Resilience Concept for Evaluating Radiological Emergency Plan

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1. Introduction

The frequency of disasters has been increasing around the world, and the extent of the damage has also been widening. Especially nuclear and radiological accidents such as the Fukushima Daiichi accident in March 2011 are disasters that cause significant consequences to people, the environment or the facility in a wide area and complex manner. After the Fukushima Daiichi accident, the public awareness and interest of nuclear and radiological accidents significantly increased. Accordingly, the national emergency preparedness and response to minimize the impact of the accidents are becoming more important as that of awareness.

In case of radiological emergency response plans in South Korea, the evacuation of residents and the diffusion of radioactive materials are assessed separately with deterministic assumptions. However, there are lots of uncertainties such as how people evacuate, how the radioactive materials are diffused, whether the related resources such as power system, telecommunication, transportation work properly and so on.

In this paper, we newly define resilience and suggest it as a metric for evaluating the effectiveness of the emergency evacuation plan taking into account the uncertainties. Thus, we present an emergency evacuation simulation model using Agent-based modelling (ABM) for measuring resilience. With the resilience metric and the simulation model, it could be possible to quantitatively evaluate the emergency evacuation plan and find an optimal plan.

2. Resilience

Since its origins in the study of materials, resilience has been applied in various areas such as psychology, ecology, etc. There are lots of different definitions of resilience depending on the subject area. A broad concept of resilience is the ability of individuals, communities and states and their institutions to absorb and recover from shocks, whilst positively adapting and transforming their structures and means for living in the face of long-term changes and uncertainty [1]. For the disaster risk management (DRM), resilience is defined as 'the ability of countries, communities and households to manage change, by maintaining or transforming living standards in the face of shocks or stresses – such as earthquakes, drought or violent conflict – without compromising their long-term prospects' [2] or 'the capacity of a system, community or society potentially exposed to hazards to adapt, by resisting or changing in order to reach and maintain an acceptable level of functioning and structure' [3]. Tierney and Bruneau measured resilience of an infrastructure by the functionality of an infrastructure system after an external shock and also by the time it takes to return to pre-event level of performance [4]. Within the context of the various application, resilience also could be one measure for evaluating an emergency evacuation plan. In this study, we defined the meaning of resilience for an emergency situation as 'How fast stresses go back to its original level (or a certain threshold)'. Accordingly, we defined resilience as 'Probability that the stresses go back to its original level (or a certain threshold) within a required time t under given conditions'.

$$\text{Resilience}(t) = \Pr(T < t|conditions) \quad (1)$$

The conditions could be the availability of resources, the strength of stressors (e.g. radioactive materials in a radiological emergency situation), and so on. Figure 1 shows the stress over time in an emergency situation. In the situation of a radiological emergency, the expected stress could be an average or a total dose of residents. It will increase after the accident occurs and decrease as the residents evacuate, medical care is conducted and radioactive source terms decay. In the figure, t_0 is the time when the average reaches a threshold (dose limit) and $t_{recovered}$ is the time when the average falls below the threshold. Here, evacuation time is defined as follows.

$$T_{evacuation} = t_{recovered} - t_0 \quad (2)$$

The evacuation time varies with the conditions. To take into account the uncertainty of conditions, the emergency evacuation simulation is conducted multiple times resulting in the distribution of $T_{evacuation}$. Finally, as the cumulative distribution function (CDF) of the distribution of $T_{evacuation}$, we can obtain resilience curve as shown in Figure 2.

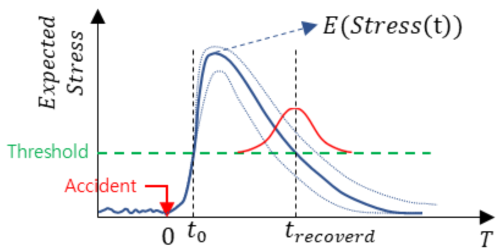

Fig. 1. Expected stress over time in an emergency

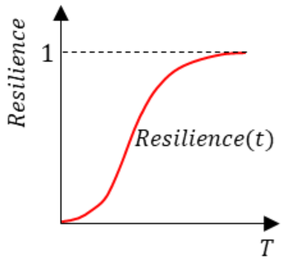

Fig. 2. Concept of resilience in view of probability

3. Simulation of Radiological Emergency Evacuation

In this study, we used ABM for simulating the radiological emergency evacuation considering the uncertainty of the conditions. ABM is a method that can simulate complex phenomena with a collection of autonomous decision-making entities called agents. It models microscopic behaviour rules of the agents, and the modelled agents interact with each other and their environment continuously providing macroscopic insights of a system or a phenomenon. Within ABM, it is possible to model and simulate how people (agents) evacuate, how the radioactive materials evacuate (environment) and the impact of the availability of resources simultaneously.

