Probabilistic fault displacement hazard analysis for dams in Australia

Hong Kie Thio, Paul Somerville and Don Macfarlane

AECOM

Abstract

Fault displacement can occur due to primary faulting on a main fault intersecting a dam foundation or rim, as well as by secondary faulting. This secondary faulting may be triggered locally by the occurrence of primary faulting on a main fault; its occurrence is conditional on the occurrence of an earthquake on the main fault. A probabilistic approach is most viable for fault displacement hazard analysis. Unlike the case of probabilistic ground motion hazard, which is nonzero even for short return periods due to the occurrence of a broad range of earthquake magnitudes in a wide region around the site, probabilistic fault displacement hazard is zero for return periods less than the recurrence interval of surface faulting earthquakes on the fault. In Australia, these recurrence intervals typically lie in the range of 10,000 to 100,000 years. Consequently, the fault displacement hazard due to primary faulting may be zero or negligible for return periods shorter than 10,000 or 100,000 years. For longer return periods, the hazard is best evaluated using a risk-based approach, as recommended by ANCOLD (2018); the alternative of using a deterministic approach, which disregards return period, could potentially yield a large fault displacement. The probability of triggered secondary faulting, conditional on the occurrence of a large earthquake on the main fault, may be one or two orders of magnitude lower than that on the main fault, especially for strike-slip faulting, and so may be even more likely to be zero or negligible for return periods shorter than 10,000 to 100,000 years.

Introduction

The 2019 ANCOLD Guidelines for Design of Dams and Appurtenant Structures for Earthquake includes Section 2.5, Requirements of a Seismic Hazard Assessment. Paragraph 3 of these requirements relates to “Faults in the Dam Foundation,” and states: “Information on any known active or neotectonic faults which have the capability to cause displacement in the foundation of the dam, appurtenant structures, or reservoir rim should be provided.” ANCOLD (2019) defines an Active Fault as: “A fault, reasonably identified and located, known to have produced historical earthquakes or showing evidence of movements in Holocene time (i.e. in the last 11,000 years) and large faults that have moved in Latest Pleistocene time (i.e. between 11,000 and 35,000 years ago).” ANCOLD (2019) defines a Neotectonic Fault as: “A fault, not active as defined above, that has experienced displacement under conditions imposed in the current crustal stress regime and hence may move again in the future.”

The 2019 ANCOLD Guidelines do not specify how to address active faulting in the foundation, and state that “If an active fault is identified in a dam foundation, specialist expertise should be sought to assist with the design or assessment of the dam in question.” This paper aims to provide an understanding of probabilistic fault displacement hazard analysis (PFDHA), which has also been described by Cuthbertson and Capewell (2018).

Active Faults in Australia

An Australia-wide assessment of active faulting based on neotectonics data was made by Clark et al. (2011; 2012; 2016) and updated to form a National Fault-Source Model (NFSM) in the course of the NSHA18 Project (Allen et al., 2019) Clark et al. (2012) analysed a catalogue of over 300 neotectonic features, 47 of which are associated with named fault scarps. The data were derived from analysis of DEMs, aerial photos, satellite imagery, geological maps and consultation with state survey geologists and a range of other earth scientists. Verifying the features as active faults is an ongoing process. The catalogue varies in completeness because sampling is biased by the available databases, the extent of unconsolidated sedimentary cover, and the relative rates of landscape and tectonic processes. We consider potentially active faults as those that have undergone displacement under the current stress regime in Australia, and hence may have the potential for displacement in the future. The age of the current stress regime in Australia is estimated to lie in the range of 5 to 10 million years (Sandiford et al., 2004). Clark et al. (2011, 2012, 2016) find that the recurrence intervals of surface faulting earthquakes typically lie in the range of 10,000 to 100,000 years, but may be shorter as discussed below.

The faults in the NFSM have mostly been identified from observations of vertical offset, indicating the prominence of reverse and thrust faulting in the current stress regime in Australia. This is also consistent with the reverse and thrust focal mechanisms of historical earthquakes that have produced surface faulting in Australia (King et al., 2019).

