A Statistical Analysis of Typhoon-related Hazards using Extreme Value Theory

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1. Introduction

Since the Fukushima accident, the importance of a probabilistic safety analysis for extreme external events has been raised [1]. It was reported that some external events can concurrently affect diverse and redundant safety systems of nuclear power plants and initiate multi-unit accidents [2, 3]. To assess the safety of nuclear power plants under extreme external events, the occurrence intervals or hazards of the events need to be assessed. This study proposes the extreme value theory (EVT) to estimate the annual frequency of exceeding a rare event for a statistical analysis of hazards of external events [4].

This paper introduces an analysis method using the univariate EVT. The hazards of variables related with typhoons were also analyzed using the EVT proposed in this study. Finally, insights from the analysis and considerations for further EVT analyses are summarized herein.

2. Extreme Value Theory

The EVT predicts the probability of a level beyond the observed data for a given random variable [4]. For example, for 100-year sea levels, the probability of more than 800 mm of daily rainfall can be estimated. The EVT allows extrapolating the return period of a level that exceeds the maximum of observations. Moreover, it is also possible to estimate a return level in changing climate using non-stationary EVT models.

There are two general approaches of a practical EVT: block maxima (BM) and peaks over threshold (POT). The BM method uses the maxima or minima within blocks of equal length such as annual maxima of monthly wind speeds. It is recommend to usually use the annual maxima/minima for satisfying the robustness and statistical power. For the BM method, the generalized extreme value (GEV) distribution function is employed to fit the maxima if the blocks are large. The GEV function for an observation *z* is given by

$$G(z) = \exp\left\{ -\left[1 + \zeta \frac{z-\mu}{\sigma} \right]_{+}^{-1/\zeta} \right\}.$$

Here, μ is a location parameter, σ >0 is a scale parameter, and ζ is a shape parameter. When $\zeta \to 0$, the function corresponds to the Gumbel distribution, when $\zeta > 0$, it belongs to the Frechet distribution, and when $\zeta < 0$, it is reduced to the Weibull distribution.

The POT method deals with exceedances over a given threshold rather than the annual maxima/minima. Hence, the POT method can provide a method that meaningfully uses a larger amount of data if the threshold is sufficiently low. The GP (generalized Pareto) distribution *H* for *Z* exceeding a sufficiently large threshold, *u,* is used for the POT approach.

$$H\left(y; \underset{u}{\sigma}, \zeta \right) = 1 - \left(1 + \zeta \frac{y}{\sigma} \right)_{+}^{-1/\zeta},$$

where *Y*=*Z*-*u*. σ >0 is a scale parameter and ζ is a shape parameter of GP distribution. When $\zeta \to 0$, the function corresponds to the exponential distribution, when $\zeta > 0$, it belongs to the Pareto distribution, and when $\zeta < 0$, it is reduced to the Beta distribution.

3. Method

In this study, four variables related to Korean typhoons were analyzed. The reason why typhoons were analyzed is that there are over 100 years of records, and typhoons are recognized as one of the most risky natural events for East Asia [5]. The analyzed variables are as follows.

- Maximum wind velocity (m/s): a maximum 10-minute mean velocity of winds during a typhoon
- Maximum instantaneous wind velocity (m/s): maximum velocity of winds during a typhoon
- Maximum daily rainfall (mm): maximum daily precipitation when under the influence of a typhoon
- Maximum hourly rainfall (mm): maximum hourly precipitation when under influence of a typhoon

The data on 108 years were obtained from the Korean Meteorological Administration and analyzed using the BM and POT methods. The parameters of both distributions were estimated through maximum likelihood estimation. To select a threshold of a GP distribution, a mean residual life plot and parameter stability plots were depicted. Diagnostic graphs such as QQ (quantile-quantile) plots, PP (probability-probability) plots, density plots, and return level plots were also generated to determine which model fit well [4].

To consider long-term climate changes, the EVT models with time-related covariates were also developed. The developed models were also checked through PP plots and QQ plots, and selected by likelihood ratio tests between the nested models. When the p-value of the test was lower than 5%, it was concluded that the inclusion of a temporal covariate was statistically significant.

