Study on high wind hazard probability risk assessment methods of nuclear power plant

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Abstract. China's nuclear power plants were built in coastal areas. High wind such as hurricane would make nuclear power plant transmission lines, structure and component to fail, leading to the transient or loss of off-site power accidents, which have an impact on the safety of nuclear power plants. This paper focuses on high wind hazards analysis of the operational nuclear power plants. We study the high wind probability safety assessment methods and the main technical elements. The following five tasks were performed to complete the high wind PSA models: Site Specific High wind hazard analysis, High wind Walk-downs and equipment list screen out, High wind Fragility Analysis, Integrate High wind Impacts into PSA Model, and Risk Quantification of High wind PSA Model. The methodology can be used to addresses high wind hazard probability risk analysis of nuclear power plant.

1. Introduction

In China, high wind events mainly include hurricanes and tornadoes that may have a significant impact on nuclear power plants. According to the National Meteorological Administration, there are 6 to 7 hurricanes occurred in the South China Sea each year. Because most of the nuclear power stations are located in the coastal areas of China. Therefore, they are vulnerable to hurricane attacks. High wind is one of the major external hazards that affect the safety of nuclear power plants. China's nuclear safety regulations require nuclear power plants to gradually develop and improve their high wind PSA(Probability Safety Assessment), and encourage using PSA to improve operational management and nuclear safety standards. This paper focuses on power plants at high wind hazards. Study the probability safety assessment methods and the main technical elements of high wind Hazard in a nuclear power plant. Wind hazards and effects show in Figure 1.

Figure 1. Wind hazards and effects.
2. High wind PSA analysis

2.1. Methodology

2.1.1. High wind PSA analysis scope. The high wind PSA model includes all initiating events caused by high wind and major mitigation system failure that could lead to core damage[1]. The analysis of the high wind PSA is similar to other external hazard. High wind PSA is composed of five aspects as follow[2]:

① Site Specific High wind hazard analysis;
② High wind Walk-downs and equipment list screen;
③ High wind Fragility Analysis;
④ Integrate High wind Impacts into PSA Model;
⑤ Risk Quantification of High wind PSA Model.

2.1.2. Site specific high wind hazard analysis. High wind risk analysis is assessing the occurrence frequency of different wind velocity, which must be based on the newest available data and specific plant information. This High wind Hazard Analysis is critical to define initiating events in the PSA model for the annual exceeding frequency of high wind that can impact plant structures, systems, and components (SSCs)[3].

In the analysis, the uncertainties of the model and parameter value must be properly considered, and the uncertainties can be fully propagated to obtain high wind hazard curves, and the average risk curve can be obtained[4]. High wind hazard frequencies can be obtained from historical high wind statistical information about the nuclear power plant site. For example, the hurricane hazard calculation results are shown in Table1.

| Initiating Event | Lower Bound(m/s) | Upper Bound(m/s) |
|------------------|------------------|------------------|
| HW1              | 27               | 36               |
| HW2              | 36               | 45               |
| HW3              | 45               | 56               |
| HW4              | 56               | 67               |
| HW5              | 67               | 90               |
| HW6              | 90               | 110              |

Atmospheric Administration performed a specific site hurricane analysis using the appropriate data sets. Modeling and random uncertainties were considered in developing the high wind hazard risk estimates and are propagated through the hazard models.

2.1.3. High wind walk-downs and equipment list screen

The objectives of the plant walk-down included: Review for spatial interactions among structures, targets, and missiles, including external and internal SSCs; Identification potential missile and high wind failure modes for each SSC.

The site walk-down was conducted to collect data on vulnerable structures and potential missiles (such as vulnerable SSCs and wind-borne missile failure), structure interactions, and failure modes. Taking china coastal nuclear power plant as an example, the main walk-down SSC as follows:

(1) The main transformer, auxiliary transformer, transformer station;
(2) Service water pump station, pump station door;
(3) Emergency diesel generator building, building chimneys;
(4) The fifth emergency diesel generator station;
(5) The refueling water tank;
(6) Turbine building, Turbine building door;
(7) Transmission tower.

Prior to the plant walk-down, we need to review the plant design criteria, available drawings, previous hurricane analyses, current concerns with vulnerable targets, inspection reports and so on.

