EVACUATION SIMULATION FOR THE EXTRACTION OF ISSUES AND THE EFFECT VERIFICATION OF THE MEASURES

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Abstract

With the development of technology and the centralization of population to the city, the severity of the damage by disaster increases, and the scale of the evacuation from the stricken area becomes large. The evacuation by the nuclear power plant accident is one of the examples. At the time of the nuclear accident at the Fukushima Daiichi nuclear power plant caused by the East Japan great earthquake and tsunami disaster of March 2011, approximately 150,000 people evacuated and the large scale evacuation caused great confusion for all those who were involved. After this accident, the local government surrounding by nuclear power plant has pushed forward the reconsideration of the disaster prevention plan, and the Evacuation Time Estimates (ETE) has been being carried out as a part of that reconsideration. As well as the accident of the nuclear power plant, the disaster such as a volcanic eruption or the accident of the chemical factory may cause a large-scale evacuation.

As a part of the disaster prevention planning for such a large-scale evacuation, it is important to grasp in advance the expected situation of the evacuation, the time that evacuation takes, and issues at the evacuation. However, it is difficult to produce the situation of a large-scale evacuation in the real world. Therefore, use of the computer simulation is effective. One advantage of the computer simulation is that it is feasible to simulate various situations of the evacuation with different conditions (e.g. day/night time that the population distribution differs, the existence of the road damaged by the natural disaster). Then it is utilized to figure out a tendency of the evacuation situation and to extract the issues such as lengthening of the evacuation time due to congestion. Another advantage of the computer simulation is that it makes possible to consider measures for such issues and to verify the effect of measures. Moreover, the simulation result can be used for consensus building among stakeholders regarding the issues and measures.

So far, we have carried out the evacuation simulation at the multiple neighboring local governments of the nuclear power plant, and have implemented the effect verification of the measures against the issues on the evacuation, as a part of the development of the evacuation planning. In this paper, we describe the usefulness and effectiveness of evacuation simulation and show how it works, as well as our past effort including the lessons learned from our past work and the current issues which should be resolved.

Keywords: Evacuation, Simulation, Disaster Preparedness, Effect Verification, Traffic

1. Introduction

The nuclear accident at the Fukushima Daiichi nuclear power plant caused by the East Japan great earthquake and tsunami disaster of March 2011 was an unprecedented event in Japan. Approximately 150,000 people were evacuated in response to the accident and the large scale evacuation caused great confusion for all those who were involved [1].

Based on lessons learned from this accident, the Nuclear Regulation Authority defined the Nuclear Emergency Response Guideline in October 2012 [2]. This guideline is to show the way of thinking of protection measures to minimize the influence of the radiation to inhabitants around the nuclear facility in case of the nuclear power emergency. This guideline describes the criterion of the protection measures enforcement and the range of the area where the disaster prevention measures should be enriched referring to international standards such as IAEA [3, 4].

It says that the protection measures such as immediate evacuation must be taken if necessary before the release of the radioactive material in order to avoid the definite influence. Based on this guideline, it is important to define the evacuation plan which considers the evacuation time in order to establish the disaster prevention system which can correspond to the early emergency phase [3, 4]. Then, the local government surrounding by nuclear power plant has pushed forward the reconsideration of the disaster prevention plan.

The Evacuation Time Estimates (hereafter called “ETE”) is to estimate the evacuation time beforehand and this has been being carried out as a part of the reconsideration of the disaster prevention plan in the local government. The ETE can be utilized not only to estimate the evacuation time but also to extract the issues on the evacuation plan and to verify the effect of the countermeasures.

So far, we have carried out the ETE at the multiple neighboring local governments of the nuclear power plant, such as Kyoto, Fukui, Shiga, Aomori, Sage Kagoshima, and Miyagi prefectures, using computer simulation. In addition, we undertook the formulation of the ETE guidance from the Japanese cabinet office [4].

In this paper, we describe the usefulness and effectiveness of the ETE and show how it works, as well as our past effort including the lessons learned from our past work and the current subject which should be resolved.

2. What is the ETE?

In this section, we describe what the ETE is.

The ETE is a method to estimate the evacuation time of inhabitants around the nuclear facility in case of the nuclear power emergency beforehand. We assume the situation that the nuclear accident happens and inhabitants around the nuclear facility execute the protective action such as evacuation based on the current disaster prevention plan, and estimates the evacuation time from the residential area of inhabitants to the designated destination to evacuate.

