Study on the Influencing Factors for Emergency Rescue of Nuclear Leakage

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Abstract. In order to study the key influencing factors of emergency rescue for nuclear leakage, based on the five aspects of nuclear emergency capability, reactor characteristics, surrounding environment, weather and climate, and accident time, we constructs a Markov probability transfer model for the influencing factors of emergency rescue for nuclear leakage by combining the cross impact and Markov transfer prediction, and a gulf nuclear power plant is selected as an illustrative case. In addition, the initial probability matrix is reasonably determined by the expert scoring method, and the stable matrix which can reflect the stability probability of each factor is finally obtained after the cross impact analysis and multiple Markov state transitions. The results show that the probability of nuclear emergency capability is increased in the emergency response analysis of nuclear leakage incidents, which truly reflects the development direction and degree of cross impact. Furthermore, it provides reference opinions for the emergency response of nuclear leakage incidents in the future.

1. Introduction
Under the background of current energy shortage, nuclear power generation has become a better choice [1]. Nuclear power has the advantages of cleanness and high efficiency, but it requires a high level of nuclear technology. Once an accident occurs, it will lead to a series of serious consequences, especially the damage to the area where the nuclear power plant is located is devastating [2]. Since the Fukushima nuclear power incident in Japan [3], the development of nuclear power in various countries has met with serious resistance, especially public doubts about the safety of nuclear power and low acceptance of further construction of nuclear power plants [4-6]. At the same time, the management department of nuclear emergency and relevant research scholars have conducted various studies on the causes, process and results of the Fukushima nuclear accident [7, 8] in order to further improve the nuclear emergency management system, ensure the safety of the existing nuclear power operation and further promote the development of nuclear power.

Cross impact analysis [9] is a prediction method based on Delphi method [10] and subjective probability method, which fully considers the mutual influence of various factors and forecasts the development prospect of things. It is often used in the field of economics, for example, it analyses
various risks of stocks and futures by establishing relevant models so as to assist decision makers in making investment judgments [11]. In recent years, some scholars have also used it to carry out risk analysis [12], especially by adopting the idea of cross-impact analysis to establish a nuclear emergency trans-regional rescue model to analyse the safety of nuclear power plants [13]. Although the method considers the mutual influence between key factors and can get the development direction of the accident, it fails to show the evolution of the accidents intuitively, only considers the influence between the factors and the development direction of the accident, and is not suitable for analysing accidents with a long chain of accidents. However, Markov chain is used in Montero method to form Markov chain Monte Carlo method [14]. In practice, it is mostly used in mathematical modelling of power system, chemical reaction, queuing theory, market behaviour and information retrieval [15, 16]. Although this method considers the cause, process and result of the accident. However, the influence of various factors has not been fully considered. For the event factors with mutual influence among various factors, the analysis effect cannot be very good. Therefore, this method is rarely used as the main analysis method in accident modelling. The Markov chain can express a group of data from the initial state to a new state through the transition matrix. So the two methods can be properly combined for modelling and analysis. Some people have used this analysis method in communication technology [17] in order to achieve the best investment effect.

On account of many key factors affecting the emergency rescue of nuclear leakage, including climate, topography and surrounding environment, etc. [18], at the same time, various factors interact with each other, and the combination of different key factors will have different effects on the emergency rescue of nuclear leakage, which is consistent with the advantages of cross impact analysis. In addition, the introduction of Markov chain can start from the overall emergency rescue of nuclear leakage, and comprehensively consider the development and changes of the key factors of emergency rescue in time. Based on this, we applies the method by combining Markov prediction with cross impact analysis to the analysis of the impact factors for emergency rescue after the nuclear leakage, and proposes the impact degree and development direction between the key emergency rescue events.

2. Building the Markov model of the emergency rescue in the leakage of nuclear plant
A framework for the Markov model of the emergency rescue in the leakage of nuclear plant is described here, including current situation, the model of the emergency rescue and purpose et al, which is shown in Fig. 1. In order to discover the key factors in the emergency rescue, the Markov model, which is core in the framework, is developed, and it consists of two parts: the Markov prediction and the cross impact analysis, which will be elaborated below, detailedly.

