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Abstract

This paper provides an overview of the Fault Displacement Hazard Initiative (FDHI). The FDHI is a community-based and multi-year research initiative with the goals of developing: (a) a comprehensive empirical database of surface fault displacement measurements and mapped ruptures, and (b) a suite of next-generation fault displacement predictive models. The database was developed by systematically collecting worldwide data from professional literature, followed by an extensive review and quality assurance process. The FDHI database contains 75 surface-rupturing earthquakes ranging from moment magnitude **M** 4.9 to 8.0 including data from strike-slip, reverse/reverse-oblique, and normal/normal-oblique faulting events.

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As part of the FDHI Program, employing the database, four new fault displacement models (FDMs) were developed. The FDMs predict principal or aggregate surface displacement, where aggregate is the combined displacement across principal and distributed ruptures. Two models were developed for all styles of faulting, while the other two are for reverse or strike-slip faulting. The new models include improved magnitude scaling and aleatory variability modeling. Compared with pre-existing models, average displacements in the new models are about 40% larger for $M \sim 7$, but smaller for lower and higher magnitudes. In addition, the new models predict significantly smaller displacement at low probability of exceedance. Besides the core FDHI tasks, in this article we also provide an overview of other parallel projects completed in coordination with the FDHI Program.

Keywords

Fault Displacement Hazard Initiative, FDHI, fault displacement model, principal displacement, aggregate displacement, fault displacement hazard analysis

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Introduction

The Fault Displacement Hazard Initiative (FDHI) Program is a community-based research program with the goals of developing a comprehensive empirical database of the measured fault displacement and developing a suite of new predictive models for use in both deterministic and probabilistic fault displacement hazard analyses. Similar to various phases of the Next Generation Attenuation (NGA) research programs for ground motion modeling (Bozorgnia et al., 2021, 2014; Goulet et al., 2021; Power et al., 2008), through coordinated and interactive efforts, a comprehensive database was initially developed, followed by multiple quality assurance (QA) iterations. Interactions among the model and database developers were continuous, which resulted in more robust database and models.

The outcome of the FDHI Program, including a database and multiple models, has been documented in a comprehensive set of journal articles published in this *Volume*. This paper provides an overview of the FDHI research program and links such articles together. In addition to the core FDHI topics, we provide an overview of other focused research tasks also published in this *Volume*.

FDHI database

As indicated by Sarmiento et al. (2024b), several previous studies have compiled surface rupture and/or fault displacement data (e.g. Baize et al., 2020; Bonilla et al., 1984; Nurminen et al., 2022; Petersen et al., 2011; Pezzopane and Dawson, 1996; Wells and Coppersmith, 1994; Wesnousky, 2008). The completeness of the existing databases varies significantly. In addition, some databases are limited to a specific style of faulting (e.g. Petersen et al., 2011; Youngs et al., 2003). The initial phase of FDHI was to collect and develop a comprehensive empirical database of measured fault displacements and mapped surface ruptures. The new FDHI database provides the largest collection (to our knowledge) of geospatially-controlled surface fault rupture, displacement data, and metadata and is unique in that it includes an extensive set of supplementary metadata developed collaboratively with model developers (Sarmiento et al., 2024b). In addition, FDHI implemented a framework to classify principal and distributed faulting for all events in the

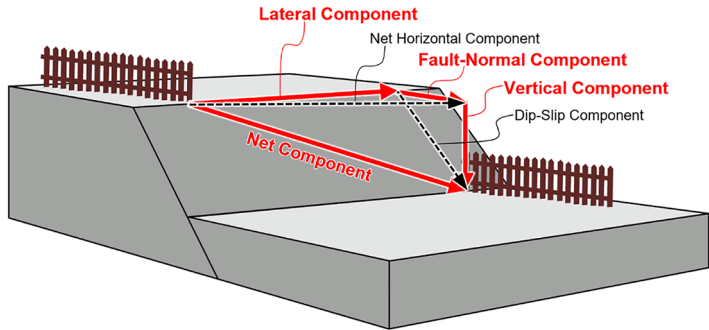


Figure 1. Schematic perspective view of oblique (extensional left-lateral) fence offset showing displacement component vectors.
Source: Sarmiento et al. (2024b), adapted from Ponti et al. (2020).

