Physics-Based Rupture Models for Fault Displacement Assessment of Surface-Rupturing Earthquakes for Nuclear Installations

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Workshop **"Numerical Modeling of Earthquake Motions: Waves and Ruptures"**

July 1 – July 4, 2019, Smolenice Castle, Slovakia

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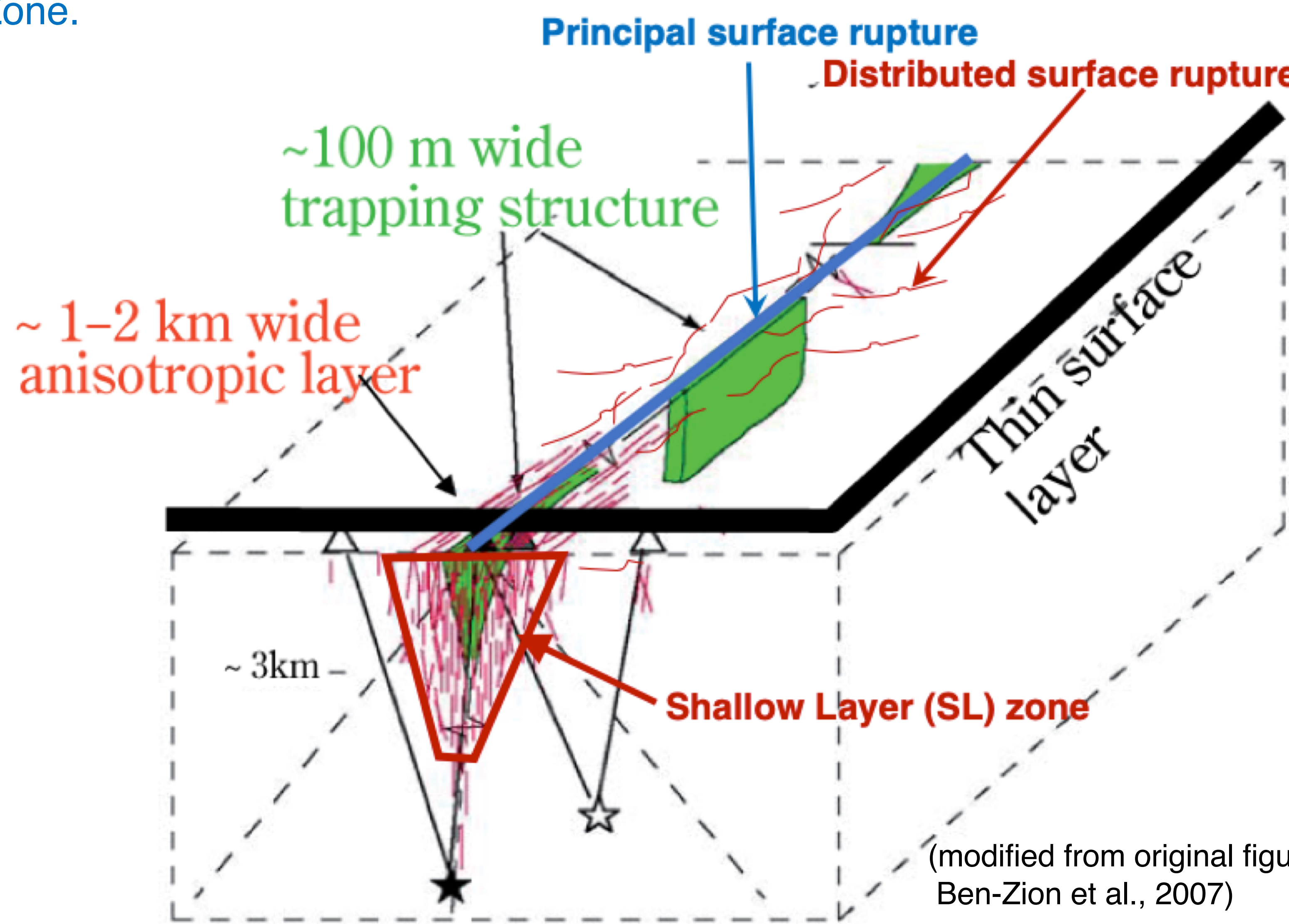
Introduction

