# MATAHINA DAM-FAULT SURFACE DISPLACEMENT DESIGN CRITERIA

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## SUMMARY

Recent studies were completed to assess the seismic hazards at Matahina Dam, an earth and rock fill structure located on the Rangitaiki River in the North Island of New Zealand. Strands of the active Waiohau Fault pass beneath the dam. Rigorous regional and local paleoseismic and seismological investigations of the fault were completed to estimate its seismic characteristics. Using these data, empirical relationships for fault surface displacement based on worldwide data were adjusted to reflect the site-specific conditions. The resulting relationships are considered appropriate for use in estimating the amount of surface displacement on the Waiohau Fault including standard error terms.

These relationships were used to evaluate the surface displacement potential of the fault beneath the dam using both deterministic and probabilistic methods. The deterministic method was used to obtain 84$^{th}$ percentile estimates of fault surface displacement. The probabilistic method resulted in probabilistic estimates of fault surface displacement consistent with the estimates of the ground motions at the site. The estimates of fault surface displacement potential and ground motions at the dam site using relationships that reflect the site-specific conditions constitute a rational and consistent assessment of seismic hazards of the dam. The fault surface displacement and ground motion estimates were used to select seismic criteria for a safety evaluation of the dam and its appurtenant structures and for the design of mitigation measures.

## INTRODUCTION

Recent studies to identify the seismic hazards at the Matahina Power Station (Figure 1), the 72 Megawatts, run-of-the-river hydroelectric plant led to modifications of the 400 meters long and 82 meters high dam to minimise the risk associated with potential surface fault displacements on the underlying strands of the active Waiohau fault zone during future earthquakes. Mejia, et al., 1999, provided a discussion of these modifications to the dam, which were completed in March 1999. The overall design criteria used in the safety evaluations studies and design of the dam modifications were described by Gillon et al. (1997). In this paper, we provide an overview of the approach used to estimate, both deterministically and probabilistically, the surface fault displacement criteria that were used in the design of these modifications.

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**Figure 1: View of Matahina Dam and Reservoir, looking south.**

The Matahina Power Station is located in a seismically active and tectonically complex region within the deformation zone between the Australian and Pacific plates (Figure 2). The site lies within a wide zone of active right-lateral strike-slip faulting that is known as the North Island Shear Belt (NISB), which was induced by oblique deformation across this plate boundary (Figure 2). Approximately 10 km to the northwest of the site is a well defined zone of active crustal extension and volcanism known as the Taupo Volcanic Zone (TVZ). Historically the TVZ has had numerous small to large earthquakes on a series of normal faults within an area referred to as the Whakatane Graben, with the most recent damaging event being the 1987 Mw6.6 Edgecumbe earthquake (Beanland et al. 1989). Faults within the NISB have had significantly less recorded seismicity than those in the TVZ. However, paleoseosmic data suggest that this apparent paucity of recorded seismicity may be filled by larger, less frequent earthquakes on the faults within the NISB. As shown on Figure 1, the western-most active fault in the NISB is the Waiohau fault zone, which extends from the TVZ on the northwest, through the site, and then southeastward past the Waiohau and Galatea basins.

The Waiohau fault zone was characterised as two seismogenic segments: Matahina and Galatea. The Matahina segment is about 22 km long and extends southeastward from the TVZ to a saddle that exists between the Waiohau and Galatea basins, where the fault appears to undergo a change in the sense of vertical offset from one of its main traces to another. The Galatea segment extends further south for about 58 km into the Urewera Ranges, where the strike changes by approximately 30°. A change in strike of 10-30° can be used as a criterion to establish rupture segment boundaries on strike-slip faults (Aki, 1989; Kadinsky-Cade and Barka 1989; Knuepfer, 1989). Therefore, this point was selected as the southern point of the Galatea segment. It is judged that the maximum rupture length on the fault is the combined 80-km length of the Matahina and Galatea segments.