4. Result

The results of the typhoon-related variables are summarized in Table I. The parameters of the selected methods were estimated and 100-year return levels of each variable were predicted. Temporal trends were found in the EVT models of the two rainfall variables and the 100-year return levels for 2034 were also predicted by the non-stationary EVT models. Fig. 1 and 2 show the diagnostic plots of the selected model for the maximum wind velocity and the maximum daily rainfall.

5. Discussions and Conclusions

A statistical approach to analyzing hazards of external events using the EVT was proposed in this paper. In addition, the wind speed and rainfall data on Korean typhoons were analyzed. Compared to the preliminary safety analysis report of Shinkori units 3 and 4 (wind velocity, 45 m/s; hourly rainfall, 208 mm/hr; daily rainfall, 790 mm/day), the results of wind velocity and daily rainfall showed higher return levels of 100-year periods [6]. The results of wind speeds are more conservative because the safety analysis report used local meteorological records, while this study was conducted based on the maxima of national wide records. However, a fragility analysis of Korean nuclear power plants based on this study is still required to ensure the safety of power plants against extreme typhoons because a large typhoon has more than a 500 km radius, while the area of the Korean peninsula is 223,000 km^2.

The results of rainfalls were generally lower than the level in the Shinkori safety reports, since the safety report did not only consider typhoon-related effects, but other types of localized heavy rains. However, the return level of daily rainfalls estimated by the non-stationary model considering temporal trends was higher than the results of the Shinkori safety reports. These results imply the possibility of stronger typhoons than the designed levels for external hazards; hence, the fragility analysis is expected to be conducted for securing safety of power plants. We also plan to evaluate the co-occurrence probability of meteorological hazards related with a typhoon.

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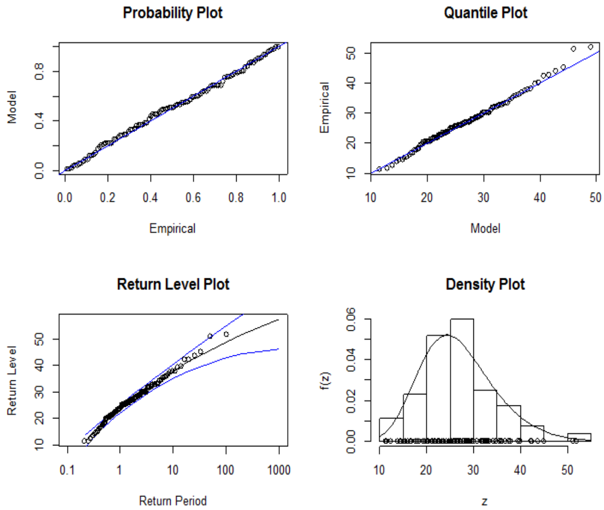

Fig. 1. Diagnostic plots for the EVT model of the maximum wind velocity

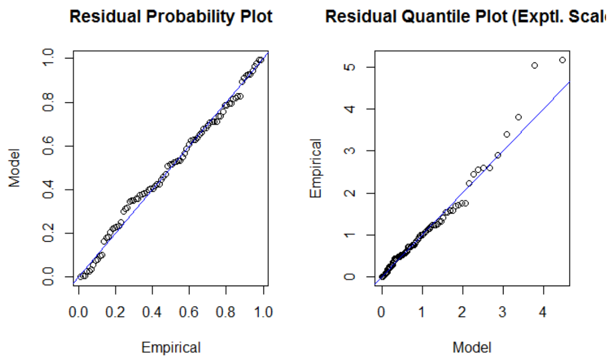

Fig. 2. Diagnostic plots for the EVT model of the maximum daily rainfall

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Table I: Parameter estimates and 100-year return levels of the EVT models fitted to the four typhoon-related variables

Variable	Selected distribution	Parameter estimates	100-year return level
Maximum wind velocity	GEV	Loc: 23.431 Scale: 7.107 Shape: -0.115	48.832
Maximum instantaneous wind velocity	GEV	Loc: 33.203 Scale: 8.414 Shape: -0.193	58.879
Maximum hourly rainfall	GP (u=10)	Scale: 0.099yr-161.348 Shape: 0.004yr-8.118	(stationary model) 103.612 (non- stationary model from 2034) 182.425
Maximum daily rainfall	GEV	Loc: 0.464yr-769.110 Scale: 0.872yr-1618.749 Shape: -0.050	(stationary model) 640.353 (non- stationary model from 2034) 812.016