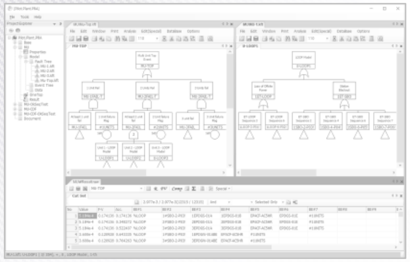
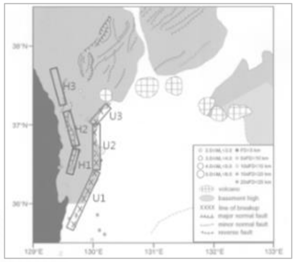
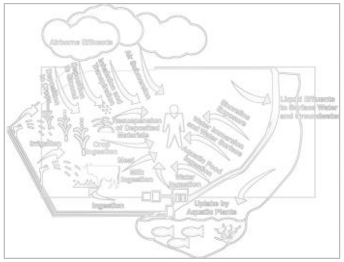
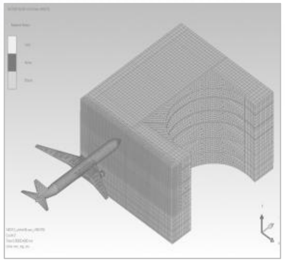
한국원자력학회 2019년 춘계 학술발표회, 2019.5.22 – 5.24, 제주 국제컨벤션센터









Requirement for Seismic PSA Quantification Software under Development in KAERI

2019.5.24

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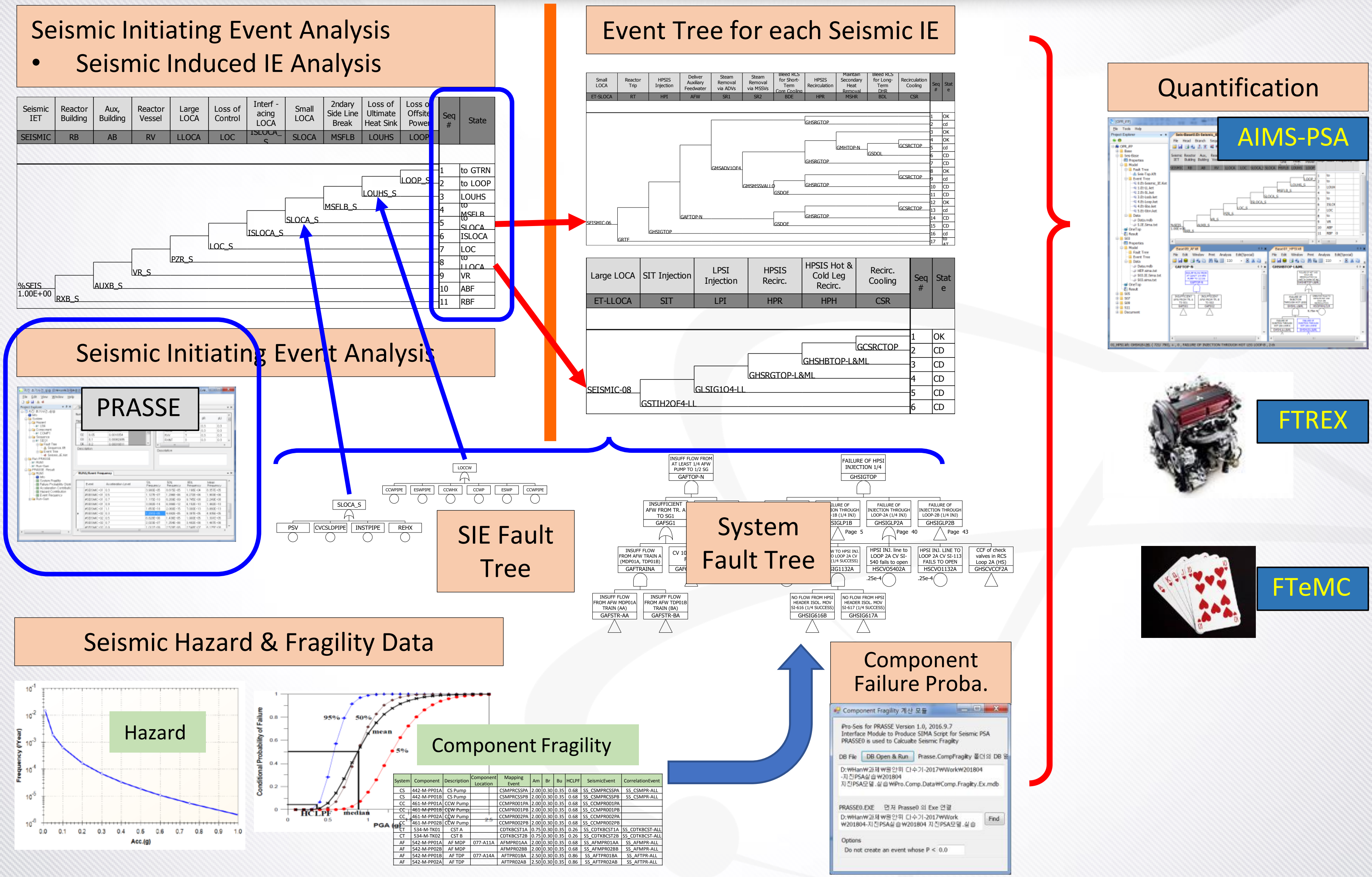
1. 개요 - Seismic PSA 절차



