Evaluation of the increase in risk from seismic events during equipment outages

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Seismic events can be a dominant risk contributor for nuclear power plants (NPPs) located at seismically active regions. For such NPPs, it is important to capture the change in risk from seismic events, when equipment are taken out of service for maintenance. Risk Monitors can calculate the changes in risk caused by equipment outages or maintenance activities, and they are widely used to evaluate the changes in risk from internal events. But when calculating the changes in the risk from seismic events, which is quantified using the seismic Probabilistic Assessment (PRA) model, considerations specific to seismic PRA modeling assumptions are necessary.

In the seismic PRA, it is a common practice to assume complete dependence between seismic component failures of redundant equipment with same design. This approach is useful to evaluate the annual risk because it often results in conservative risk values, and, it is a simple way to cope with the difficulties to determine the correlation of seismic component failures. However, when evaluating risk increase caused by outage of equipment, the complete dependence assumption will result in an underestimation of the risk increase. This is because when seismic failures of redundant components are assumed to be fully dependent, the system reliability under a seismic event becomes insensitive to the number of redundant components that are available. Accordingly, the incremental risk for a given component outage will be underestimated, and the calculated allowed outage time using such results will be overestimated.

This paper proposes a methodology to evaluate the increase in risk from seismic events during equipment outages. By adequately assuming fully dependent or fully independent seismic failures of the equipment of concern, a bounding value of risk increase can be evaluated. The results obtained applying this methodology can be used as an input to risk informed decision making and allowed outage time calculations.

I. Introduction

One of the applications of Probabilistic Risk Assessment (PRA) is to calculate the risk increase provoked by equipment outages to determine allowed outage times or to optimize maintenance strategies. In such applications, the changes in risk from the baseline level or from the particular plant configuration are important rather than the absolute value of the core damage frequency (CDF) or large release frequency (LRF) at that plant configuration. When calculating the risk of equipment outages, the analysist needs to carefully evaluate the assumptions applied in the PRA that can lead to underestimation or overestimation of risk changes.

In an event of an earthquake, it is known that there is some amount of correlation between seismic component failures. The correction of seismic component failure can be high between similar components located on the same floor slab, since the components would experience similar acceleration given an earthquake. Correlation of such seismic component failures has been an interest since the early ages when seismic PRA has been studied, and methodologies have been proposed to take into account correlation in the seismic failure probabilities. However, in seismic PRA it is a common practice to assume complete dependence between seismic failures of redundant components in mitigation systems, since there are technical difficulties to quantify the proper degree of correlation of the seismic failures and the assumption of complete correlation often results in conservative CDF value[1,2]. Even though the treatment of complete correlation often provides a bounding estimate of the CDF, when one needs to focus on the risk changes when component redundancy has degraded, this treatment will underestimate the change in risk[3]. When complete correlation of seismic failures among redundant components is assumed, all components will fail at once anytime one of the components fail, meaning that system reliability given a seismic event becomes insensitive to the level of redundancy within the system.

Seismic PRA evaluates scenarios initiated by seismic failures of structures and components, and followed by loss of mitigation functions caused by seismic and/or random failures. The CDF from seismic events could be divided into seismic failure contribution, which is the CDF resulting from loss of function of mitigation systems caused by seismic failures, and random failure contribution, which is the CDF resulting from loss of function of mitigation systems caused by random failures and component outages. In a seismic PRA assuming complete correlation, the CDF increase (ΔCDF) caused by an outage of a component in a mitigation system will be observed in the random failure contribution, but due to the assumption of the complete correlation between seismic failures, the CDF increase in the seismic failure contribution is null, as shown in Fig. 1. Therefore, even though the complete correlation is a conservative assumption from the viewpoint of CDF evaluation, the incremental risk for a given component outage can be underestimated, and the calculated allowed outage time overestimated, as shown in Fig. 2.

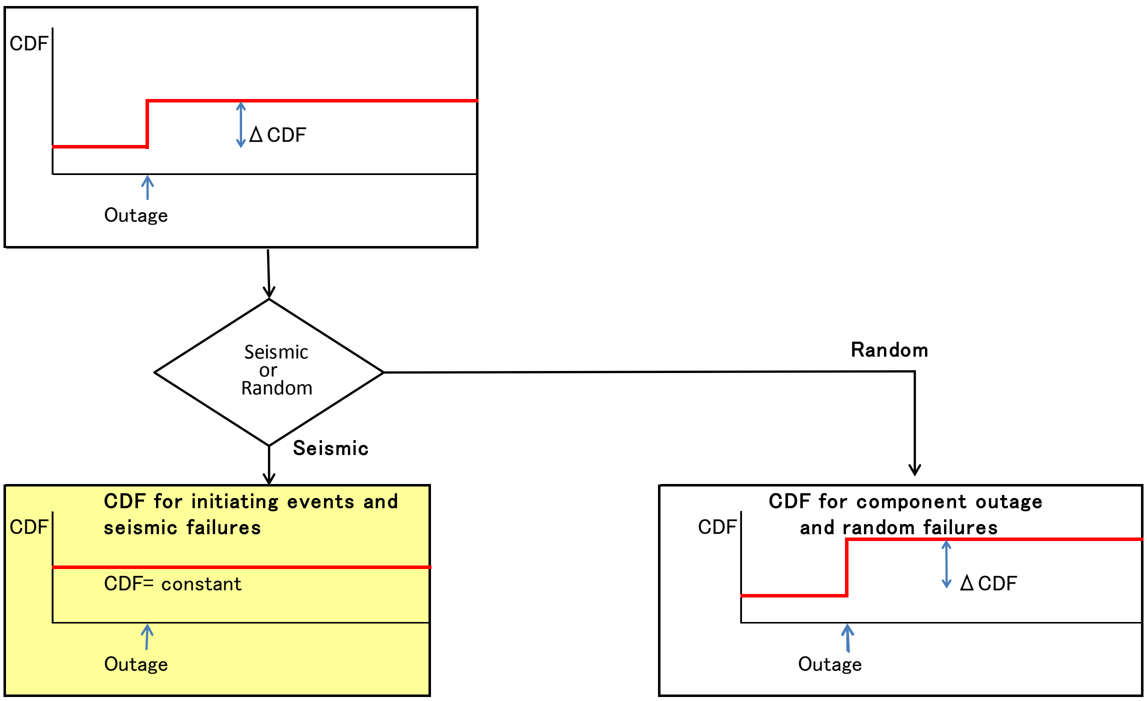


Fig. 1. Breakdown of the seismic CDF.

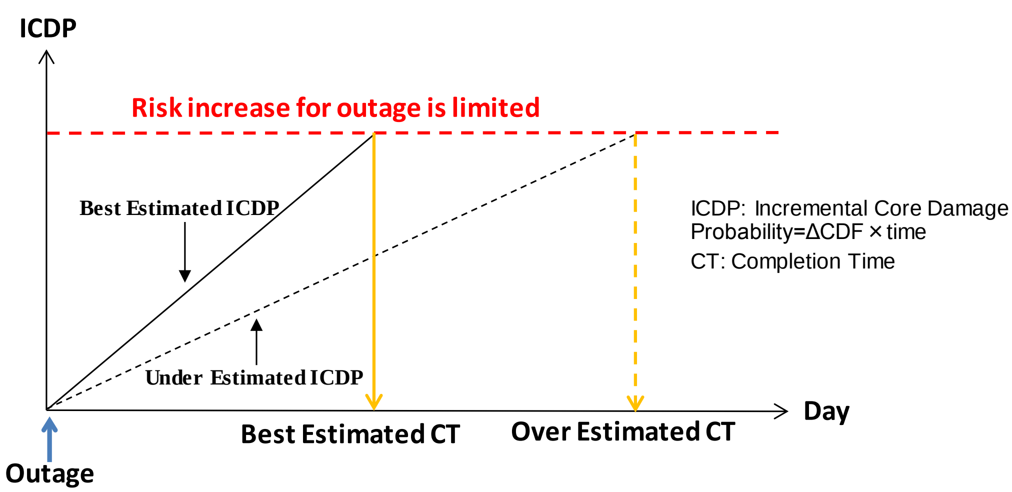


Fig. 2. Relationship between incremental risk and allowed outage time.

This paper proposes a methodology to capture the incremental seismic risk increase given component outages as an input to decision making and allowed outage time calculations in Section II. The applicability of the proposed methodology is analyzed in Section III.

II. Methodology to calculate ΔCDF

The methodology to calculate the ΔCDF caused by components outages in a system with two components is presented in this section.

If we focus on the change in system reliability against seismic events, the CDF increase when one of two components in a system is taken out of service is equivalent to the CDF decrease when the complete dependency assumption is replaced by the actual component failure dependency before the outage. However, since there are technical difficulties in determining the actual degree of correlation, a methodology to estimate the bounding CDF increase is proposed.

