Application of Resilience Metrics to Nuclear Accident Consequence Assessment

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Abstract: Nuclear accident consequence index (NACI) provides a framework to cover different types of accident consequences, namely health, environmental, economic and social. However, it cannot capture the change of consequences with time which is often influential to the decision of consequence mitigation countermeasures. This study aims to consider the methodology to apply resilience metrics to nuclear accident consequence assessment, in order to reveal the time-dependent change of the nuclear accident consequences. Four resilience indices representing: radiation exposure, relocated people, relocated area and contaminated area, are used to quantify the resilience of the society against nuclear accidents. Relocation cost, psychological effect compensation and decontamination are defined as costs of resilience. All resilience indices bounce back close to the stable original state after several years, though none of them return to the stable original state. Bias in population distribution and extreme weather conditions can significantly affect the resilience indices. Costs attributed to relocation are much lower than decontamination cost, due to the difference in dose criterion. Further analysis on the sensitivity of criteria for adoption of protective/mitigative countermeasures can provide useful insights for decision making of protective/mitigative countermeasures.

Keywords: Consequence Assessment, Resilience, Time-Dependent, Severe Accident

1. INTRODUCTION

The accident at the Fukushima Daiichi Nuclear Power Station (1FNPS) emphasizes the fact that severe accidents in nuclear reactors can bring about various consequences. Release of radioactive materials from the power plants impacts the society in many aspects, namely health, environmental, economic and social. K. Silva et al. [1,2] proposed the nuclear accident consequence index (NACI) which provides a framework to cover these four aspects of the accident consequences. NACI uses common monetary unit to quantify different accident consequences, and thus provides the whole picture of the accident consequences at a glance. Public comprehension of NACI can also be easily obtained as the monetary unit is widely used to represent the extent of consequences within the framework of risk assessment [3,4].

However, NACI is the sum of the accident consequences which is a value at a determined point of time within the timeframe of the accident, usually the end of the accident. It cannot capture the change of consequences with time which is often influential to the decision of consequence mitigation countermeasures. For example, NACI shows the same value for a year of relocation of 100,000 people and 10 years of relocation of 10,000 people. The perception on consequences of these two cases of relocation by the decision maker of the public may be different, thus may affect the types of countermeasures to be taken.

Resilience refers to the ability of an entity to bounce back, based on its origin in Latin. Resilience metrics, which are used to assess the resilience of the system, normally include the original state, the disrupted state and the recovered state of the system [5]. Resilience metrics can be applied to the nuclear accident consequence assessment framework, by considering the occurrence of an accident in a society as a disruption of a system. It can complement the NACI by enabling the visualization of changes of accident consequences with time. This study aims to consider the methodology to apply

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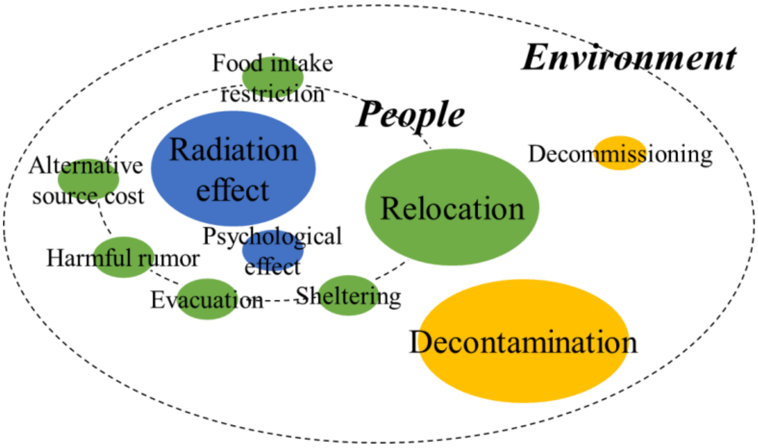

Figure 1. Components of nuclear accident consequence index (NACI) (adapted from K. Silva et al. [2])

resilience metrics to nuclear accident consequence assessment, in order to reveal the time-dependent change of the nuclear accident consequences.

2. PRECEDING STUDIES

2.1. Nuclear Accident Consequence Index (NACI)

K. Silva et al. [1] first introduced the index to cover different consequences of a nuclear accident as "cost per severe accident." It consists of ten components divided into four categories. Two costs representing health effects are radiation effect cost and psychological effect cost. Economic impacts are evaluated by summing sheltering cost, evacuation cost, relocation cost, food restriction cost and alternative source cost. Harmful rumor cost is used to quantify the social impacts. Environmental impacts are represented by decommissioning cost and decontamination cost.