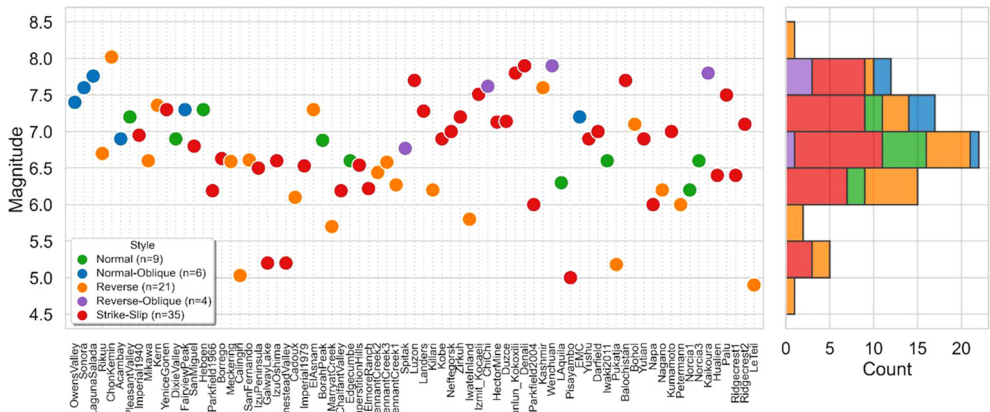


Figure 2. Magnitude and style of faulting distribution of the 75 events in the FDHI database.
Source: Adapted from Sarmiento et al. (2021).

FDHI database, as the model developers treated the principal and distributed faulting separately. In terms of displacement metrics, best-estimate net displacement amplitudes were developed for each measurement location in the FDHI database, as shown in Figure 1 (Sarmiento et al., 2024b).

The FDHI Database contains 75 historical, surface-rupturing earthquakes of all styles of faulting. The events occurred between 1872 and 2019 and range from moment magnitude M 4.9 to 8.0. Figure 2 presents the magnitude and style of faulting distributions of the database. The database contains about 40,500 individual fault displacement measurements from about 28,000 observation sites.

To simplify the database for end-users, the database contents have been aggregated into “flatfiles.” The flatfiles and related digital products are publicly available for download from the Dataverse platform at the University of California, Los Angeles (UCLA) through

the following URL: <https://doi.org/10.25346/S6/Y4F9LJ>. More details on the database can be found in Sarmiento et al. (2024b).

The FDHI modeling teams used subsets of the FDHI database based on their data selection criteria for their models, as documented in their respective model development articles in this *Volume*.

FDHI predictive models

In the tradition of NGA programs, the modeling teams were intimately engaged in the QA process of database development. Thus, the transition from database development to model building was a smooth process. The modeling teams consisted of the following (in alphabetical order):

1. Chiou, Chen, Thomas, Milliner, Dawson, and Petersen (Chiou et al., 2025; CEA25).
2. Kuehn, Kottke, Sarmiento, Madugo, and Bozorgnia (Kuehn et al., 2024; KEA24)
3. Lavrentiadis and Abrahamson (2023; LA23)
4. Moss, Thompson, Kuo, Younesi, and Baumont (Moss et al., 2024; MEA24)

The models predict different displacement metrics and use different definitions of displacement as elaborated by Sarmiento et al. (2025). Displacement metrics include average displacement (AD), maximum displacement (MD), displacement normalized by the average or maximum (D/AD and D/MD , respectively), or simply the displacement amplitude (D). As elaborated by Sarmiento et al. (2025), surface ruptures are usually classified as principal or distributed. Principal ruptures are produced by the fault that generated the earthquake. The surface ruptures not directly associated with the fault plane that produced the earthquake (i.e. secondary ruptures, splays, and shears) are referred to as distributed ruptures. Two FDHI models used the sum of displacements across multi-stranded principal ruptures (LA23 and CEA25). Two models used a new definition called *aggregate displacement*, which is the sum of displacements across principal and distributed ruptures (LA23 and KEA24). The MEA24 model does not sum displacements and applies to individual principal ruptures.

