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FRAGILITY AND OPERATIONAL TIME ASSESSMENT MODEL OF MOBILE EMERGENCY EQUIPMENT FOR NPP UNDER SEISMIC RISK

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ABSTRACT

The authors proposed a fragility and operational time assessment model of the mobile emergency equipment in a site. This model consists of details when the seismic motion is in progress (A) and the details after the seismic motion (B). B is further divided into recovery time assessment (B1) and assessment of time up to core damage and containment vessel damage (B2). It determines whether or not B1 is smaller than B2 and in addition, identifies important factors related to B1 and B2. The proposed model was applied to arbitrary sites, and A and B1 were estimated, and the usefulness was confirmed through the assessment. Improvements to be made in the proposed model were cited as well.

INTRODUCTION

The Tohoku-Chihou-Taiheiyo-Oki Earthquake occurred at 14:46 on March 11, 2011, with a magnitude of 9. Strong seismic motion was observed at the six units of Fukushima-Daiichi nuclear power plant (F1-NPP); control rods were inserted and the reactor was shut down normally. A tsunami struck 46 minutes after the earthquake shutdown, and many equipment of the sea-water supply system and emergency power supply system were flooded. External power supply system also lost its function due to the strong seismic motion. As a result, there was station black out (SBO) and loss of functionality of the reactor cooling system leading to core damage, and radioactive materials were released outside the site (F1-NPP accident) (Japanese government, 2011).

After the F1-NPP accident, handling of mobile severe accident equipment (MSAE) was established as a part of severe accident (SA) measures in Japan (Nuclear Regulation Authority, 2011). Meanwhile, NRC "Order Modifying Licenses with regard to Requirements for Mitigation Strategies for Beyond-Design-Basis External Events" (U.S.NRC.2012) and NEI "Diverse and Flexible coping strategies (FLEX) Implementation Guide" (NEI.(2012) were formulated in the (U.S.NRC.2012), response consisting of three phases has been shown. Phase1: Response within 8 hours with the help of permanent facilities within the site, Phase 2: Response within 8 to 24 hours with the help of FLEX facilities such as mobile facilities etc., Phase3: Response after 24 hours with the support from ERC and SAFER. However, the concept of evaluating the fragility of MSAE is not necessarily sufficient.

As part of seismic risk assessment, the authors proposed a fragility assessment model for the MSAE systems on the site. This model consists of details when the seismic motion is in progress (A) and the details after the seismic motion has ended (B). B consists of Recovery Time Assessment (B1) and assessment of time up to core damage (CD) and containment vessel damage (CVD) (B2). In order to verify the usefulness of the proposed model, the authors conducted plant walk-downs at arbitrary sites and gathered related information. Using this information, aforementioned A and B1 were estimated and in addition, the usefulness of the proposed model was verified through this assessment. Moreover, the improvements to be made in the proposed model were indicated as well.

This report gives an outline of the proposed model and plant walk-down. Moreover, the results of evaluating A and B1, the results of verifying the usefulness, and the improvements to be made in the proposed model are mentioned here as well.

PROPOSAL OF FRAGILITY ASSESSMENT MODEL FOR MOBILE SA EQUIPMENT SYSTEM

Concept for fragility assessment model of mobile severe accident equipment systems

The fragility assessment model for the MSAE systems consists of details when the seismic motion is in progress (A) and the details after the seismic motion has ended (B) as shown in **Figure 1.** B further consists of recovery time assessment (B1) and assessment of time up to core damage and containment vessel damage (B2). It determines whether or not B1 is smaller than B2 and in addition, identifies important factors related to B1 and B2. If it is not smaller, countermeasures targeting important factors are examined and the effectiveness of the measures is verified. Specific details of A and B are as follows.

(1) Details when seismic motion is in progress (A)

A consists of the following items shown in Figure 1. ① Assessment of loss of functionality of MSAE during seismic motion irrespective of presence of lashing, ② Assessment of damage of MSAE approach road, ③ Assessment of damage of refueling yard during seismic motion, ④ Assessment of stress condition of emergency personnel, etc. during seismic motion.

