3rd EUROPEAN CONFERENCE ON
EARTHQUAKE ENGINEERING & SEISMOLOGY
BUCHAREST, ROMANIA, 2022

An engineering approach to fault displacement hazard for lifelines crossing active tectonic faults

Vasileios E. Melissianos – National Technical University of Athens, Athens, Greece, e-mail: melissia@mail.ntua.gr

Dimitrios Vamvatsikos – National Technical University of Athens, Athens, Greece, e-mail: divamva@mail.ntua.gr

Laurentiu Danciu – Swiss Seismological Service, ETH Zurich, Zurich, Switzerland, e-mail: laurentiu.danciu@sed.ethz.ch

Roberto Basili – Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy, e-mail: roberto.basili@ingv.it

Abstract: Lifelines, such as pipelines, tunnels, and bridges are vulnerable to seismic-induced ground displacements caused by the activation of active tectonic faults. Lifelines are forced to follow the ground movement in fault crossings and develop excessive deformation. Safeguarding the integrity of such critical infrastructure is of paramount importance. Contrary to typical deterministic design approaches that discount fault productivity, a performance-based approach can achieve a balance between safety and economy. Towards this goal, a set of simplified expressions is developed for determining fault displacement at given return periods, developed by analyzing the outcome of probabilistic fault displacement hazard analysis (PFDHA) for European faults. The proposed methodology allows the computation of the design fault displacement with data available to the engineer and has been adopted as an informative Annex in EN1998-4.

Keywords: tectonic fault, displacement hazard, lifelines, design

1. Introduction

The structural integrity and functionality of lifelines in the aftermath of an earthquake, such as oil, gas, water, and sewage pipelines, or roads, tunnels, and bridges, is decisive for the response management of civil protection authorities and heavily influences the seismic resilience of communities (Casari and Wilkie 2005; Fragiadakis et al. 2015; Kilanitis and Sextos 2019). Among the most catastrophic earthquake-induced actions is the fault offset in the case of large-magnitude earthquakes affecting the overlying structures that have to follow the imposed ground displacement by developing excessive deformation (O'Rourke and Liu 2012; Roy and Sarkar 2017; Yang and Mavroeidis 2018). This is indicatively shown for buried pipelines in Fig. 1.

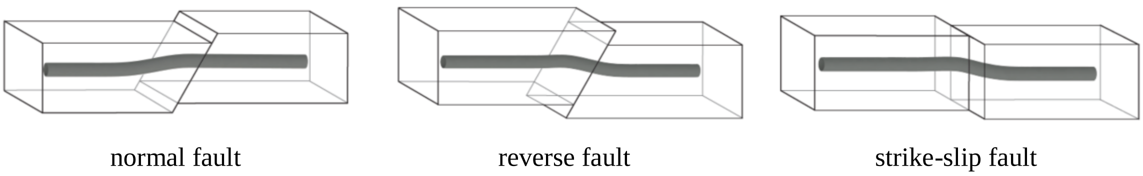

Fig. 1 - Fault mechanisms (normal, reverse, and strike-slip) and corresponding deformation of a buried pipeline subjected to faulting

The design fault displacement is typically based on estimates derived from the fault geometry via empirical fault scaling relations (e.g. Wells and Coppersmith 1994; Leonard

2014; Thingbaijam et al. 2017; Wang 2018; Anderson et al. 2021) for a given "design" scenario event. This approach comes with an unknown level of safety, as it disregards fault seismicity and the actual distribution of scenarios that it can produce. However, the seismic resilience of critical lifelines and infrastructure can be reliably secured within the framework of Performance-Based Earthquake Engineering (Cornell and Krawinkler 2000). The primary and fundamental step in this direction is the quantification of the fault displacement hazard on the crossing site. The appropriate methodology is the Probabilistic Fault Displacement Hazard Analysis (PFDHA), introduced by Youngs et al. (2003), which aims at quantifying the mean annual frequency (MAF) of exceeding arbitrary fault displacement levels at the lifeline crossing site, considering the geometrical and seismological properties of the fault together with the location of the crossing lifeline on the fault trace (i.e., the crossing site). A baseline approach of PFDHA has been presented by Melissianos et al. (2017a, b) and recently updated for lifeline-fault crossings by Melissianos et al. (2021).