The statistical formulations and parameters for predictive models are different. Fault displacement models (FDMs) use magnitude (M), and/or normalized along-strike location (x/L) as predictor variables, where x is the length along the surface rupture from either endpoint, and L is the total surface rupture length. The models computed between- and within-event aleatory components. In most models, the between-event variability is magnitude-dependent, and the within-event variability is location-dependent. The predictions in most models are constrained to be symmetrical about the rupture midpoint; however, the KEA24 model predicts a skewed profile (i.e. with a profile peak at $x/L \leq 0.5$).

A summary of the model formulations and aleatory variability components is provided in Table 1, and the applicability of the models is provided in Table 2 (Sarmiento et al., 2025). It is noted that the models should not be used outside their applicability ranges. For example, models that are only applicable to one style of faulting should not be used for other styles.

Figure 3 presents the mean predicted displacement profiles for the models for M 6. The KEA24 results are based on equally weighted right- and left-skew profiles and, therefore,

Table 1. Summary of model formulations and aleatory variability components (adapted from Sarmiento et al., 2025)

Model	Formulation ^a	Predictor variables	Between-event	Within-event ^b
LA23 ^c	$D^{0.3} \sim \text{Normal}$	M , x/L	Magnitude-dependent	Magnitude-dependent
MEA24	$\log_{10}(AD) \sim \text{Normal}$	M	Constant	—
	$\log_{10}(MD) \sim \text{Normal}$	M	Constant	—
	$D/AD \sim \text{Gamma}$	x/L	N/A^d	x/L -dependent
	$D/MD \sim \text{Gamma}$	x/L	N/A^d	x/L -dependent
KEA24	$(D^\lambda - 1)/\lambda \sim \text{Normal}$	M , x/L	Magnitude-dependent	x/L -dependent
CEA25	$\ln(D) \sim nEMG$	M , x/L	Magnitude-dependent	x/L -dependent

^aDescribes predicted variable and statistical distribution; $nEMG$ is negative exponentially modified Gaussian distribution (CEA25), and λ is Box-Cox transformation parameter (KEA24).

^bWithin-event variability is not applicable for models that predict AD or MD .

^cThe LA23 base FDM applies to individual segments (X_{seg}/L_{seg}); the simplified FDM to the total rupture (x/L) and uses an additional (magnitude-dependent) within-event term to capture variability on fault segmentation.

^dProvided by MD or AD scaling relation; typically constant.

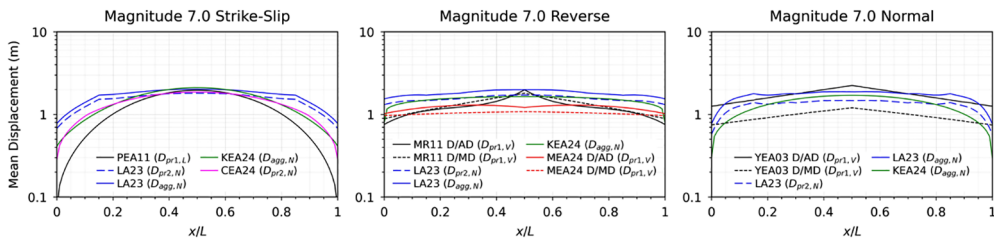
Table 2. Recommended model applicability ranges for style of faulting, magnitude, and normalized location (Sarmiento et al., 2025)

Model	Style of faulting ^a	Magnitude (M)	Normalized location (x/L)
LA23	SS RV/RVO NM/NMO	5.0 – 8.5	[0, 0.5]
MEA24	RV/RVO	4.7 – 8.0	[0, 0.5]
KEA24	SS	6.0 – 8.0	[0, 1.0] ^b
	RV/RVO	5.0 – 8.0	
	NM/NMO	6.0 – 8.0	
CEA25	SS	6.0 – 8.3	[0, 0.5] ^c

^aSS = Strike-Slip; RV = Reverse; RVO = Reverse-Oblique; NM = Normal; NMO = Normal-Oblique.

