# Evaluation of Seismic Shutdown Trigger Level for Petroleum Refinery

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**Abstract**: Many petroleum refineries have the emergency shutdown system in order to reduce a secondary seismic disaster which are fires, explosions and a leak of dangerous substances. On the other hand, the emergency shutdown when the facilities are sound cause the requiring a lot of time and expense to resume operation. Therefore, it is important to evaluate the trigger level, which is the seismic ground motion intensity to shutdown. We propose the evaluation method of shutdown trigger level considering amplification characteristics of surface layers, vibrational characteristics for the types of earthquakes (i.e., subduction-zone earthquake, inland active fault earthquake) that is expected to hit on a refinery, and adding economic rationality. The economic rationality is explained by comparing reduction effect of the secondary seismic disaster in the case of emergency shutdown and the loss in the case of inappropriate operation of the shutdown system. Furthermore, for applicability of proposal method, the optimal shutdown trigger level is evaluated on the target to hypothetical petroleum refinery located in Tokyo Bay-side landfill.

**Keywords**: Petroleum refinery, Emergency shutdown system, Shutdown trigger level, Amplification characteristics of surface layers, Seismic loss function.

## 1. Introduction

Many petroleum refineries have introduced automated emergency shutdown systems. When a certain seismic ground motion is observed, the system automatically shuts down manufacturing equipments and its related equipments, and shuts off flammable liquids and gases. As a result, secondary disasters such as fires, explosions, and leakage of dangerous substances will be avoided or reduced. On the other hand, the emergency shutdown when the facilities are sound also have the disadvantage of requiring a lot of time and expense to resume operation. Therefore, it is important to evaluate the trigger level, which is the seismic ground motion intensity to shutdown. On this issue, Nakamura et al. (2006) estimated the seismic loss function with and without emergency shutdown using the probabilistic risk assessment technique, and by comparing them, the trigger level could be evaluated under economic rationality. In the stochastic risk assessment, Fragility Curve (e.g., Doi et al. 2013, Shizuma et al. 2009) in which response acceleration and response displacement are stochastic variables is often used in evaluating the damage probability of structures. However, when evaluating the trigger level, the Fragility Curve using the seismic ground motion observed by the seismograph as a variable should be employed. Since the petroleum refinery plant consists of various structures with different natural periods, a model that approximates the relationship between the ground motion observed by a seismograph and the response of various structures is required. In addition, since various types of earthquakes such as subduction-zone earthquakes and inland active fault earthquakes occur, it is necessary to consider differences in vibrational characteristics and duration time, etc. that differ depending on the type of earthquake.

In this paper, a peak ground acceleration, which is frequently used for emergency shutdown systems, is used as an index of seismic ground motion intensity, and the relationship with the seismic response of structures is modeled by a nonlinear regression formula. In addition, we evaluate the Fragility Curve of structures with the peak ground acceleration as a variable, which directly incorporates the regression formula and its error. Then, referring to the methods of Nakamura et al. (2006), the shutdown trigger level based on economic rationality is evaluated for a hypothetical petroleum refinery located in Tokyo Bay-side landfill.

## 2. Fragility Curve using observed seismic ground motion

Figure 1 illustrates the relationship between the peak ground acceleration (PGA) observed by the seismograph and the seismic response of structure. The figure shows samples of response acceleration at the natural period T to PGA. The samples are calculated by response analysis under each type of earthquakes (subduction-zone earthquakes and inland active fault earthquakes) with stepwise increasing input accelerations.
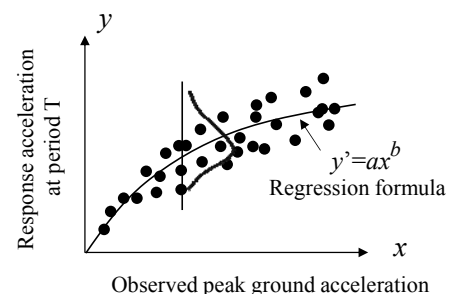


Figure 1. Observed peak ground acceleration (PGA) and response acceleration at period T.