The fault displacement hazard is estimated as:

$$\lambda_{\Delta_F}(\delta_F) = \nu_F \sum_i P(\Delta_F > \delta_F | m_i) P_M(m_i) \quad (1)$$

where ν_F is the yearly average rate of all earthquakes above a minimum magnitude of engineering significance, $P(\Delta_F > \delta_F | m_i)$ is the conditional probability that fault displacement Δ_F will exceed value δ_F given an earthquake of magnitude m_i has occurred, and $P_M(m_i)$ is the probability of magnitude M being within a bin of $m_i \pm \Delta m$ as estimated after the Gutenberg-Richter bounded recurrence law (Gutenberg and Richter 1944). The key parameters for calculating the fault displacement hazard on the lifeline crossing site are (a) the fault mechanism (normal, reverse, strike-slip), the fault length, the crossing site on the fault trace, and the rate ν_F. An illustrative exampled of a fault displacement hazard curve on the lifeline crossing site is presented in Fig. 2.

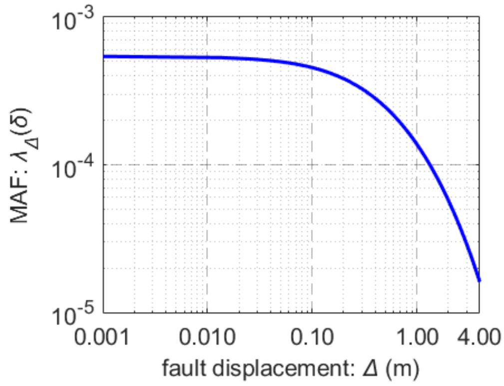

Fig. 2 - Illustrative example of a fault displacement hazard curve on the lifeline crossing site

2. Methodology outline

PFDHA is an advanced analysis with complicated probabilistic calculations based on a set of specialized seismological data. It is thus unsuitable for being incorporated "as is" in code provisions. To overcome this problem on a code basis, a simplified approach was developed that allows a (mostly conservative) approximation of the fault displacement corresponding to any given return period; it achieves this based on readily available data, namely fault productivity, fault mechanism, fault length, and crossing location. The code-compatible and hazard-consistent statistical approximation is developed for estimating the design fault displacement for European applications. A large number of PFDHAs were carried out considering the pertinent uncertainties within a logic tree formulation exploiting the seismological and geometrical properties of the database of faults (Fig. 3) considered in the development of the 2020 European Seismic Hazard Model (ESHM20, Danciu et al. 2019) within the EU-funded research project SERA (Giardini et al. 2017). The methodology comprises a set of equations for calculating the displacement given the fault seismicity, the fault mechanism, the fault length, and the crossing site.

Fig. 3 - Map of faults classified per tectonic environment. Interplate (INT) in red, Stable Continental Region (SCR) in blue.

The proposed methodology is implemented as follows:

1st step: The fault mechanism, the fault length, and the crossing point are determined for the lifeline–fault crossing at hand.

2nd step: The productivity of the fault is derived either from an available source model, defined by a specialized seismological study, or estimated via a proposed approximation.

3rd step: The return period (T_R) of exceeding a selected fault displacement (Δ_F) or vice versa through appropriate linear interpolation at the lifeline–fault crossing is estimated via a single expression:

$$T_R(\Delta_F) = \frac{1}{C_F v_F f_L(\Delta_F, L_F, X_L)} \quad (2)$$

where C_F is the confidence factor depending on the method used to determine the rate v_F and $f_L(\Delta_F, L_F, X_L)$ is the rate-independent function that depends on the fault mechanism, fault length, and crossing point and is estimated for the selected fault displacement.

3. Example case studies

A set of indicative faults in Europe (Table 1) is selected to showcase the fault displacement hazard estimations of the proposed methodology (abbreviated as EN1998-4 approach) in comparison to full PFDHA results (Fig. 4), indicating a very good agreement.

Table 1. Example faults under examination

Fault name	Country	Tectonic environment	Fault mechanism	Fault length (km)	Rate v_F (years^{-1}) for magnitude > 5.5
ESCF002	Spain	Interplate	Reverse	114.06	0.00778
TRCF00Z	Turkey	Interplate	Strike-slip	25.28	0.00298
GRCF024	Greece	Interplate	Normal	38.42	0.08486