When the influential range of the nuclear accident is large, the number of evacuees may become tens of thousands of. It is assumed that these evacuees use vehicles to evacuate since the designated destination is generally distant. Thus, in general, the computational traffic simulation is used to simulate the evacuation situation. We build a road network on computer, and generate each evacuation vehicle on the network, and measure the travel time from the origin to the destination. Since a traffic congestion occurs by a large number of evacuation vehicles, we also analyze the traffic congestion situation besides the measurement of the evacuation time.

The objective of the ETE is to improve the effectiveness of the evacuation plan. We suppose the various situation of the evacuation with considering the point of view to verify, and simulate that evacuation situation. Then the tendency of the evacuation situation and the issues on the evacuation plan are revealed.

We consider the countermeasures for the issues such as the traffic congestion and the verify the effect. The result of the ETE can be the reference of the emergency preparedness for a variety of situations, and it also can utilize as the feedback to the evacuation plan. Thus, the ETE supports the decision making concerned to the evacuation plan.

3. Flow of the Implementation of the ETE

In this section, we describe the main flow of the implementation of the ETE. There are four major phases on ETE implementation. Fig 1 shows the general flow of ETE implementation.

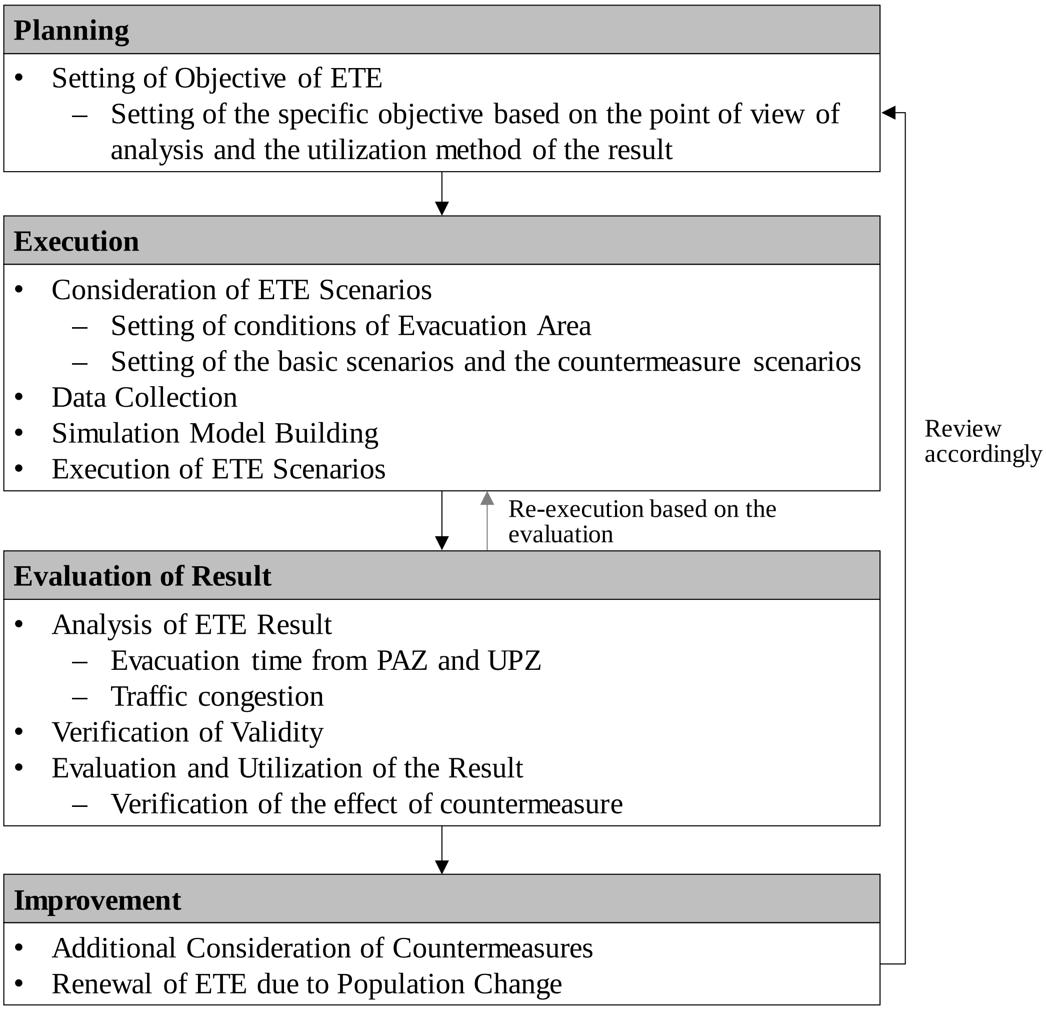

Fig. 1– General flow of ETE implementation (Created based on [4])

The first phase is Planning. In this phase, we define the objective of ETE. Here it is important to set the specific goal based on what we aim to figure out from the ETE result and what we want to utilize the result for. For example, if we aim to figure out a tendency of the evacuation situation under various conditions, we should simulate with different conditions such as day/night time that the population distribution differs. If our interest is to extract the issues on the current evacuation plan, we should spend time to carefully analyze the simulation result of the basic scenario.