(2)Details after seismic motion has ended (B)

B1 consists of the following items shown in Figure 1. ① Preparation for mobilization depending on the extent of failure of MSAE during seismic motion, ② Recovery time assessment of MSAE approach road, ③ Assessment of required time for shifting the MSAE

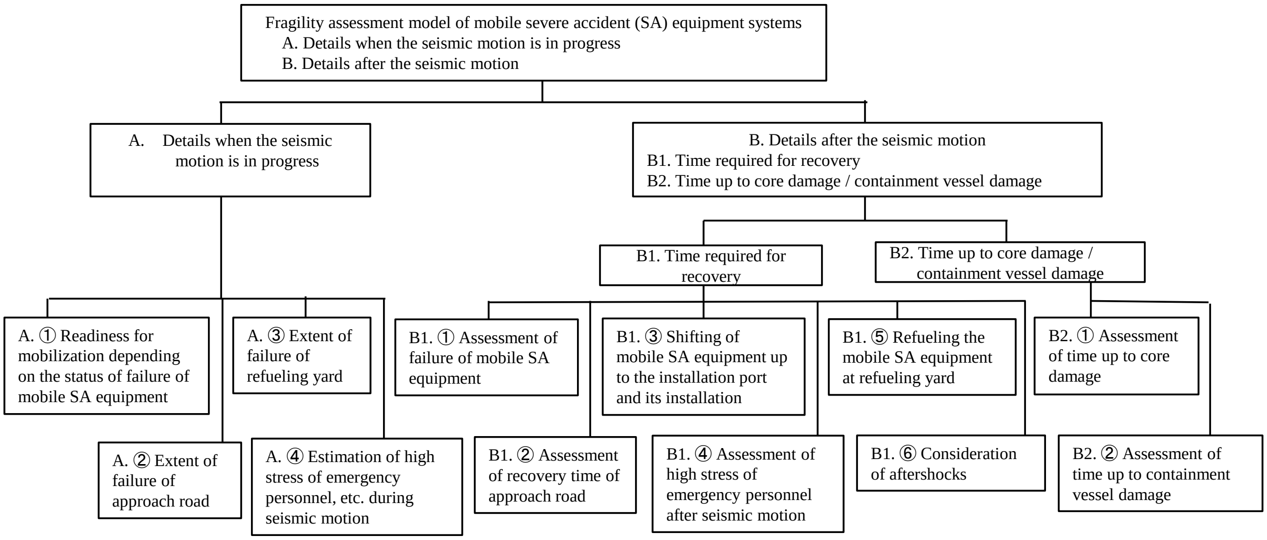

Figure1. Fragility assessment model for mobile severe accident equipment system

up to the installation port and installing the equipment, ④ Estimation of work efficiency considering the high stress of emergency personnel during seismic motion, ⑤ Assessment of required time for refuelling the MSAE, ⑥ Assessment of aftershocks.

B2 consists of ① Assessment of time up to CD and ② Assessment of time up to CVD.

Plant walk-down for verifying the usefulness of the proposed model

In the plant walk-down, after choosing an arbitrary site, the target range for the proposed model was narrowed down to A and B1 and related public information was collected (Shikoku Electric Power Co., Ltd.2016). This is scheduled to be carried out for B2 in the next phase.

The outline of the public information collected during the plant walk-down is as shown in Figure 2 to Figure 5. Geomorphic environment of arbitrary site (Fig.2), MSAE (Fig.3), approach road recovery equipment (Fig.4), refueling tank (Fig.4), training on connection of MSAE and night training (Fig.5).

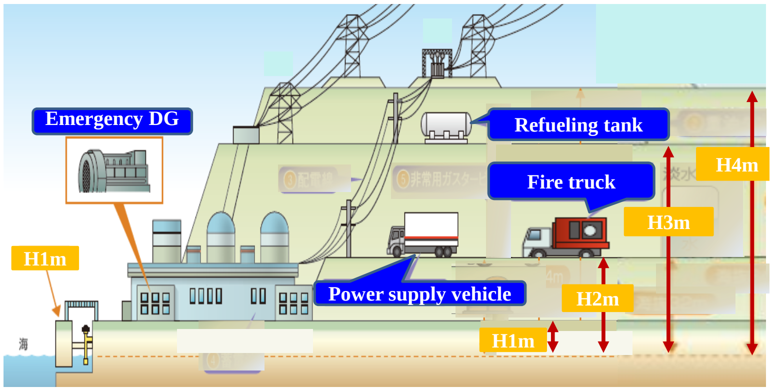

Figure2. Outline of related public information in plant walk-down

Figure3. Mobile SA equipment (Left: Power car, Center: Fire truck), Right: Status of lashing of SA equipment

Figure4. Heavy machinery for recovery work of approach road, etc. (Left: backhoe, Center: wheel loader, Right: Refueling tank)

Figure 5. Left: Status of training on installation work at SA equipment installation port and Right: Status of night-time work training

Procedure from earthquake occurrence up to recovery of mobile severe accident equipment

The procedure from earthquake occurrence up to recovery of MSAE is as follows.