![Figure 1. Suggested framework of Markov model for the emergency rescue in the leakage of nuclear plant.](image)

### 2.1. Markov prediction model
The Markov chain has the basic property of no memory in the time series. In the process of the development of things, the current state is only related to the state in which the adjacent time period is
adjacent, and there is no dependence on the earlier time. Based on this, the characteristics of future changes are predicted, and the Markov prediction model is proposed, according to the current situation of the event.

Assuming parameter set \( T \) for Markov processes is a discrete set of time, that is \( T = \{0, 1, 2, \ldots\} \), the state space composed of possible values for corresponding stochastic process \( \{X_n, n \in T\} \) is a discrete state space \( I = \{0, 1, 2, \ldots\} \). For random process \( X_n \), if any positive number \( n \in T \) and arbitrary \( i_0, i_1, \ldots i_n \in I \), if the conditional probability satisfies the Eq. (1), then \( X_n \) is known as the Markov chain:

\[
P\left\{X_{n+1} = i_{n+1} \mid X_0 = i_0, X_1 = i_1, \ldots, X_n = i_n\right\} = P\left\{X_{n+1} = i_{n+1} \mid X_n = i_n\right\}
\]

(1)

The conditional probability of Markov chain \( \{X_n, n \in T\} \) is the one-step transition probability at the moment \( n \), as shown in Eq. (2):

\[
P^{(s)}_{ij} = P\left\{X_{n+1} = j \mid X_n = i\right\}
\]

(2)

Where \( i, j \in I \) is the transition probability.

Eq. (3) gives one-step transition probability matrix \( P \) composed of a one-step transition probability \( p_{ij} \) of Markov chain, and \( I = \{0, 1, 2, \ldots, n\} \).

\[
P = \begin{bmatrix}
P_{11} & P_{12} & \cdots & P_{1n} \\
P_{21} & P_{22} & \cdots & P_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
P_{n1} & P_{n2} & \cdots & P_{nn}
\end{bmatrix}
\]

(3)

Suppose the initial state of the event is \( S^{(0)} \), and initial state probability is expressed as \( P^{(0)} = [p_1, p_2, \ldots, p_n]^T \). After \( K \) experiments, Then \( S^{(k+1)} = S^{(k)}P^{(s)} \) and \( \sum_{i=1}^{n} S_i^{(k)} = 1 \), where \( n \) is the number of mutually incompatible states in the system among them. After appropriate mathematical processing, the Markov chain can be obtained from the probability matrix that tends to be stable in the first \( n \), as shown in Eq. (4).

\[
P^{(s)} = P_1^{-1}b
\]

(4)

Where the algorithm of \( P_1 \) and \( b \) is shown in Eq. (5).

\[
P_1 = \begin{bmatrix}
P_{11} - 1 & P_{12} & \cdots & P_{1n} \\
P_{21} - 1 & P_{22} & \cdots & P_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
P_{n1} - 1 & P_{n2} - 1 & \cdots & P_{nn} - 1 \\
1 & 1 & \cdots & 1
\end{bmatrix}, \quad b = \begin{bmatrix}
0 \\
0 \\
0 \\
\vdots \\
1
\end{bmatrix}
\]

(5)
2.2. Introducing the cross impact method

Due to the certain cross impact between the influencing factors, the capability of emergency rescue after the nuclear leakage event are affected with various degrees. In addition, the score table based on the field experience of nuclear experts is set, according to the influence effect and the positive or negative effects, as shown in Table 1.

Table 1. The direction and degree of cross impact

| Degree of cross impact     | K      | S  |
|----------------------------|--------|----|
| 1. No effect               | +0     | 0  |
| 2. Weak positive effect    | +1     | 0.2|
| 3. Weak negative effect    | -1     | 0.2|
| 4. Moderate positive effect| +1     | 0.5|
| 5. Moderate negative effect| -1     | 0.5|
| 6. Strong positive effect  | +1     | 0.8|
| 7. Strong negative effect  | -1     | 0.8|

The impact is divided into 7 categories, generally. When the impact value is positive, it means that one event has a positive effect on another event. On the contrary, a negative value is expressed as inhibition. That is if the event \( D_n \) occur, the initial probability of the remaining events will inevitably be affected \( D_n \), and the impact value is given by the expert score. The American scholar Gordon proposed the empirical formula for calculating cross-impact in 1968, and the simplified form is shown in Eq. (6):

\[
P' = P_n + KS \times P_n - KS \times (P_n)^2
\]  

(6)

Where \( K \) indicates the direction of influence, if positive time, \( K \) is +1, else \( K \) is -1. Where \( S \) indicates the extent of the impact, and the value of \( K \) and \( S \) are shown in Table 1.