We implemented a simple case study to demonstrate how to measure resilience. NETLOGO which is a tool for ABM is used. The simulation area is a part of Republic of Korea where an NPP is located. We simulated the scenario that a radiation accident occurs at the NPP and after the accident, the residents evacuate to the one shelter. An arbitrary value was used for the amount of radioactive material source. Therefore, the agents' dose was not theoretically calculated, and we focused on the tendency of exposure. Agents evacuate to a shelter by A* model. Leaked radioactive material source moves by a steady wind field and the diffused concentration is calculated by puff model. Every time step, the concentration where an agent is located is accumulated and we assumed this value as a dose of the agent. It was assumed that there are sufficient reliefs at the shelter so that the evacuee's dose becomes 0 at the shelter. The initial dose and the threshold are assumed as 0. An average dose of the agents is calculated every time step and the simulation is stopped when the average dose becomes 0. We simulate this scenario 1,000 times and Figure 3 shows the results.

In the figure, the line and the dotted lines represent 50 percentile, 95 percentile, and 5 percentile value, respectively. From the simulations, evacuation time distribution and its CDF which is resilience are obtained as shown in Figure 4 and 5, respectively. By the definition of resilience we defined, if the required time is 4,800 sec, then the resilience is 0.55 which means that the probability that the residents' dose goes back to its original level within 4,800 sec is 55%.

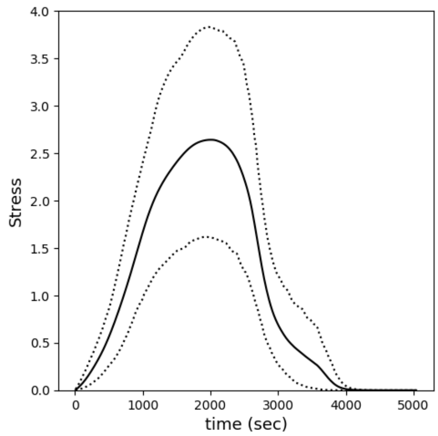

Fig. 3. Stress over time resulted from 1,000 simulations

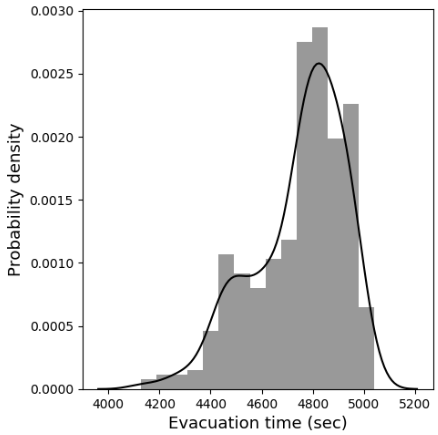

Fig. 4. Evacuation time distribution

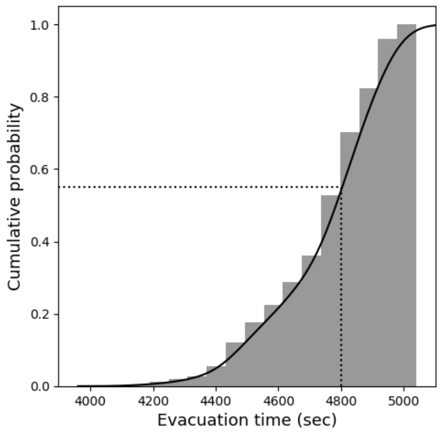

Fig. 5. Resilience curve

4. Conclusions

In this study, we suggested resilience metric that we newly defined for evaluating the emergency evacuation plan considering the uncertainties. We also presented the procedure of evaluating resilience with a simple scenario. By introducing resilience metric, it could be possible to evaluate quantitatively the emergency evacuation plan and help us to make decisions such as what the optimal path of evacuation is and how to effectively distribute limited resources.

For further study, we plan to develop an objective function using resilience to obtain the optimized evacuation plan.

5. Acknowledgement

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