The maximum magnitude for the Waiohau fault was estimated based on the median regression between rupture area and moment magnitude (Mw) developed by Wells and Coppersmith (1994) from worldwide data. Although the historical and paleoseismic data for large earthquakes in New Zealand are limited, they appear to fall slightly above the median of this regression. Accordingly, the maximum magnitude estimate reflected these differences. On this basis, and considering the reliability of the available data and the level of conservatism involved in the various assumptions made, the maximum earthquake on the Waiohau fault zone was judged to be a magnitude Mw 7.2 event.

The paleoseismic data collected from trenches dug from near the southern end of Matahina Lake and elsewhere along the fault indicate that 4 major earthquakes appear to have occurred in the past 11,800 years. The size of these events is not known. However, the data suggest that they must have been large earthquakes, possible on the order of magnitude Mw 7 events, with a few meters of surface fault displacement near the site. Based on these data, the estimated average slip rate of the fault, and on commonly used analytical recurrence models, it is estimated that the average return period of a Mw 7.2 earthquake on the Waiohau fault is about 5,000 years.

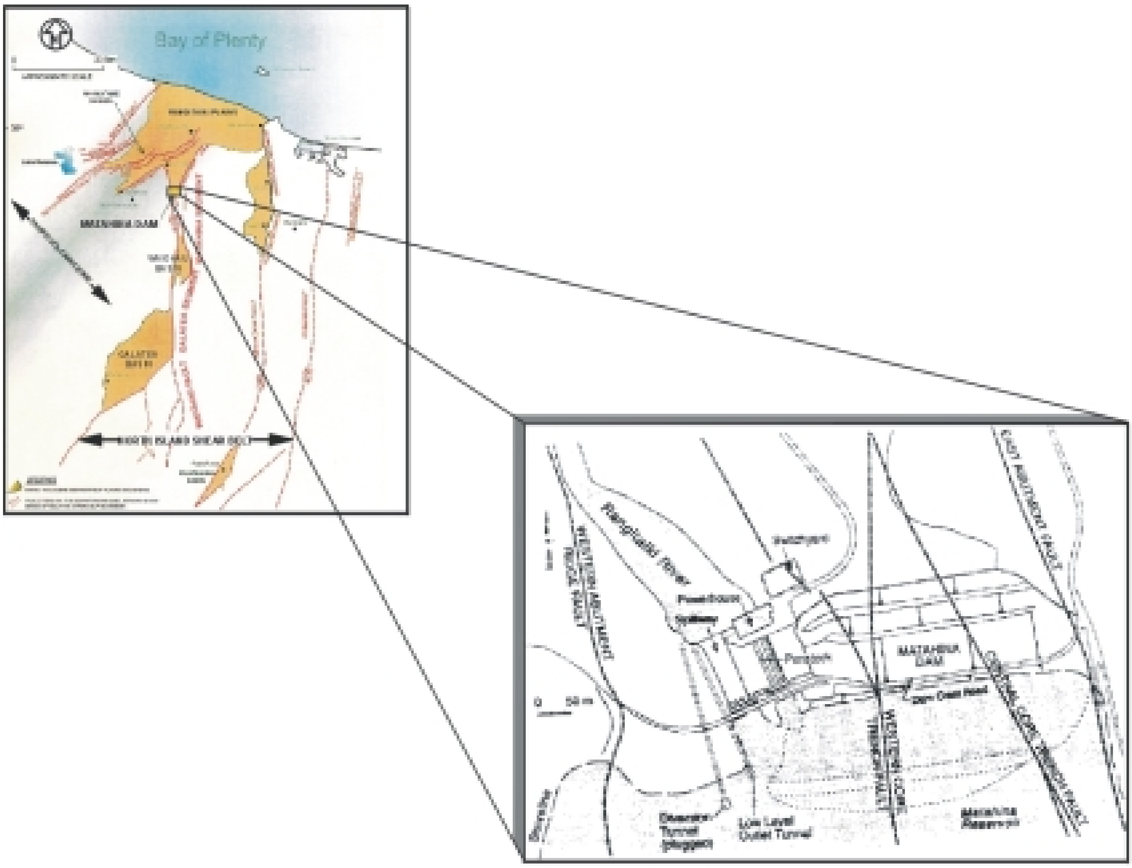


**Figure 2: site location and regional and local faults**

The dam itself is located in a steep-sided gorge eroded along the Waiohau fault zone by the Rangitaiki River. The gorge has been cut through an extensive sheet of ignimbrite into underlying sedimentary and pyroclastic deposits of mid-Quaternary to Tertiary age, known as the Luke's Farm Beds. The bottom of the river valley is blanketed by recent alluvium. Based on drillhole, other field investigation data, and on the geologic mapping of excavations during construction of the dam, the Waiohau fault zone at the dam site was found to be a broad zone consisting of several strands. Several of these strands identified in the vicinity of the dam are shown on Figure 1 (Healy, J., 1964; Beethham & Dellow 1989). The fault strands beneath the dam are referred to as the Eastern Abutment Fault (EAF), which was detected during construction of the tongue wall into the dam's right abutment, and the Central Core Trench (CCTF) and the Western Core Trench (WCTF) faults, both of which were mapped during excavation of the dam's core trench. The available geologic data suggest that the main strands of the Waiohau fault zone are the WARF and the WCTF.

The amount of surface fault displacement that can be anticipated on the active strands of the Waiohau Fault Zone beneath the Matahina Dam during future seismic events will depend on the size of the seismic events, the amount of subsurface rupture occurring on the Matahina segment, and whether the Matahina segment would rupture together with the Galatea segment in a larger event. However, the pattern of future fault surface displacements at the dam is difficult to estimate because, as discussed above and shown on Figure 1, the Waiohau Fault Zone at the dam is complex with several fault traces. Furthermore, there is uncertainty in the data used to characterise these faults