Fragility Function & Correlation

- **Ground Acceleration Capacity, A, is given by:**
  - $A = A_m \, e_R \, e_U$
  - e_R , e_U : random variables
    - median = 1.0, logarithmic standard deviations of β_U and β_R
  - A_m : Median
  - β_U : Inherent randomness (also known as *aleatory uncertainty*)
  - β_R : the state of knowledge uncertainty (also known as *epistemic uncertainty*)
- **Conditional probability of failure, f_0, for a given PGA level, *a***
  - f' = P(A < a) , (Capacity < Response)
    - f' = $\emptyset\left(\frac{\ln\left(\frac{a}{A_m}\right)+\beta_U \emptyset^{-1}(Q)}{\beta_R}\right)$ with Q uncertainty level, or
    - f' = $\emptyset\left(\frac{\ln\left(\frac{a}{A_m}\right)}{\beta_C}\right)$, with composite uncertainty $\beta_C = ({\beta_R}^2 + {\beta_U}^2)^{1/2}$
    - Ø(.) : the standard Gaussian cumulative distribution function

A	B	C	D
PGA	Am	Bc	Fail.Proba
0.7	1.5	0.4	=NORMSDIST(LN(A2/B2)/C2)

- **Correlation Coefficient**
  - Correlation between 2 Variables
  - $\rho = \sum((x_i - \bar{x})(y_i - \bar{y})) \,/ (\sqrt{\sum(x_i - \bar{x})^2}\sqrt{\sum(y_i - \bar{y})^2})$

