Application of probabilistic fault displacement hazard analysis in Taiwan

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ABSTRACT

Probabilistic Fault Displacement Hazard Analysis (PFDHA) is a seismic hazard analysis used to evaluate the fault rupture hazard. PFDHA is relatively new approach comparing to well-known Probabilistic Seismic Hazard Analysis (PSHA) which was developed in the late 1960s. In Taiwan, PSHA is already used in the seismic hazard analysis to evaluate the ground shaking hazard for many projects (e.g. Dam, Nuclear Power Plant etc.). However, PFDHA is rarely used in the seismic hazard analysis. This paper will describe the methodology of PFDHA and a case study on the fault rupture hazard of a road construction project crossing active fault.

Keywords: Fault Displacement Hazard, PFDHA, Seismic Hazard Analysis, Active Fault

1 INTRODUCTION

Probabilistic Seismic Hazard Analysis (PSHA) was developed in 1960s (Cornell 1968) and was used to perform the ground shaking hazard analyses for important projects (Unclear Power Plant, Reservoir etc…) in Taiwan since 1970s. For structures or facilities are crossing or close to an active fault, other than the ground shaking hazard, fault rupture is also an important hazard (causing structural cracks or damaging pipe lines) to be evaluated and included in seismic design.

The fault rupture hazard can be evaluated using Probabilistic Fault Displacement Hazard Analysis (PFDHA). PFDHA have been used in many projects (Unclear Power Plant, Oil Pipe Line etc…) around the world. However, PFDHA is a relatively new approach in Taiwan. Only few projects of important facilities (Nuclear Power Plant etc…) used PFDHA to evaluate the fault rupture hazard. In this article, the methodology of PFDHA is introduced first and a case study for a road construction project is discussed later.

2 PFDHA METHODOLOGY

PFDHA used in this article is based on Youngs et al. (2003) which summarizes study and work done by various researchers for the Yucca Mountain project. Two approaches of PFDHA are discussed in Youngs et al. (2003), Earthquake Approach and Displacement Approach. A brief discussion of these two approaches is presented as followed. The detailed discussion can be found in Youngs et al. (2003).

2.1 Earthquake Approach

The formulation of Earthquake Approach is the same as the PSHA formation with a little modification. The rate of exceedance, $v(d)$, is computed using the following formulation:

$$v(d) = \sum_n N_n(m_0) \int_{m_0}^{m_u} f_n(m)[P_n(D > d|m, r)]dm \qquad (1)$$

where $v(d)$ is the annual rate of earthquakes causing the fault rupture displacement (surface rupture displacement) exceeds a specified level, d at the site; $N_n(m_0)$ is the rate of all earthquakes from source n above the minimum magnitude, m_0; $fn(m)$ is the probability density of earthquake magnitude between m_0 and the maximum magnitude of source n, mu; and $P_n(D>d|m,r)$ is the conditional probability that, given an earthquake of magnitude m at distance r from the site, the fault rupture displacement will exceed displacement level d. Site location and parameters are shown in Fig. 1.

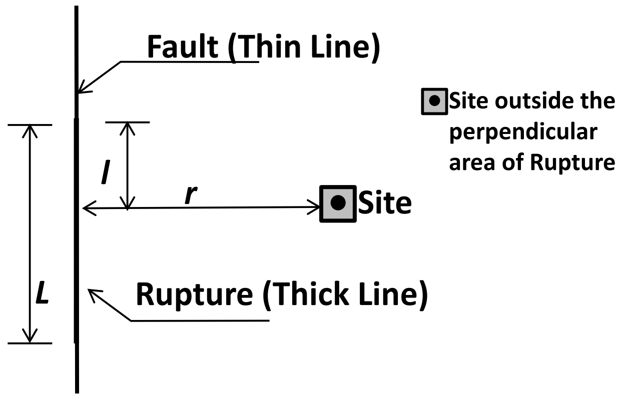

Fig. 1. PFDHA Parameters and Definition

During earthquake event, a site inside the affecting area will experience a certain level of ground shaking. However, it is not always true for the fault rupture. In order to include the probability of the fault rupture occurrence, Pn(D>d|m,r) can be rewritten as followed:

$$P_n(D > d|m, r) = P_n(Slip|m, r)P_n(D > d|m, r, Slip) \qquad (2)$$

where $Pn(Slip|m,r)$ is the conditional probability that, given an earthquake of magnitude m at distance r from site, the fault rupture will occur at the site; $Pn(D>d|m,r,Slip)$ is the conditional probability that, given the fault rupture occurs at the site, the fault rupture displacement will exceed displacement level d.