in estimating their surface displacement potential. Surface fault displacement estimates are further complicated because the dam is located near the northern end of the fault zone where the influences of both dextral and extensional tectonic environments may influence the amount, style, and distribution of fault surface displacements at the dam site. Given these conditions and their associated uncertainties, we developed conservative deterministic estimates of potential fault surface displacements beneath the dam and we looked at the surface displacement hazards probabilistically in order to place the deterministic estimates into perspective. The probabilistic fault displacement assessment (PFDA) was completed in concurrence with and consistent with a probabilistic estimate of the seismic ground motion hazards at the site.

## DETERMINISTIC SURFACE FAULT DISPLACEMENT ESTIMATES

Deterministic estimates of the surface fault displacements, which might be associated with a single Matahina segment rupture scenario, or a multiple, Matahina + Galatea segment rupture scenario, were developed from the world-wide empirical database correlating the average and maximum surface fault displacements to earthquake moment magnitude, as published by Wells and Coppersmith (1994). These results were then compared with the data from the paleoseismic investigations completed along the Waiohau Fault Zone and with surface displacement data from New Zealand's historical record of surface rupturing seismic events.

Table l summarises the deterministic estimates of fault surface displacement and the key parameters and calculated results used in developing them based on the worldwide empirical data. The calculated average surface displacements in Table 1 correspond to the average of the amount of surface displacement that occurred along a fault during a recorded surface rupturing earthquake while the calculated maximum surface displacement corresponds to the maximum that occurred at some point along the fault. It should be noted that the calculated average and maximum surface displacements listed in Table 1 correspond to the 84th percentile values of the average and maximum displacements. As discussed below, this choice reflects the uncertainties and possible local tectonic environments of the site.

**Table 1**

| Rupture Scenario Segments | Estimated Rupture Segment Length (km) | Calculated1 Magnitude (Mw) | Calculated2 Average Surface Displacement +1 $\sigma$ (m) | Calculated3 Maximum Surface Displacement +1 $\sigma$ (m) | Best Deterministic Estimate Surface Displacement (m) at the Dam |
|---|---|---|---|---|---|
| Matahina | 22 | 6.4 | 1.0 | 1.8 | 1 |
| Matahina+Galatea | 80 | 7.1 | 2.9 | 6.0 | 3 |

**Notes**: 1) Calculated from mean regression line of moment magnitude versus rupture area relationship from world-wide database in Wells and Coppersmith (1994); 2) Calculated from mean plus one standard deviation of moment magnitude versus average surface fault displacement relationship from world-wide database in Wells and Coppersmith (1994); 3) Calculated from mean plus one standard deviation of moment magnitude versus maximum surface fault displacement relationship from world-wide database in Wells and Coppersmith (1994).