① Before the earthquake occurs, the emergency response personnel are stationed in the emergency response building at an altitude of H1 m. Emergency response is not carried out during seismic motion to prevent erroneous

② After the seismic motion ends, the emergency response personnel gather at the emergency response building office which is at an altitude of H1m, and after roll-call, they go off to verify the status of site damage.
③ From the office at an altitude of H1m, the emergency response personnel assemble at the MSAE installation yard which is at an altitude of H2m. After inspecting the secured SAE, if there is no abnormality, the lashing belt is cut with scissors, and so that the equipment can be shifted.
④ After verifying the status of damage of the approach road, if required, the recovery work of the road, etc. is carried out using recovery heavy equipment (Fig. 4) installed at an altitude of H2m.
⑤ After the recovery of the road, etc., the SAE self-propels through the approach road and moves to the power supply and water supply connecting port near the reactor building of altitude H1m.
⑥ The electric cable and water supply hose is connected to the power supply and water supply connection port (Fig. 5).
⑦ Refueling is carried out from the fuel oil tank at an altitude of H3m (Fig. 4), depending on the time required for recovery.

FRAGILITY ASSESSMENT OF MOBILE SA EQUIPMENT DURING SEISMIC MOTION

Structure and vibration behavior of target mobile severe accident equipment

Power supply vehicles (PSVs) and fire trucks (FTs) were the target MSAE. **Figure 6** shows the structure and vibration model of the PSA without lashing. An example of a PSV with lashing is shown in **Figure 3**. Lashing belt is being used as a means for securing the tire portion shown in **Figure 3**. As a result of the plant walk-down, the tire portion and the concrete foundation were fixed rigidly by the lashing belt. Therefore, it was assumed that the spring of the tire part was perfectly rigid.

However, since the suspension of the PSV is unrelated to the lashing of the tire portion, the upper part of the suspension was handled as an SDOF model. Regarding the structure and the Vibration behavior of the FT, it was dealt with similar to that of the PSV.

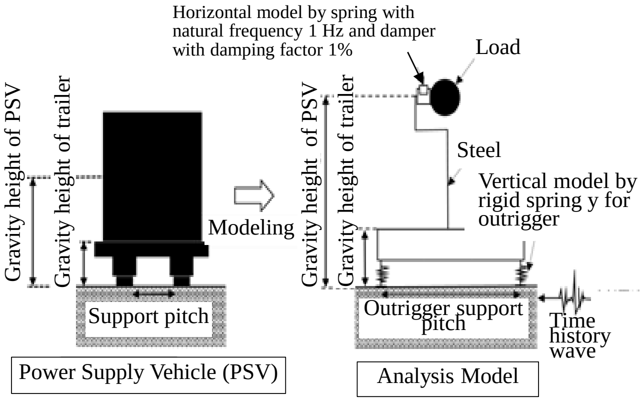

Figure 6. Vibration model of power supply vehicle
(Left: structure of power supply vehicle,
Right: vibration model without lashing)

Fragility assessment of power supply vehicle

(1) Assessment result without lashing

The coefficient method was used to assess the fragility of the power supply vehicle (Ebisawa, K., Yamada, H. et.al. 2016). Damage mode of the power supply vehicle without lashing was determined as tumbling and dynamic functionality loss based on the published documents (Shikoku Electric Power Co., Ltd.2011). The median value of yield strength in both the damage modes is based on document (Shikoku Electric Power Co., Ltd.2011), and the logarithmic standard deviation of accidental and epistemological uncertainty is set based on the engineering decisions as indicated in Table 1. The design response related to realistic responses of both modes, the median value of the response coefficients representing its maintainability, and the logarithmic standard deviation were set as shown in **Table 1** while referring to the published document (Ebisawa, K., Yamada, H. et.al. 2016).

Fragilities against horizontal and vertical seismic motions for each damage mode without lashing were estimated. Figure 7 shows the fragility assessment results in the dynamic functional failure mode. From the figure, the results for both horizontal and vertical seismic motions were very small. The result of the tumbling mode was even smaller.