Correlation Matrix

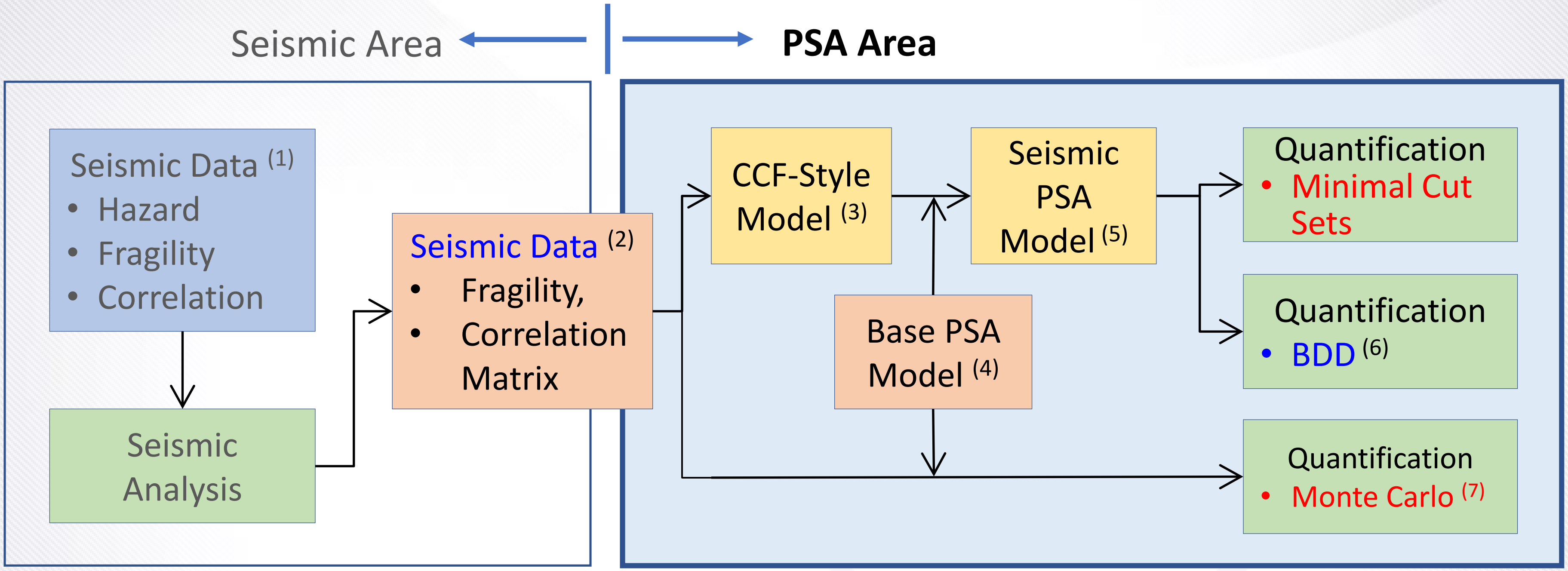
	A	B	C
A	1		
B	0.5	1	
C	0.5	0.5	1

2. Seismic PSA 정량화 S/W 기본 요건

- **Seismic PSA 정량화 S/W 기본 요건**
  - Seismic Failure
    - Seismic Hazard / Fragility / Correlation
  - 리스크 정량화
    - 리스크 평가 (Total, 주요 시나리오별, 다수기 시나리오)
    - Uncertainty, Importance 평가

- **2 Approaches**
  - Traditional PSA + CCF-Style Approach
    - Cut Set Approach
    - (BDD Approach)
  - Monte Carlo Approach
    - Cut Set Approach 의 결과 검증

Seismic PSA 정량화 S/W 구성



Note)
1) 다양한 입력 양식 허용 (SSMRP, Reed-McCann, …)
2) Am, Br, Bu + Correlation Matrix (Br, Bu) 형태로 정리 (하나의 입력을 모든 경우에 활용)
3) 각 seismic correlation group 을 CCF-Style Fault Tree 로 변환
4) Seismic failure data 가 포함되지 않은 Base PSA model.
5) Base PSA Model + CCF-style fault trees → seismic PSA model
6) 소규모 모델에 대해 BDD 해석
7) Fault Tree Evaluation using Monte Carlo simulation (FTeMC)

Seismic Data 요건 / 입력 정보

- **요건**
  - 통일된 Seismic Data 입력
  - Failure Probability 계산
  - CCF Model 생성
  - Seismic Event Mapping 처리
  - Uncertainty Analysis
- **Seismic Data**
  - PGA
  - Fragility
    - Am, Br, Bu
  - Correlation Group
    - Group 에 속하는 Event 목록
    - Br, Bu 에 대한 Correlation Coefficient
- **Non-Seismic Data**
  - Distribution for Uncertainty Analysis

```
#PGA
      0.5
#Fragility  ; Event Am Br Bu
      TK    2     0.3   0.3   S-TK ; Tank
      P1    1     0.3   0.3   ; Pump 1 (Correlated)
      P2    1     0.3   0.3   ; Pump 2 (Correlated)
      V1    1.5   0.3   0.3   ; Valve 1 (Correlated)
      V2    1.5   0.3   0.3   ; Valve 2 (Correlated)

#Group Pumps Non-Symmetry  123456
      P1    P2
#Matrix.Br
      1
      0.3   1
#Matrix.Bu
      1
      0.7   1

#Group Valves Symmetry
      V1    V2
#Coeff.All 0.5

#Non.Seismic   ; Lognormal (Mean, EF)
TK    0.01  3
P1    0.1   2
P2    0.1   2
V1    0.05  2
V2    0.05  2
```

Seismic Event

Description

Non-Symmetry

Identifier (Default = ABCD ...)