As evidenced from the pattern of well-documented fault surface displacements that occurred along the series of fault segments during California's June 1992 Mw 7.3 Landers Earthquake (Sieh, et al., 1993), fault surface displacements tend to die out towards the ends of the fault segments and the maximum displacement tends to occur at a limited interval along the fault and primarily towards the middle portions of the fault segments. Even though the Waiohau Fault is believed to be a right-lateral, strike-slip fault with a significant component of normal slip and the Landers event was primarily right-lateral strike-slip, the Landers pattern of fault displacements along its various segments appears to be a reasonably close model for the pattern of surface displacements one might expect along the Waiohau Fault segments. The calculated maximum surface displacement values in Table 1 are considered high for likely displacements beneath the dam because they are 84th percentile values and the Matahina Dam is located toward the northern end of a Matahina segment rupture or a combined Matahina+Galatea segment rupture. With these considerations, a reasonably conservative best deterministic estimate of 3 m was made for a single event oblique surface displacement on the Waiohau Fault Zone associated with the Mw 7.2 deterministic estimate for the maximum earthquake. The 3-meter value is consistent with the corresponding calculated average surface displacement shown on Table 1. The best deterministic estimated displacements shown in Table 1 are consistent with the geological paleoseismic evidence from the Waiohau Fault's history of large surface displacements and thus is considered a reasonable model of large surface displacements in the future.

The 3m of estimated fault surface displacement assumes that all the associated surface displacement would occur on a single main trace of the fault. However, as discussed above, the Waiohau Fault at the dam site is a broad zone consisting of several fault strands, several of which pass beneath the dam. Thus, it is likely that the 3-meter of surface displacement would be distributed among the various fault strands, each with some smaller than 3-meter of displacement. However, based on the available data, one can not rule out the possibility that during any given maximum magnitude earthquake, the full displacement could occur on any one of the fault strands beneath the dam.

## PROBABILISTIC SURFACE FAULT DISPLACEMENT ESTIMATES

A probabilistic fault displacement analysis (PFDA) was performed in order to place the best deterministic estimate of surface fault displacement on the Waiohau Fault Zone at the Matahina dam into perspective. The basic goal of a PFDA is to develop a relationship between the "*fault rupture displacement*," *D*, at the site and the mean number of events per year in which *D* at the site exceeds a specified value "*d*."

The PFDA consists of the five major components or steps (Tan and Moriwaki, 1996), which generally are based on Cornell (1968) and Kulkarni et al. (1979). The first step in a PFDA is to characterise the seismogenic source; that is to delineate the location, geometry, and characteristics of the seismic source or the earthquake fault relative to the site. The main characteristics of an earthquake fault consist of segmentation model and segments, style of faulting, slip rate, dip, seismogenic depth, maximum or characteristic earthquake magnitude, and recurrence model. The fault is usually modelled as a three-dimensional planar source to reflect the details of its geometry with respect to the site. The next step is to characterise the fault's recurrence relationship showing the annual recurrence of earthquakes of various magnitudes, up to the maximum magnitude, on the fault. It is usually presented in its cumulative form: earthquake magnitude *m* versus mean number of earthquakes per year having magnitude greater than *m* on a fault. This relationship is used to provide the mean number of earthquake *Ns*(*mj*) having a particular magnitude *mj* occurring on the fault segment located beneath the dam during a 1-year period. Given that an earthquake of magnitude *mj* occurs on the fault segment, the third step is to assess the probability that the earthquake will rupture the ground surface beneath the dam site. This probability, corresponding to step 3, is referred to as the "*crossing probability*." For the Matahina PFDA, two potential earthquakes producing rupture scenarios through the dam site on the Waiohau fault zone were considered: (1) rupture of the Matahina segment and (2) a multiple segment rupture of the Matahina and Galatea segments. The fault characteristics used in the probabilistic analyses were consistent with those provided in Table 1. Given an earthquake of magnitude *mj* that ruptures to the surface at the site, step 4 is to assess the probability that it will result in fault surface displacement *D* being greater than a specified amount *d* at the dam site. By combining the three probability functions associated with steps 2 through 4 for the seismic source or fault that is located beneath the dam, the mean number of events per year resulting in *D* being greater than *d* at the site is computed. The complete relationship between the fault displacement level and the mean number of events is obtained by repeating the computations for several levels of fault displacement *D*. For the PFDA, this mean number of events per year is termed "*annual frequency of exceedance*" and designated as " ($D \geq d$)". Once the complete ($D \geq d$) relationship is obtained for the site, the probability of the fault surface displacement at the site being exceeded over a specified time period, *t*, can be calculated by assuming a Poisson model using the following equation:

