzing simulation results of flexible plan.

3.1. Change of work assignment

Change of work assignment has possibilities to effect on evaluation worsening due to various situations, for example a restoration group with low priority is allocated to a high-important work. In this study, factors that effect on variation of evaluation are analyzed by focusing on variations of allocation priorities on three elements, 1) restoration capacity of group per work type (removal and repair), 2) predicted damage level of devastated area and 3) importance of area on usual road network.

Firstly, mismatch between restoration capacity of group and damage level of allocated area has possibilities to cause delay of schedule as influence of variation per capacity of group. In flexible scheduling, a large damage level work can be allocated to a group with relative low capacity. In this situation, waiting allocation of group with high priority or enough restoration capacity can shorten working period. This study uses variation of allocation priorities aggregated per restoration capacity as a variable for the analysis in order to clarify how factors derived from group effect on variation of evaluation.

Secondly, variation of work assignment on predicted damage level of devastated area has possibilities to cause delay of schedule when an area of which predicted damage level is small or middle suffers from unexpected large damage. In this situation, days required for accomplishment of work become long if assigned group does not have enough restoration capacity. This study uses a variation of allocation priorities aggregated per predicted damage level of work as a variable.

Finally, allocation of group with low priority to a work with high importance has possibilities to reduce efficiency of following activities and to worsen evaluation of schedule due to the relationship between the evaluation and the importance of road network described in section 2.1. This study also uses a variation of allocation priorities aggregated per importance of work as a variable.

3.2. Analysis with decision tree

An analysis with decision tree is attempted to clarify factors of variation of allocation priorities related to increase or decrease of evaluation by using results of simulation obtained from a solution of flexible scheduling (Nakatsu et al. 2010). The results obtained from 1,000 times simulations described in section 2.3 are used for the analysis. In order to investigate factors related to variation of evaluation, this analysis classifies samples obtained from simulations into two

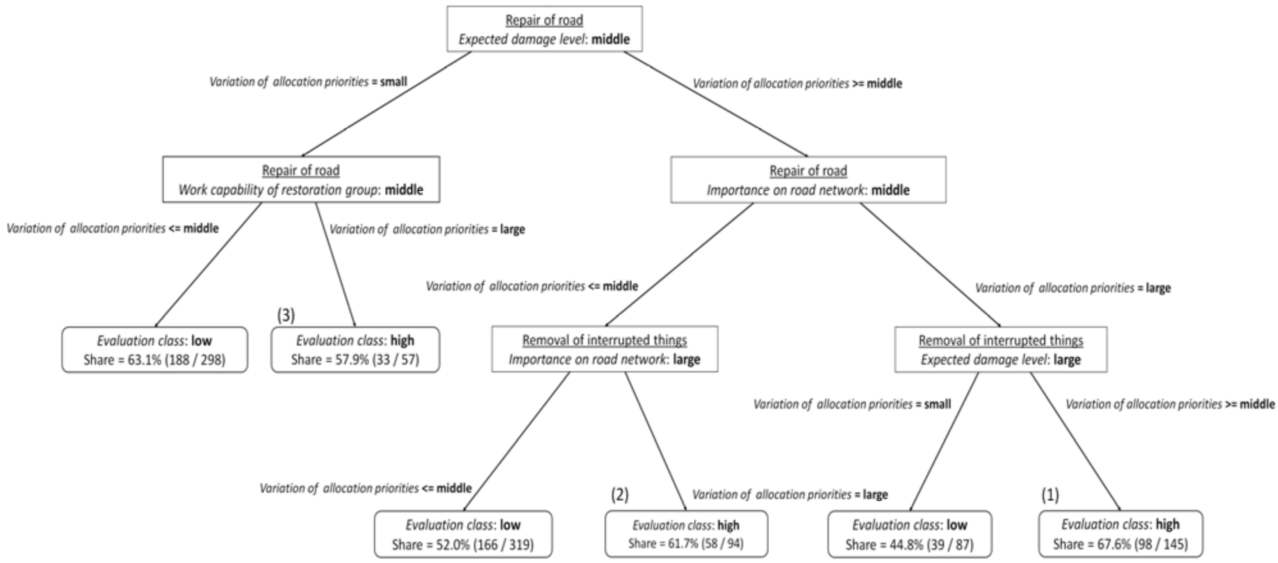

Figure 4: Obtained decision tree

groups (high and low groups) based on their evaluation. In the classification, samples are sorted in ascending order of evaluation, and then 500 samples from top are classified into low group and remains are classified into high group. Objective variable is whether a sample belongs to low or high group and is represented by binary value (low group is 0 and high group is 1). In this analysis, variation of allocation priorities on each index is aggregated per work type (removal and repair). Variation of allocation priorities are classified into 3 classes (small, middle and large). In the classification, samples are sorted in ascending order of variation of allocation priorities aggregated per each index, and then they are grouped into 3 classes equally by following sorted sequence. This study uses 18 explanatory variables for decision tree analysis (3 classes of variation of allocation priorities × 2 work types × 3 indexes on aggregation). Figure 4 shows the result obtained by using CART algorithm implemented in statistical analysis software SPSS.

In Figure 4, factors related to evaluation worsening (class of evaluation = "high") are represented on branches denoted as (1), (2) and (3). Firstly, branch (1) means that middle and large variation of allocation priorities on middle damage repair work, large variation of allocation priorities on middle important repair work and middle and large variation of allocation priorities on large damage removal work are related to evaluation worsening. Next, branch (2) means that middle and large variation of allocation priorities on middle damage repair work and large variation of allocation priorities on high important removal work are related to evaluation worsening. Finally, branch (3) represents that large variation of allocation priorities on group with middle restoration capacity for repair work worsens evaluation.