The basis of the methodology can be explained by using the sample shown in Fig. 3. When considering a system with two redundant components, the CDF of a sequence involving simultaneous failures of the redundant components depends on the degree of correlation of the seismic failure probability, and the ΔCDF related to the outage of one of the redundant components is maxim when the complete independent correlation is assumed in the evaluation. From Fig. 3 it can be concluded that:

$$CDF(i) < CDF(a) < CDF(d)$$

where:

CDF(i) is the CDF before the outage assuming complete independent correlation (i.e., degree of correlation = 0),
CDF(a) is the CDF before the outage based on the actual correlation (i.e., degree of correlation is between 0 and 1 but unknown), and
CDF(d) is the CDF before the outage assuming complete dependent correlation (i.e., degree of correlation = 1),

and

$$\Delta CDF2 > \Delta CDF1 \qquad (1)$$

where:

$\Delta CDF2 = CDF(d) - CDF(i)$, the estimated ΔCDF and
$\Delta CDF1 = CDF(d) - CDF(a)$, the actual ΔCDF.

Therefore, by assuming complete dependent (model 1 in Fig. 4 and 5) and independent (model 2 in Fig. 4 and 5) correlation for the seismic failure of the component before the outage, the CDF decrease due to redundancy consideration can be calculated, and this value can be regarded as the bounding ΔCDF due to loss of redundancy produced by the component outage.

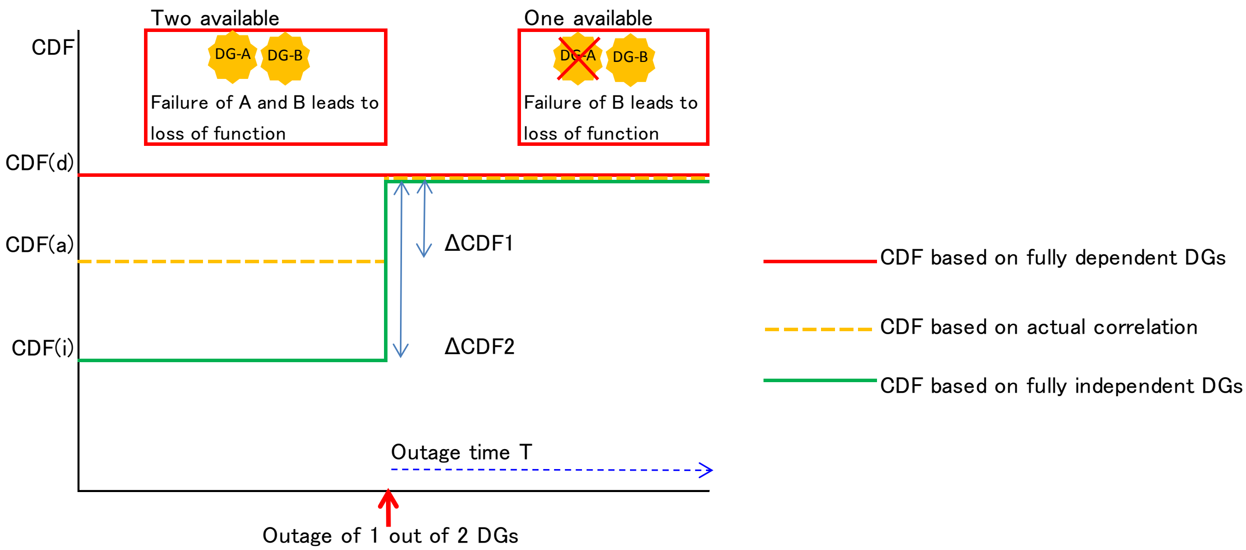
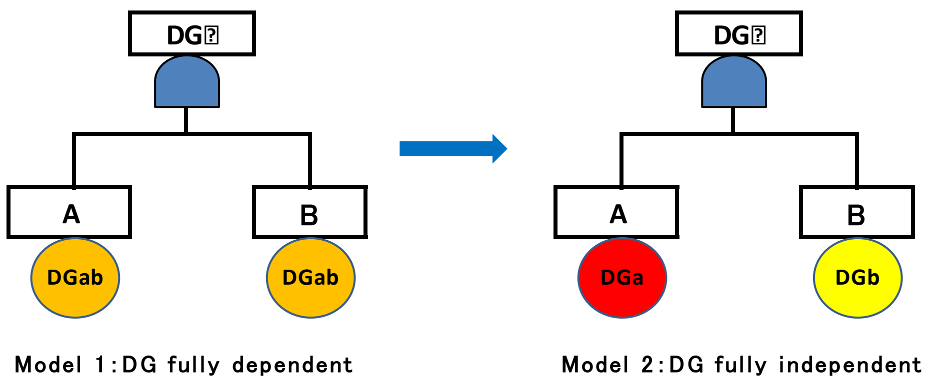


Fig. 3. ΔCDF for a system with two redundant components.



DGab: Fully dependent seismic failure event of Trains a and b
DGx: Fully independent seismic failure event of Train x (with x=a or b)

Fig. 4. Fault tree modification to calculate ΔCDF.

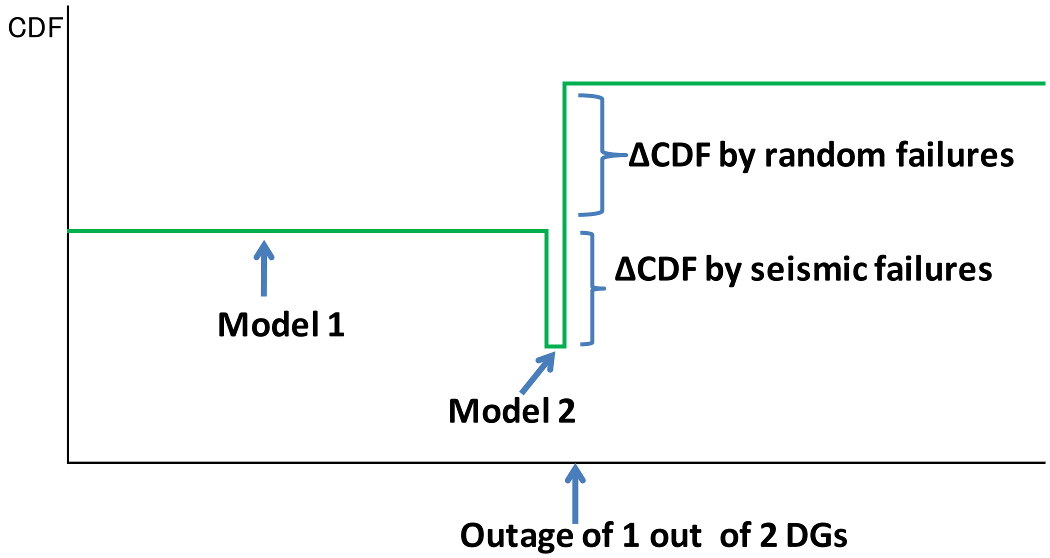


Fig. 5. Model effect on CDF and ΔCDF calculation.

III. Applicability of proposed methodology

The applicability of the proposed methodology has been analyzed against the cases listed in TABLE I.

TABLE I. Analyzed Cases.

Section	Analyzed cases
III.A.	Applicability to system with multiple redundant components
III.B.	Applicability to mitigation function based on two non-redundant systems
III.C	Applicability to mitigation function based on two redundant systems

III.A. Applicability to system with multiple redundant components

The methodology to calculate the ΔCDF due to components outages for a system with multiple redundant components is analyzed in this section.

When a system with two redundant components is considered, as shown in Fig. 3, the ΔCDF can be calculated from the difference between the CDFs based on the system evaluation with complete independent correlation failure assumption after and before the component outage. This is because the CDF based on actual correlation and the CDF based on complete independent correlation are the same when redundancy is lost during the component outage, and the actual ΔCDF (or ΔCDF1) is always smaller than the estimated ΔCDF (or ΔCDF2).

However, in case of a system with multiple redundant components, the relation ΔCDF1< ΔCDF2 is not always true and the relationship between ΔCDF1 and ΔCDF2 depends on the relative effect on the CDF caused by the degree of the redundancy loss. This can be explained by using the samples shown in Fig. 6 and Fig. 7. In both samples, a 3 redundant components system (i.e. only one component is needed for the system success) is assumed.

In Fig. 6, the ΔCDF1 produced by the outage of the first component is assumed to be smaller than the one produced by the additional outage of a second component. From Fig. 6 sample it can be concluded that:

ΔCDF1 < ΔCDF2 for the first component outage, and
ΔCDF1’ < ΔCDF2’ for the additional outage of a second component.