$$\Pr(D \geq d) = 1 - \exp[-\ (D \geq d) \bullet t] \tag{1}$$

Among many, two major types of uncertainties are addressed in the PFDA. *Inherent* (stochastic or aleatory) uncertainty is a reflection of the limited scientific understanding of the nature of earthquake generation and rupture propagation. Even if we had a large amount of geologic and seismicity data on past seismic activity, the exact prediction of the time, location, and characteristics of future earthquakes is still not possible. Uncertainties in the earthquake recurrence process and in the amount and distribution of surface fault displacements are the major sources of the inherent uncertainty. *Statistical* (parametric or epistemic) uncertainty is a reflection of the limited data available to estimate the parameters contributing to the seismic hazard at a site. This type of uncertainty, in theory, can be reduced when additional data on earthquakes and their effects become available.

The PFDA methodology includes probability models to address these two major types of uncertainty. Inherent uncertainties were included in the PFDA model through probability distributions. The statistical uncertainties in the various input parameters for the seismic source were reflected in the PFDA by using a logic tree approach (Kulkarni et al., 1984; Coppersmith and Youngs, 1986; Reiter, 1990). Figure 3 shows a portion of a typical logic tree used in this study.

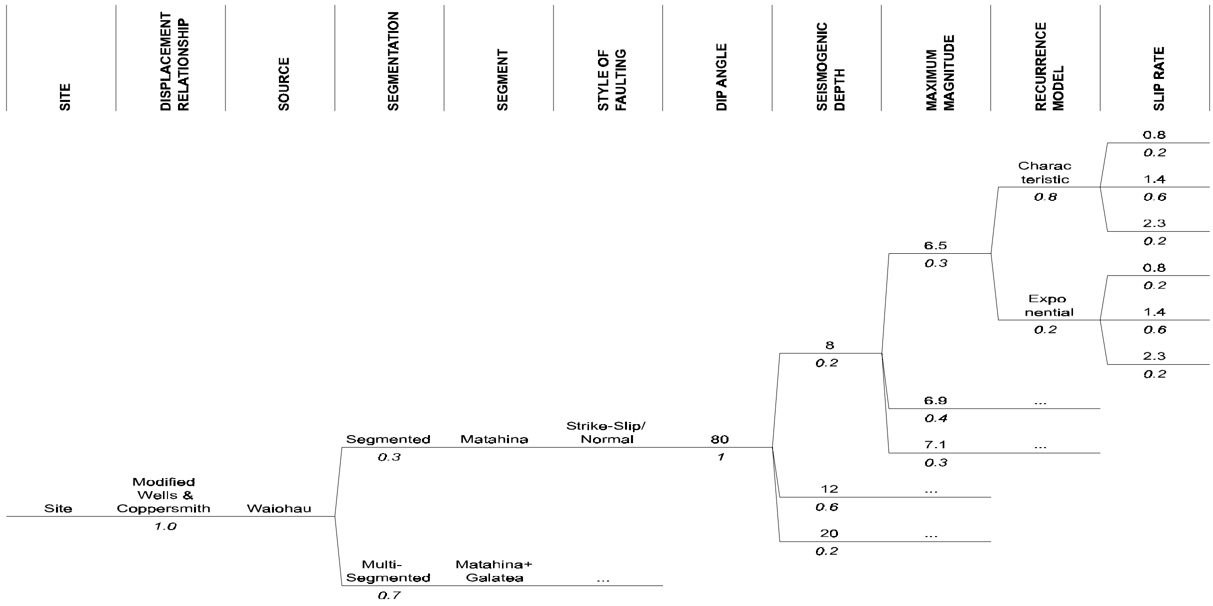


**Figure 3: Partial PFDA Logic Tree Structure. Numbers shown below the logic tree branch are weight associated with that particular branch.**