The calculation result \( P' \) of Eq. (6) is the probability of cross impact. Furthermore, there will occur different probability consequences under the intervention of external factors with different extent [13]. Through the comprehensive cross-impact and state transition between scenarios, a new probability table for the occurrence of accidents will be obtained, and the probability of cross impact is shown in Table 2.

Table 2. The probability table of cross impact

| Incidents | Probability | \( P'_1 \) | \( P'_2 \) | ... | \( P'_n \) |
|-----------|-------------|------------|------------|-----|------------|
| \( D_1 \) | \( a_1 \)    | \( a_2 \)  | ...        | ... | \( a_n \)  |
| \( D_2 \) | \( b_1 \)    | \( b_2 \)  | ...        | ... | \( b_n \)  |
| ...       | ...         | ...        | ...        | ... | ...        |
| \( D_n \) | \( x_1 \)    | \( x_2 \)  | ...        | ... | \( x_n \)  |

2.3. Probability processing

Eq. (7) gives the normalization process of initial matrix.
The cross probability matrix is similar to the probability transfer matrix in the Markov chain, and it needs to be normalized as well. The specific process is shown in Eq. (8), and each row \( P'_i \) in the matrix is the probability of cross-effects on other events caused by external factors.

\[
\begin{bmatrix}
P'_1 / \sum_{j=1}^{n} P'_j \\
\vdots \\
P'_n / \sum_{j=1}^{n} P'_j
\end{bmatrix}
\]

The cross probability matrix is similar to the probability transfer matrix in the Markov chain, and it needs to be normalized as well. The specific process is shown in Eq. (8), and each row \( P'_i \) in the matrix is the probability of cross-effects on other events caused by external factors.

\[
P = \begin{bmatrix}
P'_1 / \sum_{j=1}^{n} P'_{i,j1} & P'_2 / \sum_{j=1}^{n} P'_{i,j2} & \cdots & P'_n / \sum_{j=1}^{n} P'_{i,jn} \\
\vdots & \vdots & \ddots & \vdots \\
P'_1 / \sum_{j=1}^{n} P'_{i,jn} & P'_2 / \sum_{j=1}^{n} P'_{i,jn} & \cdots & P'_n / \sum_{j=1}^{n} P'_{i,jn}
\end{bmatrix}
\]

\[
= \begin{bmatrix}
a_1 / \sum_{j=1}^{n} a_j & a_2 / \sum_{j=1}^{n} a_j & \cdots & a_n / \sum_{j=1}^{n} a_j \\
b_1 / \sum_{j=1}^{n} b_j & b_2 / \sum_{j=1}^{n} b_j & \cdots & b_n / \sum_{j=1}^{n} b_j \\
x_1 / \sum_{j=1}^{n} x_j & x_2 / \sum_{j=1}^{n} x_j & \cdots & x_n / \sum_{j=1}^{n} x_j
\end{bmatrix}
\]

2.4. Building a ladder structure for emergency rescue factors of nuclear leakage

According to the characteristics of nuclear leakage incidents, the main factors affecting the emergency rescue of the nuclear power plant are summarized, and the metrics of subordination are formed, mainly from the aspects of nuclear emergency capacity, reactor characteristics, surrounding environment, weather and climate, and accident time. In addition, and the influencing factors are further refined as 14 secondary indicators, and finally the ladder structure of emergency rescue factors for nuclear leakage accidents is established, as shown in Table 3.