Matrix Style

Symmetry

동일한 Coeff 입력

3. 기본 계산 모듈 개발

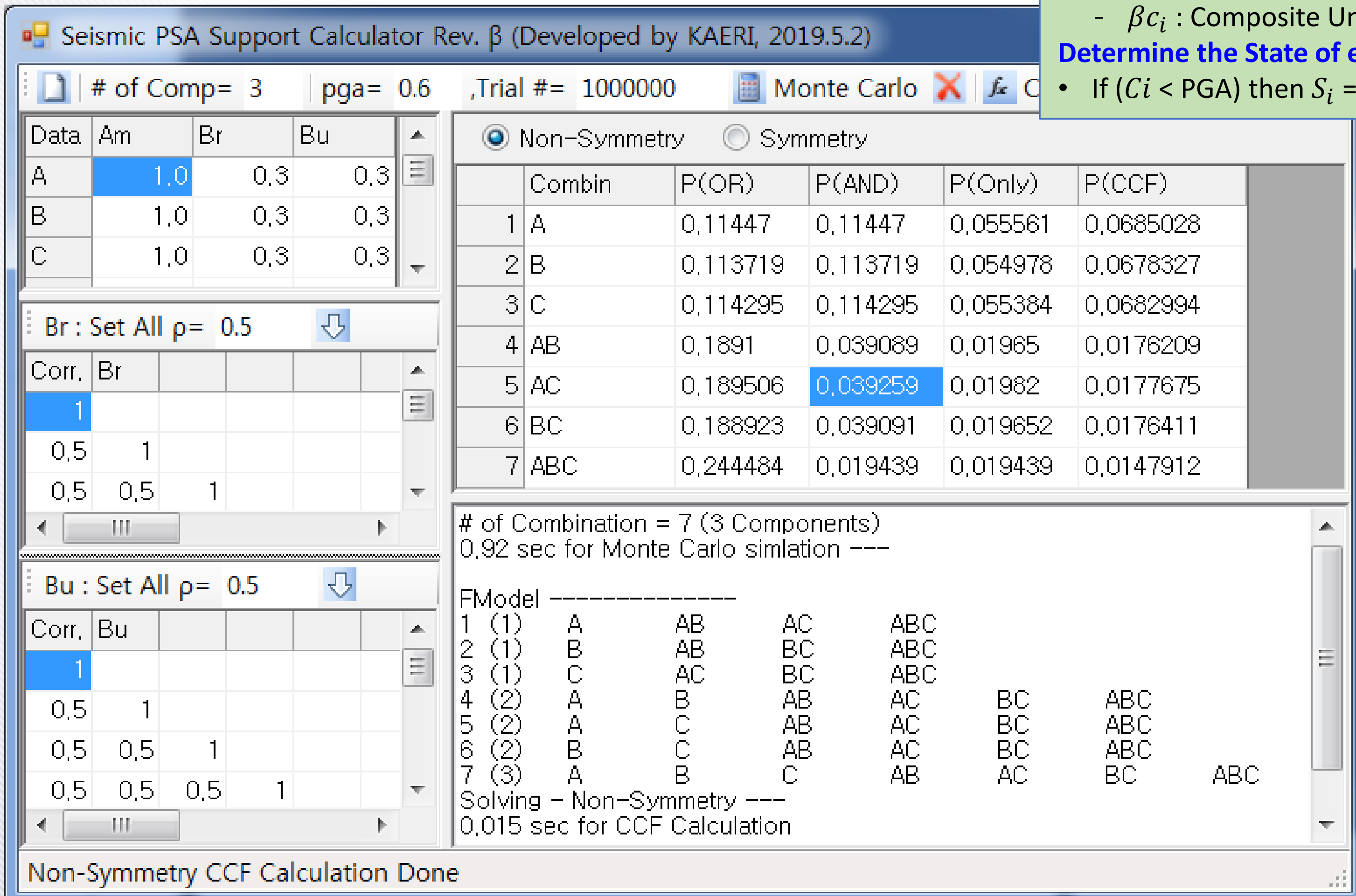
- Correlated Monte Carlo Technique
- CCF-Style Fault Tree 생성 (최대 12 Comp)

Calculate Capacity Ci for each component

- r_i ← U(0,1) ' Uniform Random Number
- Xi ← $\emptyset^{-1}(r_i)$ ' Inverse Normal
- Zi = M Xi ' Incorporate Correlation
  - M M^T = Σ
  - M = $\Sigma^{1/2}$: Result of Cholesky Decomposition
  - Σ : Coefficient Matrix
- Ci ← Am_i exp (Zi βc_i) ' Capacity Ci
  - Am_i : Median Capacity
  - βc_i : Composite Uncertainty

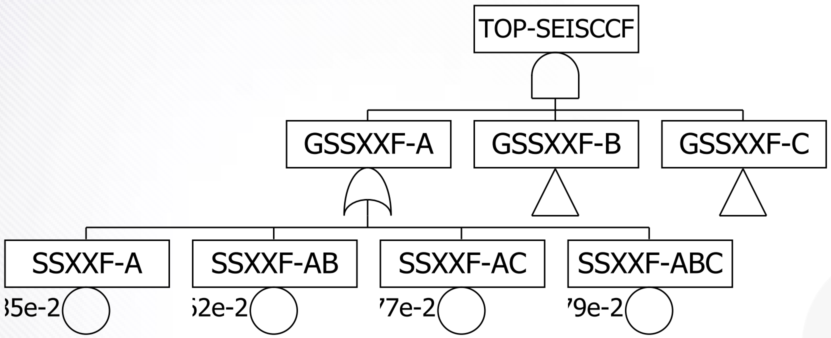
Determine the State of each component

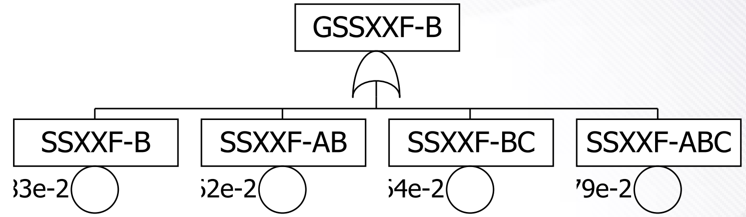
- If (Ci < PGA) then S_i = True, Else S_i = False