2.1.4. High wind fragility analysis. The purpose of fragility analysis is to identify SSC that is susceptible to high wind, and to determine the specific failure mode of SSC and probability with a high wind velocity. It is similar to the process of developing the seismic fragility curve, wind resistance is modeled as random variable which is expressed in the form of wind speed[5]. Fragility analysis process shows in Figure 2.

**Figure 2.** Fragility analysis process.

Fragility of high wind-impacted SSCs is consisting of wind pressure fragility and missile fragility. In the hurricane, the nuclear power plant buildings and equipment includes two kinds of damage: the first is the wind load damage. Turbine building and pump station belongs to light steel structure plant, the structure damage mainly results in the destruction of the envelope structure under the action of negative wind pressure. Therefore, we should check the strength of the envelope material and the connection strength between the enclosure structure and the main structure, including the roof panel, wall panels and doors and windows, connecting part of the roof panel and purlin (purlin system).

**Figure 3.** Numerical simulation of wind pressure in 30 degree wind directions.  
**Figure 4.** Numerical simulation of wind pressure in 150 degree wind directions.

High wind fragility analysis can be based on the initial fragility curves using Monte-Carlo simulation method. Considering the inherent randomness of wind loads and the uncertainty of human cognition, the wind speed capability can be expressed as the form of the following formula (1) for a specific failure mode[6]. Numerical simulation shows in Figure 3 and Figure 4.
\[ V = V_m \cdot e_R \cdot e_U \] (1)

\( V \)—10min mean wind speed (m/s); \( V_m \)— median wind speed (m/s);
\( e_R, e_U \)—Two random variables with a median of 1, indicating the inherent randomness of wind speed and the uncertainty of human cognition respectively.

If \( e_R \) and \( e_U \) obey lognormal distribution, the log standard deviations are \( \beta_r \) and \( \beta_u \) respectively. Considering the two random variable, given the failure mode and the wind speed capability, under the given wind speed capacity, the conditional failure probability of the structure or equipment can be expressed as follows: (2):

\[
P_{f_i} = \Phi \left[ \ln \left( \frac{v}{V_m} \right) + \frac{\beta_u \Phi^{-1}(Q)}{\beta_r} \right]
\]

(2)

There \( Q = [P_{f_i} < P_f \mid V] \) is \( P_f \) less than \( P_f \) conditions failure probability when wind speed is \( V \) m/s. When the fragility curves have a confidence level is from 5% to 95%, its values from -1.65 to 1.65. Confidence fragility curves group respectively by 5%, 50%, 95% confidence fragility curves composition. When the confidence level is 50%, \( \Phi^{-1}(Q) = 0 \). Condition failure probability \( P_{f_0} \) expression as the following formula (3):

\[
P_{f_0} = \Phi \left[ \ln \left( \frac{v}{V_m} \right) \right]
\]

(3)

2.2. Practical example
Taking turbine building as an example, determine the turbine building roof panel failure mode;

![Figure 5. Turbine building roof plate picture.](image)

![Figure 6. Turbine building roof plate fragility.](image)

There are two basic failure modes of the turbine building roof panel: the pressure plate is pulled off the self-tapping screw head, and the self-tapping screw is pulled out from the substrate. As a self-
tapping screw damage will lead to re-distribution of internal forces, other self-tapping screws will quickly reach the limit of carrying capacity, so that the roof boards failure. So the damage of a screw can be regarded as the destruction of the roof panel. We can see the turbine building roof plate picture in Figure 5 and Failure probability of turbine roofing plate tapping screws under tensile conditions in Figure 6.

Taking the PTR water tank as an example. A Monte Carlo simulation of the function was performed (Figure 7) and the relevant fragility curves were plotted. Finally, a confidence fragility curve group with confidence levels of 5%, 50%, and 95% was obtained. The fragility curve of the high wind causing the PTR tank to fail is shown in Figure 8.

The following general failure modes are applicable to the target SSCs[7].

1. Building interactive failure modes for targets inside non-Class I structures.
2. Wind Pressure and Atmospheric Pressure Change.
3. Wind-borne missiles.

In summary, targets SSCs that are inside of non-Class I structures to pose a significant challenge to wind fragility analysis. These targets SSCs are vulnerable to various failure modes of the surrounding structure, which is also vulnerable to both wind and missile loads. Each of these failure modes contributed to the failure of the target SSCs irrespective of the other failure modes.