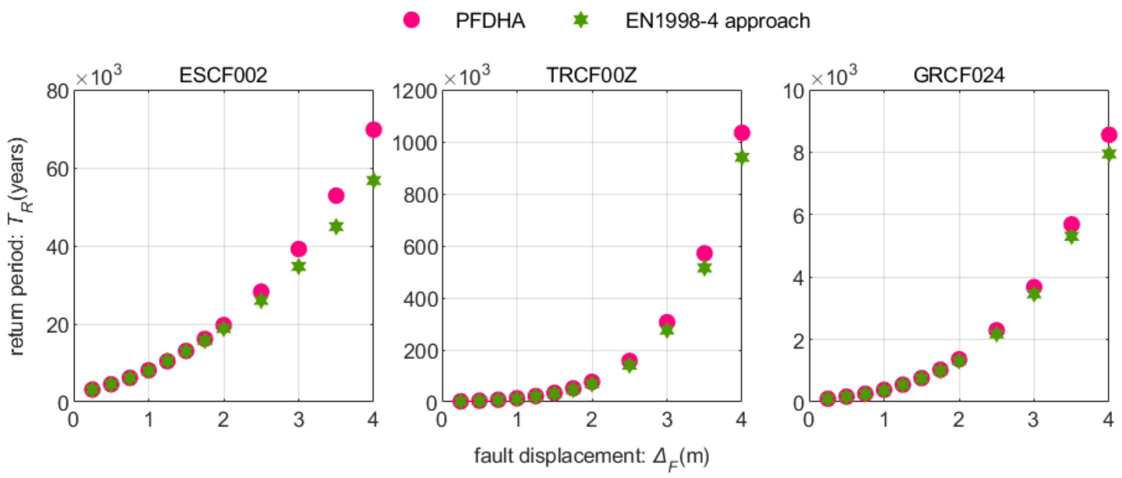

Fig. 4 – Comparison of return period for predefined fault displacement obtained from PFDHA versus the EN1998-4 approach

Moreover, a set of faults (Table 2) located close to industrial areas, large cities, and important infrastructure are selected and the fault displacement using the EN1998-4 approach is calculated for design return periods of 2500 years ($Δ_{F,2500}$) and 5000 years ($Δ_{F,5000}$). The results are presented in Fig. 5, along with a deterministic cap ($Δ_{F,det.cap}$), defined after the empirical fault scaling relations of Leonard (2014) using the fault length. $Δ_{F,det.cap}$ is introduced to limit any potential excessive fault displacement values due to the conservativeness of the approach, in particular for very active faults, namely those with a very high rate v_F. None of the cases examined fall in this category, therefore the cap value is largely irrelevant.

Pyrenees: Three indicative faults in the Pyrenees at the France–Spain border were examined. It is observed that due to the significantly low seismicity (lower than 0.0005 events on average per year with magnitude $M \geq 5.5$), the resulting displacement values for both return periods are equal to the minimum, namely $Δ_F = 0.10$m.

Germany: Two fault systems were selected in Germany, one in the greater area of Aachen and the other around Frankfurt. The short normal faults in the Aachen area and the ultra-long strike-slip faults around Frankfurt have low seismicity and thus the obtained fault displacements are very low.

Slovenia: Numerous faults are located in the northwest part of the Balkan Peninsula in Slovenia. Four indicative interplate faults were selected and examined. One should notice the SICF004 strike-slip fault with a higher seismic rate, compared to the others. The resulting fault displacement values for this fault are particularly high.

Italy: In the industrial area of Calabria in Italy there are interplate faults with considerable seismic rates.

Table 2. Case study faults in the European continent (INT: interplate, SCR: stable continental region)

Country	Area	Fault name	Tectonic environment	Fault mechanism	Fault length (km)	Rate ν_F (years^{-1}) for magnitude > 5.5
France-Spain border	Pyrenees	FRCF00W	INT	Strike-slip	82.39	0.00020
		ESCF01Y	SCR	Strike-slip	76.63	0.00042
		ESCF00P	INT	Strike-slip	26.77	0.00050
Germany	Aachen	DECF005	INT	Normal	54.51	0.00070
		DECF007	INT	Normal	21.81	0.00014
	Frankfurt	DECF000	INT	Strike-slip	165.70	0.00279
		DECF001	INT	Strike-slip	312.75	0.01011
Slovenia	Ljubljana	SICF00A	INT	Strike-slip	37.89	0.00272
		SICF00K	INT	Strike-slip	26.37	0.00028
		SICF00J	INT	Reverse	16.35	0.00145
	West	SICF004	INT	Strike-slip	123.44	0.01878
Italy	Calabria	ITCF01J	INT	Strike-slip	63.18	0.00416
		ITCF01W	INT	Strike-slip	40.14	0.00241
		ITCF00L	INT	Reverse	82.08	0.00514
		ITCF007	SCR	Strike-slip	128.06	0.00620