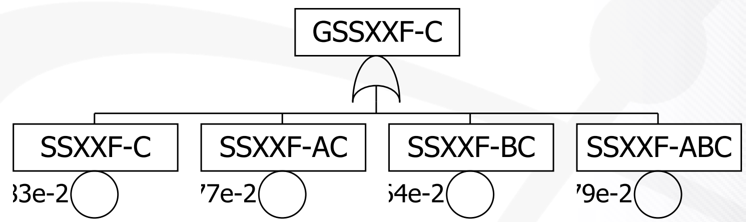


CCF-Style Model

▪ CCF-Style Model







▪ 정량화 결과 비교

Case	Monte Carlo	CCF-Style → BDD
A * B * C	0.01944	0.01944
A + B + C	0.2445	0.2445

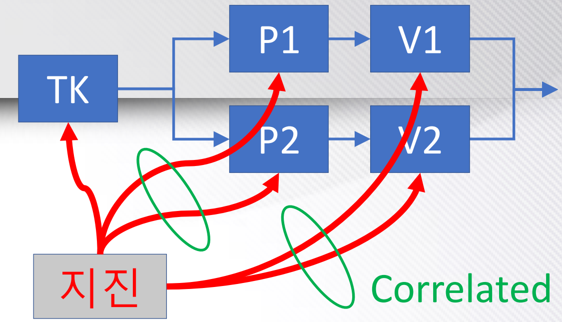
- 동일한 정량화 결과 ← 같은 값을 가지도록 CCF Model 을 생성

CCF 값 계산 방법

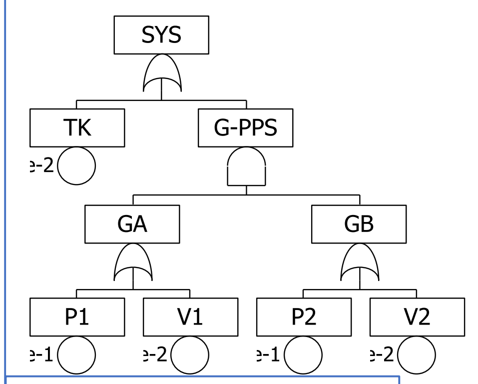
Zk	Ce (CCF Event 들)						
A	A	AB	AC	ABC			
B	B	AB	BC	ABC			
C	C	AC	BC	ABC			
A + B	A	B	AB	AC	BC	ABC	
A + C	A	C	AB	AC	BC	ABC	
B + C	B	C	AB	AC	BC	ABC	
A + B + C	A	B	C	AB	AC	BC	ABC

- **Component 별 CCF Model**
  - $X_i = C_i + \sum_{j=1,j\neq i}^{m} C_{ij} + \sum_{j=1,j\neq i}^{m} \sum_{k=j+1,k\neq i}^{m} C_{ijk} + \ \dots$
    - 예) $X_A = C_A + C_{AB} + C_{AC} + C_{ABC}$
    - C_e : CCF Event 들 (CCF Event의 수 = $2^m - 1$)
- **기기들의 OR 조합에 대한 모델**
  - $Z_i = X_i$, $Z_{ij} = X_i + X_j$, $Z_{ijk} = X_i + X_j + X_k$, … ($2^m - 1$ 조합)
    - 예) $Z_{A+B} = C_A + C_B + C_{AB} + C_{AC} + C_{BC} + C_{ABC}$
  - $Z_k = \sum_{C_e \in Z_k} C_e$: Z_k 에 속한 모든 CCF Event 들의 합
  - $P(Z_k) = 1 - \prod_{C_e \in Z_k} (1 - P(C_e))$: 확률 계산 식 (independent Event 들)
    - $P(Z_k)$: Correlated Monte Carlo 방법으로 계산된 값
- **Negate 확률 + Log 변환 → 다항 1차식**
  - $1 - P(Z_k) = \prod_{C_e \in Z_k} (1 - P(C_e))$: Negate 확률로 변환
  - $\log(1 - P(Z_k)) = \sum_{C_e \in Z_k} \log(1 - P(C_e)) = \sum_{C_e \in Z_k} R_e$: 다항 1차식
    - $R_e = \log(1 - P(C_e))$