3.3. Considerations

From the result of decision tree analysis, it is found that variation of allocation priorities on "middle damage repair work", "middle important repair work", "large damage removal work", "high important removal work" and "group with middle restoration capacity for repair work" effect on evaluation worsening.

Firstly, variation of allocation priorities on "middle damage repair work" is likely to be caused by enlarging damage level at the area. This situation worsens evaluation by mismatch between work assignment and restoration capacity of group. Therefore, it is necessary to limit assignment of work for reducing variation of allocation priorities or to remove groups with low restoration capacity from allocating candidates.

Next, variation of allocation priorities on "middle important repair work" does not effect on schedule by the work at the area. This change of allocation, however, worsens evaluation by causing delay of following works. Variation of allocation priorities on "large damage removal work" worsens evaluation when changes of work assignment are done for middle damage repair work and middle important repair work. In this case, it is important to reduce variation of allocation priorities on previous works like middle important repair work. When variation of allocation priorities on middle important repair work is small, "high important removal work" effects on evaluation worsening. Thus, reducing variation of allocation priorities on "high important removal work" is also important.

Variation of allocation priorities on "group with middle restoration capacity for repair work" effects on evaluation when changes of work assignment for middle damage repair work are few. A group with middle restoration capacity can handle work of all damage levels, but spends long period for large damage work. Therefore, reduction of its variation of allocation priorities or inhibition of allocating a group with relative low capacity to large damage repair work are effective to prevent from worsening evaluation.

From considerations described above, reduction of variation of allocation priorities on group and works contained in the decision tree is expected to be effective for improving resilience of restoration schedule.

3.4. Effect of reduction of change allocations

Based on the result obtained from decision tree analysis, this study verifies effect of reduction of variation of allocation priorities on certain work. In this study, schedule is established by optimizing variation of allocation priorities on "middle damage repair work" that is root on decision tree shown in Figure 4 as sub objective.

Relying on Nakatsu et al. (2010), this study applies genetic algorithm considering uncertainty to the optimization. In the parameter settings, population size is 500 and the number of running generation is 2,000. Chromosome of individual and genetic operators for crossover and mutation are the same as Nakatsu et al. (2010). This study sets 60% to crossover probability and sets 0.5% to mutation probability per individual gene. In the simulation to calculate evaluation, damage of area increases with a probability of 30%. Increase of damage amount is decided by using absolute number of random number generated from normal distribution with mean 0 and standard deviation 0.3. In addition, a work is presumed to decelerate in 20 % not related to its damage level. Specifically, random value is generated from normal distribution with mean 0 and standard deviation 2, and then is rounded off. The generated value is used as period of delay on the work. In order to investigate effect of reduction of variation of allocation priorities for certain work, this study appends the sub objective function for the reduction described above to optimization of Nakatsu et al. (2010). The optimization is run 5 times and obtained solutions are compared to solutions obtained by Nakatsu et al. (2010). Simulation described in section 2.3 is applied obtained solutions of each method. Table 5 shows the result of simulations.

Table 5: Results of optimizations

Indexes	Existing	Proposed
Average evaluation	8.662	8.645
Std. dev. of evaluation	0.028	0.044
Average evaluation under the worst situation	10.518	10.292

In Table 5, the row of "Existing" represents results of solutions obtained by Nakatsu et al. (2010). The row of "Proposed" shows the results of proposed method. "Average evaluation" means average evaluation calculated from 1,000 simulations using obtained 5 solutions. "Std. dev. of evaluation" is their standard deviation. "Average evaluation under the worst situation" is mean value calculated by using the worst evaluation among 1,000 times simulation of each solution. From these results, it was found that the effect of reduction of variation of allocation priorities on "middle damage repair work" was a little. This study reduces the variation of allocation priorities on "middle damage repair work" only. However, there are many operations required for reducing their variation of allocation priorities as mentioned in section 3.3. In other words, effect of reduction of variation of allocation priorities on certain work is a little, but it will become large by targeting multiple restoration operations. Therefore, an optimization considering variation of allocation priorities is expected to be useful for improving resilience of restoration scheduling.

4. CONCLUSIONS

In this study, an attempt was made to examine the resilience of restoration schedule for road network in aftermath of earthquake and to analyze for improvement of it. Flexible scheduling which establishes plan in response to circumstances by following allocation priorities of restoration group (Nakatsu et al. 2010) can enhance 4 elements (robustness, redundancy, resourcefulness and rapidity) on resilience defined by Bruneau et al. (2003). However, change of work assignment has possibilities to reduce resilience from the perspective of keeping initial plan. For example, allocation of group with low priority causes delay of schedule. This analysis showed that variation of allocation priorities had correlation with evaluation worsening. In addition, this study clarified several operations related to evaluation worsening when change of work assignment was done. In this way, useful improvement for resilience of restoration scheduling were indicated for future works.

In future works, it is necessary to examine an optimal scheduling method considering reduction of variation of allocation priorities. This paper verified its limited effect by appending minimization of variation of allocation priorities on certain work as sub-objective. However, this optimization can be applied various techniques such as limitation of change of work assignment on certain group (Nakatsu et al. 2011) and penalty function method. Therefore, it is necessary to develop a new method for scheduling flexible plan reducing variation of allocation priorities.

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