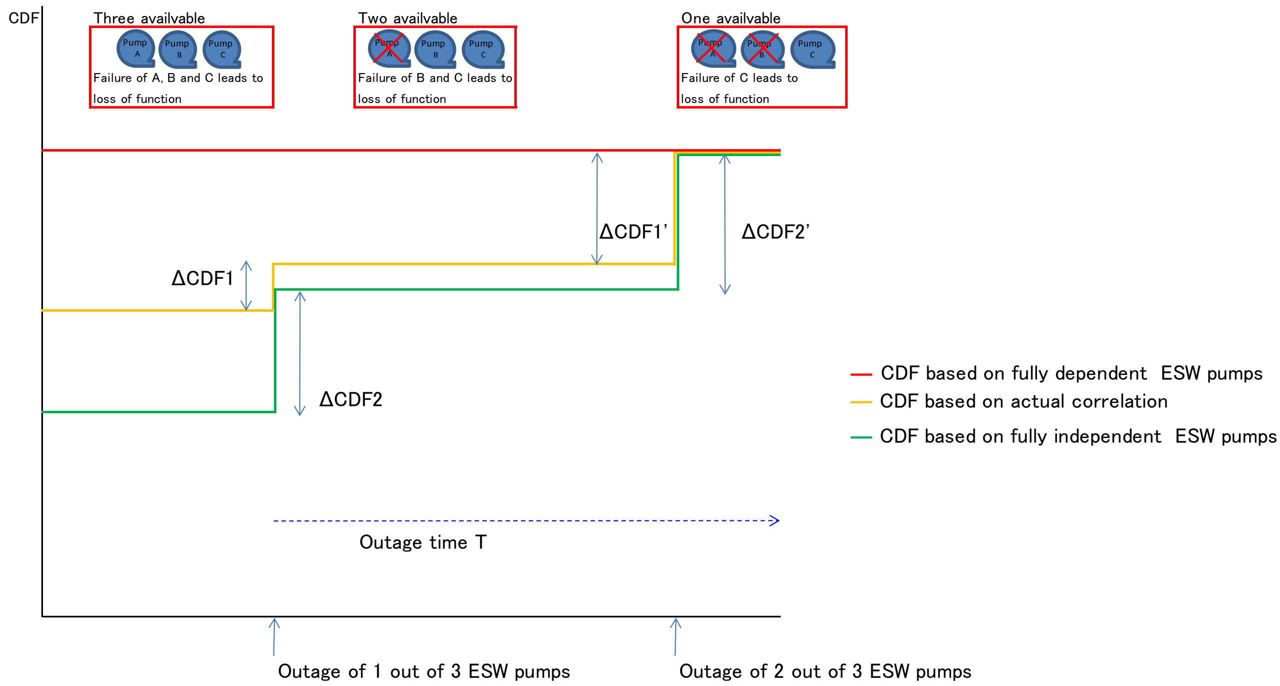


Fig. 6. ΔCDF for a system with 3 redundant components (ΔCDF1< ΔCDF2).

However, as shown in Fig. 7, if the simultaneous failure probability of 2 components is closed to the simultaneous failure probability of the 3 components, the ΔCDF1 for the actual degree of correlation of components failure probability when the first component is outage is larger than the ΔCDF1' produced by the addition of a second component outage, and then the relationship ΔCDF1 < ΔCDF2 is no longer true.

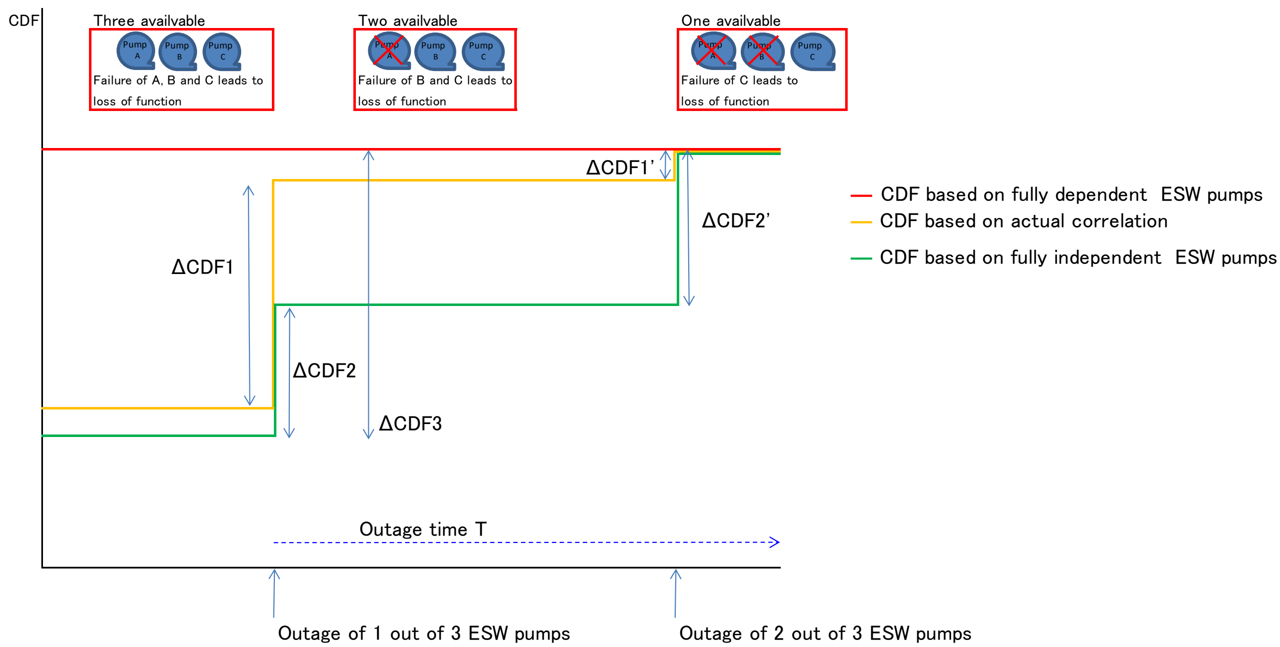


Fig. 7. ΔCDF for a system with 3 redundant components (ΔCDF1> ΔCDF2).

In this case, if ΔCDF3 is defined as the difference between the CDF based on complete correlation and that based on independency before outage, ΔCDF3 is always larger than ΔCDF1 based on actual correlation, so that ΔCDF3 can be conservatively used as the ΔCDF due to the outage of the first component.

Now, ΔCDF1' due to the outage of two components based on actual correlation is always lower than ΔCDF2', where ΔCDF2' is the difference between the CDF before and after the second component outage based on complete independent correlation. But, since ΔCDF3 is always larger than the sum of ΔCDF1 and ΔCDF1', ΔCDF2' does not need to be calculated as illustrated in Fig. 8.

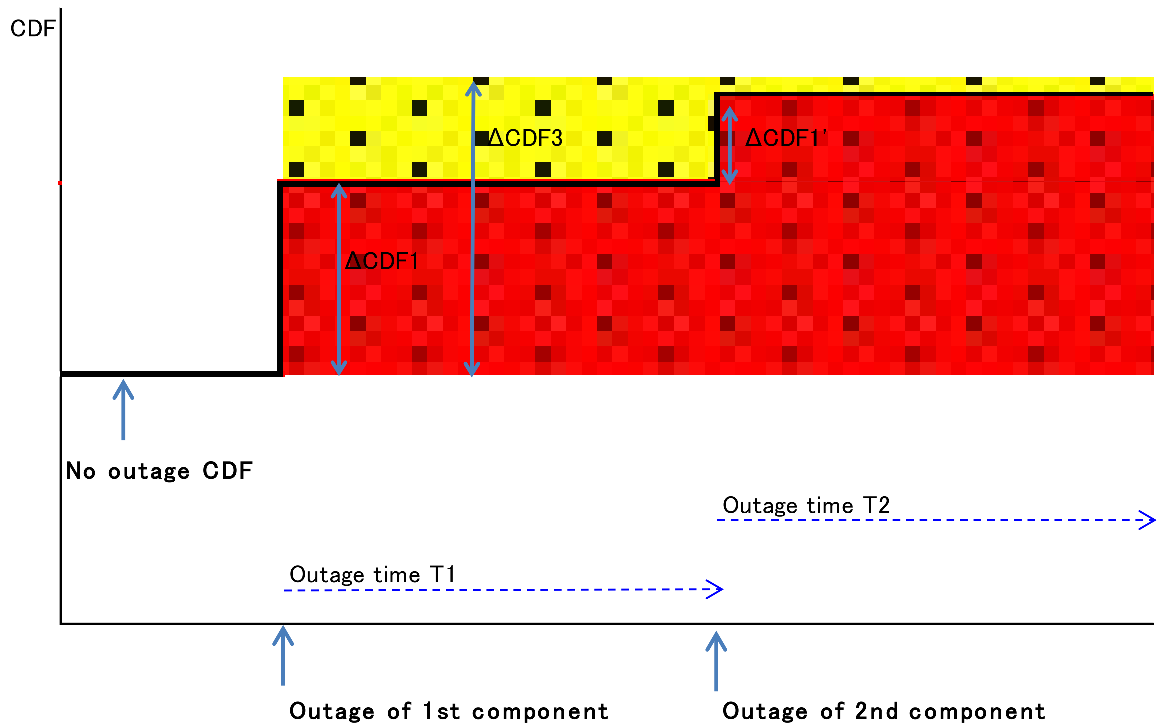


Fig. 8. CDF as a function of components outage for a system with multiple redundant components.

Even though the actual incremental core damage probability (ICDP) is evaluated by using the following expression:

$$ICDP = \Delta CDF1 \times T1 + (\Delta CDF1 + \Delta CDF1') \times T2 \quad (2)$$

where:

T1 is the period of time with 1 component outage, and
T2 is the period of time with 2 components outage.