Among them, nuclear emergency capability includes nuclear emergency plan, nuclear emergency materials and nuclear safety awareness. Nuclear emergency plan refers to a series of emergency rescue and control measures immediately made by relevant government departments in the event of a nuclear leakage accident. Emergency materials include not only emergency rescue equipment (radiation clothing, vehicles, etc.), but also some daily necessities, tents, purified water and various drugs. Nuclear safety awareness mainly includes two parts: the first is the crisis awareness of the government and relevant units on nuclear emergency rescue; the second is the public awareness of the nuclear leakage accident. In particular, the public awareness has a significant impact on the result of the accident.

At present, there are many types of reactors in the world, mainly including pressurized water reactors, boiling water reactors, heavy water reactors, etc. The working principles of various types of reactors are different, which also leads to the difference of emergency rescue methods for nuclear leakage events. In addition, the reactant reserves of various nuclear power plants are also changing during the working process. Moreover, the location of nuclear leakage is also closely related to nuclear emergency rescue. For example, the accident results caused by the occurrence of large groove events in the heat pipe section and the cold pipe section are completely different, and the accident treatment methods are also different.

External factors (weather and climate, surrounding environment and accident time) also affect the effect of nuclear emergency rescue. The surrounding environment factors include traffic, terrain and geographical location indicators. Whether traffic is convenient directly affects the rescue speed. Topography mainly considers whether there are mountain areas that can block the radiation of nuclear leakage. Geographical location refers to the location of the nuclear power plant where the nuclear leakage accident occurred. Weather and climate include wind direction and wind speed, which have
certain guiding effect on the spread and development of nuclear radiation. Finally, the time of the accident includes day and night. Generally speaking, the emergency rescue response after a nuclear accident occurs in day is timelier than at night.

**Table 3.** The ladder structure of emergency rescue factors for nuclear leakage accidents

| The key factors                  | Secondary indicators          |
|---------------------------------|------------------------------|
| Nuclear emergency capability    | Nuclear emergency plan;      |
|                                 | Nuclear emergency materials;  |
|                                 | Nuclear safety awareness;     |
| Reactor characteristics         | Reactant properties;          |
|                                 | Reactant reserves;            |
|                                 | Nuclear leakage location;     |
| Surroundings                    | Terrain; Traffic;            |
| Weather climate                 | Geographical location;       |
| Accident time                   | Wind direction; Wind speed;  |
|                                 | Rainfall; Day-time; Night-time; |

3. Case study

3.1. Introduction of a Gulf Nuclear Power Station

A nuclear power plant currently has six generating units with a total installed capacity of 6.21 million kilowatts, including two 984,000 kilowatts of machine assembly capacity, two 990,000 kilowatts of machine assembly capacity, and two units with installed capacity of 1.086 million kilowatts. The total tritium emission statistics are 5.3% of the annual emission limit of 2.4*10¹³ Becquerel approved by the Ministry of Environmental Protection of China. The lowest annual emission of gaseous tritium from the two units of the nuclear power plant was 7.2*10¹¹ Becquerel and the highest was 1.67*10¹² Becquerel from 2001 to 2010. The conventional island of the nuclear power plant is equipped with a relatively perfect fire detection system as well as fire extinguishing system, and the traffic there is comparatively convenient. In addition, the nuclear power plant is near the sea with nearly 500 square kilometres water area, which belongs to the typical subtropical oceanic climate. The annual precipitation, concentrated in summer and autumn, is relatively greatly, especially there are frequent activities of convective rain as well as tropical cyclone and powerful wind in summer.