The second phase is Execution. In this phase, we consider the ETE scenarios based on the objective defined in the previous phase. Here it is important to consider the evacuation flow on the actual evacuation plan. As the Nuclear Emergency Response Guideline mentions, two off-site emergency zones are defined; Precautionary Action Zone (PAZ, Within about 5km radius from the nuclear facility) and Urgent Protective Action Planning Zone (UPZ, Within about 30km radius from the nuclear facility). The protective action is different depending on the emergency zone. PAZ residents evacuate based on the EAL (Emergency Action Level) before the release of radioactive material, and UPZ residents evacuate based on OIL (Operational Intervention Level) after the release of radioactive material. Fig. 2 shows an example of operation flow of the protective action of each area. Fig. 3 shows the conceptual illustration of PAZ and UPZ.

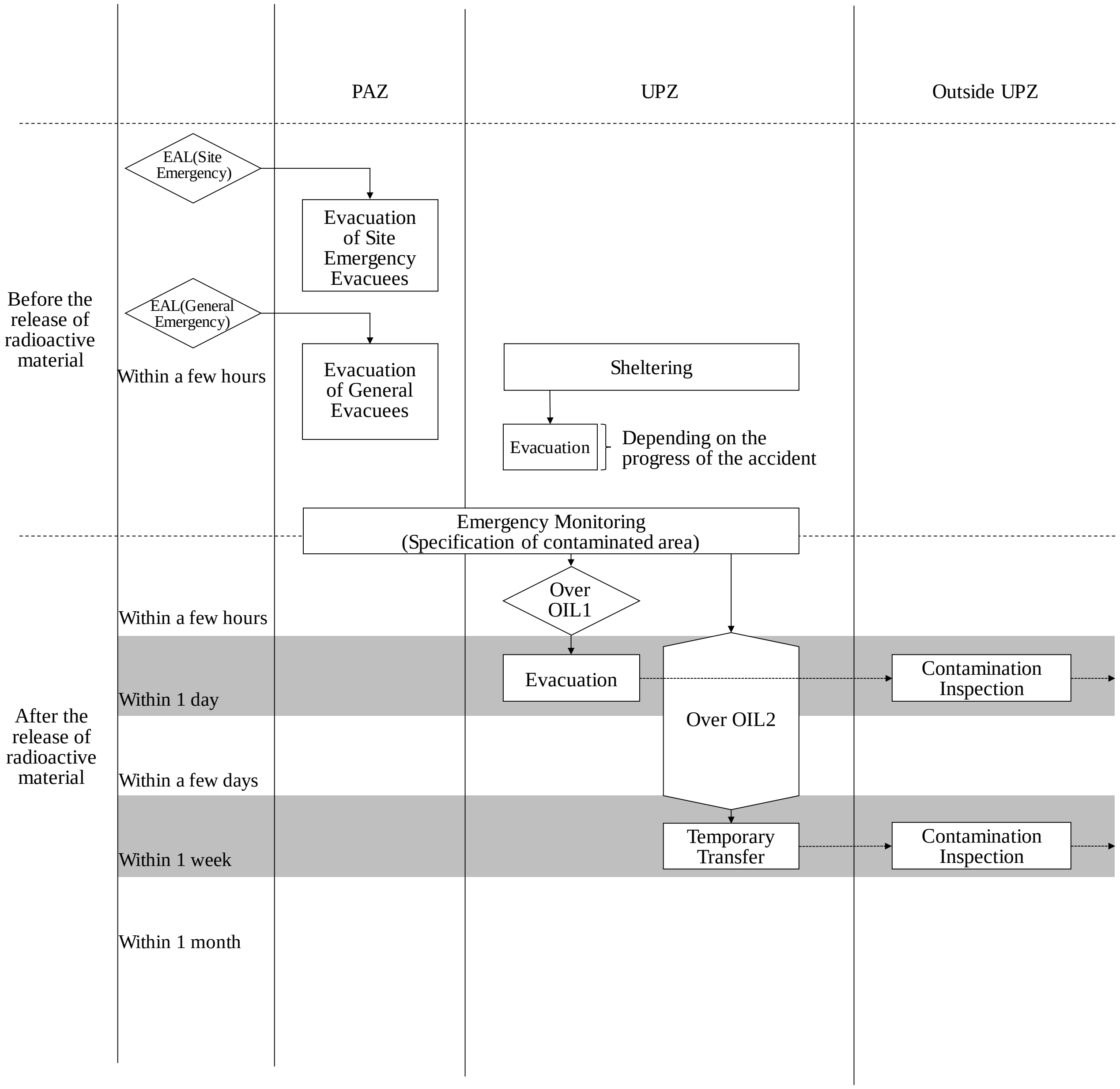

Fig. 2– Example of operation flow of the protective action (Created based on [4])