By using ΔCDF3 instead of ΔCDF1, the ICDP evaluation during the T1 period is conservative and there is no need of additional CDF increase during the T2 period. Then ICDP can be conservatively evaluated by using the following expression:

$$ICDP = \Delta CDF3 \times T1 + \Delta CDF3 \times T2 \quad (3)$$

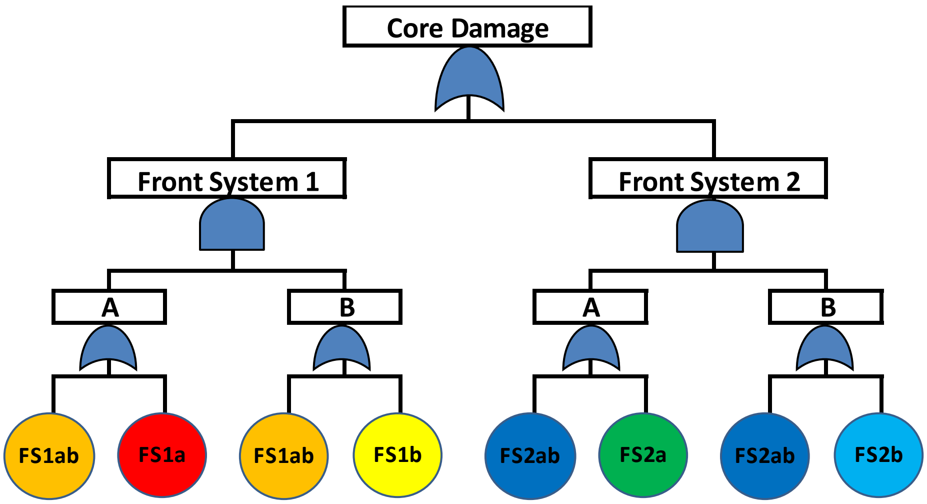
where:

ΔCDF3 is the difference between CDF based on complete independent correlation and CDF based on complete dependent correlation.

This expression can be used also in the case of higher redundant systems and considering outage of multiple components, and in any case only the CDF based on complete independent correlation and the CDF based on complete dependent correlation need to be calculated.

III.B. Applicability to mitigation function with 2 out of 2 systems required to prevent core damage

Fig. 9 shows the mitigation function based on System 1 and System 2, and both systems (2 out of 2 systems) are required to prevent core damage. Based on this system, the methodology to calculate ΔCDF is analyzed for 4 cases listed in TABLE II.



FS*N*x: Seismic independent failure event for component x (x= a or b) of Front System *N* (*N*=1 or 2)
FS*N*ab: Seismic dependent failure event for component a and b of Front System *N* (*N*=1 or 2)

Fig. 9. Fault tree for a 2 out of 2 systems mitigation function.

TABLE II. Analyzed cases for a 2 out of 2 systems mitigation function.

Section	Case
III.B.1	From no component outage to the outage of one of the two redundant components in System 1
III.B.2	From the outage of one of the two redundant components in System 1 to the outage of one of the two redundant components in System 2
III.B.3	From no component outage to the simultaneous outage of one of the two redundant components in System 1 and one of the two redundant components in System 2
III.B.4	Comparison between successive and simultaneous outage results

III.B.1. ΔCDF *produced by the outage of one component in System 1*

In this case, the outage of component B in System 1 is assumed. Before the outage and considering the actual correlations, the minimal cutsets (MCSs) leading to core damage are

FS1ab + FS2ab + FS1a × FS1b + FS2a × FS2b,

and after the outage of component B in System 1, the MCSs are

FS1ab + FS2ab + FS1a + FS2a × FS2b.

The difference between the MCSs after and before the outage is then

FS1a - FS1a × FS1b.

If Q*N* is the probability of FS*N*x, then the simplified ΔCDF based on actual correlations is quantified as following:

$$\Delta CDF = Q1 - Q1^2 = 1/4 - (Q1 - 1/2)^2 \qquad (4)$$

where:

$QN = (1 - \beta N) \times PN$,

βN: Parameter that characterize the degree of correlation between seismic failure of Front System N components ($0 \le \beta N \le 1$), and

PN: Failure probability of one component in Front System N.

When considering $P1 \leq 1/2$ then $Q1 = (1 - \beta 1) \times P1 \leq 1/2$. Based on this assumption, the maximum Q1 value minimizes the $(Q1 - 1/2)^2$ value, and the minimum $(Q1 - 1/2)^2$ value maximizes ΔCDF based on Eq. (1). At this time $\beta 1 = 0$, and the most conservative ΔCDF is then expressed as below:

$$\Delta CDF = P1 - P1^2. \tag{5}$$

In the proposed methodology, this ΔCDF value can be calculated from the difference between the CDF based on full dependent failure probability in components of Front System 1 (model 1 in Fig. 10 and 11) and the CDF based on full independent failure probability in components of Front System 1 (model 2 in Fig. 10 and 11). Since the component outage for this case belongs to Front System 1 and Front System 2 is not modified, the same model (model 3) is used for System 2 before and after the System 1 component outage.

By considering the System 1 components only, the MCS for Model 1 is

FS1ab,

and the MCS for Model 2 is

FS1a × FS1b.

The difference between the Model 1 and Model 2 MCSs is then

FS1ab - FS1a × FS1b,

and the ΔCDF in the proposed methodology is quantified as following:

$$\Delta CDF = P1 - P1^2. \tag{6}$$

Eq. (6) based on the proposed methodology agrees with the maximum ΔCDF based on the actual correlation as shown in Eq. (5).

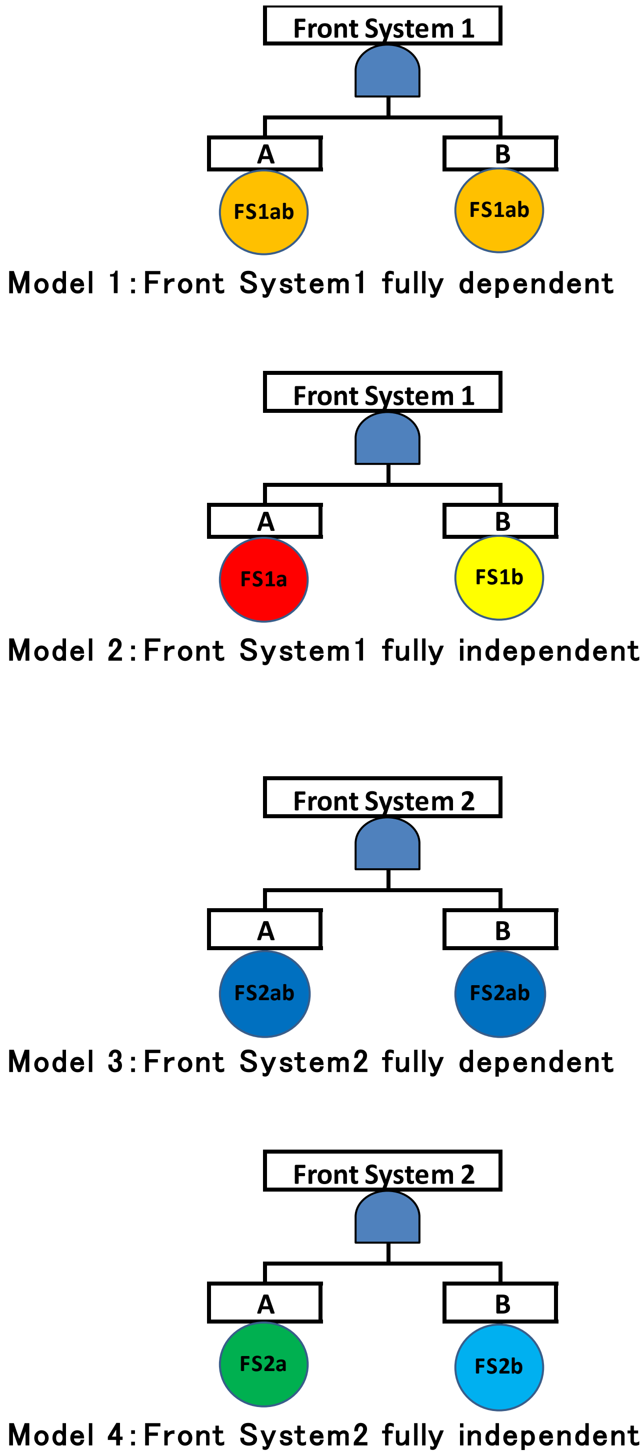


Fig. 10. Fault tree model modifications for ΔCDF calculation.