4. PSA 적용 예제 (1)



Input Model/Data

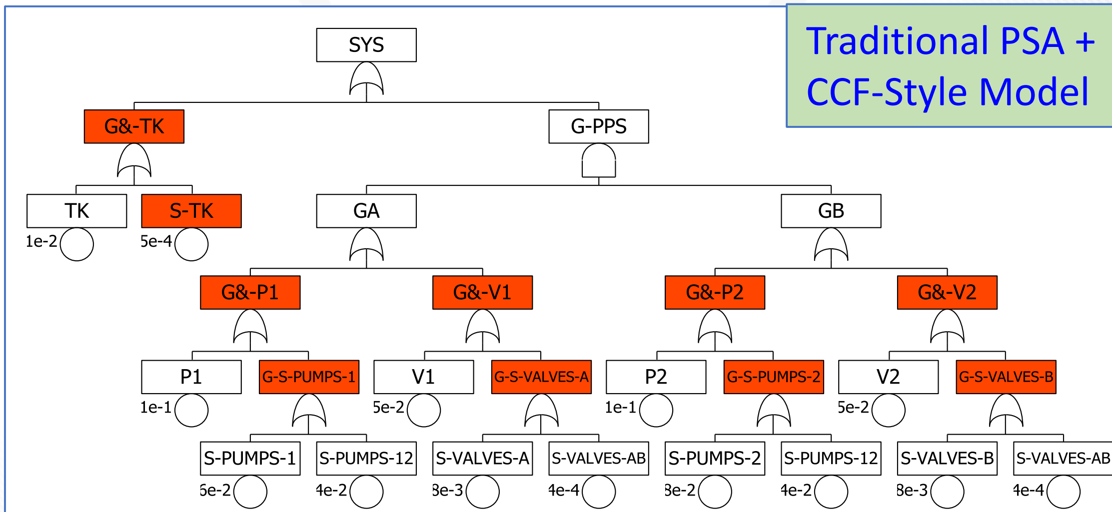


#PGA
0.5
#Fragility
TK 2 0.3 0.3 S-TK
P1 1 0.3 0.3
P2 1 0.3 0.3
V1 1.5 0.3 0.3
V2 1.5 0.3 0.3
#Group Pumps
P1 P2
#Matrix.Br
1
0.3 1
#Matrix.Bu
1
0.7 1
#Group Valves
V1 V2
#Coeff.All 0.5

Monte Carlo Approach
(n=1e8, FTeMC)
→ 5.466e-2

Traditional PSA + CCF-Style Approach
(SPSA.Supp.Calc + BDD)
→ 5.469e-2 (0.05% 차이)

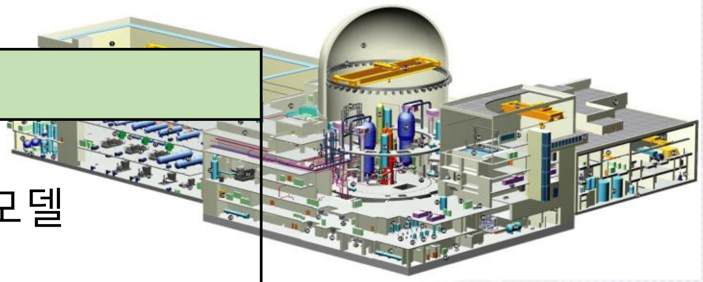
→ 여러 Seismic Group 과 Non-Seismic 으로 구성된 경우에도, 두 방법이 같은 결과를 산출함



Traditional PSA + CCF-Style Model

PSA 적용 예제 (2)

