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Validation Study for Seismic Correlation Analysis SW COREX

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1. Introduction

Seismic correlation is a kind of dependency among seismically induced failures of structures, systems and components. Therefore, the technically adequate modeling of the seismic correlation is essential for Seismic PRA to have reasonable realistic results[1]. In the previous study, COREX S/W was developed to support partial seismic correlation analysis for seismic PRAs. In this study, we performed COREX S/W Program validation for some typical paritial seismic correlation group.

2. Methods and Results

2.1 COREX S/W Develpment

Jung suggested the methodology and process to model the seismically correlated failure events as CCF events in the fault tree. To Support the methodology and process, COREX S/W was developed [2].

The main purpose of developing COREX is to easily calculate correlated seismic failures probability, to convert the correlated seismic failures probabilities into seismic CCFs probabilities, and to support modeling seismic CCFs into seismic PSA fault trees.

COREX has two main functions. First, COREX calculates combination probabilities (joint or union probabilities) of correlated seismic failures. Second, COREX solves simultaneous equations for generating probabilities of single seismic failure and seismic CCFs.

COREX calculates combination probabilities (joint or union probabilities) of correlated seismic failures by SSMRP or Reed-McCann integration. COREX casts these combination probabilities into LHS of simultaneous equations, and MCUB or REA probability equations into RHS of simultaneous equations that consist of single seismic failure and seismic CCFs. COREX solves these simultaneous equations, and generates the probabilities of single seismic failure and seismic CCFs[2].

2.2 Validation for SSMRP MVN Integration

For the SSCs with paritial seismic correlation, the joint failure probability can be calculated with the SSMRP integration as shown in equation below. The SSMRP integration is also called MVN(Multi-Variate Normal) integration [3].

$$P_{12\ldots n}(a) = \int_{-\infty}^{\ln\left(\frac{a}{A_{1m}}\right)} \int_{-\infty}^{\ln\left(\frac{a}{A_{2m}}\right)} \cdots \int_{-\infty}^{\ln\left(\frac{a}{A_{nm}}\right)} \frac{1}{\sqrt{|\Sigma|(2\pi)^n}} \exp\left(-\frac{1}{2} x^t \Sigma^{-1} x\right) dx_1 dx_2 \ldots dx_n \quad (1)$$

Where, $x^t = [x_1, x_2, \ldots x_n]$. Σ is a symmetric positive definite covariance matrix as shown below.

$$\Sigma = \begin{bmatrix} \beta_1^2 & \beta_{12}^2 & \cdots & \beta_{1n}^2 \\ \beta_{21}^2 & \beta_2^2 & \cdots & \beta_{2n}^2 \\ \cdots & \cdots & \cdots & \cdots \\ \beta_{n1}^2 & \beta_{n2}^2 & \cdots & \beta_n^2 \end{bmatrix}, \quad \beta_{ij}^2 = \mathrm{cov}(X_I, X_j)$$

Where, $|\Sigma|$ is a determinant of Σ, and Σ^{-1} is an inverse matrix of Σ.

If x_i is replaced with $\beta_i z_i$, Eq. (1) can be converted into

$$P_{12\ldots n}(a) = \int_{-\infty}^{\frac{\ln(a/A_{1m})}{\beta_1}} \int_{-\infty}^{\frac{\ln(a/A_{2m})}{\beta_2}} \cdots \int_{-\infty}^{\frac{\ln(a/A_{nm})}{\beta_n}} \frac{1}{\sqrt{|\Sigma_\rho|(2\pi)^n}} \exp\left(-\frac{1}{2} z^t \Sigma_\rho^{-1} z\right) dz_1 dz_2 \ldots dz_n \quad (2)$$

Where, $z^T = [z_1, z_2, \ldots z_n]$. Σ_ρ is a symmetric positive definite correlation matrix as shown below.

$$\Sigma_\rho = \begin{bmatrix} 1 & \rho_{12} & \cdots & \rho_{1n} \\ \rho_{21} & 1 & \cdots & \rho_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ \rho_{n1} & \rho_{n2} & \cdots & 1 \end{bmatrix}, \quad \rho_{ij} = \frac{\beta_{ij}^2}{\beta_i \beta_j}$$

COREX S/W was coded with C-language to calculate the above SSMRP MVN integration very effectively. The validation for the COREX SSMRP MVN integration calculation was performed by MATLAB. The SSMRP MVN equation above was written in the MATLAB code as symbol intergration.