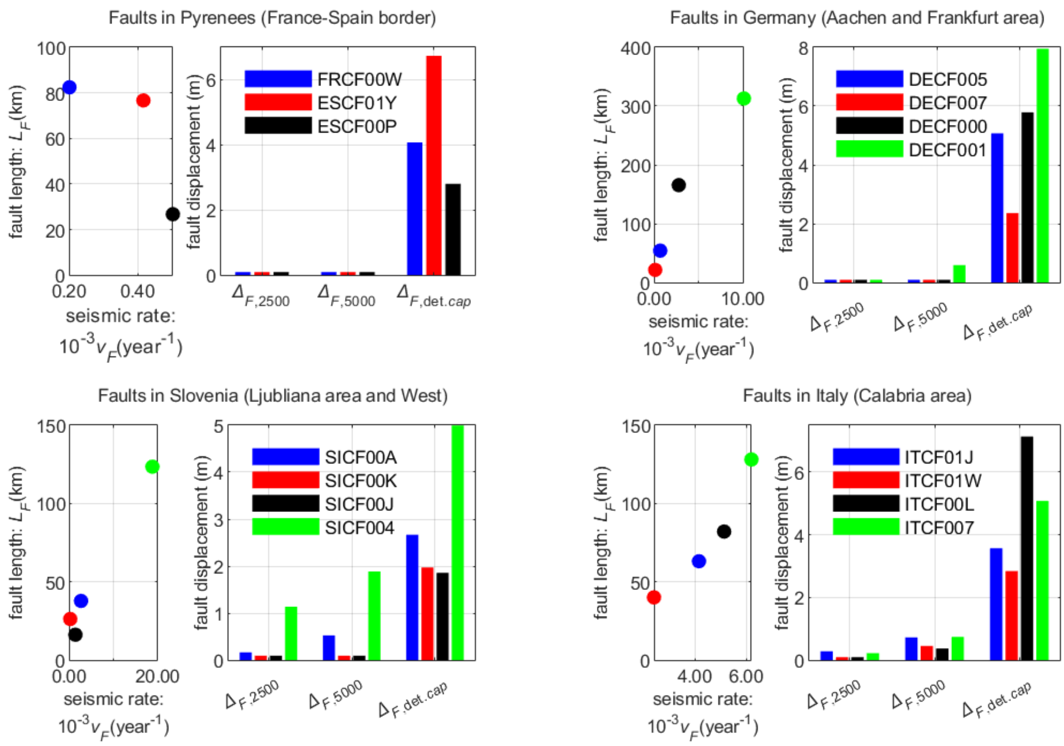

Fig. 5 – Comparison of fault displacements obtained from the EN1998-4 approach with the actual seismic rate for return periods 2500 years and 5000 years, also showing the deterministic cap

4. Conclusions

Lifelines are vulnerable to seismic-induced permanent ground displacements caused by fault activation. The Probabilistic Fault Displacement Hazard Analysis (PFDHA) is the appropriate tool to quantify the potential of fault displacement hazard within a performance-based framework. This approach requires a lot of advanced calculations and thus it is not appropriate for code implementation. To work around this problem to offer a code-compatible and hazard-consistent methodology for estimating the design fault displacement, a set of simplified expressions is developed from the statistical processing of results from PFDHA. The pertinent uncertainties are taken into account through a logic tree formulation, exploiting the properties of the faults incorporated in the 2020 European Seismic Hazard Model. The fault displacement obtained from the proposed approach is compared to results from full PFDHA, indicating a fair match. The proposed methodology has been adopted as an informative Annex in the 2020 version of EN1998-4 and it may serve as a screening tool for lifeline route selection, or even as a preliminary design tool to indicate when a more specialized study is needed.

Acknowledgments

The financial support provided by the European Union through the HORIZON 2020 research and innovation programmes “INFRASTRESS–Improving resilience of sensitive industrial plants & infrastructures exposed to cyber-physical threats, by means of an open testbed stress-testing system” under Grant Agreement No. 833088, “HYPERION – Development of a Decision Support System for Improved Resilience & Sustainable Reconstruction of historic areas to cope with Climate Change & Extreme Events based on Novel Sensors and Modelling tools” under Grant Agreement No. 821054, and “SERA–Seismology and earthquake engineering research infrastructure alliance for Europe” under Grant Agreement No. 730900 is gratefully acknowledged.

Also, the financial support provided by the Hellenic Foundation for Research and Innovation (H.F.R.I.) under the “2nd Call for H.F.R.I. Research Projects to support Faculty Members & Researchers”, Project "TwinCity - Climate-Aware Risk and Resilience Assessment of Urban Areas under Multiple Environmental Stressors via Multi-Tiered Digital City Twinning ", (Number: 2515) is gratefully acknowledged.