The fault rupture displacement can be categorized into Primary Displacement and Secondary Displacement. Primary Displacement is caused by Principal Rupture which is defined as the rupture area where the energy of the earthquake is released. Secondary Displacement is caused by Secondary Rupture and Distributed Rupture which are ruptures caused by Principal Rupture. Fault displacement prediction equation (FDPE), $Pn(D>d|m,r,Slip)$ and $Pn(Slip|m,r)$ of different displacement types can be found in different studies.

There is one major difference between PFDHA and PSAH is that the fault rupture (secondary disp.) displacement at a site occurs only when the fault rupture occurs and the site is inside the perpendicular area of the fault rupture.

2.2 Displacement Approach

Displacement Approach uses the observed fault displacement at the site of interest via the trench investigation (as shown in Fig. 2) to decide the input parameters. The formulation of Displacement Approach follows the formulation in Youngs et al. (2003) as followed:

$$\nu(d)=\lambda_{DE} \cdot P(D>d|Slip) \qquad (3)$$

where λ_{DE} is the rate of displacement events for fault and $P(D>d|Slip)$ is the conditional probability that the displacement will exceed displacement level d. λ_{DE} and $P(D>d|Slip)$ can be estimated from the fault displacement information via the trench excavation.

Fig. 2. Trench Investigation Site

After input parameters and models in Eq. (1) and (3) are decided, the rate of exceedance, $\nu(d)$, can be calculated and the hazard curve can be developed. In this article, Earthquake Approach is used to evaluate the fault rupture hazard of a highway project.

3 CASE STUDY OF PFDHA

Fault parameters and models of a PFDHA case study used to evaluate the fault rupture hazard of a freeway construction project crossing active faults in central Taiwan are discussed.

3.1 Project Site

The construction site is located in central Taiwan as shown in Fig. 3. Two active faults (CGS, 2008), Sanyi Fault and Chelungpu Fault, intersect with the road at few sections. The fault rupture hazards of these sections caused by the active faults are evaluated as references for the future road construction design.

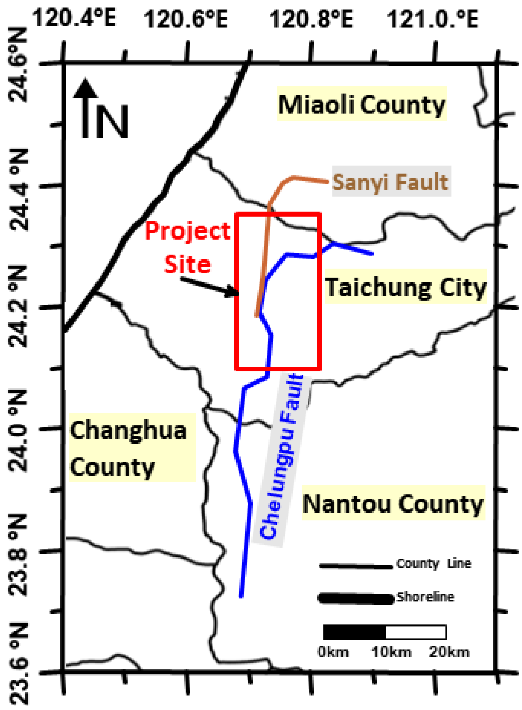

Fig. 3. Project Site Map

3.2 Logic Tree

PSHA or PFDHA usually uses the logic tree to include the uncertainty of parameters and models used in analyses. Logic trees of Sanyi Fault and Chelungpu Fault used in analyses are shown in Fig. 4 and 5. Values in brackets are weights for parameters or models. Weights are summed up to 1.0 for each branch.