The COREX input for the validation of SSMRP MVN Intergration calculation was prepared below which can reflect the typical seismic motion and SSCs fragility in the seismic PRA.

- Number of Correlation Group (NO_COMP): 3
- Seismic Intensity (RESPONSE): 0.6 g
- Logarithmic Standard Deviation for Response (Response_BETA): 0.34, 0.34, 0.34
- Correlation Matrix for Response (Response_Correlation)
  1.00, 0.75, 0.75
  0.75, 1.00, 0.75

0.75. 0.75, 1.00

- Median for Seismic Fragility (STRENGTH): 0.92, 0.92, 0.92
- Logarithmic Standard Deviation for Strength (Strength_BETA): 0.34, 0.34, 0.34
- Correlation Matrix for for Strength (Strength_Correlation)
  1.00, 1.00, 1.00
  1.00, 1.00, 1.00
  1.00. 1.00, 1.00

The calculation results by COREX S/W Program and MATLAB are shown table I below.

Table I: Results for SSMRP MVN integration

No of Failed Comp	COREX Result	MATLAB Result
1 Comp	1.870075E-1	1.8701058E-1
2 Comps	1.332994E-1	1.3329705E-1
3 Comps	1.107249E-1	1.1072067E-1

As can be seen in the table above, COREX calculation for SSMRP MVN integration is well validated by MATLAB calculation.

2.3 Validation for Reed-McCann Integration

For the SSCs with paritial seismic correlation, the joint failure probability can be calculated with the Reed-McCann integration below [4]. Reed-McCann integration is essentially identical to MVN integration.

$$P_{12\ldots n}(a) = \int_0^\infty \ldots \int_0^\infty f_{12\ldots n}(x)dx_{12} \ldots dx_{(n-1)n}$$
$$f_{12\ldots n}(x) = g_1(x)g_2(x)\ldots g_n(x) \quad (3)$$
$$g_i(x) = \Phi\left(\frac{\ln\left(\frac{a}{A_{im}\prod_{j\neq i} x_{ij}}\right)}{\beta_i^-}\right)$$

Where, $x_{ij} = x_{ji}$, $\beta_i^- = \sqrt{\beta_i^2 - \sum_{j=1, j\neq i}^{n} \beta_{ij}^2}$, and $\beta_{ij} = \beta_{ji}$.

$\Phi(\ )$ is a standard normal cumulative distribution function.

If two failures are correlated, $P_{12}(a)$ is calculated as

$$P_{12}(a) = \int_0^\infty f(x)g(x)dx_{12}$$
$$f(x) = \Phi\left(\frac{\ln\left(\frac{a}{A_{1m}x_{12}}\right)}{\beta_1^-}\right)\Phi\left(\frac{\ln\left(\frac{a}{A_{2m}x_{12}}\right)}{\beta_2^-}\right) \quad (4)$$
$$g(x) = \varphi\left(\frac{\ln x_{12}}{\beta_{12}}\right)\frac{1}{\beta_{12}x_{12}}$$

Here, $\Phi(\ )$ is a standard normal cumulative distribution function, and $\varphi(\ )$ is a standard normal probability density function.

COREX S/W was coded with C-language to calculate the above Reed-McCann integration very effectively. The validation for the COREX Reed-McCann integration calculation was performed by MATLAB. The Reed-McCann equation above was written in the MATLAB code as symbol intergration.

The COREX input for the validation of Reed-McCann Intergration calculation was prepared below which can reflect the typical seismic motion and SSCs fragility in the seismic PRA.

- Seismic Intensity (GROUND_ACC): 0.9 g
- Number of Correlation Group (NO_COMP): 2
- Median for Seismic Fragility (AM): 1.10, 1.10
- Independent and common logarithmic standard deviation matrix for uncertainty (BU_COV):
  0.60, 0.30
  0.30, 0.60
- Independent and common logarithmic standard deviation matrix for randomness (BR_COV):
  0.60, 0.30
  0.60, 0.30

The calculation results by COREX S/W Program and MATLAB are shown on table II below.