(2) Assessment results with lashing

As a failure mode of the power supply vehicle with the tire part lashing, assuming that tumbling is less likely, the fragilities against the horizontal and vertical seismic motions were estimated for the dynamic functional failure mode. The assessment results were smaller than that shown in Figure 7.

Fragility assessment of FT

The fragility of FT irrespective of the presence of lashing was estimated under the same conditions as those of the PSV. The result was smaller than the result of the PSV.

Table1. Elements for fragility evaluation of power supply vehicle

			Power Supply Vehicle	
			Failure Case 1	Failure Case 2
Realistic Capacity	Failure Part		Gravity Center	Same as on the left side (LS)
	Failure Mode		Relative Displacement causing Tumbling	Dynamic Function
	Median		676 mm	Horizontal: 3G / Vertical: 5G
	Logarithmic Standard Deviation (LSD) βr for Aleartory Uncertainty (AU)		0.1	Same as LS
	LSD βr for Epistemic Uncertainty (EU)		0.1	Same as LS
Realistic Response	Input Seismic Motion		2.5×Ss (2.5×570Gal)	Same as LS
	Design Response		Relative Displacement at Gravity Center: 316 mm	Horizontal: 1.59 G/Vertical: 0.97G
	Response Factor	Median	1.97	Same as LS
		LSD βr for AU	0.28	Same as LS
		LSD βu for EU	0.19	Same as LS

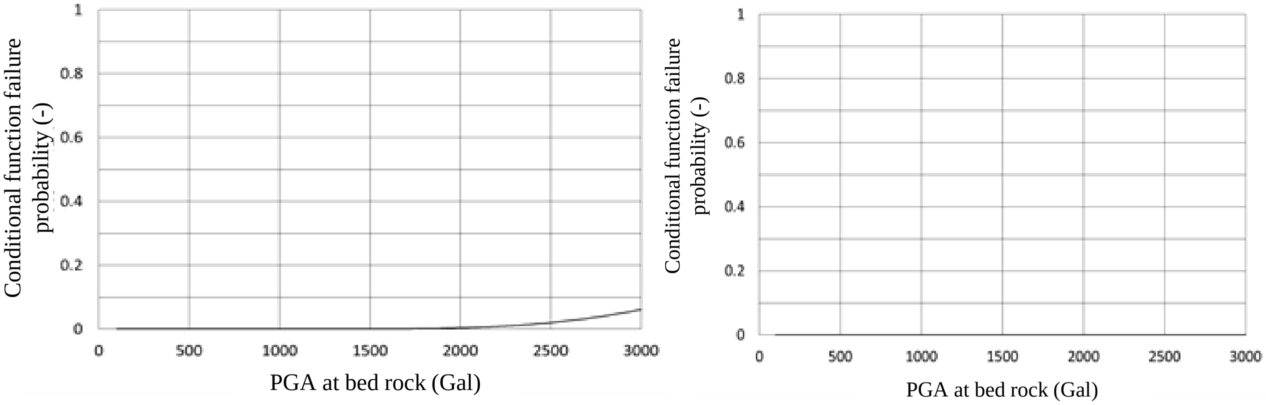

Figure7. Results of fragility assessment of power supply vehicle without lashing
(Left: horizontal seismic motion, Right: vertical seismic motion)

RECOVERY TIME ASSESSMENT MODEL AND VERIFICATION OF THE USEFULNESS OF THE MODEL

Recovery time assessment model and component items

(1) Recovery time assessment model

The time (T) required for recovery in the RT assessment model is expressed by the following equation.

T-T1+T2+T3+T4+T5

Where, T1 to T5 are as follows.