As can be seen on Figure 3, uncertainties in the segmentation model, the segment and its length, the style of faulting, slip rate, dip angle, seismogenic depth, maximum magnitude, and the recurrence model are addressed with the logic tree. The probability model described above assumes that these parameters are known, or can be estimated precisely. In practice, only limited data are available to estimate these parameters. Consequently, the estimates of the parameters are subject to statistical uncertainty. In the PFDA, the statistical uncertainties in the input parameters are propagated to obtain not only the best estimate of the annual frequency of exceeding a given amount of fault surface displacement, but also the confidence limits on this best estimate. Because of the statistical uncertainty, several alternative values of each parameter may be postulated. Each value may not have the same degree of credibility in the light of the current scientific knowledge and available data. One can assess the probability that each postulated value is in fact the true (but unknown) value of the parameter by taking into account the consistency of the postulated value with scientific understanding and evidence.

The output of the logic tree analysis is the best estimate of the mean annual number of events exceeding a specified amount of fault surface displacement, and the standard deviation of the best estimate. These two parts of the output can be used to calculate confidence limits on the estimated seismic hazard.

A relationship for the average displacement as adopted by Wells and Coppersmith (1994) can be used as the basis to evaluate the median displacements. However, because of uncertainties in the magnitude-surface displacement relationship by Wells and Coppersmith (1994) as applied to the study area and to account for local tectonic environment at the site (site-specific rupture mechanism and possibly larger displacements), approximately 84th percentile estimates of the average values (based on a worldwide database) are used to represent the median values in the PFDA.

A standard error larger than that presented by Wells and Coppersmith (1994) for their relationships is needed in the PFDA to account for the intra-event variation along the surface fault rupture. It is noted that the standard errors provided for the relationships by Wells and Coppersmith (1994) reflect inter-event variation because they used data from various different events. Since sufficient statistical information on the intra-event variation is not available, we have compared the maximum displacements with the average displacements along fault ruptures based on worldwide data (Wells and Coppersmith, 1994) to provide an estimate of the intra-event variation. In general, the maximum displacement, which is about double the average, is equal to the median plus one standard deviation. Therefore, we have used double the standard deviation of the average displacement, but have truncated the displacement distribution at 1.5 standard deviation in the analyses. These choices are somewhat arbitrary, but considered to be reasonable given the limited available data at this time.

The resulting relationships used in the analyses are as follows:

$$\log10\ AD = 0.9M - 6.1 \qquad \sigma = 0.56 \tag{2}$$

where: *AD* = Average surface displacement (in metres); *M* = Earthquake moment magnitude (Mw); and = Standard error of *AD* (i.e., standard deviation of log10 *AD*)

## CONCLUSION

Figure 4 shows the relationship between fault displacement and annual frequency of exceedance computed using PFDA. Field estimates of fault displacement indicate a range of 1 to 4 m displacements every 2.000 to 5.000 years with the field best estimate of 3 m in 3,000 years. These values are also shown on Figure 4. On Figure 4, estimated average return period values are doubled based on the assumption of a given value has a 50 percent likelihood of being exceeded. The values shown on Figure 4 appear to be generally consistent with the deterministic estimate of fault displacement (a best estimate value of 3-meter with an average return period of 5000 years).

Site specific deterministic and probabilistic assessment of fault displacement at the site of Matahina Dam indicate the results are reasonably consistent with each other. The results of probabilistic fault displacement assessment provide a basis for putting the deterministic calculated or field estimates of fault displacement in perspective. For example, this probabilistic evaluation shows that the return periods for exceeding the field estimates of 1 to 4 m of displacement for the maximum earthquake are about 5,000 to 14,000 years, and about 6,000 to 11,000 years for a 3 m displacement. These results can be used to develop consistent seismic hazard criteria covering both fault rupture hazard and earthquake ground motion hazard.