Table II: Results for Reed-McCann integration

No of Failed Comp	COREX Result	MATLAB Result
1 Comp	3.690222E-1	3.6901953E-1
2 Comps	1.725748E-1	1.7257425E-1

As can be seen in the table above, COREX calculation for Reed-McCann integration is well validated by MATLAB calculation.

2.4 Validation for Seismic Independent and CCF event Probability Calculation

Seismic independent and CCF events probabilities are calculated by solving the simultaneous equations using the calcaulted joint failure probabilities and REA or MCUB equations. In COREX, one of the 4 simultaneous equations can be used to calculate seismic independent and CCF events probabilities.

- Union Operation and REA probability
- Union Operation and MCUB probability
- Intersection Operation and REA probability
- Intersection Operation and MCUB probability

In this study, Intersection Operation and MCUB probability option is used for validation which is the most accurate simultaneous equations. Below is the simultaneous equations for Intersection Operation and MCUB probability with 3 components.

$$
\begin{aligned}
P_1 &= 1-(1-Q_1)(1-Q_{12})(1-Q_{13})(1-Q_{123}) \\
P_2 &= 1-(1-Q_2)(1-Q_{12})(1-Q_{23})(1-Q_{123}) \\
P_3 &= 1-(1-Q_3)(1-Q_{13})(1-Q_{23})(1-Q_{123}) \\
P_{12} &= 1-(1-Q_1Q_2)(1-Q_{12})(1-Q_{123})(1-Q_1Q_{23})(1-Q_2Q_{13})(1-Q_{13}Q_{23}) \\
P_{13} &= 1-(1-Q_1Q_3)(1-Q_{13})(1-Q_{123})(1-Q_1Q_{23})(1-Q_3Q_{12})(1-Q_{12}Q_{23}) \\
P_{23} &= 1-(1-Q_2Q_3)(1-Q_{23})(1-Q_{123})(1-Q_2Q_{13})(1-Q_3Q_{12})(1-Q_{12}Q_{13}) \\
P_{123} &= 1-(1-Q_1Q_2Q_3)(1-Q_{123})(1-Q_1Q_{23})(1-Q_2Q_{13})(1-Q_3Q_{12})(1-Q_{12}Q_{13})(1-Q_{13}Q_{23})(1-Q_{12}Q_{23})
\end{aligned}
$$

The calculated seismic independent and CCF events probability by COREX was validated using the results for SSMRP MVN validation calculation.

The validation calculation result is shown on tble III below.

Table III: Results for Seismic independent and CCF event probabilties

Basic event	COREX Result	MATLAB result
Independent failure event	4.109175E-2	4.109256E-2
CCF for 2 Comps	2.619280E-2	2.619291E-2
CCF for 3 Comps	1.059465E-1	1.059465E-1

As can be seen in the table above, COREX calculation for seismic induced independent and CCF event probabilities are well validated by MATLAB calculation.

3. Conclusions

In the previous study, COREX was developed which has the capabilities below.

• Calculation of combined failure probabilities (joint or union probabilities) of correlated seismic failures using the SSMRP MVN equation or Reed-McCann equation.

• Calculation of simultaneous equations for generating probabilities of single seismic failure events and seismic CCF events for fault tree incorporation with the combined failure probabilities (joint or union probabilities) calculated above.

In this study, COREX validations were performed for SSMRP MVN integration, Reed-McCann integration and Seismic induced independent and CCF events. All the CORX calculation results were well validated by MATLAB calculation.

This validation study has established the technical basis for the COREX adoption for seismic PRAs. It is expected that the COREX adoption for seismic PRA could play very important roles. The expected benefits and changes in seismic PRA are as follows.

• With the COREX, partial seismic correlation can be efficiently implemented into the seismic PRA.

• COREX results were easily implemented into fault tree logic model. Thus we can get sufficient risk insights with the seismic PRA results comparable to the one of internal event PRA.

• By reflecting the well-known technical elements which reduce the degree of seismic correlation, the significantly reduced CDF was resulted compared to the one with the standard thumb rule application, though the reduction of the seismic correlation was not very big. It means the partial seismic correlation shall be considered in the seismic PRA.

• When COREX is used for seismic PRA, all the seismic induced failure events were modeled in the fault tree. Thus the cutset post-processor which converts the MCSs into BDD such as ACUBE or BeEAST should be used for exact CDF calculation because the seismic induced failure events are non-rare events.

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