The relationship between the PGA and the response acceleration is modeled by the regression formula shown below.

$$y' = ax^b \qquad (1)$$

Where, $a$ and $b$ are regression coefficients. The regression coefficients are determined as the value that minimizes the ratio between the sample $y_i$ of response acceleration and $y'_i$ calculated by the regression formula. It is assumed that the response acceleration at the natural period T to PGA $x$ observed by the seismometer can be approximated to a lognormal distribution. When this is represented by a random variable $Y$, the probability density function of the response acceleration can be expressed as follows by using the regression formula in equation (1).

$$f_Y(y) = \frac{1}{\sqrt{2\pi}\ \zeta_Y\ y} \exp\left[-\frac{1}{2}\left(\frac{\ln y - \ln(a \cdot x^b)}{\zeta_Y}\right)^2\right] \qquad (2)$$

The logarithmic standard deviation $\zeta_Y$ is given by the following equation.

$$\zeta_Y = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\ln K_i\right)^2} \qquad (3)$$

Where, $K_i$ is the ratio of $y_i$ to $y'_i$, and $n$ is the number of samples. It is assumed that the damage of the structure occurs when the response acceleration $Y$ exceeds the seismic strength $C$ expressed in acceleration as a random variable, the damage state can be expressed as follows.

$$Z = C/Y \leq 1.0 \qquad (4)$$

If the seismic strength $C$ follows a lognormal distribution, the damage probability is obtained by integrating the random variable $Z$ as follows.

$$p_f = \int_0^1 \frac{1}{\sqrt{2\pi}\ \zeta_Z\ z} \exp\left[-\frac{1}{2}\left(\frac{\ln z - \ln(c_m) + \ln(a \cdot x^b)}{\zeta_Z}\right)^2\right] dz \qquad (5)$$

Where, $c_m$ is the median of seismic strength expressed in response acceleration. Then, the logarithmic standard deviation $\zeta_Z$ is as follows.

$$\zeta_Z = \sqrt{\zeta_Y^2 + \zeta_C^2} \qquad (6)$$

Where, $\zeta_C$ is the logarithmic standard deviation of the seismic strength.

Next, the integral variable is converted from $z$ to $s$ according to the following equation.

$$s = a \cdot x^b \cdot z \qquad (7)$$

Finally, equation (5) is given by the following equation.

$$F_S(a \cdot x^b) = \int_0^{a \cdot x^b} \frac{1}{\sqrt{2\pi}\ \zeta_Z\ s} \exp\left[-\frac{1}{2}\left(\frac{\ln s - \ln(c_m)}{\zeta_Z}\right)^2\right] ds \qquad (8)$$

The above equation is the Fragility Curve (FC) that can determine the damage probability of a structure by giving PGA $x$ observed by a seismometer. The seismic loss function with and without an emergency shutdown is evaluated by using the FC in equation (8). The seismic loss function is formed by plotting the conditional expected loss for various level of seismic ground motion intensity. The intersection of each seismic loss function is optimal trigger level.

## 3. Hypothetical petroleum refinery and seismic ground motion used for response analysis

### 3.1 Petroleum refinery and properties of ground soil

The hypothetical petroleum refinery is divided into five areas from A to E in terms of similarity of amplification characteristics of surface layers, manufacturing process and function. The divided areas are illustrated in Fig. 2. Area A is the receiving and shipping, Area B is the utility, Area C is the control and power generation facilities, Area D is the manufacturing process and Area E is the storage tanks. The main structures in each area are shown on the right of figure. Figure 3 shows the physical properties of ground soil in each area. The engineering base-rock surface (Vs = equivalent to 400 m/s) is the lower surface of the Ds layer which is the lowest layer of each area.
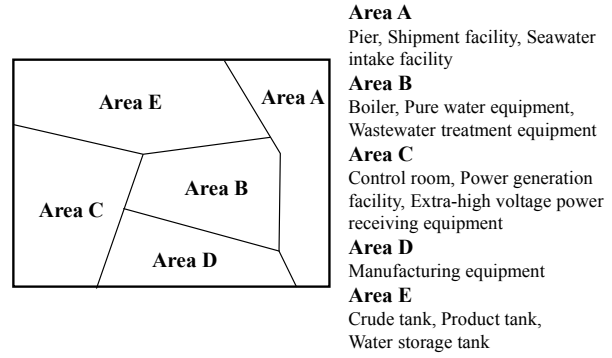
**Area A**
Pier, Shipment facility, Seawater intake facility
**Area B**
Boiler, Pure water equipment, Wastewater treatment equipment
**Area C**
Control room, Power generation facility, Extra-high voltage power receiving equipment
**Area D**
Manufacturing equipment
**Area E**
Crude tank, Product tank, Water storage tank