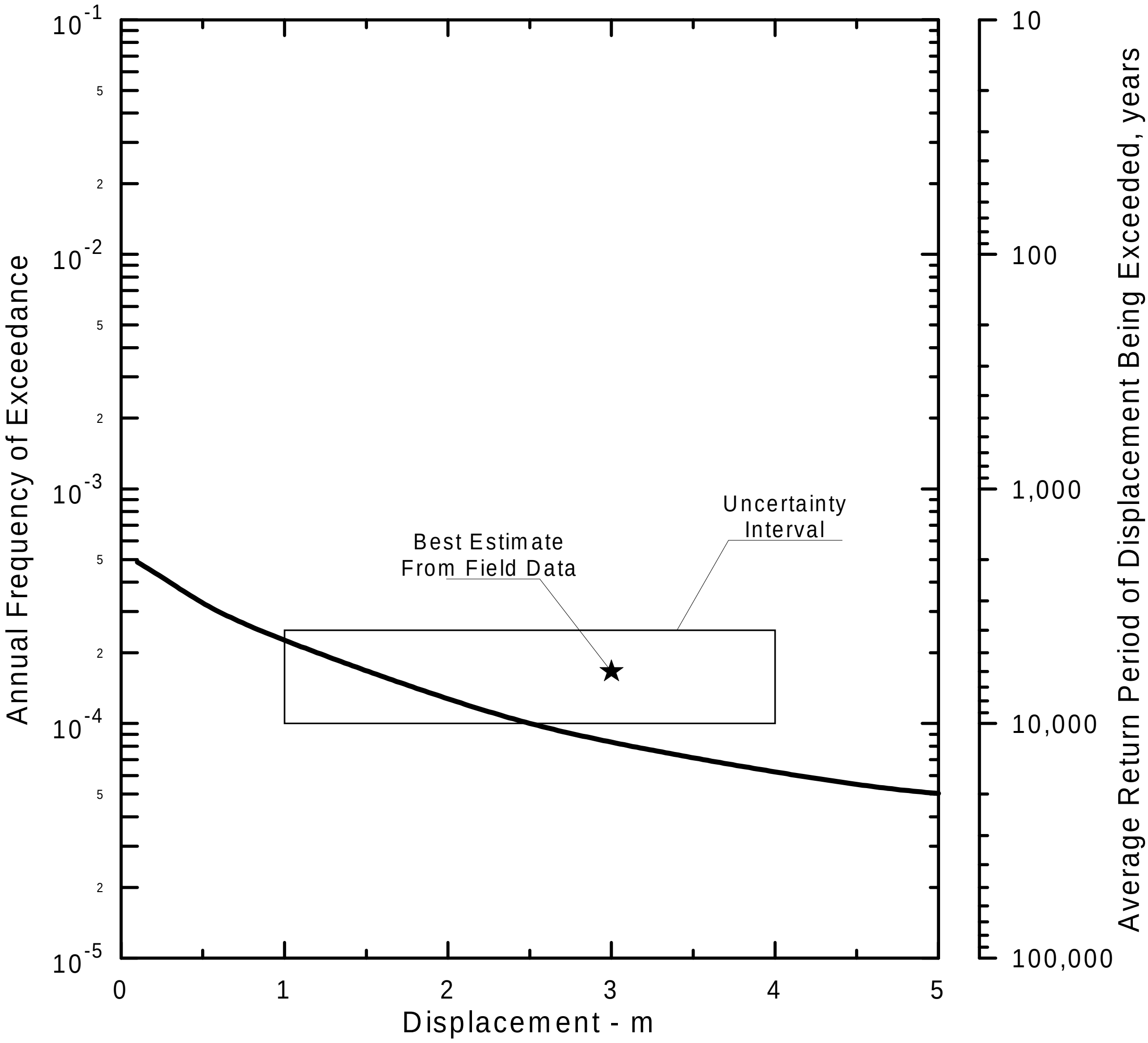


**Figure 4: Probabilistic Fault Displacement Hazard Curve**

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