3.2. Determining the Weights of Indicators in Nuclear Power Plant Area

**Table 4.** The key factors influencing the fire rescue

| Key factor                        | Impact possibilities | Secondary indexes                  | Weight |
|-----------------------------------|----------------------|------------------------------------|--------|
| Nuclear emergency capability      | 0.900                | Nuclear contingency plan           | 0.300  |
| Nuclear emergency supplies        |                      | Nuclear emergency supplies         | 0.300  |
| Nuclear safety awareness          |                      | Nuclear safety awareness           | 0.300  |
| Reactor characteristics           | 0.900                | Reactor properties                 | 0.300  |
| Reactor reserves                  |                      | Reactor reserves                   | 0.300  |
| Nuclear leakage location          |                      | Nuclear leakage location           | 0.300  |
| Surrounding environment           | 0.600                | Terrain                            | 0.200  |
|                                   |                      | Traffic                            | 0.100  |
|                                   |                      | Geographical location              | 0.300  |
| Weather and climate               | 0.500                | Wind direction                      | 0.200  |
|                                   |                      | Wind speed                         | 0.200  |
|                                   |                      | Rainfall                           | 0.100  |
| Accidental time                   | 0.300                | Day-time                           | 0.100  |
|                                   |                      | Night-time                         | 0.200  |
By analysing the characteristics of nuclear leakage accidents, the weight of each index in the structure is determined by expert scoring method, which is based on the ladder structure of emergency rescue factor for nuclear leakage established, as shown in Table 4. Considering all cross impact events as a system, the matrix which consists their proportion of the initial probability can be called as the initial probability matrix, determined by the weight of each index factor in Table 4. The initial probability is
\[
\begin{bmatrix}
0.900 & 0.900 & 0.600 & 0.500 & 0.300
\end{bmatrix}^T.
\]

### 3.3. Determining the degree of cross impact

The interaction value between the events is given by dividing the influencing factors of emergency rescue for nuclear leakage and the relevant degree table of cross impact above, as shown in Table 5. In addition, the probability of cross impact between each key event is calculated by Eq. (5), and the calculation results are shown in Table 6.

| Incident          | Nuclear emergency capacity | Reactor characteristics | Surrounding environment | Weather and climate | Accidental time |
|-------------------|-----------------------------|-------------------------|-------------------------|---------------------|-----------------|
| Nuclear emergency capacity | 0                           | +0.2                    | -0.2                    | 0                   | 0               |
| Reactor characteristics | +0.5                       | 0                       | +0.2                    | 0                   | 0               |
| Surrounding environment | +0.2                       | -0.2                    | 0                       | 0                   | 0               |
| Weather and climate | +0.8                       | +0.5                    | 0                       | 0                   | 0               |
| Accidental time    | +0.5                       | 0                       | 0                       | 0                   | 0               |

| Incident          | The probability table of each event |
|-------------------|-------------------------------------|
|                   | $P'_1$ | $P'_2$ | $P'_3$ | $P'_4$ | $P'_5$ |
| Nuclear emergency capacity | 0.900 | 0.918 | 0.552 | 0.500 | 0.300 |
| Reactor characteristics | 0.945 | 0.900 | 0.648 | 0.500 | 0.300 |
| Surrounding environment | 0.918 | 0.882 | 0.600 | 0.500 | 0.300 |
| Weather and climate | 0.972 | 0.945 | 0.600 | 0.500 | 0.300 |
| Accidental time    | 0.945 | 0.900 | 0.600 | 0.500 | 0.300 |

Considering the probability of cross impact generated by each event as the transition probability from the initial state to another state, then the matrix composed of the proportions of each cross impact is called as the transfer matrix, and the probability matrix $P$ of cross impact is obtained from Table 6.

\[
P = \begin{bmatrix}
0.900 & 0.918 & 0.552 & 0.500 & 0.300 \\
0.945 & 0.900 & 0.648 & 0.500 & 0.300 \\
0.918 & 0.882 & 0.600 & 0.500 & 0.300 \\
0.972 & 0.945 & 0.600 & 0.500 & 0.300 \\
0.945 & 0.900 & 0.600 & 0.500 & 0.300
\end{bmatrix}
\]

The results are calculated by applying the Markov process to the cross impact analysis method and using the Eq. (7) and Eq. (8) are used to normalize the initial probability and the cross-probability matrix:
According to Eq. (5), $P_1$ can be obtained.

$$P^{(0)} = \begin{bmatrix} 0.281 \\ 0.281 \\ 0.188 \\ 0.156 \\ 0.094 \end{bmatrix}, \quad P' = \begin{bmatrix} 0.284 & 0.290 & 0.174 & 0.158 & 0.095 \\ 0.287 & 0.273 & 0.197 & 0.152 & 0.091 \\ 0.287 & 0.276 & 0.188 & 0.156 & 0.094 \\ 0.293 & 0.285 & 0.181 & 0.151 & 0.090 \\ 0.291 & 0.277 & 0.185 & 0.154 & 0.092 \end{bmatrix}$$