^bPredicted profile is right-skewed; calculation for complementary position $1 - x/L$ should be equally weighted in most applications.

^cCEA25 also provides an unfolded right-skewed formulation for the range [0, 1].

**Figure 3.** Comparison of x/L scaling for **M** 7 for predicted mean displacement. The KEA24 results are equally weighted with right- and left-skew profiles.

Source: Adapted from Sarmiento et al. (2025). In this figure, CEA24 is Chiou et al. (2025), KEA24 is Kuehn et al. (2024), LA23 is Lavrentiadis and Abrahamson (2023), MR11 is Moss and Ross (2011), MEA24 is Moss et al. (2024), PEA11 is Petersen et al. (2011), YEA03 is Youngs et al. (2003). Model displacement metrics are identified in parentheses using the definitions in the models.

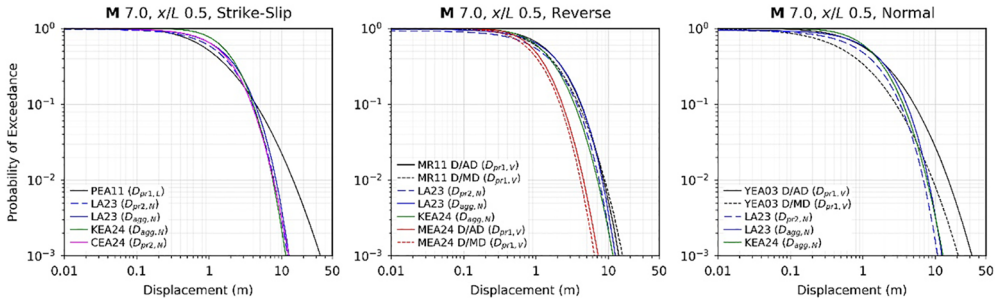


Figure 4. Comparison of probability of exceedance curves for **M** 7 at rupture midpoint ($x/L = 0.5$). Model displacement definitions are identified in parentheses.

Source: Adapted from Sarmiento et al. (2025). The model abbreviations are listed in the caption of Figure 3.

are symmetrical about the rupture midpoint. In this figure, legacy models by Youngs et al. (2003; YEA03); Petersen et al. (2011; PEA11), and Moss and Ross (2011; MR11) are also shown for comparisons. For this specific example, at the middle of an **M** 6 rupture ($x/L = 0.5$), the new models predict smaller fault displacements than the legacy models.

Figure 4 shows an example of probability of exceedance curves for **M** 7 for the rupture midpoint ($x/L = 0.5$). For the models that use normalized displacement metrics (D/AD or D/MD), the between-event aleatory variability is included using the computational methods described in Electronic Supplement B in Sarmiento et al. (2025). The rupture midpoint ($x/L = 0.5$) predictions for the 99th percentile (10^{-2}) among the FDHI models are generally within a factor of about 1.5, with the exception of the MEA24 results that are roughly half of the predictions in the other FDHI models. Compared to legacy models, the FDHI models lead to 99th percentile midpoint displacements that range from within about 5% to as much as six times less, depending on the magnitude and style of faulting. These decreases are driven by improved magnitude scaling and aleatory variability modeling in the FDHI models. Additional comparisons and more detailed discussions can be found in Sarmiento et al. (2025).

The FDHI models are implemented in a Python package and an Excel workbook. The calculations have been verified against independently computed results. To access the Python and Excel workbook, refer to the “Data and resources” section of this paper.

Other focused studies

Besides the core FDHI database and predictive models, the Program included a set of focused research projects. Each study is documented as an article in this *Volume*. In this section, we provide, in alphabetical order, a short summary of such studies.