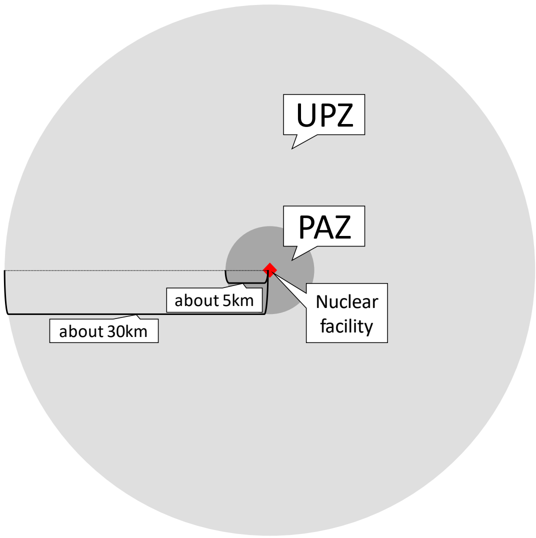

Fig. 3– Conceptual illustration of PAZ and UPZ

Next we need data collection. There are a lot of information needed to make scenarios and to build the simulation model, such as population of evacuees, the number of vehicles, the origin and destination, information on evacuees requiring support, information on evacuation route, and so on. Table 1 shows examples of required information for the ETE.

We select important conditions of the scenarios referring to the actual evacuation plan and these information, and build the simulation model. In general, micro traffic simulation model is used for ETE in order to analyze the detail of traffic condition. For example, the signal control often affects the flow of evacuation traffic. Since the normal signal setting may not be convenient anytime for the flow of evacuation traffic, it is important to analyze how the signal control affects the evacuation flow. Micro traffic simulation model is suitable to reflect such signal control. Fig. 4 shows an example of intersection information including signal control.

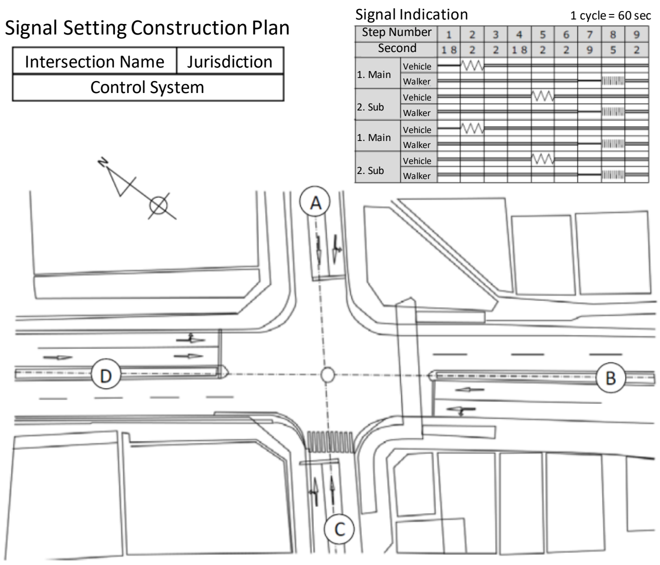

Fig. 4– Example of intersection information including signal control (translated [4])

Table 1 – Examples of required information for the ETE (Created based on [4])

Category	Examples
Basic Information	・ Evacuation area unit ・ Population of evacuees ・ Number of owned vehicles in that area ・ Assumption of means of transportation of evacuation (e.g. owned vehicle, public transportation) ・ Origin, destination, and the transit point (e.g. contamination inspection place) of the evacuation.
Information on Evacuees Requiring Support	・ Population of evacuees ・ Medical institutions and social welfare facilities ・ Special vehicles
Information on evacuation route	・ Evacuation route in the evacuation plan ・ Road information such as traffic capacity, the number of lane, and road shape ・ Intersection and signal information
Others	・ Number of temporary sojourner (tourists) ・ Schools (number of students, children) ・ Workplaces (number of workers) ・ Customer facilities (number of customers) ・ Weather condition in the area ・ Road where traffic impossibility is expected
Information to be estimated	・ Voluntarily evacuation (aka Shadow evacuation) ・ Number of evacuees on a vehicle ・ Regular traffic volume ・ Preparation time for evacuation ・ Inspection time at the contamination inspection ・ Time to confirm the complete of the evacuation

In addition, micro traffic simulation model simulates vehicles one by one. Thus we can analyze the average evacuation time of individual evacuation vehicle. This is another advantage of use of micro traffic simulation model. Then the ETE scenarios are executed on the simulation model.