T1 (time required for emergency personnel to gather after seismic motion)
  TF11: Time required moving from the individual room in the emergency personnel building to the assembly point.
  TF12: Time required from the emergency personnel assembly point to the response location.
T2 (time required for checking on-site situation by means of patrols)
  TF21: Confirmation on the number of patrol personnel gathered
  TF22: Time for manual confirmation
  TF23: Time required by the patrol personnel to check the on-site situation
T3 (time required for recovery work of approach road)
  TF31 (Number of carry-outs of large dump truck) (N) = Vs/Vt
    TF311: amount of collapsed clod on the road from the mountainside slope of the road (Vs) (Cross-section m^2 × Road length m)
    TF312: Amount of clod loading in large dump truck (Vt)
  TF32: time required for loading large-sized dump truck using a large backhoe (td minutes / times)
  TF33: Number of large backhoes (Nb)
  TF34: Total time required for transportation by large-scale dump truck (Tds) = N (times) × td (minutes / times x unit) / Nb (units)
  TF35: Total time required considering the loss time such as change of operator shifts, etc. (ts)
  TF36: The time required during each day and night is set to half (tdn).
T4 (time required for shifting of mobile SA equipment)
  TF41: Self-propulsion speed and weighting based on weather (clear, rain)
  TF42: Self-propulsion speed and weighting based on working time zone (daytime, night-time)
T5 (time required to install MSAE at installation port)
  TF51: TF51: Time required for connection and weighting based on weather (clear, rain)
  TF52: Time required for connection and weighting based on working time zone (daytime, night-time)

Conditions for recovery time assessment

(1) Installation environment for target SA equipment:
  ① SAE: PSV, FT, etc. / ② Location and status of SAE installation: altitude, size, presence of hangar / presence of lashing / ③ Distance from the SAE installation yard to the connection port / ④ Self-propulsion speed of the SAE

(2) Status of damage of approach road and MSAE:
  ⑤ Status of damage of approach road:
    The maximum acceleration of the seismic hazard is largely divided into three regions, and the status of damage in each range is set as follows (**Figure 8**). It is called Design Seismic Motion (DSM).
      ・Region A (DSM - 2DSM):
        Possibility of damage is less
      ・Region B (2DSM - 5DSM):
        Possibility of damage is moderate
      ・Region C (5DSM onwards):
        Possibility of damage is high

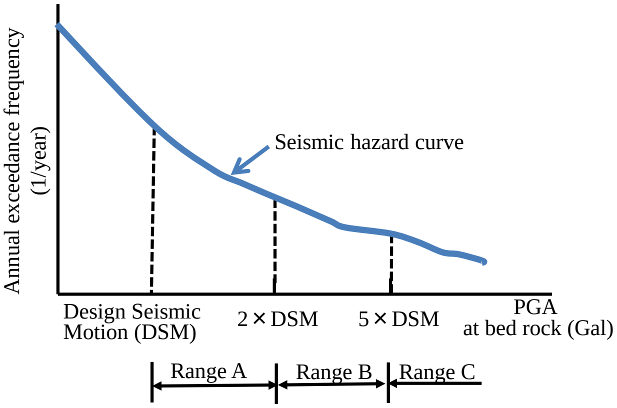

Figure 8. Outline of three ranges based on seismic hazard curves

⑥ Collapse of mountainside slope of the road: Set for each region / ⑦ Collapse of road shoulder and bumps: Set for each region / ⑧ Functional failure of MSAE: Set for each region

(3) Recovery equipment:

⑨ Heavy equipment and capacity: Large backhoe, large dump truck, large wheel loader, etc. / ⑩ Temporary materials: Iron plate, H steel for retaining wall, square bar, etc.

(4) Season, weather and working time zone:

⑪ Season: Set from spring, summer, autumn and winter / ⑫ Weather and duration time: Set to clear or rain, and in either way it is assumed to continue / ⑬ Working time zone: Set to either daytime or night-time/⑭ Night-time work environment: Presence or absence of lighting / ⑮ Weighting of weather and working time zone: In the case of rain and night-time, weighting will be in multiples of that of clear and daytime

(5) Aftershock:

⑯ Consideration of aftershocks: Aftershocks are classified into aftershocks due to the huge earthquake of magnitude M9-class and those due to other earthquakes, and are set accordingly.

(6) Recovery personnel, temporary recovery work, personnel proficiency, loss time in recovery work:

⑰ Manpower of recovery personnel: number of heavy machinery operator, workers, etc. / ⑱ Presence of temporary recovery work: Set specific to the damage status of ⑤ / ⑲ Proficiency of personnel: incorporation of the training results / ⑳ Loss time in recovery work: Set in multiples of total recovery time

Application of assessment model to the arbitrary site for verifying usefulness

(1) Prerequisites for application

1) Installation environment for target SAE

① SAE: FT and PSV with lashing (Fig.3) / ② Location and status of SAE installation: altitude H2m (Fig.2) / ③ Distance from the SAE installation yard to the connection port: 0.5km / ④ Self-propulsion speed of SAE: 5 (km/h)

2) Status of damage of approach road, fire truck and power supply vehicle:

⑤ Status of damage of approach road: region B / ⑥ Collapse volume of road slope: It is assumed that 450 m^3 (cross-section about 15m^2 × Extension length about 30m) has covered the road.