K. Silva et al. [2] restructured the "cost per severe accident" to the illustration in Figure 1 in order to be consistent with the IAEA framework which aims to protect people and the environment from harmful effects of ionizing radiation [6], and renamed the index to Nuclear Accident Consequence Index (NACI) in order to avoid the confusion between the accidental cost and the monetary values that is used to represent various kinds of consequences. Three components, namely radiation effect index, relocation index and decontamination index, are specified as major components since it occupy nearly 90 percent of the total consequences.

2.2. Practical Resilience Metrics

A number of definitions have been given to "resilience." Key properties of a resilience system include absorption, adaptation, rapid recovery, anticipation of disruption, flexibility, stability, persistence, tolerance, survivability, and so on [7]. There are also quite a few of methods to evaluation these properties, both qualitative and quantitative. In order to apply the resilience metrics to the nuclear accident consequence assessment framework, the author decided to focus on quantitative methods that can be used to assess the recoverability of the system (society) after a disruption (a nuclear power plant accident). The authors adopted the resilience metrics of D. Henry and J. E. Ramirez-Marquez [5]. They evaluate the change of the interested system parameters (figures-of-merit) from the steady state (i.e. stable original state) to the disrupted state, and monitor the change with time until it reaches a steady state once again which maybe same or different from the previous steady state (i.e. stable recovered state). The transition of the system resilience after the disruption is depicted in Figure 2.

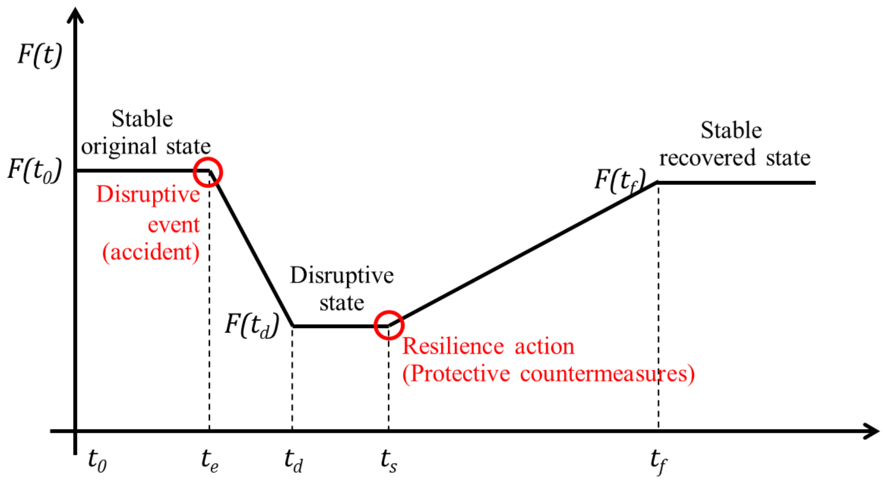

Figure 2. Transition of system resilience (adapted from D. Henry and J. E. Ramirez-Marquez [5])

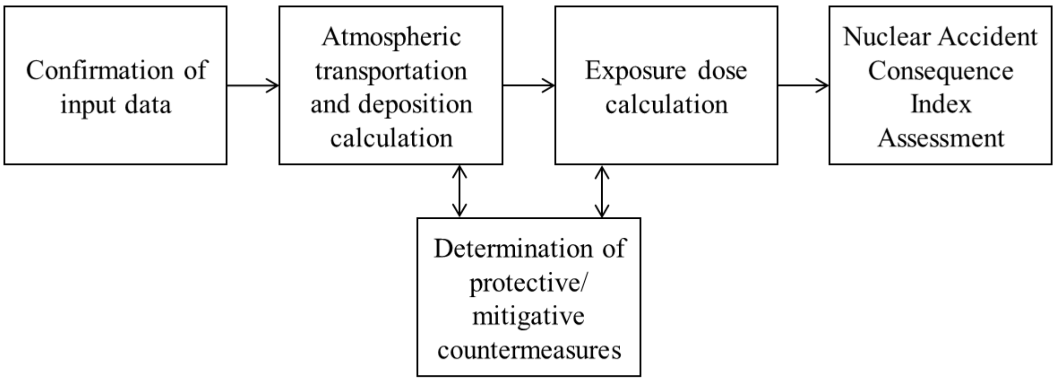

Figure 3. Flow of the Nuclear ACcident Consequence Assessment code (NACCA)