Figure 2. Area division and main structures in each area.

**Area A**

| Depth (m) | Soil mark | Density (t/m³) | Vs (m/s) |
|---|---|---|---|
| 5.7 | Bs | 1.79 | 80 |
| 10.0 | Ac1 | 1.79 | 80 |
| 16.3 | Ac1 | 1.48 | 120 |
| 19.5 | As | 1.48 | 120 |
| 21.0 | Ac1 | 1.48 | 120 |
| 21.7 | As | 1.48 | 120 |
| 36.0 | Ac2 | 1.70 | 120 |
| 50.7 | Dc | 1.70 | 180 |
| 52.4 | Dg | 1.80 | 340 |
| 61.4 | Ds | 1.80 | 340 |

**Area B**

| Depth (m) | Soil mark | Density (t/m³) | Vs (m/s) |
|---|---|---|---|
| 6.8 | Bs | 1.53 | 90 |
| 13.3 | Ac1 | 1.53 | 90 |
| 16.1 | As | 1.53 | 90 |
| 35.2 | Ac2 | 1.57 | 130 |
| 44.8 | Ds | 1.70 | 200 |
| 50.8 | Dc | 1.50 | 140 |
| 51.4 | Ds | 1.70 | 230 |
| 55.4 | Ds | 1.80 | 230 |
| 66.2 | Ds | 1.80 | 330 |

**Area C**

| Depth (m) | Soil mark | Density (t/m³) | Vs (m/s) |
|---|---|---|---|
| 4.6 | Bs | 1.72 | 130 |
| 11.6 | Ac1 | 1.72 | 130 |
| 15.5 | As | 1.72 | 130 |
| 25.1 | Ac1 | 1.72 | 130 |
| 31.5 | Ds | 1.79 | 270 |
| 38.9 | Dc | 1.79 | 270 |
| 50.8 | Ds | 1.80 | 390 |
| 53.6 | Dc | 1.75 | 320 |
| 69.9 | Ds | 1.75 | 320 |

**Area D**

| Depth (m) | Soil mark | Density (t/m³) | Vs (m/s) |
|---|---|---|---|
| 1.0 | Bs | 1.80 | 60 |
| 3.6 | Bs | 1.63 | 120 |
| 12.9 | Ac1 | 1.63 | 120 |
| 14.3 | As | 1.63 | 120 |
| 32.5 | Ac2 | 1.63 | 120 |
| 54.0 | Ac2 | 1.62 | 160 |
| 57.5 | Ac2 | 1.50 | 230 |
| 59.5 | Ds | 1.50 | 230 |
| 63.8 | Dc | 1.50 | 230 |
| 64.9 | Dc | 1.80 | 330 |
| 75.3 | Ds | 1.80 | 330 |

**Area E**

| Depth (m) | Soil mark | Density (t/m³) | Vs (m/s) |
|---|---|---|---|
| 6.2 | Bs | 1.80 | 80 |
| 7.0 | As | 1.80 | 80 |
| 10.5 | Ac1 | 1.80 | 80 |
| 14.8 | Ac1 | 1.56 | 130 |
| 16.9 | As | 1.56 | 130 |
| 35.0 | Ac2 | 1.56 | 130 |
| 45.3 | Ds | 1.80 | 390 |

Figure 3. Physical properties of ground soil in each area.