In the cratonic regions of the western part of Australia, surface faulting has been observed frequently (in 11 earthquakes) in the past 50 years (King et al., 2019). Cratonic earthquakes of all magnitudes have shallow hypocentres, producing surface faulting even for small earthquakes (magnitudes less than 5), reflecting the brittle nature of the cratonic crust at shallow depths. In contrast, surface faulting has not been observed in historical time in other regions of Australia, due in part to their greater hypocentral depths. It is expected that earthquakes in non-cratonic regions have characteristics similar to those of earthquakes in tectonically active regions, where the probability of surface faulting is low for magnitudes less than 6 and increases rapidly with earthquake magnitude.

The available recurrence information for surface faulting in Australia is strongly biased by data from fault studies in Precambrian western and central Australia (King et al., 2019) and recurrence characteristics might be different in Phanerozoic eastern Australia. For example, a study of the Cadell Fault (Clark et al. 2015) indicated a roughly 8 ka recurrence interval for surface rupture between 70-20 ka. The Cadell Fault does not have a particularly high long-term average slip rate compared to faults in the southeastern highlands (e.g. Lake George Fault), so recurrence that is more frequent than on the Cadell fault in an active period is possible on these faults.

Methodology of Probabilistic Fault Displacement Hazard Analysis

There are two basic approaches to PFDHA (Hoffmann, 1991; Youngs et al., 2003):

1. Direct (or Displacement) Method – the probability of slip is directly related to the rate of displacement on a fault and a slip distribution function.
2. Earthquake Method – in this method the displacements are related to the occurrence of earthquakes through scaling relations and/or slip distribution functions. The framework closely follows the approach of PSHA with the ground motion prediction model replaced by magnitude and position dependent slip distribution functions and the hazard computed through an integration over magnitude and rupture locations

Direct method

The frequency of displacement exceedance $\nu(d)$can be written as:

$\nu(d) = \lambda_{DE}.P(D > d)$
where
d = displacement
λ_{DE} = rate of displacement events on the fault
$P(D > d)$ = conditional probability that displacement D in an event exceed d.

This method forms a direct connection (hence its name) to the geological data from fault trench studies and other field observations. The rate of displacement events can simply be obtained by dating observed slip evens. Alternatively, it can be computed simply as the slip rate divided by the average slip per event, assuming periodic recurrence of characteristic events. The conditional probability of exceedance slip ($P(D > d)$) can be obtained by measuring the amount of slip for many events at a site.

It is clear that this approach relies heavily on site-specific information and rupture, but Youngs et al. (2003) do give alternative methods to obtain the aforementioned functions, usually based on scaling relations and normalized data from other faults, although it seems that this would diminish the appeal of this method as one firmly based on local observations and makes it more similar to the Earthquake Method described later. Angell et al. (2003) present a comprehensive example of this approach in a PFDHA analysis for submarine pipelines in the Gulf of Mexico, which includes an extensive analysis of subsurface geophysical and geological data. Braun (2000) used this method to develop a PFDHA model for the Wasatch front using an extensive logic tree model and concluded that the results are strongly dependent on the choice of weights between the different branches, and thus there is a strong sensitivity to epistemic uncertainties.

However, there are usually no data available on actual event occurrences on the foundation fault, so that there is not enough direct recurrence data available to use this method of probabilistic fault displacement hazard. This is especially the case in intraplate environments, where the recurrence of large earthquakes is poorly understood.

Earthquake method

The Earthquake Method closely follows the procedures developed for PSHA. In general, the equation for the exceedance rate for displacement at a site ($k(d>D)$) on a fault has the following form (e.g. Youngs et al., 2003 for normal faulting; Petersen et al., 2011 for strike-slip faulting, Moss and Ross, 2011 for thrust faulting, and Takao, 2013 for mixed event types):

$$k(D \geq d) = \sum_{m_j=m_0}^{m_u} \dot{N}(m_j) \times \left[\sum_{k=1}^{N} \Pr(D \geq d \mid r_k, m_j) \times \Pr(sr \neq 0 \mid m_j) \times \Pr(r_k \mid m_j) \right]$$

where :

1. $\dot{N}(m_j)$ is the mean number of earthquakes of magnitude m_j
2. $\Pr(D \geq d \mid r_k, m_j)$ is the probability that displacement D exceeds d given that an earthquake of magnitude m_j centred at a distance r_k occurs.
3. $\Pr(sr \neq 0|m_j)$ the probability of surface rupture given magnitude m_j.
4. $\Pr(r_k \mid m_j)$ is the probability that an earthquake of magnitude m_j occurs with its centre of rupture located at r_k.
5. m_0 is the minimum magnitude of earthquake engineering significance, and
6. m_j is the maximum magnitude for earthquake event considered.