▪ Pilot Seismic PSA Model



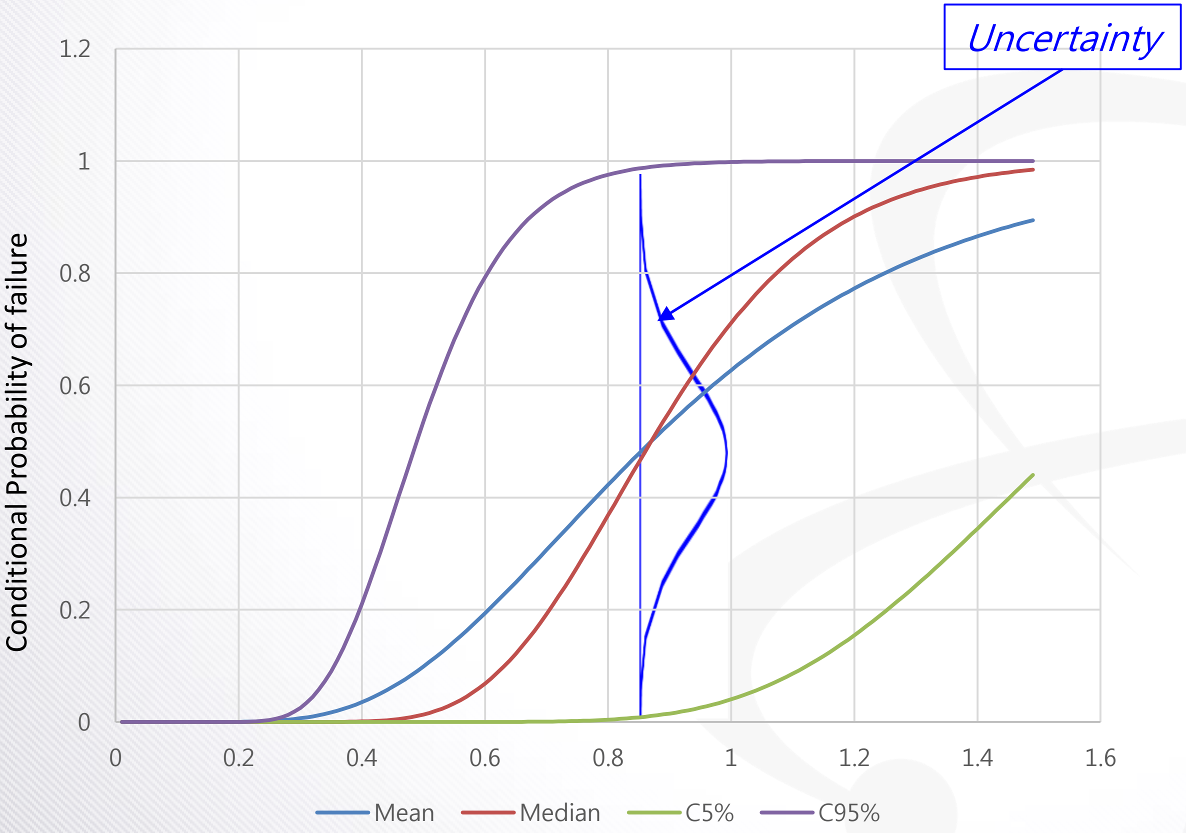
Model	Description
Internal PSA Model	Pilot Plant PSA Model 원전 주요 계통 및 기기 포함한 단순화 모델 160 여 개의 Basic Event
Seismic Initiating Event Tree	7개 IE 고려 (R/B Failure, LLOCA, SLOCA, Loss of Control, LOUHS, LOOP, GTRN)
Seismic Correlation	ρ = 0.5 (주요 Pump, EDG/AAC, SDS V/V, CST) Fragility 는 기기별로 임의의 값을 가정
Calculation	PGA = 0.6 에 대한 CCDP

방법	정량화 결과	비고
Monte Carlo (FTeMC)	3.1043e-2	N=1e8 (샘플 수)
CCF-Style Model (FTREX/BDD)	3.1086e-2 (0.14% 차이)	N=1e8 (CCF Event 계산 샘플 수) REA=3.321e-2

➔ Pilot Plant Seismic PSA 모델에서도 두 방법이 같은 결과를 산출함

5. PGA Level + Uncertainty 평가 방법

- **지진 리스크 평가 = 주어진 System에 대한 Fragility Curve 평가**
  - PGA level 에 따른 파손확률
  - 파손확률의 Mean + 불확실성 (Median, 5%, 95%) 평가



f' = $\emptyset\left(\frac{\ln\left(\frac{a}{A_m}\right)+\beta_U \emptyset^{-1}(Q)}{\beta_R}\right)$

A = A_m' e_U

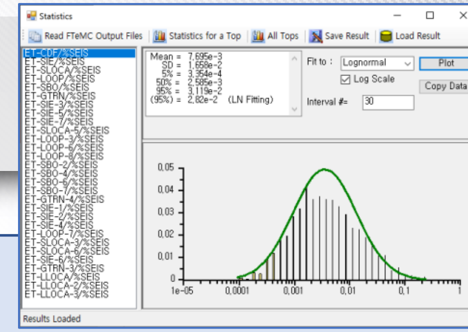
A = A_m' exp(β_U * k_q)