### 3.2 Seismic ground motion used for response analysis

The amplification characteristics of surface layers in each area are evaluated using different types of seismic waves with different vibrational characteristics and duration time, such as subduction-zone earthquakes and inland active fault earthquakes. The acceleration response spectrums (damping factor h=0.02(2%)) of 10 seismic waves are shown in Fig. 4, which are observed waves (NIED 2019) at KiK-net stations and the simulated waves published by Central Disaster Management Council (2017). The spectrums are normalized by the maximum acceleration of each wave. The symbol * in the figure are simulated waves and others are observed waves. The response analysis in each area (A~E) were carried out with a total of 100 seismic waves by increasing the amplitude of each wave to 10 stages.
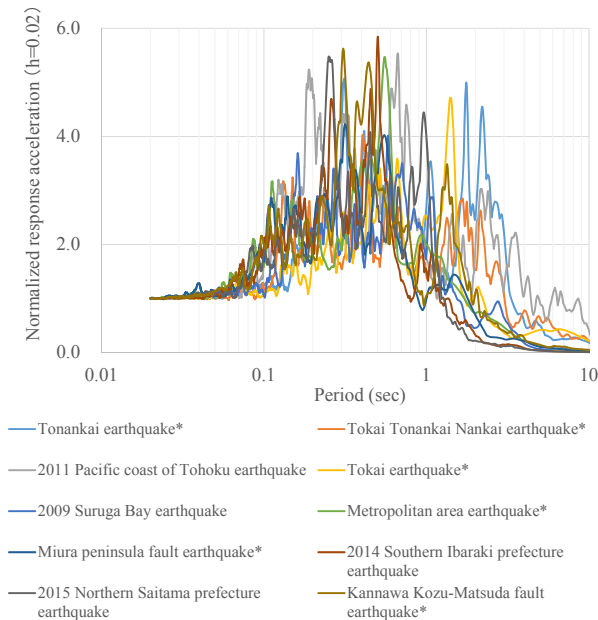


Figure 4. Response spectrums of input seismic waves used for response analysis (h=0.02).

## 4. Evaluation of shutdown trigger level
### 4.1 Risk evaluation model for trigger level determination

In the evaluation of trigger level, we focus on whether it is possible to prevent the spread of fire due to the leakage of flammable substances by the operation of the emergency shutdown system. Since manufacturing equipments are concentrated in Area D, the spread of fire is considered from Area D to adjacent Area B. To obtain the optimum trigger level, the seismic loss function with and without emergency shutdown is required. With an emergency shutdown is a case in which a shutdown system is operated regardless of the seismic ground motion intensity. Without an emergency shutdown is a case in which a shutdown system is not operated regardless of the seismic ground motion intensity. The losses caused by each case are modeled in the Event Tree as shown in Fig. 5. Figure 5(a) is a case with emergency

shutdown, Figure 5(b) is case without emergency shutdown.

Fire break-out in Area D is defined as an event in which a fire breaks out immediately when an equipment damage exceeding the severity occurs, and one or more fires break out in the area. A flammable substance leakage is an event in which one or more equipments containing a large amount of flammable substance are severely damaged in the area. Ignition is a fire event caused by electric sparks, naked flame, etc. Ignition probability does not depend on the seismic ground motion intensity and is assumed to be 0.1 (Kanagawa Prefecture 2015). Fire fighting is an event in which water storage tanks, fire fighting pipes and pumps, and seawater intake facilities are sound and fire fighting activities can be carried out immediately. The occurrence probability of events other than ignition is obtained from FC.

| Fire break-out in Area D | Flammable substance leakage | Ignition | Fire fighting | Ratio of physical loss Area D | Ratio of physical loss Area B | Production interruption days | Production interruption days due to shutdown |
|---|---|---|---|---|---|---|---|
| No | No | | Success | 0% | 0% | 0 | 30 |
| | | | Failure | 0% | 0% | 0 | 30 |
| | Yes | No | Success | 5% | 0% | 60 | 0 |
| | | | Failure | 5% | 0% | 60 | 0 |
| | | Yes | Success | 20% | 0% | 180 | 0 |
| | | | Failure | 100% | 100% | 360 | 0 |
| Yes | | | Success | 20% | 0% | 180 | 0 |
| | | | Failure | 100% | 100% | 360 | 0 |