3. METHODOLOGY

3.1. Nuclear Accident Consequence Assessment Code (NACCA)

Nuclear ACcident Consequence Assessment code (NACCA) was developed referring to the structure and the methodology of the Off-Site Consequence Analysis code for Atmospheric Releases in reactor accidents (OSCAAR) [8]. NACCA is divided into five modules as shown in Figure 3. In the first module, the code confirms that all input data is in place, including source term data, meteorological data, population data, land use data and economic data. Source term data and meteorological data are then used to evaluate the atmospheric transportation and the deposition of the released radioactive materials. Air and ground concentrations of the target area are used to calculate the early and chronic exposure dose which will be the baseline for the determination of protective and mitigative countermeasures, e.g. sheltering, evacuation, relocation, decontamination. Population data is used for the evaluation of population movement, and land use data is used for the design of decontamination scheme. After the countermeasures are decided, their effects are reconsidered in deposition and exposure dose calculations. Decontamination helps reduce the ground concentration while other countermeasures help reduce the public exposure. All results are combined with population data, land use data and economic data to perform the nuclear accident consequence assessment which is the final step of the calculation. In this study, the exposure dose calculation module is modified to output yearly exposure dose distribution, and the nuclear accident consequence index module is modified to enable calculation of the resilience metrics described in the following section.

Table 1. Figures-of-merit and respective resilience actions

Figures-of-merit (F(t))	Resilience actions
Number of people being exposed to radiation dose over the prescribed dose limit	Relocation, decontamination
Number of relocated people	Decontamination
Size of relocated area	Decontamination
Size of contaminated area	Decontamination

3.2. Resilience Metrics for Nuclear Accident Consequence Assessment

D. Henry and J. E. Ramirez-Marquez require: system of interest, disruptive event, figure-of-merit (F(t)) and resilience action, to be determined in order to evaluate the resilience of the system. The society, more specifically the communities affected by the accident, is the system of interest, and the nuclear power plant accident is the disruptive event. The authors defined four figures-of-merit and their respective resilience actions in Table 1 based on the three major components of NACI, namely radiation effect index, relocation index and decontamination index. The change of the resilience of the society is measured by the change with time of these four figures-of-merit. The cost of resilience which represents the resources needed to achieve the resilience of the society is the sum of the cost needed for all resilience actions.

The four figures-of merit are turned into the resilience index by comparing with the stable original state. The radiation exposure resilience index RI_{RE} is obtained from

$$RI_{RE} = 1 - \frac{P_{RE}}{P_{Total}}. \quad (1)$$

P_{RE} is the number of people whose exposure dose exceeding the dose limit [people] while P_{Total} is the number of the total population within the radius of 200 km from the release location (target area) [people]. The relocated people resilience index RI_{RP} is obtained from

$$RI_{RP} = 1 - \frac{P_{RL}}{P_{Total}} \quad (2)$$

when P_{RL} is the number of people who relocated and have not return to their home [people]. The relocated area resilience index RI_{RA} is obtained from

$$RI_{RA} = 1 - \frac{A_{RL}}{A_{Total}}. \quad (3)$$

A_{RL} is the size of the area where people relocated [km^2] while A_{Total} is total target area [km^2]. The land contamination resilience index RI_{LC} is obtained from

$$RI_{LC} = 1 - \frac{A_{RE}}{A_{Total}} \quad (4)$$

when A_{RE} is the size of the area where exposure dose exceeds the dose limit [km^2].

4. RESILIENCE ASSESSMENT

4.1. Calculation Conditions

The calculation conditions are shown in Table 2. The authors assumed the long-term station blackout accident [9] as the hypothetical accident in this study, since it has a large core damage frequency and large release frequency, and the scenario is similar to the accident happened in 1FNPS. Meteorological

Table 2. Calculation conditions

Items	Conditions
Reactor type	1,100 MWe BWR-5
Release location	Headquarters of Thailand Institute of Nuclear Technology
Hypothetical accident	Long-term station blackout
Coverage of meteorological, population, land use and economic data	Within the radius of 200 km from the release point
Meteorological data type	Hourly wind speed, wind direction, precipitation, weather stability of 2014
Meteorological sampling method	Random sampling (100 samples)
Decontamination methods	Based on methods used in Chernobyl and 1FNPS accidents
Dose limit	1 mSv/year
Relocation initiation dose	20 mSv/year
Relocation lifting dose	20 mSv/year
Number of decontamination worker	10,000 person/year