Lavrentiadis et al. (2023)

Lavrentiadis et al. (2023) provide new magnitude scaling relations for surface rupture length, using empirical and simulated data sets, that account for unbounded and width-limited ruptures. The functional form of the scaling relation is derived by combining semi-empirical seismological source scaling laws with the definitions of seismic moment and moment magnitude. Thinner seismogenic zones limit the width of ruptures, leading to

steeper length scaling for larger magnitudes. Simulated data sets are used to estimate the magnitude where a rupture transitions from unbounded to width-limited. The authors show that the aleatory variability for width-limited ruptures is roughly half that of unbounded ruptures.

Mammarella et al. (2024)

Mammarella et al. (2024) provide a numerical approach and programmed implementation for computing the probability of surface rupture in an earthquake considering fault-specific geometry and rupture geometry. Their approach floats ruptures down-dip, and the probability of surface rupture is computed by counting the fraction of earthquakes where the top of the rupture breaches the ground surface, considering aleatory variability in the rupture width, hypocentral depth, and normalized position of the hypocenter along the rupture width. Their numerical approach differs from previously published global empirical models for the probability of surface rupture (e.g. Pizza et al., 2023; Wells and Coppersmith, 1993) by incorporating seismogenic depth, as well as fault and rupture geometries, which have a first-order effect on the probability of surface rupture in historical shallow earthquakes (e.g. Champenois et al., 2017; Ritz et al., 2020).

Milliner et al. (2024)

Milliner et al. (2024) provide standardized collection of geodetic-based near-field surface displacement. The database contains data from 20 global strike-slip earthquakes measured using geodetic imaging techniques. The authors systematically processed pre- and post-earthquake optical and radar remote sensing data using pixel tracking and interferometric synthetic aperture radar methods to produce a standardized data set of surface displacement and strain maps. Surface rupture traces were manually mapped from the surface displacement maps, and lateral fault slip was measured across mapped ruptures by fitting stacked displacement profiles to an empirical cumulative function. The authors present detailed descriptions of the analytical methods and workflow, as well as a comprehensive sensitivity analysis on parameters affecting the strain quantity calculations and alternative fitting functions for computing lateral fault slip.

Thomas et al. (2023)

Thomas et al. (2023) present a numerical approach and programmed implementation for defining the main fault trace used in FDMs. Along-strike and across-strike site distances, based on the main fault trace, are used as predictor variables in FDMs. Because manually determined main fault traces can be subjective when faulting is complex, the authors use the least cost path (LCP) analysis to generate objective and reproducible main fault traces. The authors developed main fault traces using LCP analysis for all events in the FDHI Database (Sarmiento et al., 2024b), and the new Chiou et al. (2025) FDM used the LCP-based traces in their model development. Thomas et al. (2023) also compare LCP-based main fault traces with the Event-Specific Coordinate System (ECS) traces in the FDHI Database (Lavrentiadis et al., 2024). They find the ECS-based main fault traces are highly smoothed, whereas the LCP analysis produces main fault traces that more strictly follow mapped traces.

Valentini et al. (2025)

Valentini et al. (2025) summarize a study on probabilistic fault displacement hazard analysis, as a tool to assess the impact of capable faults on nuclear installations. The study included the application of most of the new FDHI models in this volume, as well as previously published models. Three seismic sources in different tectonic settings were considered. The authors show that the probability of surface rupture has the largest impact on the hazard, with alternative models leading to significant differences at long return periods. Differences in the aleatory variability in the FDMs also contribute. Hazard fractiles can be evaluated from a comprehensive treatment of the epistemic uncertainty between the models and in the seismic source characterization. For smaller earthquakes and larger site-to-fault distances, conservative sensitivity studies can be considered to evaluate if the distributed fault displacement hazard is within structural design limits.