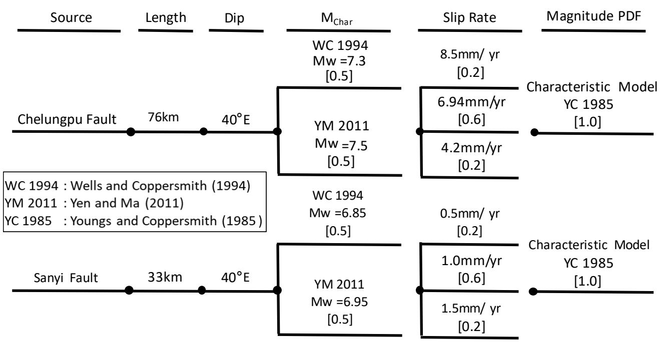

Fig. 4. PFDHA logic tree - Fault Parameters and Models

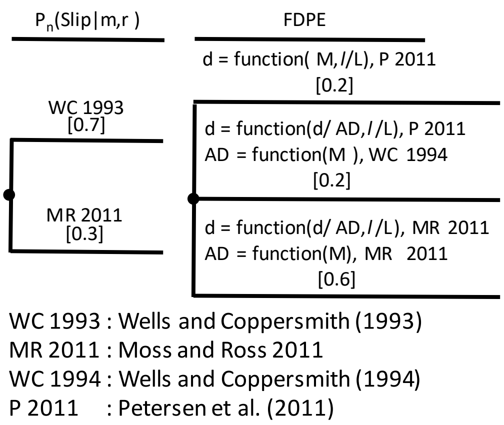

Fig. 5. PFDHA logic tree - Displacement Prediction Models

(1) Fault Parameters

The fault trace, fault length and fault dip are summarized from CGS report. Characteristic magnitude (M_{Char}) of a fault is decided using Wells and Coppersmith (1994) and Yen and Ma (2011) relationships as shown in Table 1. Wells and Coppersmith (1994) relationship is a well-known and frequently used in PSHA. Yen and Ma (2011) relationship is determined from events in Taiwan area. Both relationships are considered important and reliable for M_{Char} estimation. Therefore, equal weights (0.5 and 0.5) are assigned to both equations in the logic tree.

(2) Fault Slip Rates

Slip rates of Chelungpu Fault are provided in CGS (2008). In the logic tree, the average slip rate and slip rates of the north section of Chelungpu Fault are used because the project site is on the north section of Chelungpu Fault. From the paleoseismic evidence, slip rates of the north section are 4.2mm/yr at the Siangong-Temple site and 8.5mm/yr at the Pineapple Field site. The average slip rate of Chelungpu Fault is 6.94mm/yr. Because the average slip rate is estimated from many paleoseismic data, the average slip rate is considered more reliable. Therefore, in the logic tree, the average slip rate is assigned a higher weight (0.6) and slip rates of the north section are assigned lower weights (0.2 and 0.2).

Because there is no information about slip rates of Sanyi Fault in CGS (2008). Slip rates of Sanyi Fault provided in Cheng (2002) and obtained from trench investigation are taken into account in the logic tree. The average slip rate (1.0 mm/yr) is estimated based on the analysis of the seismicity balancing of the regional source and faults. In order to include the uncertainty, two more slip rates (0.5 and 1.5 mm/yr) are used. The weights are 0.6 for the average slip rate and 0.2 for other two slip rates in the logic tree.

(3) Magnitude Probability Density Function

Two probability density functions are commonly used, characteristic model and truncated-exponential model. Characteristic model (Youngs and Coppersmith, 1985) works well for faults and truncated-exponential model works well for regional sources. In the logic tree, characteristic model is used for Chelungpu Fault and Sanyi Fault.

(4) Conditional Probability of Slip

Two models are used in the logic tree. Wells and Coppersmith (1993) relationship is obtained using worldwide data (276 events) and Moss and Ross (2011) relationship is obtained using reverse fault data (129 events). Wells and Coppersmith (1993) is assigned a higher weight (0.7) because the relationship is determined using more events. Probability equations are listed in Table 1.

Table 1. Relationships and equations used in PFDHA

Characteristic Magnitude	
Model	**Equation**
Wells and Coppersmith (1994)	$M_w = 5.00 + 1.22 \cdot \log L$ L is the fault length
Yen and Ma (2011)	$\log(L_e) = 0.42 \cdot \log(M_0) - 6.66$ $M_w = 2/3 \cdot \log(M_0) - 10.7$ (Kanamori, 1977) L_e is the fault length
Conditional Probability of Slip	
Model	**Equation**
Wells and Coppersmith (1993)	$P_n(Slip\|m,r) = e^{a+bm}/(1+ e^{a+bm})$ a = -12.51, b = 2.053, m is M_w
Moss and Ross (2011)	$P_n(Slip\|m,r) = 1/(1+ e^{a+bm})$ a = 7.30, b = -1.03, m is M_w
Fault Displacement Prediction Equation	
Model	**Equation**
Petersen et al. (2011) d = f(M, l /L*)	ln(d) = ax+bm+c (*d* in cm) *x* is function of site location (*l/L*) *a*=3.3041, *b*=1.7927, *c*= -11.2192
Petersen et al. (2011) d =f(d/AD(l /L*), AD)	ln(d/AD) = ax-b (d in cm) *x* is function of *l/L* *a*=3.2699, *b*=3.2749
Moss and Ross (2011) d =f(d/AD(l /L*), AD)	$P_n(D>d\|m,r,Slip)=f(z)$ z=d/AD $f(z) = (k/\lambda)(z/\lambda)^{k-1}e^{(z/\lambda)k}$ k and λ are function of *l/L*
Average Fault Rupture Displacement Equation	
Model	**Equation**
Wells and Coppersmith (1994)	$\log(AD)=0.69M_w-4.8\pm0.36$
Moss and Ross (2011)	$\log(AD)=0.3244M_w-2.2192\pm0.17$