2.3. Integrate high wind impacts into PSA model

2.3.1. Model Integration. Internal events PSA model (Core Damage) was modified to incorporate high wind failure modes. The Internal Events PSA model was implemented to adequately capture postulated high wind-induced initiating events, impacted human failure events, and high wind-induced failure modes including wind-borne missile damage. High wind pre-event tree model shows in Figure 9. Figure 10 gives an idea of how high wind fault tree logic is built into the PSA model.

The initial model development was primarily focused on capturing the high wind impact within the existing event tree/fault tree in internal events PSA model. The quality of the existing internal events model is important for the high wind model developing. It is important that the systems models modified for high wind include all significant failures, including SSCs failure caused by the high wind and non-high wind failure such as human failure events.

The wind pressure fragility are generally built separately in the fault tree but with the same structure. As a general rule, for identical, redundant equipment, a correlation of 1 should be assumed. For all other equipment, a correlation of zero should be assumed. If they are located on different locations and mounted differently, they could be treated as independent.
2.3.2. Risk quantification of high wind PSA model. We can build the high wind PSA model and quantifies the core damage frequency of the plant. The high wind PSA model is quantified by combining the high wind hazard curve with the important SSC fragility curve to assess the CDF (core damage frequency). The CDF values of the sequences are obtained by convoluting the minimum cut sets of the accident sequences, and obtained the CDFs of high wind.

\[
\int_a^b F(x) f_2(x) dx
\]

The above formula \( x \) is the intensity of wind, m/s; \( f_2(x) \) is the conditional failure probability of the equipment, \( F_1(x) \) is the annual exceedance frequency.

In the process of quantification, the uncertainties and correlations need to be taken into account, and the sensitivity analysis is also performed. Generally, most of the safety-related equipment is in a minimum of 48 cm thick buildings. Identify safety-related equipment with weakness on wind pressure and the impact of high wind-borne missiles are analyzed in detail.

According to the analysis result, we can get that loss of off-site power is a dominant contributor to high wind models at lower wind speeds, because of the design of the ofsite power lines, switch-yard, and Turbine Building siding. Typically, the design wind speed for the site transmission lines is in the range of 80-90 mph peak gust wind speed. This leads to high LOO(P loss of off-site power) conditional probabilities at relatively low wind speeds. Figure 11 gives a representation of the conditional LOOP probability versus the wind speed. Once the upper end of the 155 mph wind speed is reached, the LOOP conditional probabilities are essentially 1.0.
Figure 11. Conditional probabilities of loss of off-site power with wind speed.

According to high wind external disasters PSA modeling analysis, the super typhoon is most likely to cause three initial events: transient, loss of off-site power and loss of heat sink. Based on PSA quantitative analysis, the results show that the typhoon caused the loss of off-site power, and core damage frequency is 9.22E-7/r-year. If the equipment in the diesel engine room is failed due to high wind, it may cause a power outage accident. For transient accidents, the core damage frequency is 4.50E-9/r-year. In the event of loss of heat sink, typhoon does not cause a significant increase in the frequency of the accident. Assuming that the frequency of loss of heat sink is doubled, the core damage frequency is calculated to be 1.12E-6/y. During the typhoon, the above three types of initiating events may occur, so the CDF caused by the typhoon period is 2.05E-6/r-year, which is about 15% of the internal event CDF in the power condition. It can be seen from the PSA analysis that the typhoon has certain threats to the safety of the power plant.

3. Conclusions

High wind PSA is unlike other external events such as seismic. They are complicated by multiple hazards with different wind characteristics and effects. High wind initial model development was primarily focused on capturing the high wind impact on the existing event tree or fault tree of the internal events PSA model. Risk quantification of high wind PSA model shows that loss of off-site power is a dominant contributor at lower wind speed because of the high fragility of the off-site power lines, switch-yard. Fragility of turbine building siding can have a significant missile impact. In future, we need to collect data about vulnerable structures and potential missiles, and we also need to continue to walk-down in nuclear power plant for missiles that should be conducted during non-outage and outage periods. Finally, we can establish a complete PSA model for high wind risk analysis in nuclear power plant.

References

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