⑦ Bump of road: None / ⑧ Status of functional failure of FT and PSV: From the fragility assessment result in figure 7, it is assumed to be low in region B

3) Recovery equipment

⑨Heavy equipment and capacity: Set as follows based on the public catalog. Large backhoe (Capacity: 1.2m^3), Large 10t dump truck (Capacity: 6.5m^3), Large wheel loader (1.3m^3) / ⑩ Temporary equipment: Not used

4) Season, weather, working time zone

⑪ Season: Set as autumn / ⑫ Weather and duration: Two cases, clear day and rain day. It is assumed that both weather conditions continue during the targeted work period.

⑬ Working time zone: daytime (12 hours, from 6:00 am - 6:00 pm), and night time (from 6:00 pm to 6:00 am) / ⑭ Night-time work environment: Work with lighting (Fig.5)

⑮ Weighting of weather and work time zone: Rain (2 times of clear), night-time (1.5 times of daytime), rain & nighttime (clear / daytime × 3.0 times)

5) Consideration of aftershocks

⑯ Consideration of aftershocks: Not considered

6) Recovery personnel, temporary recovery work, recovery work efficiency:

⑰ Recovery work and manpower of personnel: There are three large backhoe operators. They carry out the works such as loading up the ten large dump trucks using three large backhoes, and the cleaning of road surface with three large wheel loaders.

⑱ Presence of temporary recovery work: No work / ⑲ Proficiency of personnel: Assumed to be high based on the training results

⑳ Loss time in recovery work: The total loss time in loading large dump trucks using the large backhoe as mentioned in ⑰, transporting the soil to the soil dumping location using the dump trucks, and cleaning the road surface with wheel loaders is estimated to be 1.3 times the total required time.

(2) Assessment of each factor in the recovery time (RT) based on the RT assessment formula

The recovery time (RT) assessment based on the RT assessment formula is as follows.

1) T1: Number of workers after seismic motion, and time required for equipment operators to gather

TF11: The time to gather at the assembly station from each private room is estimated to be 15 min.

TF12: Time required to move from the assembly point to the emergency response location is estimated to be 15 min.

2) T2: Time required for checking on-site situation by means of patrols

TF21: Estimated to be 10 min.

TF22: Estimated to be 15 min.

TF23: Assumed to be three patrol personnel

- Estimated for each of the four cases
    - Case 11 (Clear, daytime) : Estimated to be 60 min
    - Case 12 (Clear, night-time): 60×1.5 = 90 min
    - Case 21 (Rain, daytime) : 60×2.0 = 120 min
    - Case 22 (Rain, night-time) : 60×2.0×1.5 = 180 min
- One among the three patrol personnel returns back to the assembly station in the middle of the patrol to provide an interim report on the on-site situation, and this interim report will be conveyed to the T3 recovery work related personnel. Therefore, the patrol time does not add up to the time required for recovery.

3) T3: Time required for recovery work of approach road

TF31 (N times) = Vs/Vt = 450 m^3/= 6.5 m^3 = 69 times

TF32 (td min / times） = 20 min / times x units

TF33 (Nb) = Three units

TF34 (tds) = N (times) × td (min / times x units)/ Nb (units) = 460 min

TF35 (ts) = Tds × 1.3 = 598 min

TF36 (tdn) = ts/2 = 299 min

- Case 1 (Clear): daytime (weighted 1.0×299 min=299 min) +night-time (weighted 1.5×299 min= 449 min）
- Case 2 (Rain): daytime (weighted 2.0×299 min=598 min) ＋night-time (weighted 3.0×299 min = 897 min)

4) T4: Travel time of fire truck or power supply vehicle

It was assumed that there was no difference in efficiency between the work with lighting shown in Figure 5 and the daytime work.

- Case1 (Clear): (Distance from FT or PSV yard to connection port) ÷ (Self-propulsion speed of FT or PSV) = 0.5km ÷ 5 (km/h) = 6 min
- Case2 (Rain): 3 times that of clear = 18 min

5) T5: Time required for connection

Assuming that there is almost no damage to the connection port of PSV and FT, the connection time was estimated while referring to the connection training data shown in Figure 5. It was assumed that there was no difference in efficiency between the work with lighting and the daytime work.