And the inverse matrix $P^{-1}_1$ can be obtained, then the initial state of Markov steady-state matrix $P^{(a)}$ is obtained by Eq. (4) after several transfers. Where $P^{(a)}$ represents the probability proportion of each cross impact event, and the correction probability $P'^{(0)}$ of each influencing factor can be get by multiplying $P^{(a)}$ by the sum of the initial probabilities.

$$P_1 = \begin{bmatrix} 0.284-1 & 0.287 & 0.287 & 0.293 & 0.291 \\ 0.290 & 0.273-1 & 0.276 & 0.285 & 0.277 \\ 0.174 & 0.197 & 0.188-1 & 0.181 & 0.185 \\ 0.158 & 0.152 & 0.156 & 0.151-1 & 0.154 \\ 1 & 1 & 1 & 1 & 1 \end{bmatrix}$$

$$P^{(a)} = \begin{bmatrix} 0.287 \\ 0.281 \\ 0.185 \\ 0.155 \\ 0.092 \end{bmatrix}, \quad P'^{(0)} = \begin{bmatrix} 0.920 \\ 0.898 \\ 0.592 \\ 0.494 \\ 0.295 \end{bmatrix}$$

The corrected probability reflects the final direction and influence degree of the cross impact.

### 3.4. Result analysis

![Figure 2. Initial and steady state probability diagrams of key factors](image)

(A: Nuclear emergency capacity; B: Reactor characteristics; C: Surrounding environment; D: Weather and climate; E: Accidental time.)
(1) It can be known that steady matrix $P^{(0)}=\begin{bmatrix} 0.920 & 0.898 & 0.592 & 0.494 & 0.295 \end{bmatrix}^T$ can be get from the initial probability $P^{(0)}=\begin{bmatrix} 0.900 & 0.900 & 0.600 & 0.500 & 0.300 \end{bmatrix}^T$ after a series of Markov-state transfers, due to the cross impact of the key factors affecting the emergency rescue of nuclear leakage, as shown in Fig. 2. This prediction result is in line with the actual situation of nuclear power plants in this region, and has certain guiding significance for the emergency rescue and safety management of nuclear power plants.

(2) It can be clearly seen from the calculation results that the nuclear emergency capability factor in the key impact events of emergency rescue for nuclear leakage has slightly increased in the original correction probability, indicating that the key influencing factor of emergency rescue for nuclear leakage is still nuclear emergency capability after the cross-impact of each key event. Therefore, it is necessary to clearly indicate the key directions when making decisions for the government.

(3) The Markov steady-state probability of four key events such as reactor characteristics, surrounding environment, weather and climate as well as accident time have a slight decrease after cross impact analysis, however, it does not mean that these key events do not need to be taken seriously, and it is only the evolution of probability after the interaction of key events, which means to arouse the attention of relevant departments to notice the impact extent and direction of the final event and will not reduce its original importance.

In addition, the impact of weather and climate on the regional safety of nuclear leakage has decreased from 50% to 49.4%. Although this factor is less affected by cross impact, the interference factors of extreme weather and climate on emergency rescue of nuclear leakage, such as wind direction, wind speed and rainfall, should still be taken into account. Especially in extreme weather conditions, for example, when the nuclear power plant is located in the downwind direction of the gale in summer, once the nuclear leakage accident occurs, it will bring great tests to the personnel themselves of emergency rescue. At the same time, these objective factors will comprehensively increase the risk probability of the contiguous effects for the surrounding nuclear plant accidents with the increase of summer rainfall. Therefore, weather and climate factors should not be neglected in daily safety management, and this factor should be fully considered by relevant departments in safety investment and disaster prevention.

4. Conclusion
The cross impact method and Markov transfer prediction method are applied to the emergency rescue analysis of nuclear leakage incidents. In the process of cross impact analysis, the weight of each key events and the degree of being affected by other events in the development are reasonably determined by making full use of expert resources. The qualitative analysis process of cross impact and the quantitative calculation process of Markov are combined organically, and the Markov probability transfer model of key events in emergency rescue of nuclear power leakage is established. The stable state probability matrix of each key event is calculated by the model, which truly reflects the development direction and degree of the cross impact between the key events, and provides another way of direction for emergency rescue and safety management of nuclear leakage incidents.

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