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Design displacement for lifelines at fault crossings: the code-based approach for Europe

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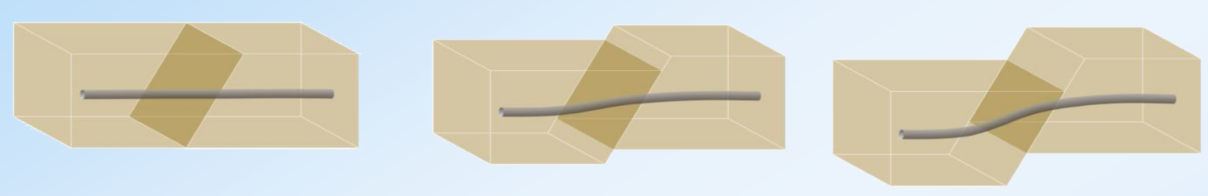

Schematic illustration of successive stages of buried pipeline deformation due to normal faulting

Lifelines (pipelines, cables, tunnels, etc.)**:** Vulnerable to permanent ground displacements

Motivation: No code provisions to calculate the design fault displacements for lifelines subjected to tectonic fault rupture

Design fault displacement – Alternative approaches:

- Empirical fault scaling relations [deterministic approach]
- Probabilistic fault displacement hazard analysis (PFDHA akin to PSHA) [probabilistic approach]

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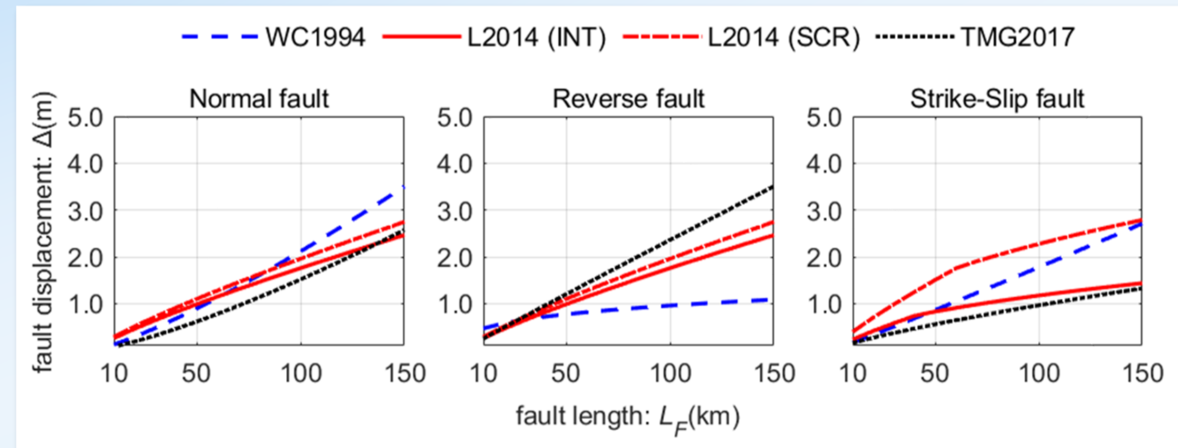
Deterministic approach:

- Easy to use
- Minimum data requirement

BUT

- Unknown or partially defined level of safety
- Fault seismicity and the actual distribution of scenarios that it can produce are disregarded
- No guidelines or recommendations on the selection of a set of empirical fault scaling relations



Fault displacement estimates based on fault length via alternative empirical fault scaling relations [Wells and Coppersmith (1994), Leonard (2014), and Thingbaijam et al. (2017)]

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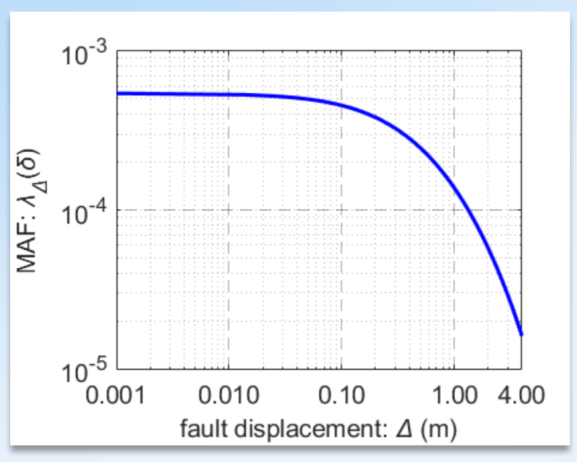

Illustrative example of a fault displacement hazard curve on the lifeline crossing site

Probabilistic approach:

- Compatible with Performance-Based Earthquake Engineering
- Consideration of the actual distribution of scenarios the fault can produce
- Calculation of fault displacement for a given return period