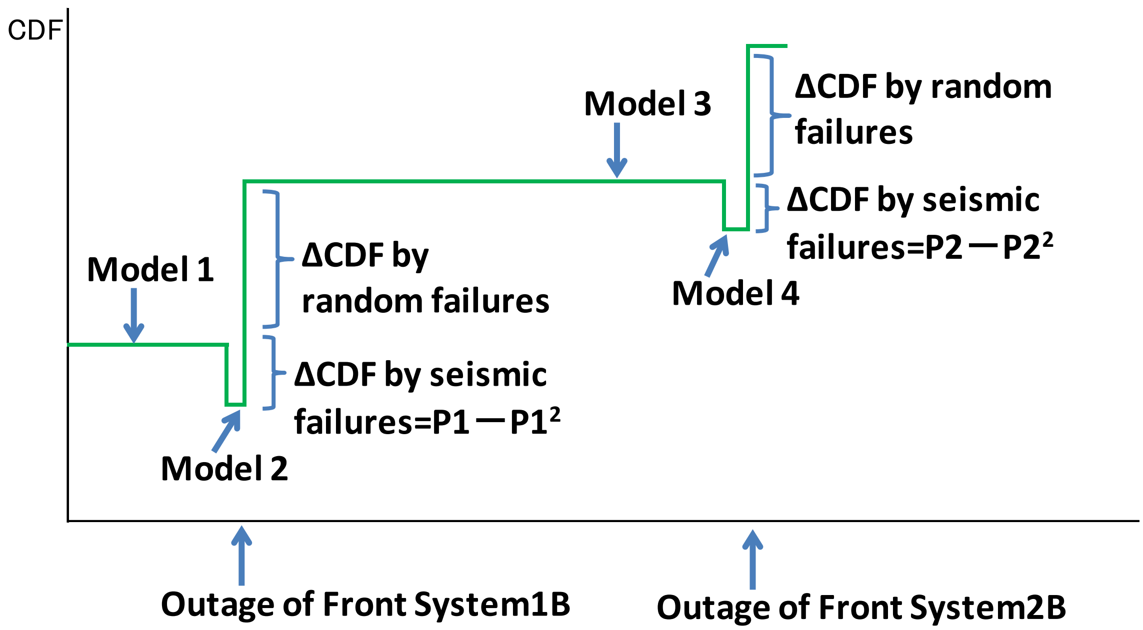


Fig. 11. Model effect on CDF and ΔCDF calculation (successive outage).

III.B.2. ΔCDF *produced by the outage of one component in System 2 after the outage of the System 1 component*

In this case, the outage of component B in System 2 is assumed in addition of the outage of component B in System 1 presented in the previous section.

Before the outage of component B in Front System 2 but with the outage of component B in Front System 1 and considering the actual correlations, the MCSs are

FS1ab + FS2ab + FS1a + FS2a × FS2b.

After the outage of component B in Front System 2 in addition to that of Front System 1, the MCSs are

FS1ab + FS2ab + FS1a + FS2a.

The difference between MCSs after and before the outage of component B in Front System 2 is then

FS2a - FS2a × FS2b.

Since this MCS form is the same as MCS form obtained after the outage of component B in Front System 1 (see case of III.B.1) when the actual correlation is considered, the most conservative ΔCDF is obtained when $\beta 2 = 0$ and the expression is as following:

$$\Delta CDF = P2 - P2^2. \tag{7}$$

In the proposed methodology, this ΔCDF value can be calculated from the difference between the CDF based on full dependent failure probability in components of Front System 2 (model 3 in Fig. 10 and 11) and the CDF based on full independent failure probability in components of Front System 2 (model 4 in Fig. 10 and 11). Since the component outage for this case belongs to Front System 2 and Front System 1 is not modified, the same model (model 2) is used for System 1 before and after the System 2 component outage.

By considering the System 2 components only, the MCS for Model 3 is

FS2ab,

and the MCSs for Model 4 are

FS2a × FS2b.

The difference between the Model 3 and Model 4 MCSs is then

FS2ab - FS2a × FS2b,

and the ΔCDF in the proposed methodology is quantified as following:

$$\Delta CDF = P2 - P2^2. \tag{8}$$

Eq. (8) based on the proposed methodology agrees with the maximum ΔCDF based on the actual correlation as shown in Eq. (7).

III.B.3. ΔCDF *produced by simultaneous outage of one component in each Front System*

In this case, the simultaneous outage of component B in System 1 and component B in System 2 is assumed. The MCSs before the outage and considering the actual correlations are

FS1ab + FS2ab + FS1a × FS1b + FS2a × FS2b.

After the simultaneous outage of Front System 1B and 2B, the MCSs are

FS1ab + FS2ab + FS1a + FS2a.

The difference between MCSs after and before the outage is then

FS1a - FS1a × FS1b + FS2a - FS2a × FS2b.

Since this cutsets is equal to the sum of the cutsets shown in cases of III.B.1 and III.B.2 when the actual correlations are considered, the most conservative ΔCDF value is obtained when β1 = 0 and β2 = 0, and the ΔCDF expression is

$$\Delta CDF = (P1 - P1^2) + (P2 - P2^2). \tag{9}$$

In the proposed methodology, this ΔCDF value can be calculated from the difference between the CDF based on full dependent failure probability in components of Front Systems 1 and 2 (model 1 in Fig. 12 and 13) and the CDF based on full independent failure probability in components of Front Systems 1 and 2 (model 2 in Fig. 12 and 13).

The MCS for Model 1 is

FS1ab + FS2ab,

and the MCSs for Model 2 are

FS1a × FS1b + FS2a × FS2b.

The difference between the Model 1 and Model 2 MCSs is then

FS1ab - FS1a × FS1b + FS2ab - FS2a × FS2b,

and the ΔCDF in the proposed methodology is quantified as following:

$$\Delta CDF = (P1 - P1^2)+(P2 - P2^2). \tag{10}$$

Eq. (10) based on the proposed methodology agrees with the maximum ΔCDF based on the actual correlation as shown in Eq. (9).

III.B.4. Comparison between successive and simultaneous outage results

The ΔCDF produced by the outage of Front System 1B and 2B can be expressed in two ways. One is the combination of the cases of III.B.1 and III.B.2, and the other is case III.B.3.

The total ΔCDF produced by the outage of component B in System 1 followed by the later outage of component B in System 2 is computed as the sum of cases III.B.1 and III.B.2 as following:

$$\Delta CDF(III.B.1 + III.B.2) = (P1 - P1^2) + (P2 - P2^2). \tag{11}$$

In case of the simultaneous outage of component B in systems 1 and 2, the total ΔCDF is computed as following:

$$\Delta CDF(III.B.3) = (P1 - P1^2) + (P2 - P2^2). \tag{12}$$

The comparison of Eq. (11) and Eq. (12) shows that the ΔCDF obtained by the successive outage or by the simultaneous outage is the same.

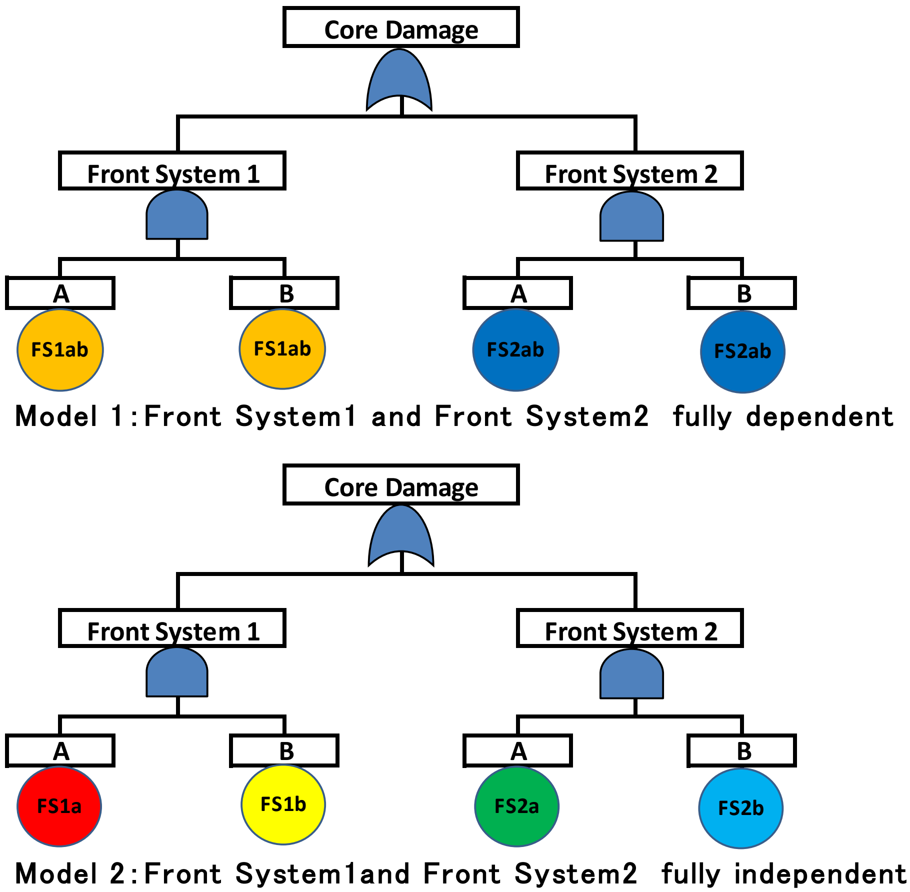


Fig. 12. Fault tree model modifications for ΔCDF calculation (simultaneous outage).