References

- Anderson JG, Biasi GP, Angster S, Wesnousky SG (2021) Improved scaling relationships for seismic moment and average slip of strike-slip earthquakes incorporating fault-slip rate, fault width, and stress drop. Bulletin of the Seismological Society of America, 111:2379–2392. https://doi.org/https://doi.org/10.1785/0120210113
- Casari M, Wilkie SJ (2005) Sequencing lifeline repairs after an earthquake: An economic approach. Journal of Regulatory Economics, 27:47–65. https://doi.org/https://doi.org/10.1007/s11149-004-4418-9
- Cornell CA, Krawinkler H (2000) Progress and challenges in seismic performance assessment. PEER Center News, 3:1–4
- Danciu L, Hiemer S, Nandan S, et al (2019) Status, milestones and next activities on the development of the 2020 European Seismic Hazard Model (ESHM20). Geophysical Research Abstracts, 21:EGU2019-8317

- Fragiadakis M, Vamvatsikos D, Karlaftis MG, et al (2015) Seismic assessment of structures and lifelines. Journal of Sound Vibration, 334:29–56. https://doi.org/https://doi.org/10.1016/j.jsv.2013.12.031
- Giardini D, Kauzar S, and the SERA Consortium (2017) EU H2020 SERA: Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe. In: 19th European Geosciences Union General Assembly (EGU 2017). EGU, Vienna, Austria, pp EGU2017-14442
- Gutenberg R, Richter CF (1944) Frequency of earthquakes in California. Bulletin of the Seismological Society of America, 34:185–188. https://doi.org/https://doi.org/10.1785/BSSA0340040185
- Kilanitis I, Sextos A (2019) Integrated seismic risk and resilience assessment of roadway networks in earthquake prone areas. Bulletin of Earthquake Engineering, 17:181–210. https://doi.org/10.1007/s10518-018-0457-y
- Leonard M (2014) Self-consistent earthquake fault-scaling relations: Update and extension to stable continental strike-slip faults. Bulletin of the Seismological Society of America, 104:2953–2965. https://doi.org/https://doi.org/10.1785/0120140087
- Melissianos VE, Danciu L, Vamvatsikos D, Basili R (2021) Fault displacement hazard estimation at lifeline-fault crossings: A baseline approach for engineering applications. Earthquake Spectra, under revision
- Melissianos VE, Vamvatsikos D, Gantes CJ (2017a) Performance assessment of buried pipelines at fault crossings. Earthquake Spectra, 33:201–218. https://doi.org/https://doi.org/10.1193/122015EQS187M
- Melissianos VE, Vamvatsikos D, Gantes CJ (2017b) Performance-based assessment of protection measures for buried pipes at strike-slip fault crossings. Soil Dynamics and Earthquake Engineering, 101:1–11. https://doi.org/https://doi.org/10.1016/j.soildyn.2017.07.004
- O'Rourke MJ, Liu JX (2012) Seismic design of buried and offshore pipelines. Monograph MCEER-12-MN04. Multidisciplinary Center for Earthquake Engineering Research, Buffalo, NY, USA
- Roy N, Sarkar R (2017) A Review of seismic damage of mountain tunnels and probable failure mechanisms. Geotechnical Geological Engineering, 35:1–28. https://doi.org/https://doi.org/10.1007/s10706-016-0091-x
- Thingbaijam KKS, Mai PM, Goda K (2017) New empirical earthquake source-scaling laws. Bulletin of the Seismological Society of America, 107:2225–2246. https://doi.org/https://doi.org/10.1785/0120170017
- Wang JH (2018) A review on scaling of earthquake faults. Terrestrial, Atmospheric and Oceanic Sciences Journal, 29:589–610. https://doi.org/https://doi.org/10.3319/TAO.2018.08.19.01
- Wells DL, Coppersmith KJ (1994) New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacements. Bulletin of the Seismological Society of America, 84:974–1002. https://doi.org/https://doi.org/10.1785/BSSA0840040974
- Yang S, Mavroeidis GP (2018) Bridges crossing fault rupture zones: A review. Soil Dynamics and Earthquake Engineering, 113:545–571. https://doi.org/https://doi.org/10.1016/j.soildyn.2018.03.027
- Youngs RR, Arabasz WJ, Anderson RE, et al (2003) A methodology for probabilistic fault displacement hazard analysis (PFDHA). Earthquake Spectra, 19:191–219. https://doi.org/https://doi.org/10.1193/1.1542891