(a) Case with emergency shutdown

| Fire break-out in Area D | Flammable substance leakage | Ignition | Fire fighting | Ratio of physical loss Area D | Ratio of physical loss Area B | Production interruption days | Production interruption days due to shutdown |
|---|---|---|---|---|---|---|---|
| No | No | | Success | 0% | 0% | 0 | 0 |
| | | | Failure | 0% | 0% | 0 | 0 |
| | Yes | No | Success | 5% | 0% | 60 | 0 |
| | | | Failure | 5% | 0% | 60 | 0 |
| | | Yes | Success | 100% | 0% | 360 | 0 |
| | | | Failure | 100% | 100% | 360 | 0 |
| Yes | | | Success | 100% | 0% | 360 | 0 |
| | | | Failure | 100% | 100% | 360 | 0 |

(b) Case without emergency shutdown

Figure 5. Event Tree for evaluation of seismic shutdown trigger level.

Next, the feature difference between the Event Trees shown in Figs. 5(a) and (b) will be described. In the Event Tree shown in Fig. 5(a) (case with emergency shutdown), forced emergency shutdown is operated regardless of the occurrence of damage. Therefore, it is assumed that 30 days are required to resume operation, and this is incorporated into the consequences that cause no damage. This results in business losses caused by inappropriate operation for the emergency shutdown. In the Event Tree

shown in Fig. 5(b) (case without emergency shutdown), the leakage of flammable substances cannot be suppressed. For this reason, if flammable substances are ignited, Area D is burned down regardless of whether fire fighting activities, and the production interruption day increases.

The replacement costs of the target Area D and B are set at 50 and 20 billion yen, respectively. The business loss in the event of production interruption is set at 60 million yen per day. Accordingly, the loss due to inappropriate operation of the emergency shutdown will be 30 days× 60 million yen/day = 1.8 billion yen. By applying the damage probability obtained from FC to the branches of each Event Tree, the conditional expected loss value to the PGA observed by the seismograph be evaluated. Then, the seismic loss function is evaluated by obtaining the loss for various levels of PGA.

### 4.2 Regression analysis of response acceleration

The maximum accelerations of the 10 seismic waves shown in Fig. 4 were amplitude-adjusted in 10 levels between 50 and 700cm/sec$^2$, and nonlinear response analysis in time domain was carried out for each ground model in 5 areas (A~E). A modified Ramberg-Osgood model (Tatsuoka and Fukushima 1978) was used for the model on the plasticization of soils. In the evaluation of the trigger level, the severe damage is targeted regarding the damage state of the structures. Therefore, h=0.1 (10%) was used as the damping factor of the acceleration response spectrum in Area B, C, and D where towers and frame structures are concentrated. The damping factor h=0.1 was set by referring to the maximum values of the time-series data obtained from the strong-motion observation records (Iiba et al. 2012) of damaged buildings due to earthquakes. The damping factor h=0.02 (2%) was applied for Area A and E where tanks, piping, and fire fighting facilities (pumps, water intake, etc.) are the main structures. The reason is that most of the structures in the both areas are steel structure and they are structural types for which damping effect cannot be expected.

Assuming that the seismometer is located in Area D, we calculate samples of response acceleration to PGA in Area D and evaluate the regression formula. As an example, samples of response acceleration at period T=1.0 second to PGA in Area D and result of regression analysis are shown in Fig. 6. The regression coefficients were *a*=1.111 and *b*=1.068, and the logarithmic standard deviation $\zeta_Y$ was 0.194. In the figure, the variation in sample of the response acceleration to the PGA increases with ground motion intensity. The variation in sample of the response acceleration other than period T=1.0 second also shows similar tendency. Figure 7 shows the ratio $y_i/y'_i$ of the sample $y_i$ of response acceleration and the value $y'_i$ obtained by the regression formula. In the figure, the variation of ratio $y_i/y'_i$ does not depend on the ground motion intensity. This indicates that the logarithmic standard deviation obtained from the ratio $y_i/y'_i$ shown in equation (3) is independent of the seismic ground motion intensity. On the other hand, some samples of the ratio $y_i/y'_i$ distributed around 1.6 can be seen. All of these are