The third phase is Evaluation of Result. Mainly, there are analyses in terms of the evacuation time and traffic condition. The evacuation time is how long the evacuees take time to arrive at the destination or the transit point such as the contamination inspection place. As well as 100% completion time, which all evacuees arrive at the destination, 90% completion time is also important to understand. This is because in large scale traffic simulation, sometimes a part of vehicles delay – this is called “an evacuation tail”, and based on this phenomenon, it is said that 90% completion time is suitable to verify the effect of countermeasures [4]. When we draw the evacuation completion curve, we may find duration that evacuation stagnates. It means there may be a bottleneck. Fig.5 shows an example of the evacuation completion rate curve. We see the evacuation tail and the bottleneck on this curve.

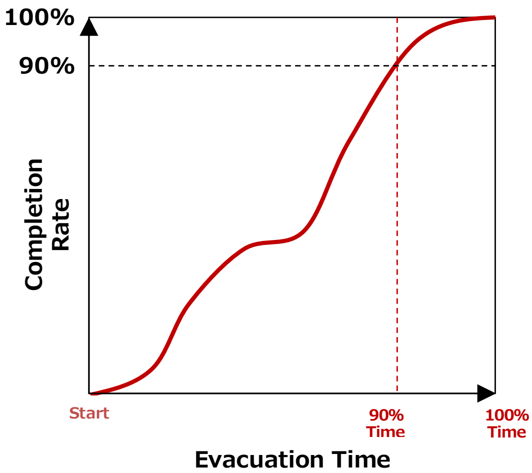

Fig. 5– Example of evacuation completion rate curve

Then we investigate where is the bottleneck by observing traffic condition. Fig. 6 shows examples of expression of traffic condition. By observing such simulation output, we find out where the congestion points on the evacuation route are.

Fig. 6– Examples of expression of traffic condition [4]

Then we consider the countermeasures for such congestion points. There are some possible countermeasures; for example, change of the setting of signal control, change of the evacuation route or use of alternative route, and change of the location of the transit point such as the contamination inspection place. Then it is important to verify the effect of such countermeasures. We make the countermeasures scenarios, build the simulation model, and execute it. Fig. 7 shows examples of expression of the effect of a countermeasure.

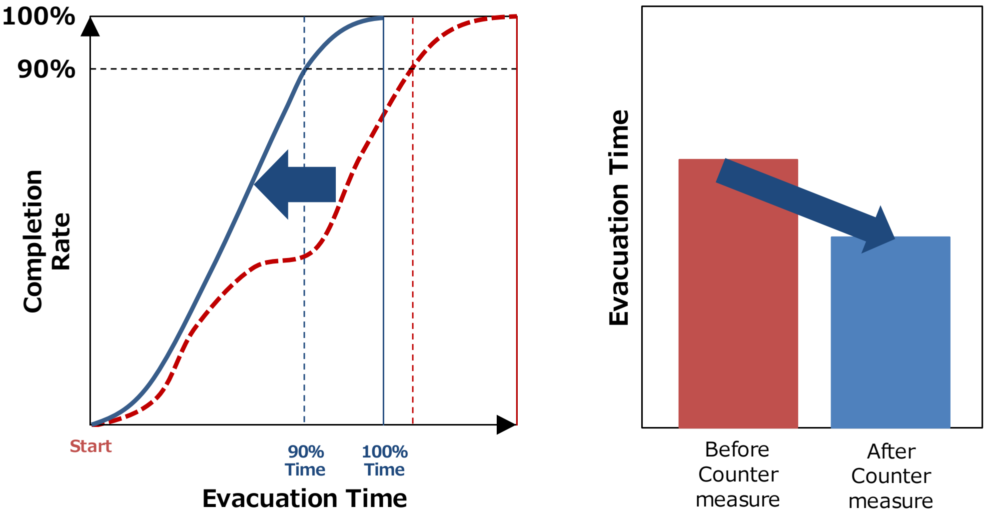

Fig. 7– Examples of expression of effect of countermeasure

The fourth phase is Improvement. When additional countermeasure becomes possible in the real world, redo of ETE may work to verify the countermeasure. Besides, if population in that area changes significantly, renewal of ETE may be required.

4. Development of the ETE in Japan

In this section, we describe how the ETE has developed.