(5) Fault Displacement Prediction Equation (FDPE)

Fault displacement prediction equations used in the logic tree are listed in Table 1. Moss and Ross (2011) relationship is determined using reverse fault data. Petersen et al. (2011) relationships are determined using strike-slip fault and some oblique fault data. Because both Chelungpu Fault and Sanyi Fault are oblique faults (reverse fault with horizontal movement), Moss and Ross (2011) is assigned a higher weight (0.6) and Petersen et al. (2011) are assigned lower weights (0.2 and 0.2) in the logic tree.

Two equations in Table 1 estimate the fault rupture displacement using the normalized displacement ratio (d/AD). For these equations, the average fault rupture

(AD) is needed to estimate d. Average fault rupture displacement equations are listed in Table 1.

(6) PFDHA Software

After all input parameters and models are decided, the case study of PFDHA is performed using THAZ software package. THAZ was developed by Lettis Consultants International and has been used to calculate seismic hazards at many nuclear power plant sites around the world.

4 CASE STUDY RESULTS

Hazard curves of Chelungpu Fault and Sanyi Fault are shown in Fig. 6 (Y-axis is $v(d)$ and X-axis is d). The reciprocal of $v(d)$ is the return period.

In the building code of Taiwan, three seismic hazard levels are considered. They are the moderate earthquake level hazard (30 years return period), the design earthquake level hazard (475 years return period) and the maximum credible earthquake level hazard (2500 years return period). Fault rupture displacements at different seismic hazard levels of Chelungpu Fault and Sanyi Fault are listed in Table 2. PFDHA results show that Sanyi Fault has a very minor hazard compared to Chelungpu Fault because Chelungpu Fault has higher slip rates and M_{Char} than Sanyi Fault.

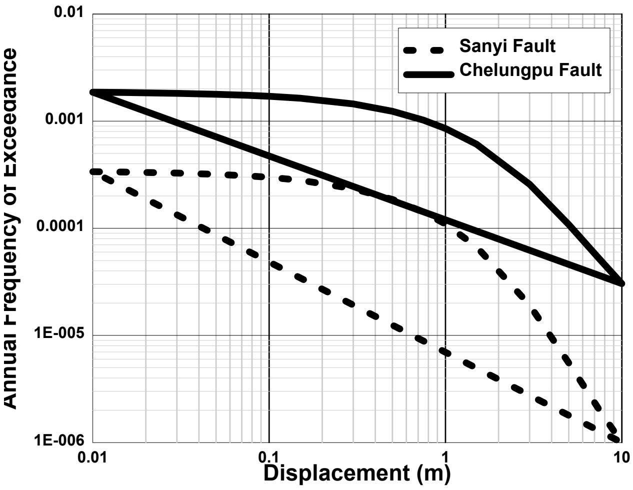

Fig. 6. PFDHA hazard curves

Table 2. Fault rupture displacements of Chelungpu Fault and Sanyi Fault

Hazard Level (Return Period)	Displacement of Chelungpu Fault (m)	Displacement of Sanyi Fault (m)
30 years ($v(d)$ = 0.033)	<0.01	<0.01
475 years ($v(d)$ = 0.0021)	~0.01	<0.01
2500 years ($v(d)$ = 0.0004)	2.00	~0.01

5 CONCLUSIONSS

This article introduces methodology of PFDHA and a case study on a freeway project in central Taiwan. PFDHA is performed to estimate the fault rupture displacement of road sections intersect with Sanyi Fault and Chelungpu Fault.

For road sections on Chelungpu Fault, the design earthquake level (475 years return period) displacement is about 1cm and the maximum credible earthquake level (2500 years return period) displacement is about 2 m. For road sections on Sanyi Fault, the design earthquake level displacement is less than 1 cm and the maximum credible earthquake level displacement is about 1cm. The major displacement hazard comes from Chelungpu Fault because of its higher slip rates and characteristic magnitude. Fault rupture displacement values can be used to evaluate the safety and serviceability of the road.

Building codes in Taiwan regulate a setback width (30m to 100m) between a structure and an active fault. However, for a structure or facility needs to cross the active fault because of special purposes, the safety and serviceability evaluation of the structure or facility is suggested. In this condition, PFDHA can provide the amplitude of the fault rupture displacement and the affecting area for the evaluation.

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