Table 3. Source term data

Release time [hr]	Duration [hr]	Release ratio to core inventory [-]							
		Noble gas	Organic I	Inorganic I	Cs-Rb	Te-Sb	Sr-Ba	Ru	La
12.7	4.0	2.9E-1	1.7E-4	3.1E-3	5.4E-3	1.1E-3	2.5E-4	4.5E-9	3.1E-7
16.7	25.0	7.1E-1	6.3E-3	1.2E-1	4.2E-2	7.4E-2	2.7E-3	3.1E-8	3.3E-6

data is taken from the database of the National Oceanic and Atmospheric Administration (NOAA). Population data, land use data and economic data are those of 2014 or most recent information. As Thailand has no experience in decontamination after an accident, data from Chernobyl and 1FNPS accidents are used. The dose limit is used to determine the extent of effects from radiation exposure. The exposure to dose exceeding the dose limit is considered non-negligible. The relocation initiation and lifting doses are used to determine the relocation scheme, and were set based on the real criteria used during the 1FNPS accident. The number of decontamination worker is used to limit the coverage of area being decontaminated in a year in order to obtain a more realistic scheme of decontamination. The source term data of the hypothetical accident is shown in Table 3, where the release is divided into two steps in order to accurately account for the release characteristics.

4.2. Results and Discussion

The average, 5th, 50th, 90th, 95th percentile values of the four resilience indices from year 0 to year 50 are shown in Figure 4. All resilience indices bounce back close to the stable original state (= 1) after several years, though none of them return to the stable original state. Same criterion (excess of dose limit) is used to determine the affected cohort for the radiation exposure resilience index and the land contamination resilience index, thus the shapes of the line graphs are quite similar. However, since the degree of bias in population distribution is quite high and around half of the target population is in the area around the capital which is approximately 50 – 80 km from the release location, the radiation exposure resilience index marks very low values when the urban population are affected while that cannot be observed in the case of land contamination resilience index. Similar difference can be observed between the relocated people resilience index and the relocated land resilience index, though the values of these two resilience indices are generally larger than the first two resilience indices. This is because the relocation lifting dose is set to 20 mSv/year while the dose limit is set to the public dose limit for normal situation recommended by the International Commission on Radiological Protection (ICRP) at 1 mSv/year [10]. Therefore, a large group of people return home several years after the accident to receive exposure dose over the public dose limit for normal