- Case1 (Clear): Estimated to be 12 min
- Case2 (Rain) : 2 times that of clear = 24 min

(3) T: Assessment result of total recovery time and identification of important factors

The assessment result for each case of T (Total recovery time) are as shown in Table 2.

- T-Case1 (Clear): 796 min (Approx. 13 hours)
- T-Case2 (Rain) : 1567 min (Approx. 26 hours)

The absolute value of T in Case 1 (Clear) and Case 2 (Rain) can vary depending on the pre-requisites for assessment, but that the difference between them is twice as much is believed to be important information. The factors for this difference are influenced by the difference in the weighting of clear and rain, and that of daytime and night-time. The time required for recovery depends on the weighting of weather and working time zone, but is greatly influenced by the two factors as well. Detailed estimation of these factors is very important.

Table2. Breakdown of recovery time assessment

Various work items		Case	
		Case 1 (Clear) (minute)	Case 2 (Rain) (minute)
T1 (Number of workers after seismic motion, and time required for equipment operators to gather)	TF11	15	15
	TF12	15	15
T2 (Time required for patrol personnel to check on-site situation)		-	-
T3 (Time required for recovery work of approach road) 299 (minutes)	Daytime	Weighting (1.0 times) x 299 = 299	Weighting (2.0 times) x 299 = 598
	Night-time	Weighting (1.5 times) x 299 = 449	Weighting (3.0 times) x 299 = 897
T4 (Time required for fire truck or power supply vehicle to move from one place to another)		6	18
T5 (Time required for connecting fire truck or power supply vehicle to connection port)		12	24
T (Time required for recovery)		796 minutes (Approx. 13 hours)	1567 minutes (Approx. 26 hours)

(4) Verification of the usefulness of the proposed model

The usefulness of the proposed model is believed to have been verified by identifying important factors influencing the required time through quantitative assessment of the recovery time, and based on the course of action suggested by the detailed assessment. Further investigation on improvement will be described in the following section.

INVESTIGATION OF IMPROVEMENTS IN THE PROPOSED MODEL

Improvements within the scope of this investigation

(1) The status of damage of the approach road was evaluated by largely dividing the magnitude of the seismic motion into three regions. However, the status of damage of each of these regions needs to be more sophisticated.

(2) While handling the important factors that have an impact on the time required for the approach road recovery, it is necessary to investigate the extent of impact by considering the range of uncertainty. As examples of important factors, weighting of weather (clear and rain) and working time zone (daytime, night-time), and weighting of loss of restoration work time, etc., can be cited.

(3) Although the lashing of the MSAE had been assumed to be perfectly rigid, it is likely to become loose over time. The connection port of PSV and FT, and the fuel leakage protection wall of the refuelling tank belong to Seismic design class S, and it was assumed that these have less fragility. These factors need to be investigated in detail.

(4) While carrying out the fragility assessment of MSAE, conventionally, there was a tendency to conservatively estimate without distinguishing between "when the seismic motion is in progress”

and "after the seismic motion has ended". However, it is necessary to roughly classify. Refueling operation, etc., can be stated as typical examples.

Improvements beyond the scope of this investigation

(1) In the proposed model, the fragility of the self-contained MSAE system is evaluated utilizing the resources in the site environs. Extending the model to make collaboration with support from outside the site will be investigated.
(2) In the Atomic Energy Society of Japan, aftershocks are roughly divided into those due to huge principal earthquakes of M9 class and those due to principal earthquakes less than M8.6. The former aftershocks have a large impact on the facilities, but occur less frequently. The latter is considered to have a lower impact. It is necessary to carry out the investigations considering this.
(3) Enhancement of the model for evaluating high-stress of emergency response personnel during seismic motion will be investigated.
(4) While evaluating the time until CD and CVD, the criteria for the former i.e. CD (for example, pellet surface temperature 1250 degrees) and the criteria for the later i.e. CVD (for example, VD at high temperature and pressure) are clearly specified and then assessment is carried out.

SUMMARY AND FUTURE PLANS

The summary of this report and future plans are as follows.
(1) A model consisting of the fragility assessment of MSAE systems and recovery time assessment of approach road was proposed.
(2) In order to verify the usefulness of the model, plant walk-down was conducted at a plant, related public information was collected, and quantitative assessment using this information was carried out.
(3) Through this assessment, the usefulness of the proposed model was verified.
(4) Improvements on the proposed model were suggested as well.

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