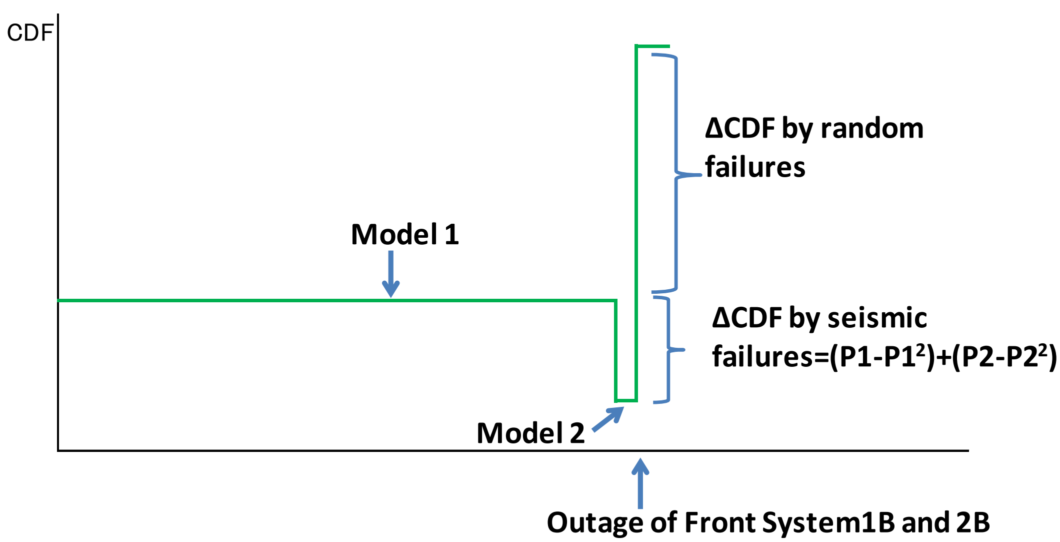
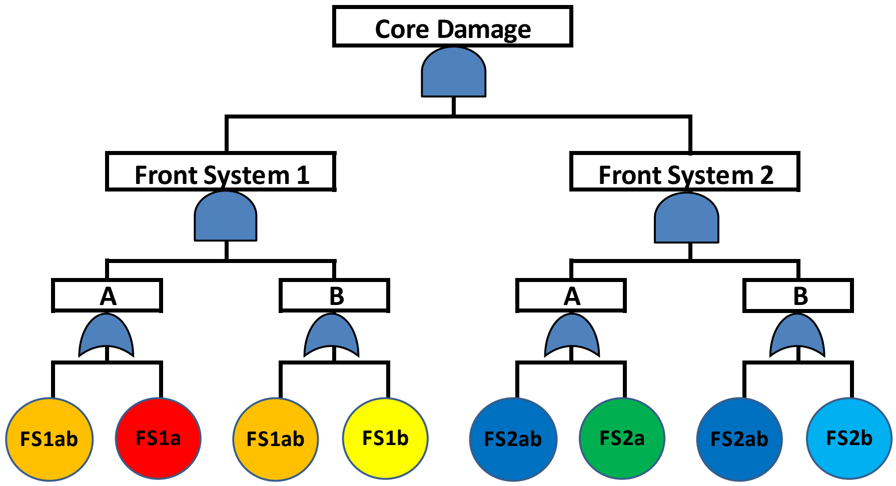


Fig. 13. Model effect on CDF and ΔCDF calculation (simultaneous outage).

III.C. Applicability to mitigation function with 1 out of 2 systems required to prevent core damage

Fig. 14 shows the mitigation function based on System 1 and System 2, and only one of the systems (1 out of 2 systems) is required to prevent core damage. Based on this system, the methodology to calculate ΔCDF is analyzed for 4 cases listed in TABLE III.



FS*N*x: Seismic independent failure event for component x (x= a or b) of Front System *N* (*N*=1 or 2)
FS*N*ab: Seismic dependent failure event for component a and b of Front System *N* (*N*=1 or 2)

Fig. 14. Fault tree for a 1 out of 2 systems mitigation function.

TABLE III. Analyzed cases for a 1 out of 2 systems mitigation function.

Section	Case
III.C.1	From no component outage to the outage of one of the two redundant components in System 1
III.C.2	From the outage of one of the two redundant components in System 1 to the outage of one of the two redundant components in System 2
III.C.3	From no component outage to the simultaneous outage of one of the two redundant components in System 1 and one of the two redundant components in System 2
III.C.4	Comparison between successive and simultaneous outage results

III.C.1. ΔCDF *produced by the outage of one component in System 1*

In this case, the outage of component B in System 1 is assumed. Before the outage and considering the actual correlations, the MCSs leading to core damage are

FS1ab × FS2ab + FS1ab × FS2a × FS2b + FS1a × FS1b × FS2ab + FS1a × FS1b × FS2a × FS2b,

and after the outage of component B in Front System 1, the MCSs are

FS1ab × FS2ab + FS1ab × FS2a × FS2b + FS1a × FS2ab + FS1a × FS2a × FS2b.

The difference between MCSs after and before the outage is

(FS1a × FS2ab + FS1a × FS2a × FS2b) - (FS1a × FS1b × FS2ab + FS1a × FS1b × FS2a × FS2b).

If Q*N* is the probability of FS*N*x and R*N* is the probability for FS*N*xy, then the simplified ΔCDF based on actual correlations is quantified as following:

$$\Delta CDF = Q1R2 + Q1Q2^2 - (Q1^2R2 + Q1^2Q2^2) = (Q1 - Q1^2)(R2 + Q2^2) \quad (13)$$

where:

$RN = \beta N \times PN$,

$QN = (1 - \beta N) \times PN$,
βN: Parameter that characterize the degree of correlation between seismic failure of Front System N components ($0 \leq \beta N \leq 1$), and
PN: Failure probability of a component in Front System N.

The most conservative ΔCDF value, i.e. the maximum value, is obtained as following. Since $(Q1 - Q1^2)$ and $(R2 + Q2^2)$ are independent functions, the maximum of the product is equal to the product of the maximum. The $(Q1 - Q1^2)$ part is maximized for the maximum Q1, i.e. $\beta 1 = 0$, as presented in III.B.1:

$$\text{maximum}(Q1 - Q1^2) = (P1 - P1^2).$$

The $(R2 + Q2^2)$ part can be expressed as function of β2 by developing R2 and Q2 as following:

$$f(\beta 2) = \beta 2 P2 + (1-\beta 2)^2 P2^2.$$

By applying the derivatives to get the maximum of the f(β2) function (i.e. set the derivative equal to 0),

$$P2 - 2(1 - \beta 2)P2^2 = 0,$$

then

$$\beta 2 = 1 - 1/(2P2),$$

and since $0<P2<1$ then

$$1 - 1/(2P2) < 1/2.$$

In addition, the f(β2) function monotonically increases in the interval $[(1 - 1/(2P2), 1]$, so the maximum value in this interval always occurs for $\beta 2 = 1$ and $f(1) = P2$. Also, when P2 satisfies $0 \leq 1 - 1/(2P2) < 1/2$, the f(β2) function monotonically decreases in the interval $[0, 1 - 1/(2P2)]$, so the maximum value in this interval always occurs for $\beta 2 = 0$ and $f(0) = P2^2$. Therefore, in the [0, 1] interval the absolute maximum value occurs for $\beta 2 = 1$ as following since $0 < P2 < 1$:

$$f(0) = P2^2 < P2 = f(1).$$

In summary, the $(R2 + Q2^2)$ part is always maximized when $\beta 2 = 1$:

$$\text{maximum}(R2 + Q2^2) = P2.$$

From the above results, the most conservative ΔCDF value is obtained as following:

$$\Delta CDF = (P1 - P1^2)P2. \tag{14}$$

In the proposed methodology, this ΔCDF value can be calculated from the difference between the CDF based on full dependent failure probability in components of Front systems 1 and 2 (model 1 in Fig. 15 and 16) and the CDF based on full independent failure probability in components of Front System 1 (model 2 in Fig. 15 and 16). Since the component outage for this case belongs to Front System 1 and Front System 2 is not modified, the same model is used for System 2 before and after the System 1 component outage.

Before the outage, the MCS for Model 1 is

$$FS1ab \times FS2ab,$$

and after the outage, the MCS for Model 2 is

$$FS1a \times FS1b \times FS2ab.$$

The difference between the Model 1 and Model 2 MCSs is then

$$FS1ab \times FS2ab - FS1a \times FS1b \times FS2ab,$$

and the ΔCDF in the proposed methodology is quantified as following:

$$\Delta CDF = (P1 - P1^2)P2. \tag{15}$$

Eq. (15) based on the proposed methodology agrees with the maximum ΔCDF based on the actual correlation as shown in Eq. (14).

III.C.2. ΔCDF *produced by the outage of one component in System 2 after the outage of the System 1 component*

In this case, the outage of component B in System 2 is assumed in addition of the outage of component B in System 1 presented in the previous section. From the previous section, before the outage of component B in Front System 2 but with the outage of component B in Front System 1 and considering the actual correlations, the MCSs are

$$FS1ab \times FS2ab + FS1ab \times FS2a \times FS2b + FS1a \times FS2ab + FS1a \times FS2a \times FS2b,$$

and after the additional outage of component B in Front System 2, the MCSs are

$$FS1ab \times FS2ab + FS1ab \times FS2a + FS1a \times FS2ab + FS1a \times FS2a.$$

The difference between MCSs after and before the additional outage is then

(FS1ab × FS2a + FS1a × FS2a) - (FS1ab × FS2a × FS2b + FS1a × FS2a × FS2b).

If Q*N* is the probability of FS*N*x and R*N* is the probability for FS*N*xy, then the simplified ΔCDF based on actual correlations is quantified as following:

$$\Delta CDF = R1Q2 + Q1Q2 - (R1Q2^2 + Q1Q2^2) = (R1 + Q1)(Q2 - Q2^2). \quad (16)$$

The ΔCDF in Eq. (13) is maximized when both terms are maximized. The System 1 related term becomes independent of the correlation (β1) since

$(R1 + Q1) = \beta1 \times P1 + (1 - \beta1) \times P1 = P1$.