Visini et al. (2025)

Visini et al. (2025) present empirical models for surface rupture probability and displacement amplitude distributions in dip-slip earthquakes on distributed faults. The authors distinguish between different types of distributed ruptures based on pre-earthquake geologic and geomorphic evidence. Distributed ruptures without such evidence are classified as simple (i.e. Rank 2), while others have different ranks. The authors propose a stochastic process with Monte Carlo sampling to model the along-strike distribution of simple distributed ruptures, simulating rupture lengths and positions. The authors then calculate the frequency of simulated ruptures within a specified area to estimate occurrence probabilities. For simple distributed ruptures, the model accounts for distances to principal and secondary faults, while to principal fault only for other ranks. Displacement amplitude follows a lognormal distribution, fitted using mixed-effects regression with random effects for earthquakes.

Wang and Goulet (2021)

As part of the initial phase of FDHI, Wang and Goulet (2021) investigated the validation of the physics-based simulations of fault displacements against the empirical data from the 1992 Landers, California earthquake. The study helped the FDHI modelers on the distribution of displacements where the empirical data is sparse. Because the Wang and Goulet (2021) article was published in the *Bulletin of the Seismological Society of America*, is not part of this *Volume*.

Summary and conclusions

This article provides an overview of a multi-year and community-based FDHI Program. FDHI included junior and senior academic researchers, practicing professionals, and government representatives. The participants have all been working together and interactively. The key advantage of such coordinated effort, like the NGA Programs for ground motion hazard, is that the final products are of much higher quality than each researcher task could achieve individually

The FDHI database contains 75 worldwide surface-rupturing earthquakes ranging from **M** 4.9 to 8.0 including data from strike-slip, reverse/reverse-oblique and normal/normal-oblique, faulting events. FDHI implemented a framework to classify principal and

distributed faulting for all events in the database. The database is publicly available through the following URL: <https://doi.org/10.25346/S6/Y4F9LJ> (Sarmiento et al., 2024a), and more details on the database are in Sarmiento et al. (2024b).

Employing the database, four new FDMs were developed. The FDMs predict principal or aggregate surface displacement, where aggregate is the combined displacement across principal and distributed ruptures. Similar to the existing FDMs, the FDHI models use moment magnitude (M) and normalized along-strike location (x/L) as predictor variables. The models are applicable between M 6.0 and 8.0, where most of the empirical data exist, but some FDMs are applicable to lower or higher magnitudes. Two models are applicable to all styles of faulting (LA23 and KEA24), whereas the MEA24 and CEA25 models are applicable to reverse and strike-slip faulting, respectively. While the FDHI models generally produce lower average displacements compared with legacy models (e.g. Petersen et al., 2011; Youngs et al., 2003 and Moss and Ross, 2011), the average displacements in the new FDHI models are about 40% higher for $M \sim 7$. In addition, the new models predict significantly smaller displacement at low probability of exceedance. Importantly, the upper tails of the displacement probability distributions are in good agreement with empirical observations of maximum displacement, which supports the use of the FDHI models in probabilistic fault displacement hazard analysis for low exceedance probabilities.

In addition to the core FDHI database and predictive models, there were six well-scoped focused investigations. An overview of such focused studies was also provided in this article.

Acknowledgments

The FDHI Program provided a forum for database developers and modeling teams to have extensive interactions and fruitful technical discussions, which resulted in higher quality models than each researcher could achieve individually. Acknowledgments and appreciation are given to over 40 researchers and practicing professionals who worked on various parts of the FDHI Program. Their contributions, dedication, and teamwork are greatly appreciated. Figure 1 was prepared with the help of Danielle Madugo.

Declaration of conflicting interests

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Data and resources

The FDHI database of 75 worldwide surface-rupturing earthquakes is available in Sarmiento et al. (2024). All four FDHI models have been coded in Python and Excel and are publicly available at <https://doi.org/10.5281/zenodo.13552790> and <https://doi.org/10.5281/zenodo.14231829>, respectively. An overview of the Python and Excel tools can also be found at <https://girs.squarespace.com/nhr3/products/fdhi>. Figures 3 and 4 were produced using version 1.0.0 of the Python package. Additional documentation supporting this article is available in the multiple project papers cited above.

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