According to the ETE guidance of Japan, as an example of international trend regarding the ETE, in the US, the implementation of the ETE, which is to estimate the evacuation time, is regulated by the Federal Regulations 10CFR50.47 and 10CFR50 Appendix E. In addition, NUREG/CR-0654, "Criteria for Preparation and Evaluation of Radiological Emergency Response Plans and Preparedness in Support of Nuclear Power Plants", shows detailed information on technique for such as how to set the evacuation route and traffic control. The ETE guidance of Japan refers to these documents [4, 5, 6, 7, 8].

There are roughly two waves of the implementation of the ETE among Japanese local governments. The first wave is during 2012 to 2014, which follows the Fukushima Daiichi nuclear power plant accident of 2011 and the definition of the Nuclear Emergency Response Guideline of October 2012. At that time, a lot of local governments implemented the ETE in order to review their disaster prevention plans. It seems that the result of ETE was mainly used to refer to the estimated evacuation time since nobody knew even rough estimated time. However, at that time, the evacuation plans of many local governments had not been complete in detail. For example, in some local governments, the evacuation routes and the contamination inspection places had not been determined. Therefore, temporary assumptions were used for the implementation of the ETE.

The second wave of the implementation of the ETE is from 2017 and even now, which is after about 5 years or later from the first wave. By this time, the detailed evacuation plan had been developed in many local governments. Therefore, the interest of local governments is to verify its feasibility and the ETE is used to find out whether there is a problem when the current evacuation plan is implemented. Since the first wave, there are a lot of changes regarding the evacuation; the evacuation plan itself, the specific evacuation route, the specific refuge place, the specific contamination inspection place, population (the number of evacuees), and road network in the area, and so on.

The determination of the specific evacuation route and the contamination inspection place has possibility to much affect the evacuation condition. When the specific evacuation route is determined, a lot of evacuation vehicles concentrate in same route, which may cause traffic congestion, although the evacuation traffic control may become easier. And, making a stop for the contamination inspection may cause traffic congestion around the contamination inspection place.

Therefore, another interest of local governments is to consider countermeasures for the problems which are extracted by the ETE. The important point of the implementation of the ETE is becoming to verify the effect of countermeasure rather than to just estimate the evacuation time, that means the significance of the ETE is becoming to larger.

5. Application of the ETE result

In this section, we describe how the result of ETE can be applied.

At first, as mentioned above, the ETE result can be applied for the review of the current evacuation plan and verification of the effect of countermeasures for the extracted issues.

The ETE result includes the estimated evacuation time (e.g. 90% and 100% completion time to the destination), congestion points and bottleneck. Then we identify the factors of the issues on evacuation, such as concentration of evacuation traffic, the signal control which is not suitable to evacuation flow, and the congestion around the contamination inspection place.

These outcomes can be applied for the consideration of the countermeasures, change of the setting of signal control, change of the evacuation route or use of alternative route, and change of the location of the transit point such as the contamination inspection place. We re-simulate applying these countermeasures in order to verify their effect as countermeasure scenarios.

When it is verified that the countermeasures are effective, those are used for reconsideration of the evacuation plan and improvement/repair of actual evacuation road and/or facility concerned with evacuation. The increase of the number of roads which are available during evacuation or the improvement of accessibility to the contamination inspection place bring better affect to evacuation.

In particular, the contamination inspection is a significant factor on evacuation since all evacuees based on OIL (Operational Intervention Level. See Fig. 2.) are supposed to stop by the contamination inspection place and be inspected. The ETE can be applied to review the location and to verify its usage, such as the access road to the place, the gateway of the place, the traffic line in the place, and processing capacity. Fig. 8 shows an example of traffic line in contamination inspection place.

In fact, it is difficult to select the contamination inspection. There are a lot of requirement; it should be large enough, easy to access from the evacuation route, and near from UPZ border – If it is far from UPZ border and is outside of UPZ, it is possible that contaminated vehicle/evacuee expand the pollution beyond UPZ, and if it is far from UPZ border and is inside of UPZ, it is possible that vehicles/evacuee is contaminated after the inspection. It is necessarily that the candidate of the contamination inspection place is few.

Nevertheless, it is important to verify whether the selected place is suitable under evacuation traffic condition since a contamination inspection place may cause congestion which obstructs the evacuation traffic which goes to a different contamination inspection place. If necessary, we should reconsider the allocation of evacuees to the contamination inspection places according to the capacity. The ETE can be used for these verification.