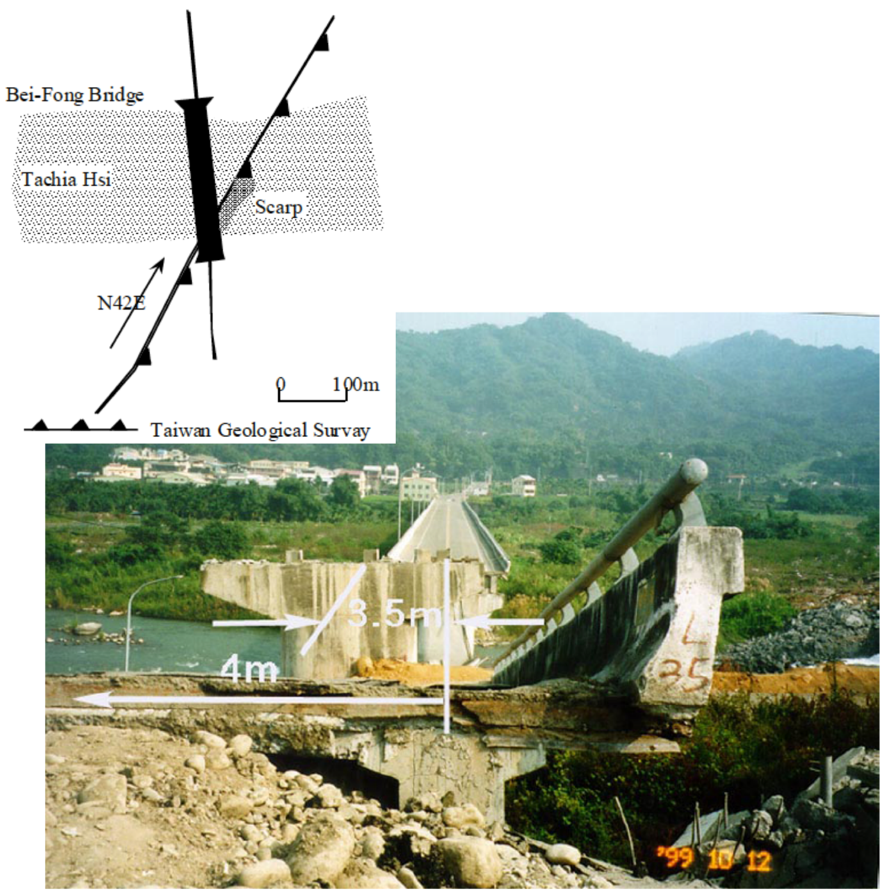
- Fault displacement is the slip on the free-surface (surface rupture)
- Main elements: principal fault, distributed fault and Shallow Layer (SL) Zone.



(modified from original figures of Ben-Zion et al., 2007)

Introduction

Coseismic fault displacement can cause significant damages to structures and life lines located near faults, such as bridges, dams, buildings, railroads, pipelines, Tunnels, NPPs, Nuclear waste repositories



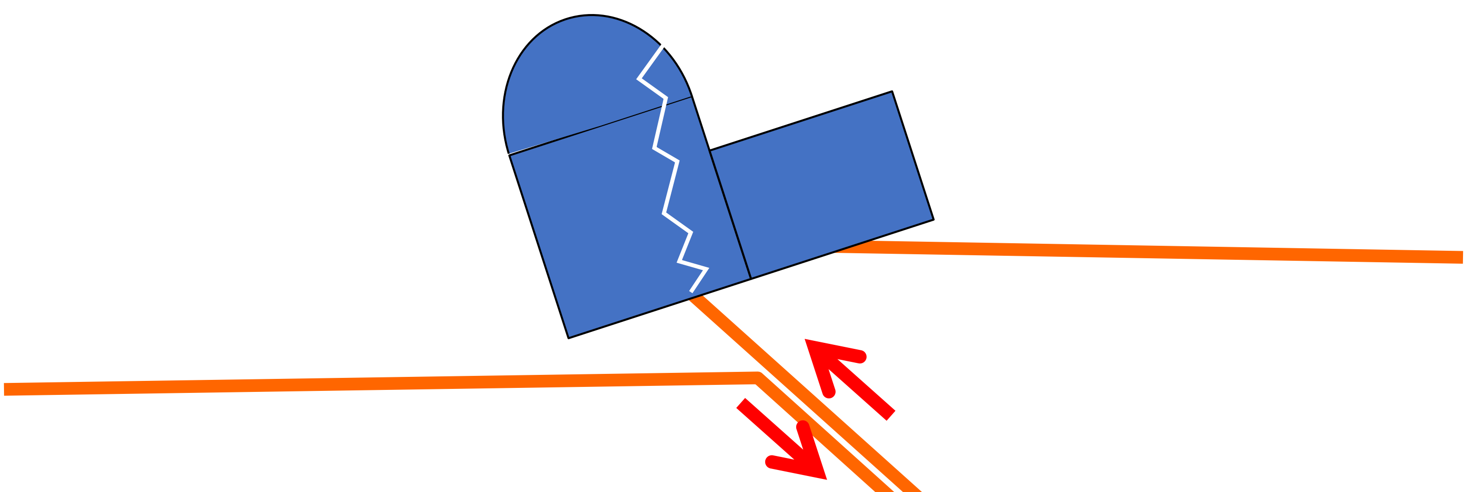
Bei-Fong Bridge (1999 Chi-Chi)