The $(Q2 - Q2^2)$ part is maximized when Q2 is maximized (i.e. β2 = 0) as presented in section III.B.1, so

maximum $(Q2 - Q2^2) = (P2 - P2^2)$.

Therefore, the most conservative ΔCDF value is obtained by the following expression:

$$\Delta CDF = P1(P2 - P2^2). \quad (17)$$

In the proposed methodology, this ΔCDF value can be calculated from the difference between the CDF based on full dependent failure probability in components of Front System 2 and full independent failure probability in components of Front System 1 since one of its components is already outage (model 3 in Fig. 15 and 16), and the CDF based on full independent failure probability in components of Front Systems 1 and 2 (model 4 in Fig. 15 and 16).

Before the additional outage in Front System 2, the MCS for Model 3 is

FS1a × FS2ab,

and after the additional outage, the MCS for Model 4 is

FS1a × FS2a × FS2b.

The difference between the Model 3 and Model 4 MCSs is then

FS1a × FS2ab - FS1a × FS2a × FS2b,

and the ΔCDF in the proposed methodology is quantified as following:

$$\Delta CDF = P1(P2-P2^2). \quad (18)$$

Eq. (18) based on the proposed methodology agrees with the maximum ΔCDF based on the actual correlation as shown in Eq. (17).

III.C.3. ΔCDF *produced by the simultaneous outage of one component in each Front System*

In this case, the simultaneous outage of component B in System 1and component B in System 2 is assumed. The MCSs before the outage and considering the actual correlations are

FS1ab × FS2ab + FS1ab × FS2a × FS2b + FS1a × FS1b × FS2ab + FS1a × FS1b × FS2a × FS2b,

and after the simultaneous outage of Front System 1B and 2B, the MCSs are

FS1ab × FS2ab + FS1ab × FS2a + FS1a × FS2ab + FS1a × FS2a.

The difference between MCSs after and before the outage is then

(FS1ab × FS2a + FS1a × FS2ab + FS1a × FS2a) - (FS1ab × FS2a × FS2b + FS1a × FS1b × FS2ab + FS1a × FS1b × FS2a × FS2b).

If Q*N* is the probability of FS*N*x and R*N* is the probability for FS*N*xy, then the simplified ΔCDF based on actual correlations is quantified as following:

$$\Delta CDF = R1Q2(1 - Q2) + R2Q1(1 - Q1) + Q1Q2(1 - Q1Q2). \quad (19)$$

The most conservative ΔCDF value (i.e. the maximum value) is determined as following. First, by replacing R1 and R2 by the following functions:

R1 = P1 - Q1, R2 = P2 - Q2.

Eq. (19) becomes

$\Delta CDF = P1Q2(1 - Q2) - Q1Q2(1 - Q2) + P2Q1(1 - Q1) - Q1Q2(1 - Q1) + Q1Q2(1 - Q1Q2)$.

This ΔCDF function is a quadratic function in the Q1 variable and it is maximized if Q2 < P2 since the constant in the quadratic term becomes negative (i.e., for Q2 < P2 then $Q2 - P2 - Q2^2)\ Q1^2 < 0$). By applying the derivatives (in the Q1 variable) to get the maximum of the ΔCDF function (i.e. set the derivative equal to 0), then

$$(-2P2 + 2Q2 - 2Q2^2)Q1 + Q2^2 - Q2 + P2 - Q2 + Q2 = 0,$$
$$(-2P2 + 2Q2 - 2Q2^2)Q1 = -P2 + Q2 - Q2^2,$$
$$Q1 = 1/2.$$

When P1 is limited to the [0, 1/2] range, Q1 is maximized when β1 = 0 since Q1 = (1 - β1)P1 < 1/2 and ΔCDF is maximized. The same logic could be applied for Q2 when P2 is limited to the [0, 1/2] range, and the β2 = 0 also maximizes ΔCDF.

Therefore, the most conservative ΔCDF value is obtained for β1 = β2 = 0 as following:

$$\Delta CDF = P1P2(1 - P1P2). \quad (20)$$

In the proposed methodology, this ΔCDF value can be calculated from the difference between the CDF based on full dependent failure probability in components of Front System 2 and 1 (model 1 in Fig. 17 and 18), and the CDF based on full independent failure probability in components of Front Systems 1 and 2 (model 2 in Fig. 17 and 18).

Before the simultaneous outage in Front Systems 1 and 2, the MCS for Model 1 is

FS1ab × FS2ab,

and the MCSs for Model 2 are

FS1a × FS1b × FS2a × FS2b.

The difference between the Model 1 and Model 2 MCSs is then

FS1ab × FS2ab - FS1a ×FS1b × FS2a × FS2b,

and the ΔCDF in the proposed methodology is quantified as following:

$$\Delta CDF = P1P2(1-P1P2). \quad (21)$$

Eq. (21) based on the proposed methodology agrees with the maximum ΔCDF based on the actual correlation as shown in Eq. (20).

Ⅲ.C.4.Comparison between successive and simultaneous outage results

The ΔCDF produced by the outage of Front System 1B and 2B can be expressed in two ways. One is the combination of the cases of III.C.1 and III.C.2, and the other is case III.C.3.

The total ΔCDF produced by the outage of component B in System 1 followed by the later outage of component B in System 2 is computed as the sum of cases III.C.1 and III.C.2 as following:

$$\Delta CDF(III.C.1 + III.C.2) = P1P2\ (1 - P1) + P1P2\ (1 - P2). \quad (22)$$

In case of the simultaneous outage of component B in systems 1 and 2, the total ΔCDF is computed as following:

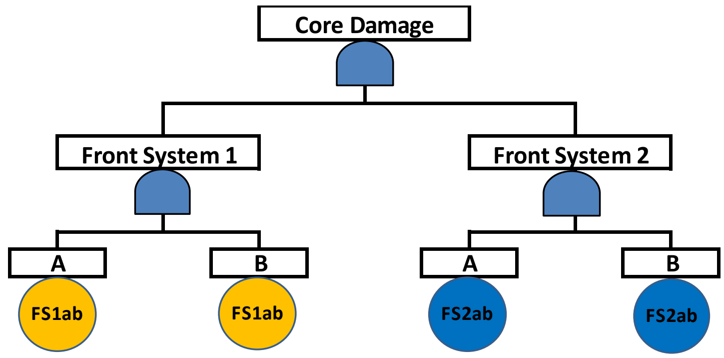
$$\Delta CDF(III.C.3) = P1P2(1 - P1P2). \quad (23)$$

The ΔCDF get by Eq. (22) and Eq. (23) are different, and the difference is expressed by the following equation:

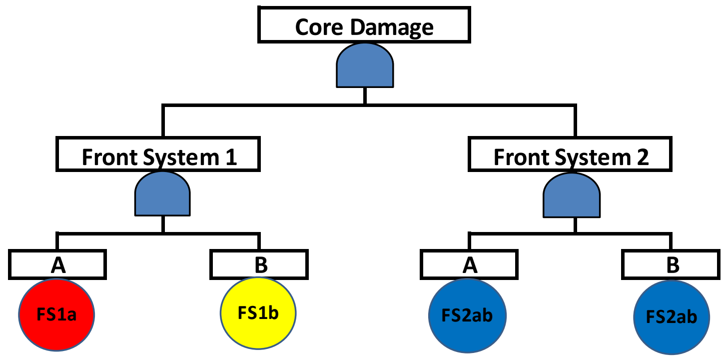
$$\Delta CDF(III.C.1 + III.C.2) - \Delta CDF(III.C.3) = P1P2(1 - P1 - P2 + P1P2) = P1P2(1 - P1)(1 - P2).$$

Since both P1 and P2 are in the (0, 1) range, this difference is always positive. This means that even though the successive and simultaneous outages lead both to the same plant configuration, the ΔCDF of former case is more conservative.

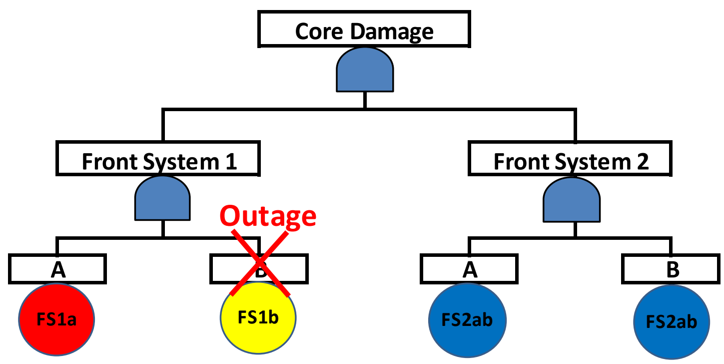
When successive outages of one component in each front system are implemented, it is sufficient to compute the ΔCDF between the no outage state and the state after the outage of all the components. However, the ΔCDF is more conservative if is computed as the sum of the ΔCDFs for each additional outage.