The main differences between the Petersen et al. (2011) papers and Takao et al. (2013) are in the forms of terms 2 and 3. The latter uses the beta and gamma distribution functions whereas Petersen et al. use (log) normal distributions. For the Petersen et al. (2011) model we show the functional form of these two terms in the following two sections.

Slip distribution function

Several authors have derived empirical relations (Figure 1) for slip along a rupture. They express the average slip at a location as a function of magnitude and the site location relative to the ends of the rupture.

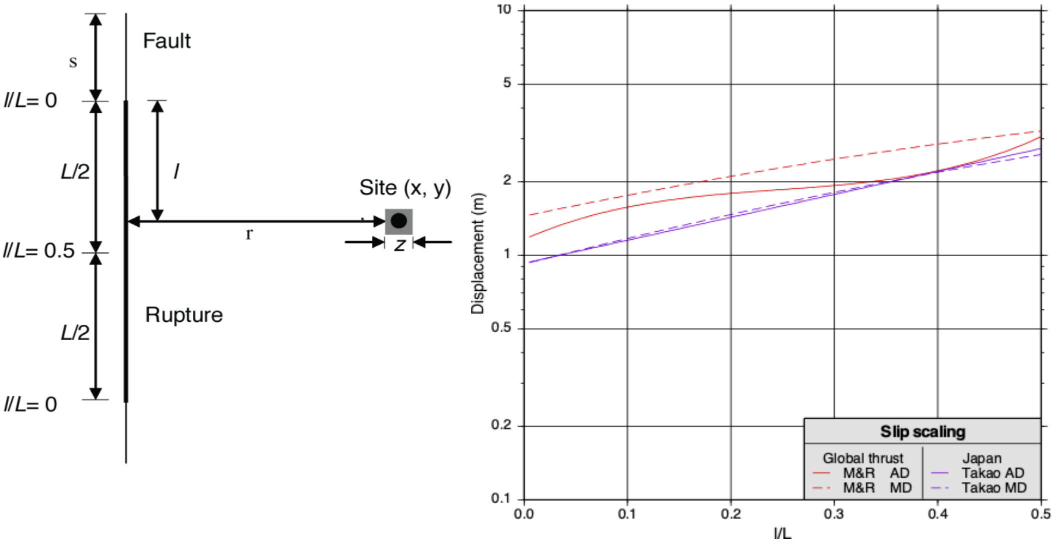

Figure 1. Left: Rupture and site geometry. Right: typical examples of slip distribution functions for a magnitude 7 earthquake, showing the relations of Moss and Ross (2011) and Takao et al. (2013). AD and MD refer to averaged displacement and maximum displacement respectively.

The displacement for a rupture is not uniform over the entire rupture, but instead tapers towards both ends of the rupture, and is parameterized using the ratio l/L between the total rupture length (L) and the distance from the centre of the rupture to the point on the rupture closest to the site (Figure 1).

We can use empirical relations from Moss and Ross (2011) and Takao et al. (2013), both of which are expressed as Beta functions, in the case of normalization on maximum slip, and Gamma distributions, in the case of normalization on mean slip. Both are described in the following form:

$$F(y) = \frac{1}{\Gamma(a)}\int_0^{y/b} e^{-t}\, t^{a-1} dt \qquad \text{where:} \quad a = e^{\left(0.7+0.34\frac{l}{L}\right)}, b = e^{\left(-1.4+1.82\frac{l}{L}\right)}, y = D/AD$$

for scaling of slip (D) with respect to average displacement (AD), and:

$$F(y) = \frac{\Gamma(a+b)}{\Gamma(a)\Gamma(b)}\int_0^{y} (1-t)^{b-1}\, t^{a-1} dt \quad \text{where:} \quad a = e^{\left(0.7-0.87\frac{l}{L}\right)}, b = e^{\left(-2.3-3.84\frac{l}{L}\right)}, y = D/MD$$

for scaling of slip with maximum displacement (MD).