BUT

- Advanced analysis with complicated calculations
- Requirement for specialized seismological data
- **Unsuitable for being incorporated "as is" in the code**

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Scope:

- Simplified approach for a (mostly conservative) estimation
- Approximation of fault displacement for a given return period
- Approach based on readily available data (fault productivity, fault mechanism, fault length, crossing site)

Methodology outline:

- Statistical processing of PFDHAs' results
- Consideration of pertinent uncertainties (e.g., maximum earthquake magnitude, G-R b-value) within a logic tree formulation
- Exploitation of seismological and geometrical properties of the EFSM20 database (Basili et al. 2020) used in the ESHM20 (Danciu et al. 2021)

Map of faults classified per tectonic environment (INT: red, SCR: blue), a selection from the EFSM20 database

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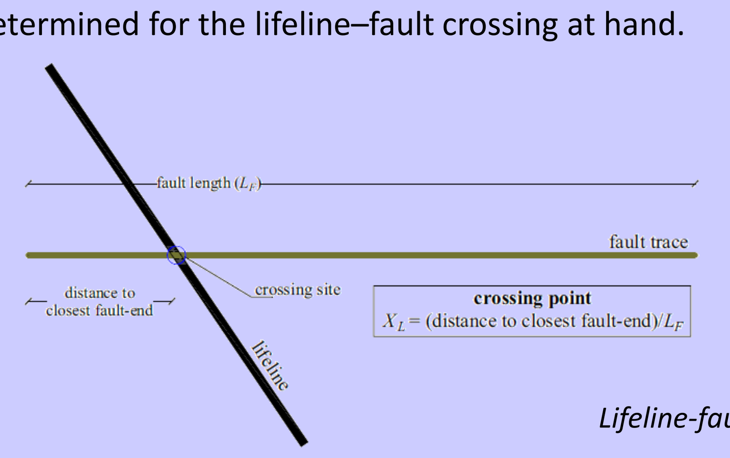
Methodology implementation – Informative Annex E of pr EN1998-4:2022:

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



Lifeline-fault crossing plan view

- *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.
  Fault productivity → recurrence rate (v_F) → average annual number of events above a minimum earthquake magnitude of engineering significance
- *3rd step.* The return period (T_R) of exceeding a selected fault displacement (Δ_F) or vice versa is estimated via a single expression:

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

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

Δ_F (m)	coeff.	Recurrence rate class low	Recurrence rate class high	Δ_F (m)	coeff.	Recurrence rate class low	Recurrence rate class high
0.25	a_1	-5.1391	-9.3774	1.00	a_1	-13.5015	-11.8186
	a_2	2.2983	3.9922		a_2	6.7661	4.2274
	a_3	-0.9885	11.1942		a_3	-0.7515	9.7195
	a_4	-0.6845	-0.8118		a_4	-1.6635	-0.8127
	a_5	2.4665	-1.9394		a_5	2.3699	-1.2698
	a_6	-2.4378	-9.3626		a_6	-0.7217	-8.0084
	a_7	0.0536	0.0495		a_7	0.1265	0.0491
	a_8	-0.2615	0.1078		a_8	-0.2027	0.0839
	a_9	-0.5319	1.0160		a_9	-1.1461	0.4657

Indicative part of tables provided to calculate function $f_L(\Delta_F, L_F, X_L)$

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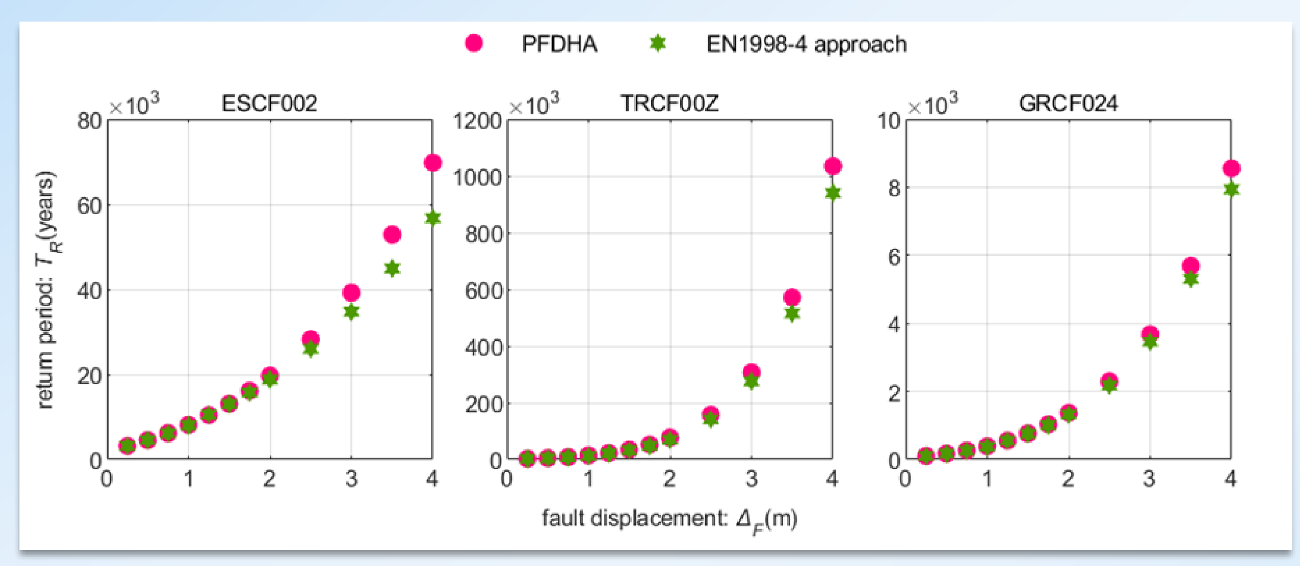
Methodology evaluation:

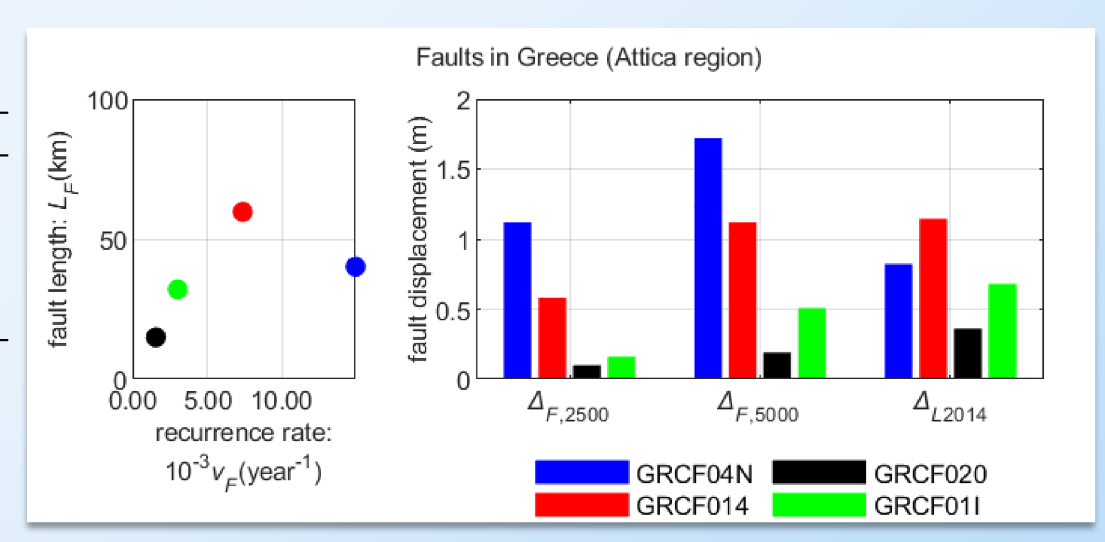


Comparison of return period for predefined fault displacement obtained from PFDHA versus the EN1998-4 approach

Fault name	Country	Mechanism	L_F (km)	v_F (years^{-1})
ESCF002	Spain	Reverse	114.06	0.00778
TRCF00Z	Turkey	Strike-slip	25.28	0.00298
GRCF024	Greece	Normal	38.42	0.08486

Case study – Greece (Attica region):

Fault name	Mechanism	L_F (km)	v_F (years^{-1})
GRCF04N	Normal	40.15	0.0149
GRVF014	Normal	59.70	0.0074
GRCF020	Normal	14.96	0.0016
GRCF01I	Normal	32.04	0.0030



Fault displacements obtained from the EN1998-4 approach for return periods of 2500 years ($\Delta_{F,2500}$) and 5000 years ($\Delta_{F,5000}$), compared against the "seismicity-agnostic" estimate ($\Delta_{F,L2014}$) from Leonard (2014) empirical fault scaling relations

Publications

Melissianos, V. E., Vamvatsikos, D., Danciu, L., and Basili, R. (2024). Design Fault Displacement for Lifelines at Fault Crossings: The Code-Based Approach for Europe. *Bulletin of Earthquake Engineering*, 22:2677-2720. https://doi.org/10.1007/s10518-023-01813-9

Melissianos, V. E., Danciu, L., Vamvatsikos, D., and Basili, R. (2023). Fault Displacement Hazard Estimation at Lifeline-Fault Crossings: A Simplified Approach for Engineering Applications. *Bulletin of Earthquake Engineering*, 21:4821-4849. https://doi.org/10.1007/s10518-023-01710-1

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