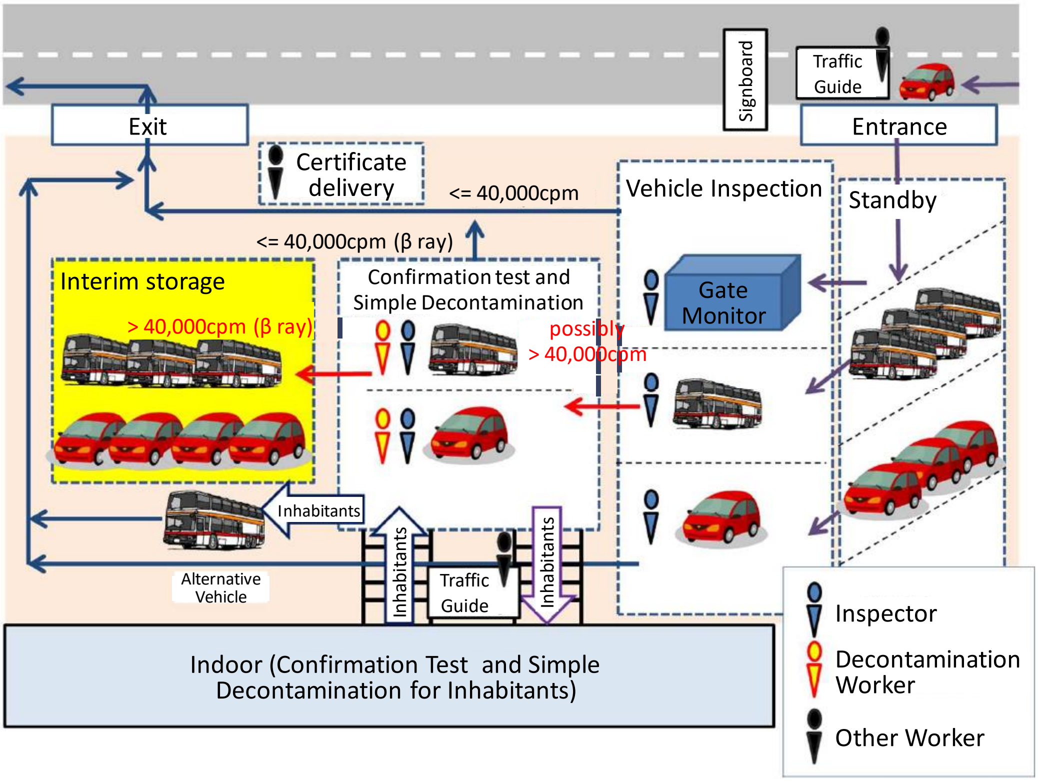

Fig. 8– Example of traffic line in contamination inspection place (Translated [9])

Secondly, the ETE result can be applied for dissemination of information to inhabitants; for example, making public of the evacuation plan, the enlightenment of the effect of sheltering, the attention to reduce the shadow evacuation (discussed later), and the consensus building to improve the evacuation plan. We believe that the ETE contributes to security and safety of inhabitants. As important information for inhabitants, we calculate the average of individual evacuation time by simulating vehicles one by one, in addition to 90% and 100% evacuation completion time.

Thirdly, the implementation of the ETE can be helpful to put the evacuation plan into more concrete shape. In the procedure of making scenarios and building model, we have to do various assumptions; for example, where is the refuge place of an evacuee requiring support? by what means of transportation? with whom? when? and so on. Thus, we are to imagine the evacuation situation concretely through the implementation of ETE. It is much important to imagine the situation in advance. This process reveals oversight or omission on the evacuation plan. Even if we put a temporary assumption at the ETE, we can find out what we have to consider later. This is another advantage of the implementation of the ETE.

6. Current Issues and Future View

In this section, we describe the issues on the evacuation in the nuclear disaster from the point of view of the ETE and the technical issues on the implementation of the ETE including the future view.

The first issue on the evacuation is that, in general, it is possible that the evacuation in the nuclear disaster becomes large scale and it takes a long time. The evacuation from PAZ may take dozens of hours and the evacuation from UPZ may take about one week or more. This is because there are some possible factors which becomes bottleneck of the evacuation.

Regarding the evacuation from PAZ, one of the most significant possible factors is the voluntarily evacuation which is also called "the shadow evacuation". PAZ residents start their evacuation according to the EAL (See Fig. 2.). At that point, it is supposed that the evacuation order to UPZ is not announced yet. However, some UPZ residents may start evacuation. This is the shadow evacuation which is one that does not follow the evacuation order. At the Fukushima Daiichi nuclear power plant accident, it is said that there were the voluntarily evacuees about 40% in total [1, 4]. The traffic of the shadow evacuation much affects the evacuation traffic from PAZ. The traffic volume of the shadow evacuation is much larger since the population of UPZ is large. In addition, UPZ is outside of PAZ geographically (See Fig. 3). Thus the evacuation traffic from UPZ necessarily prevents from the evacuation traffic from PAZ. However, it may be difficult to restrict such evacuation because the decision of evacuation depends on individual intention when the evacuation order is not announced. Thus, the enlightenment to UPZ residents is important. The ETE result is useful for this enlightenment because it shows how the shadow evacuation prevents from the evacuees of PAZ, who have priority to evacuate. Fig. 9 shows the example of expression of the impact to the PAZ evacuation time by the shadow evacuation.