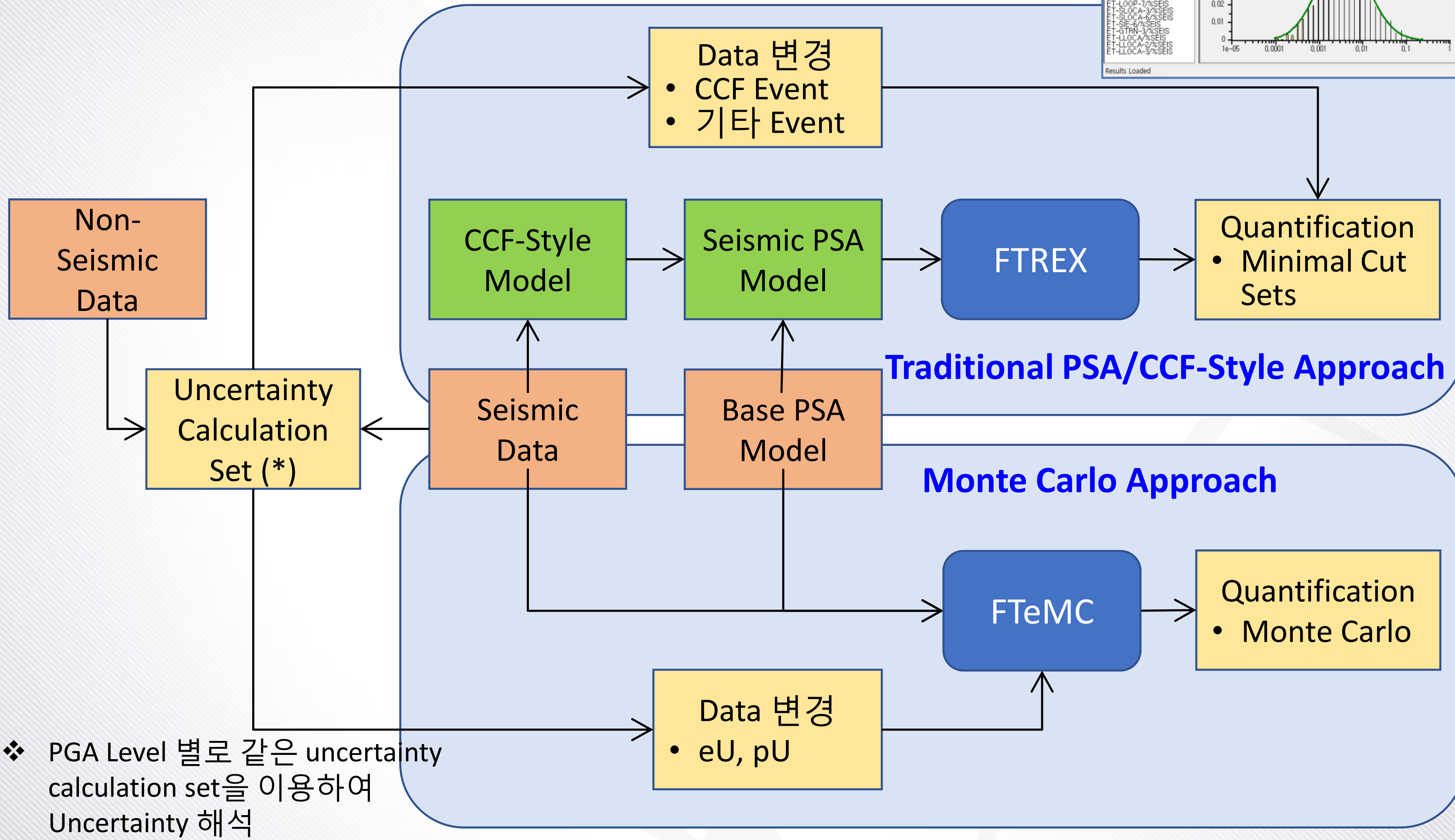
- k_q : 확률 q에 해당하는 inverse normal 값 : $\emptyset^{-1}(Q)$

<u>평가 절차</u>

- 각 PGA level 에 대해
- Am, Br 을 이용하여 파손확률 평가
- Bu 를 이용하여 Sampling → 위의 과정을 반복 → 5%, 95%, Median, Mean 계산

Uncertainty 평가 방법





- ❖ PGA Level 별로 같은 uncertainty calculation set을 이용하여 Uncertainty 해석
- ❖ 그렇지 않은 경우, PGA Level 별 값이 역전되는 현상 발생 가능

6. 추후 연구 항목

- **Seismic PSA 정량화 S/W 개발 중**
  - 방법론 개발
  - 주요 모듈 개발
  - 시험
  - 기능 요건 작성
- **Seismic 분야에서 필요한 Feature 필요 (PRASSE의 기능들)**
- **미해결 사항들**
  - 다양한 Fragility, Correlation 입력 방식의 처리
    - Am, Br, Bu / Correlation Coefficient Matrix 로 변환
  - LHS Sampling 적용 검토
  - CCF 변환 Tool 보완
    - 경우에 따라 음수로 나타나는 CCF Event 값 처리 (Monte Carlo 결과)
    - CCF Model 단순화 및 부분적인 Symmetry 처리 방법
    - Uncertainty 분석시 Group 내에서 Symmetry 가 크게 깨지는 현상 검토
  - Cholesky Matrix 의 입력 오류 처리
    - $M M^T = \Sigma$ (M = $\Sigma^{1/2}$: Cholesky Matrix, Σ : Coefficient Matrix)

THANK YOU