sample due to 2015 Northern Saitama Prefecture earthquake. As can be seen from Fig. 4, the 2015 Northern Saitama Prefecture earthquake wave has peak around period T=1.0 second, which suggests that the influence of the vibrational characteristics appeared. Therefore, it is necessary to note that there are some cases in which the response of structure is underestimated due to the vibrational characteristics of seismic wave.
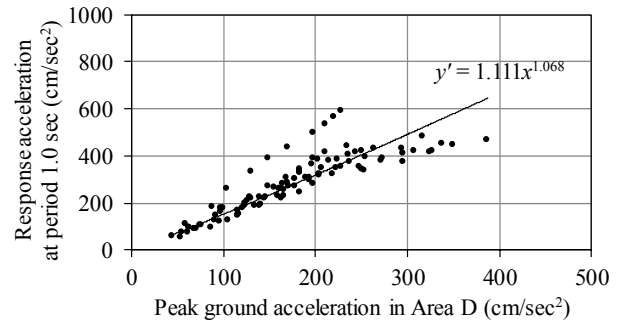


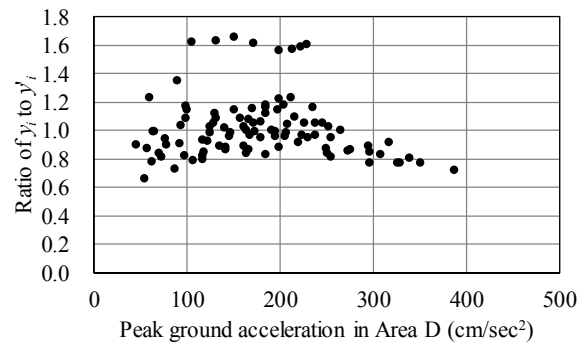Figure 6. Relationship between PGA and response acceleration at period T=1.0 sec in Area D.



Figure 7. Relationship between PGA and ratio of $y_i$ to $y'_i$ in Area D.

### 4.3 Fragility data for individual structures

This study considers the spread of fire from Area D, where manufacturing equipments are concentrated, to adjacent Area B. Therefore, to consider the success or failure of fire fighting activities, damage of equipments related to fire fighting activities should also be considered. Table 1 summarizes the data required for FC of structures including fire fighting facilities.

Regarding manufacturing equipment, the equipment that fires immediately when severe damage occurs is 2 heating furnaces, 5 towers, and the equipment that contains a large amount of flammable substance is 10 towers and 10 heat exchangers. These are located in Area D. Table 1 shows natural period T, the median $c_m$ of the seismic strength expressed in response acceleration, the logarithmic standard deviation $\zeta_C$, regression coefficients *a* and *b*, and the logarithmic standard deviation $\zeta_Y$, respectively. Similar information is shown for the facilities related to fire fighting activities in the Table, but

the locations of these facilities are distributed from Area A to Area E. In addition, the damage level to the facilities related to fire fighting activities assumed to severe damage which cause loss of functionality of facility. The logarithmic standard deviation $\zeta_C$ of seismic strength in the table1 is set to 0.4 for all facilities and equipments. The reason is explained below. Yoshikawa et al. (Yoshikawa et al. 2007) discussed that the logarithmic standard deviation used for FC was around 0.6, referring to statistical analysis using actual damage data for various structures. If the logarithmic standard deviation of the attenuation relationship (about 0.45) is removed from this value, 0.4 $(=(0.6^2-0.45^2)^{1/2})$ is obtained as the logarithmic standard deviation of the seismic strength of structures. The logarithmic standard deviation $\zeta_Y$ is in the range of about 0.1 to 0.2 depending on the natural period T. Applying $c_m$, $\zeta_C$, $a$, $b$, and $\zeta_Y$ to equation (8), we can obtain FC of the structures using PGA observed in Area D as variables.