The mean value for these relations is *a.b*, which implies a linear relationship between *ln(D/AD)* and *l/L.*

Secondary Deformation

All of the models cited above contain models for secondary fault deformation. In addition to them, Boncio et al. (2018) and Boncio et al. (2012) have analysed data for secondary faulting for reverse and normal faulting earthquakes respectively, but those models have not been developed to the stage where they can be directly used in PFDHA without further modelling.

For secondary deformation outside the zone of active faulting, Takao et al (2013) obtained two distance dependent functions normalized on the average displacement on the fault of the form:

$$\ln(d) = \ln(D_{ave}) - p * \ln(r) - q$$

where:

d – secondary slip

D_{ave} – average slip on the main fault

r – distance from the main fault

and p and q are given by the respective studies.

with a standard deviation for d of 1.1388

Probability of surface rupture

$\Pr(sr \neq 0|m_j)$ is the probability that surface rupture (sr) occurs for a given magnitude, given) as:

$$\Pr(sr \neq 0|m_j) = \frac{e^{a+bm}}{1+e^{a+bm}}$$

with a = -12.51 and b = 2.053 for global earthquakes of mixed mechanisms (Petersen et al., 2011), and a = -32.03 and b = 4.90 for the Japanese data (Takao et al., 2013). Moreover, Moss and Ross (2011) derived specific relations for thrust earthquakes, which were subsequently updated to account for soil conditions (Moss et al., 2013, 2018).

Thus, the probability of surface rupture for a thrust earthquake at magnitude 7.0 is only 0.48, compared to 0.86 for a strike slip event (Figure 2). Some authors have divided this function in two, one for the probability of surface rupture for the entire earthquake, and one for the probability of surface rupture reaching the site. The latter is sometimes inherently included in the previous term (slip distribution) and the integration process which integrates over a range of rupture locations. The Takao et al. (2013) model combines data from Japan for all types of crustal earthquakes, which is in contrast to the Moss and Ross (2011) study. These empirical relations are a complex function of surface conditions and depth distributions of earthquakes, and may therefore differ on local, regional and global scales. For the Moss and Ross (2011) and Moss et al. (2013, 2018) relations, we can apply either the stiff soil relations or soft soil relations. The Takao et al. (2013) relations do not differentiate for soil conditions.

All relations are based on events outside Australia, and may therefore have a bias, but without an extensive study of the underlying characteristics in, for instance, depth distributions of earthquakes in the various source regions that contributed to these relations, it is difficult to ascertain how large these biases are and whether they are positive or negative. We regard the current difference between the Takao et al (2013) and Moss and Ross (2011) relations as indicative of the overall global variability in these relations.

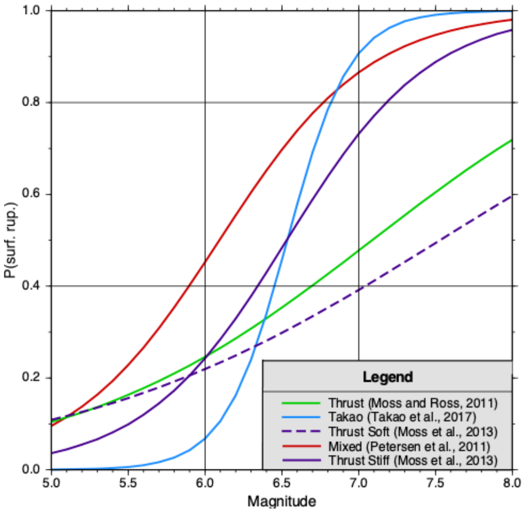

Figure 2. Probability of surface rupture for different types of earthquakes. The Takao relation is for a mixed set of events from Japan. The Thrust Stiff relation was used in conjunction with the Moss and Ross empirical displacement relations.