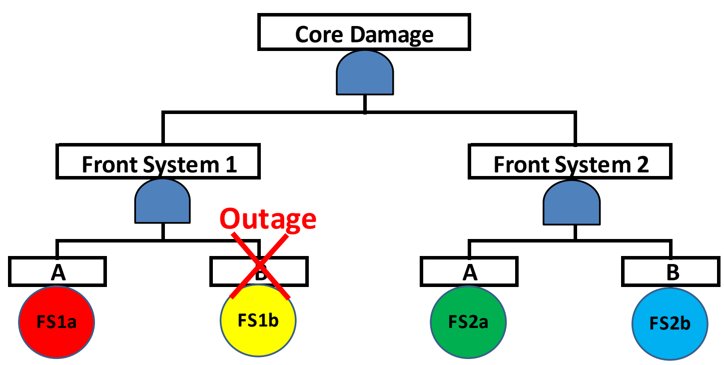
Model 1:Front System1 and Front System2 fully dependent



Model 2:Front System1 fully independent , Front System2 fully dependent



Model 3:Front System1 fully independent(B train outage) , Front System2 fully dependent



Model 4:Front System1 fully independent(B train outage) , Front System2 fully independent

Fig. 15. Fault tree model modifications for ΔCDF calculation (successive outage).

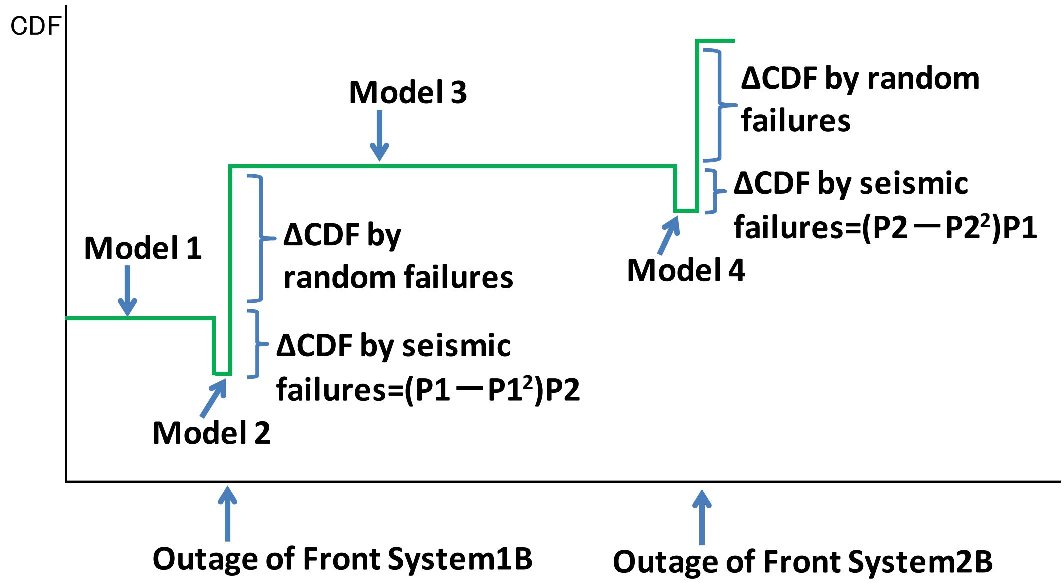


Fig. 16. Model effect on CDF and ΔCDF calculation (successive outage).

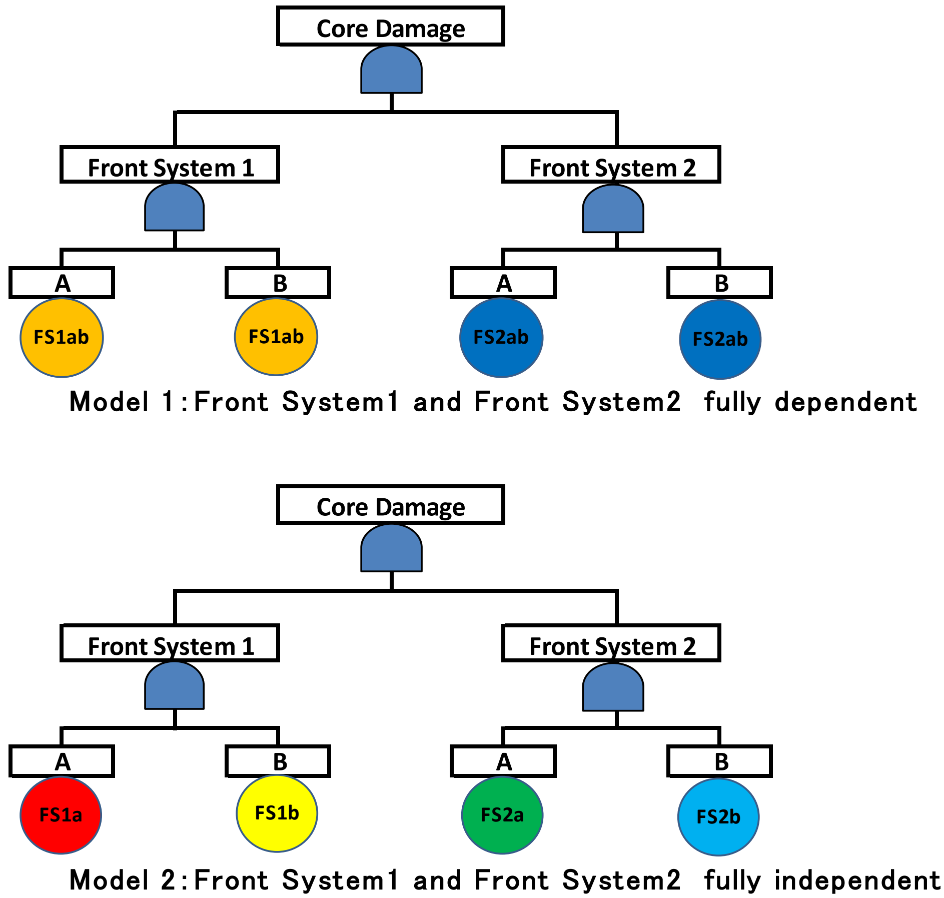


Fig. 17. Fault tree model modifications for ΔCDF calculation (simultaneous outage).

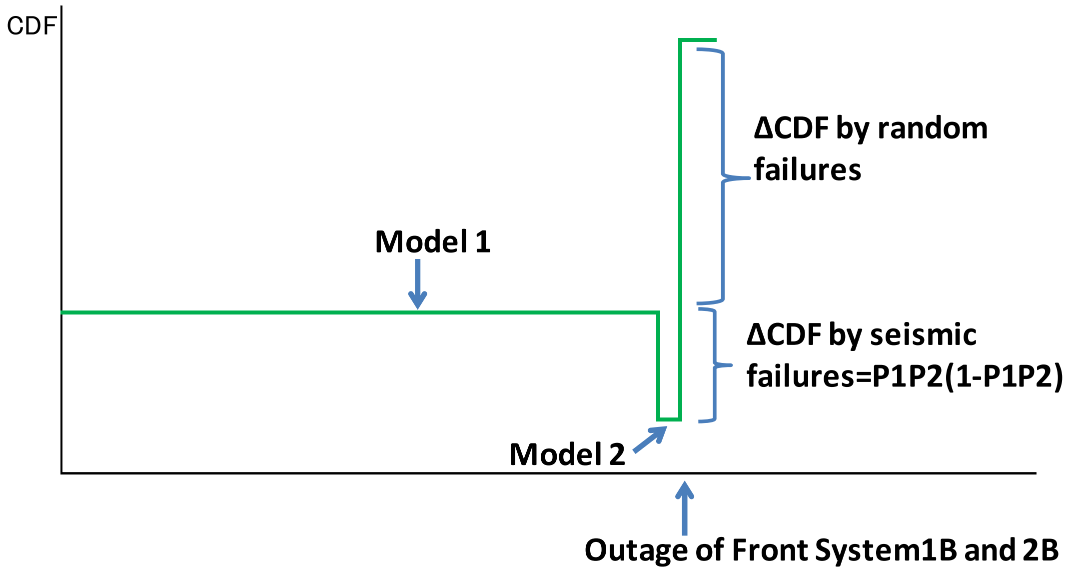


Fig. 18. Model effect on CDF and ΔCDF calculation (simultaneous outage).

IV. Conclusions

A methodology to evaluate the bounding value of the incremental seismic risk given a component outage has been proposed. The value of the incremental seismic risk, due to components outage (for instance the ΔCDF) can be calculated by the difference between the CDF after the outage assuming complete dependence between seismic failures, and the CDF before the outage assuming complete independence between seismic failures of the component of concern.

The applicability of the proposed methodology to multiple redundant components and multiple systems has been confirmed using a simple model. For a system with multiple redundant components (more than 2), the calculated ΔCDF when the first component is taken out of service, will give the upper value of the ΔCDF. For simultaneous outage of components of different systems, the upper ΔCDF for the component outages can also be evaluated by switching the treatment of seismic failure of the component of concern from complete dependence to complete independence.

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REFERENCES

1. Electric Power Research Institute, “Seismic Probabilistic Risk Assessment Implementation Guide”, EPRI 1002989 (2003).
2. Atomic Energy Society of Japan, “A standard for Procedure of Seismic Probabilistic Risk Assessment (PRA) for nuclear power plants 2015“, AESJ-SC-P006:2015 (2015).
3. Electric Power Research Institute, “An Approach to Risk Aggregation for Risk-Informed Decision-Making”, EPRI 3002003116 (2015).