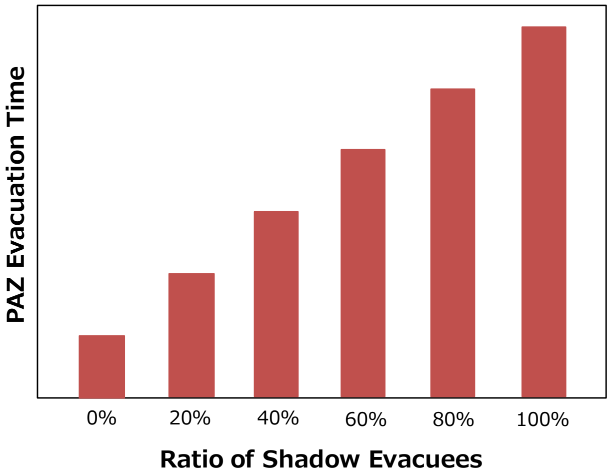

Fig. 9– Example of expression of the impact to the PAZ evacuation time by the shadow evacuation

Regarding the evacuation from UPZ, one of the most significant factors is the contamination inspection. The evacuees from UPZ is to be inspected whether he/she is contaminated. However, the inspection takes time and the large number of evacuees has to be inspected Thus the congestion around the contamination inspection place occurs. This much affect the evacuation time. If the contamination inspection is held at, for example, the place of refuge which is far away from the nuclear facility and is safe, the evacuation time until the place of refuge may become shorter. This means the reduction of the possibility of radiation exposure of evacuees from UPZ. However, the contaminated area possibly expands. The residents of the place of refuge do not want to be exposed to contamination. Thus it is necessary to make a decision to choose either the repression of the expansion of contamination or the reduction of possibility of radiation exposure of evacuees from UPZ.

There are other issues on the evacuation. Basically, the evacuation route should be determined and be shown to the residents in advance. This is for safety of evacuees. Without the specific evacuation route, some evacuees may lose their way. Moreover, if the evacuation route is determined, it becomes easier to control the evacuation traffic. However, when the specific evacuation route is determined, a lot of evacuation vehicles concentrate in same route, which may cause traffic congestion and longer evacuation time. Thus it is necessary to make a decision to choose either easier control or the shorter evacuation time.

A technical issue on the ETE is that the implementation of the ETE takes a long time (e.g. 6 to 10 months). This is because the building of a detail simulation model including each evacuation route and each signal is needed. In addition, when the micro traffic simulation model is used and tens of thousands of vehicles one by one are simulated, the execution of ETE simulation takes much time, though it depends on the range of simulation area and the number of vehicles simulated. Of course, to use micro traffic simulation model has a lot of advantage, but it is fact that the implementation of the ETE takes costs.

On the other hand, the evacuation plan is updated at every opportunity; for example, the change of the evacuation route, the reconsideration of the contamination inspection place, and the alteration of the destination to evacuate, and so on. The local government may want to verify the influence of the update upon the evacuation situation, even roughly. Therefore, it is desirable that the implementation of simulation to verify the impact of the update becomes quicker. For this purpose, some approach will be effective, such as use of macro traffic model or calculation of a rough estimate. We consider that it is better that the ETE with such simple method is implemented occasionally and the detailed ETE using micro traffic simulation is implemented once in some years.

7. Conclusions

In this paper, we described the usefulness and effectiveness of the ETE. We described the objective and the flow of the implementation of the ETE. Then, we showed how the ETE developed in Japan and mentioned the application of the ETE. In addition, we described the current issues on the evacuation in the nuclear disaster and the technical issues on the implementation of the ETE.

The evacuation plan should be updated occasionally since the situation of the evacuation area changes constantly. Therefore, the ETE also should be implemented along with the update of the evacuation plan or the change of situation in the evacuation area.

As well as the nuclear disaster, other disaster such as a volcanic eruption and the accident of the chemical factory may cause a large-scale evacuation. The technic of the ETE will be useful for such a large-scale evacuation. We hope that these technics contributes to improvement of the effectiveness of the evacuation planning and to people's security and safety.

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