Table 1. Data required for FC of structures.

| Structures | | Number | Area | Natural period (sec) | Seismic strength to severe damage | | Regression formula | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | Median (cm/sec$^2$) $c_m$ | Log-arithmic standard deviation $\zeta_C$ | Regression coefficients | | Log-arithmic standard deviation $\zeta_Y$ |
| | | | | | | | $a$ | $b$ | |
| Equipment that fires in severe damage state | Heating furnace | 2 | D | 1.0 | 800 | 0.40 | 1.111 | 1.068 | 0.194 |
| | Tower | 5 | D | 1.0 | 1400 | 0.40 | 1.111 | 1.068 | 0.194 |
| Equipment containing large amount of flammable substance | Tower | 10 | D | 1.0 | 1000 | 0.40 | 1.111 | 1.068 | 0.194 |
| | Heat exchanger | 10 | D | 0.2 | 1100 | 0.40 | 4.105 | 0.773 | 0.146 |
| Facility related to fire fighting activities | Water storage tank | 1 | E | - | 1200 | 0.40 | 0.978 | 1.027 | 0.111 |
| | Fire pump room | 1 | C | 0.1 | 700 | 0.40 | 2.378 | 0.869 | 0.135 |
| | Power generation facility | 1 | C | 0.3 | 1500 | 0.40 | 6.119 | 0.728 | 0.183 |
| | Power distribution room | 1 | B | 0.2 | 1000 | 0.40 | 7.111 | 0.573 | 0.104 |
| | Power distribution facilities | 1 | B | - | 900 | 0.40 | 2.376 | 0.746 | 0.110 |
| | Seawater pump room | 1 | A | 0.1 | 500 | 0.40 | 13.129 | 0.583 | 0.212 |

## 5. Evaluation Results of shutdown trigger level

Figure 8 shows the seismic loss function with and without an emergency shutdown when the seismometer is located in Area D. The vertical axis indicates the loss amount, and the horizontal axis indicates the PGA observed in Area D. The damage correlation between the structures is independent. It can be seen that the intersection of both functions is 190 cm/sec$^2$ in the figure. In the range below 190 cm/sec$^2$, the loss amount without an emergency

shutdown is lower than that with an emergency shutdown. Conversely, in the range exceeding 190 cm/sec$^2$, the loss amount with an emergency shutdown is lower than without one. Therefore, it is determined that the optimal trigger level is 190 cm/sec$^2$. It should be noted that this result is not generally applicable because it depends on the inherency including the ground where the petroleum refinery is located.
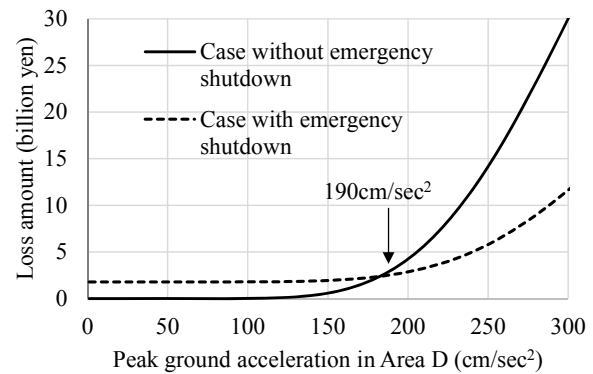


Figure 8. Seismic loss functions and optimal trigger level.

## 6. Conclusion

This paper presents a method to determine the optimum trigger level by comparing the loss amounts with and without an emergency shutdown. The feature in this method is that the relationship between the PGA observed by a seismometer and the response acceleration of equipments and facilities is modeled by a nonlinear regression formula, and regression coefficients and error in regression formula are directly incorporated into FC. In addition, we applied this method to a hypothetical petroleum refinery and evaluated the optimum trigger level from the viewpoint of economical rationality. In the regression formula to show the relationship the observed PGA and the response acceleration of the structures, the following conclusions were obtained.
1. There are some cases in which the response of structure is underestimated due to the vibrational characteristics of the seismic wave.
2. The logarithmic standard deviation $\zeta_Y$ of the response acceleration of the structures ranged from about 0.1 to 0.2.

Also, the optimum trigger level for a hypothetical petroleum refinery were 190 cm/sec$^2$ at PGA. However, this value depends on specific characteristics of the petroleum refinery including the amplification characteristics of ground.

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