Logic Tree

The Moss and Ross (2011) model was developed for thrust events using a global dataset, whereas the Takao et al. (2013) model was developed using a mixed set of events. Given the different character of faulting between thrust and strike-slip mechanisms, we may choose to use a higher weight for the Moss and Ross (2011) model relative to the Takao model when analysing thrust faults. There is currently no model that addresses secondary faulting for thrust faulting adequately. Since the Takeo et al. (2013) model includes thrust events, we can compute the secondary faulting associated with thrust faulting using these relations alone, with equal weight to the average and maximum displacement relations.

Table 1. Logic tree weights for the different empirical models for average displacement (AD) and maximum displacement (MD).

data	weight	model	scaling	weight
Japan	1/3	Takao	AD	1/2
			MD	1/2
Global	2/3	Moss and Ross	AD	1/2
			MD	1/2

Source Model

Maximum magnitudes may be calculated from the fault area using the relations of Leonard (2010; 2014) for tectonically active regions. The width of the fault is controlled by its dip angle and the seismogenic thickness, each of which is represented by distributions of three values. This results in a matrix of nine estimates on maximum magnitude, one for each combination of dip angle and seismogenic thickness. We use these estimates to represent uncertainty in the maximum magnitude. The Leonard (2010, 2014) scaling relations are based on a more modern data set than Wells and Coppersmith (1994) but more importantly, for PFDHA in particular, they are self-consistent. Average displacements obtained from the Leonard scaling relation are consistent with the rupture area, whereas this is not the case with the Wells and Coppersmith (1994) relations.

Example Results for Strike-Slip Faulting

Example hazard curves from a probabilistic fault displacement analysis are shown in Figure 3, which shows hazard curves for both primary displacement and for secondary faulting. For primary faulting, the probabilistic displacement hazard is zero for return periods less than about 200,000 years, and then increases with increasing return period; it is about 7 metres for a return period of one million years in this example. For secondary faulting, also shown in Figure 3, the rate of occurrence of surface faulting is two orders of magnitude lower than in the primary fault hazard. As noted above, the recurrence interval of surface faulting earthquakes in Australia typically lie in the range of 10,000 to 100,000 years, although it may be somewhat shorter. Consequently, the fault displacement hazard may be zero or negligible for return periods shorter than 10,000 or 100,000 years. In contrast, a deterministic fault displacement hazard analysis based on maximum earthquake magnitude may yield large fault displacements having extremely long return periods (millions of years).

Secondary Faulting associated with Thrust and Reverse Faults

For thrust faults, secondary faulting producing flexural grabens associated with the crests of hanging-wall and fault propagation anticlines can in some instances be better represented in the landscape than primary rupture (Berberian 2014). Slip on the primary displacement surface may be largely taken up as folding within the significant thickness of footwall colluvial fan sediments, causing grabens in the hanging wall crest that are more prominent than the primary fault. This might also be the case where steep secondary (synthetic and antithetic) structures splay from shallowly dipping primary faults, which are prone to folding deformation, while the secondary structures are more likely to have surface rupture. The Kurrajong Fault system, which is a steep antithetic fault related to the shallowly dipping master fault underlying the Lapstone Monocline, might be an example of this (e.g. Clark and Rawson 2009, McPherson et al. 2014).