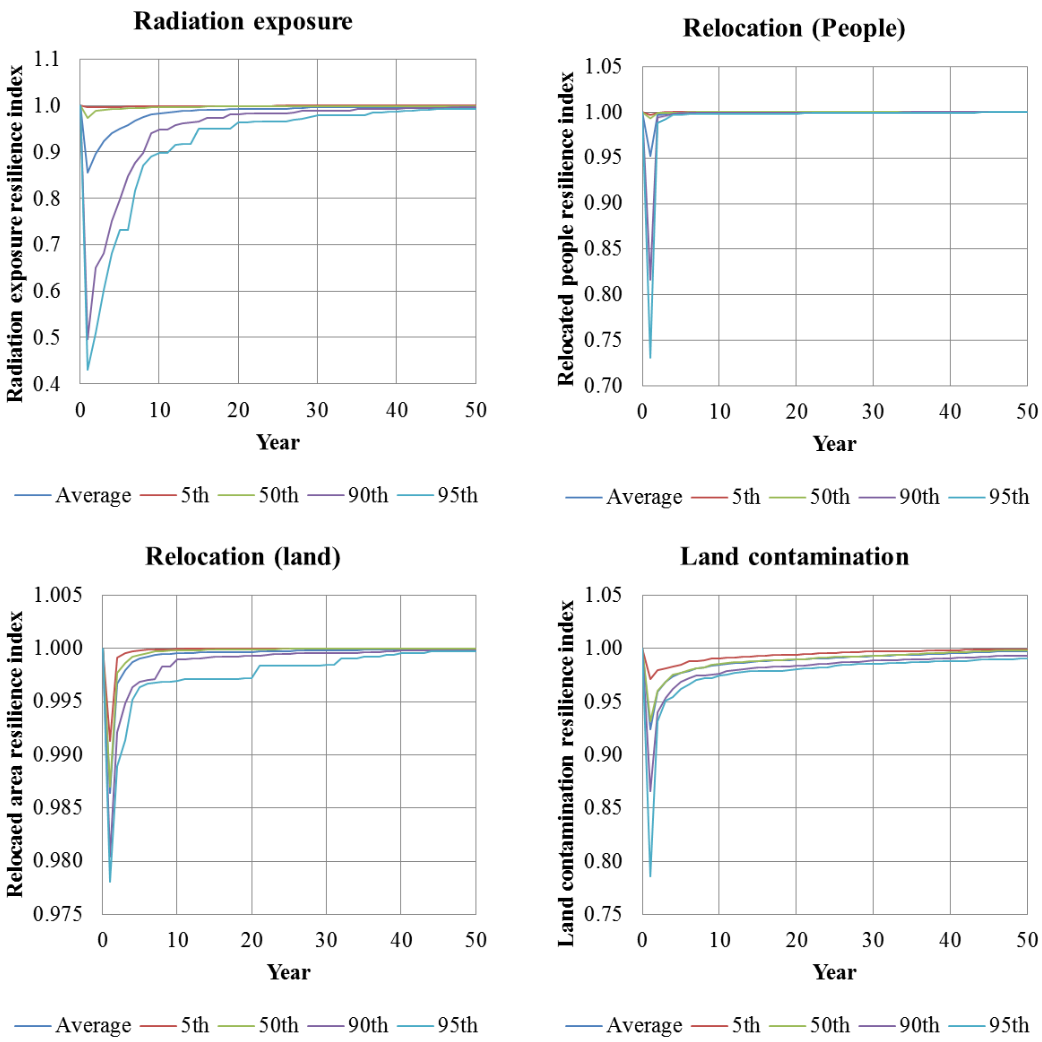

Figure 4. Change of figures-of-merit

Table 4. Costs of resilience

Costs of resilience	Average	5th	50th	90th	95th
Relocation cost	3.69	0.40	1.00	12.71	18.47
Psychological effect compensation	1.00	0.05	0.59	3.06	4.26
Decontamination cost	18.73	5.00	11.27	40.96	81.76

situation. Note that the dose received by this specific group of people is less than the upper bound (20 mSv/year) of the recommend dose band for existing exposure (1 – 20 mSv/year), and much lower than the recommended dose band for emergency exposure (20 – 100 mSv/year) of the ICRP [10].

Costs of resilience are shown in Table 4. Relocation cost and psychological effect compensation to relocated people are considered as costs of relocation. Decontamination cost includes both cost for decontamination itself and the cost for radioactive waste management. All costs are normalized using the 50th percentile value of the relocation cost. Costs attributed to relocation are much lower than decontamination cost. The reason to this is that decontamination is needed in all area where dose exceeds 1 mSv/year while relocation will be applied to only area where dose reaches the relocation initiation dose of 20 mSv/year.

It can be observed in all resilience indices that the 90th and 95th percentile values are much smaller than the average or 50th percentile values, and the average value is always smaller than the 50th percentile values. These apply other way round to the costs of resilience. These imply that there are only few cases with extreme weather condition that the level of resilience reduces drastically, while the reduction in most cases is moderate.

Note that some of the conditions in Table 2 can vary according to the criteria for protective/mitigative countermeasures adopted by the decision maker. If the upper bound of the recommended dose band for existing exposure is adopted as the dose limit, the change is radiation exposure resilience index and land contamination resilience index will be rather moderate. Selection of relocation initiation and lifting doses can affect several resilience indices. When these doses are set higher the radiation exposure resilience index will be smaller, but the resilience indices related to relocation will give larger values and the relocation cost will be lower, and vice versa. The number of decontamination workers is also an influential parameter. The larger the number is, the faster the decontamination will be. If it is set to a higher value, all resilience indices will likely become larger, though the decontamination cost will also be much larger. As a future task, sensitivity analysis of criteria for adoption of protective/mitigative countermeasures must be performed in order to provide useful insights for decision making of protective/mitigative countermeasures.

5. CONCLUSION

Resilience metrics of D. Henry and J. E. Ramirez-Marquez were applied to nuclear accident consequence assessment. Nuclear ACcident Consequence Assessment code (NACCA) was used for the calculation. Four figures-of-merit, namely Number of people being exposed to radiation dose over the prescribed dose limit, number of relocated people, size of relocated area and size of contaminated area; and two resilience actions, namely relocation and decontamination, were defined. Important findings from the study can be summarized as follows:

- Time-dependent characteristics of accident consequences, specifically the radiation exposure, the relocation and the contamination of the area, were revealed.
- All resilience indices bounce back close to the stable original state (= 1) after several years, though none of them return to the stable original state.
- Bias in population distribution can significantly affect the values of resilience indices related to people, thus it is important to have separate resilience indices to monitor the change with time of both people and area.
- Extreme weather condition can lead to significant reduction of resilience comparing to the case of most probable weather condition, thus it is important to evaluate the resilience indices of various weather conditions.
- Costs attributed to relocation are much lower than decontamination cost. This is because of the lower dose criterion for decontamination (1 mSv/year), comparing to the dose criterion for relocation (20 mSv/year).

Protective/mitigative countermeasures adopted by the decision maker can vary and may affect the resilience of the society against nuclear accidents. Sensitivity analysis of the criteria for adoption of protective/mitigative countermeasures must be performed in the future in order to provide useful insights for decision making of protective/mitigative countermeasures.

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