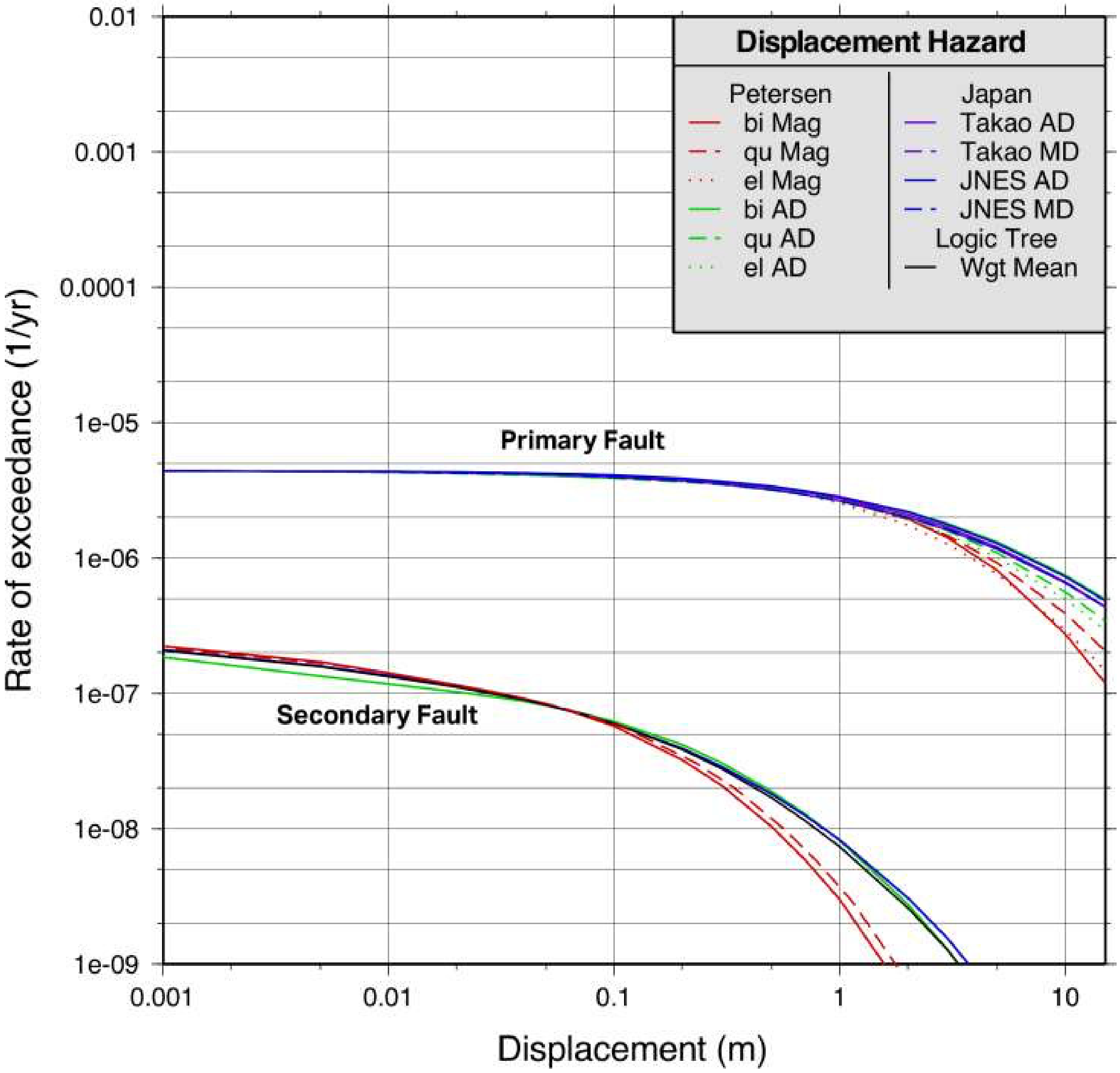

Figure 3. Examples of Probabilistic Fault Displacement Hazard Curves for Primary and Secondary Strike-Slip Faulting

Design Displacement Values in ANCOLD (2019) for Extreme Consequence Dams

For extreme consequence dams, ANCOLD (2019) prefers a risk-based approach, which is fully probabilistic and considers all return periods. However, it also permits a scenario-based approach, using a combination of probabilistic and scenario based (deterministic) estimates, with hazard values for specified return periods or scenarios. The Guidelines for ground motions require that the Safety Evaluation Earthquake (SEE, the design ground motion) be the larger of two values: the probabilistic estimates for a return period of 10,000 years, and the scenario-based deterministic Maximum Credible Earthquake (MCE). The Guidelines do not state whether this also applies to fault displacement hazard. If it were to apply, then the risk-based approach would be preferable if it is deemed necessary to consider fault displacements having return periods longer than 10,000, because the deterministic approach to fault displacement hazard analysis may yield very large displacements having very low probabilities of exceedance.

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