3.6 m offset of drainage Pipe (1999 Kocaeli)

(Kawashima, 2001)

Fault Displacement Assessment for Nuclear Installations

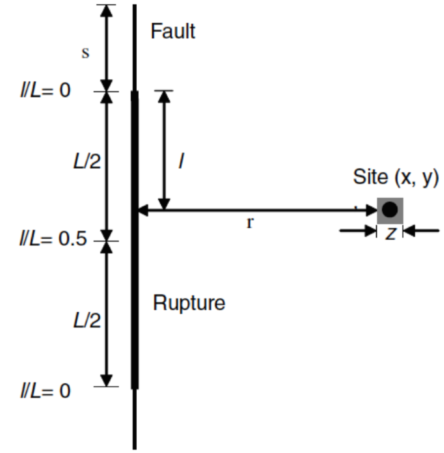
- In current practice, Nuclear Installations are not designed against fault displacement
- But what if a NPP is just above a potential fault (principal or distributed) capable to break the free-surface during an earthquake?
- Need to mitigate the probabilities of such events for existing nuclear installations and to avoid capable faults for new installations.
- The IAEA is concerned about it. IAEA Safety Series No. NSR-1 mention that surface faulting is identified as one of the natural phenomena that must be assessed in site evaluation for nuclear installations.
- **The use of probabilistic fault displacement hazard analysis (PFDHA)** is introduced in IAEA Safety Standards Series No. SSG-9
- IAEA Safety Standard Series No. NS-G-2.13 Evaluation of Seismic Safety for Existing Nuclear Installations states that *"If a clear resolution of the matter is still not possible, the fault displacement hazard should be evaluated using probabilistic methods"*
- Currently we are writing a IAEA-TECDOC that describes current methodologies of PFDHA including data needs, empirical and physics-based **(dynamic rupture models)** approaches.



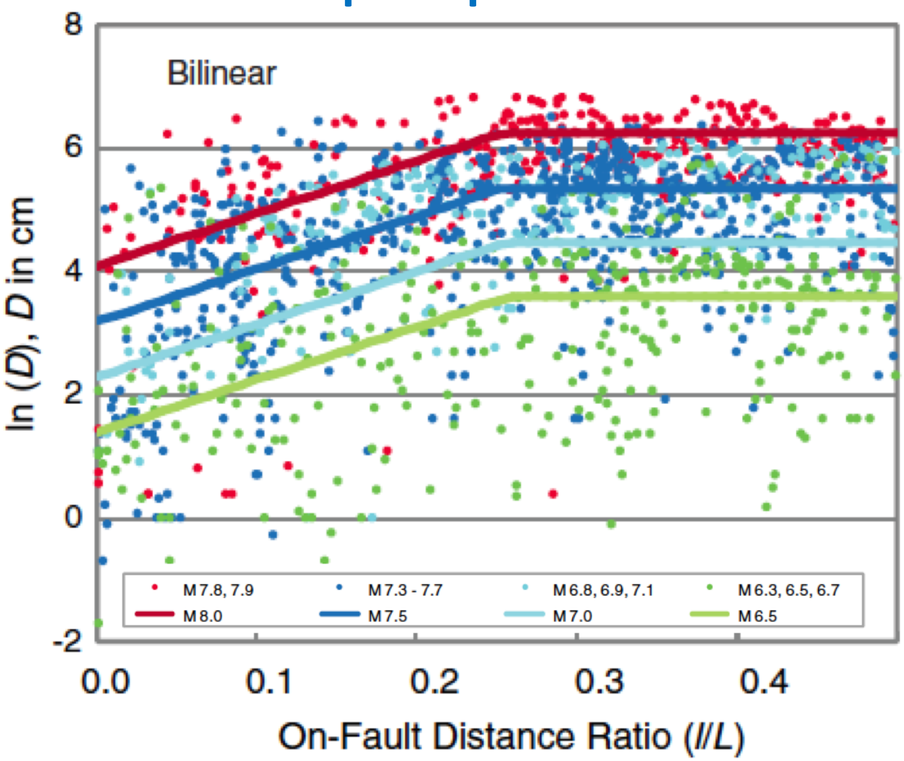
Empirical Models to Predict Fault Displacement

Current Empirical Models:

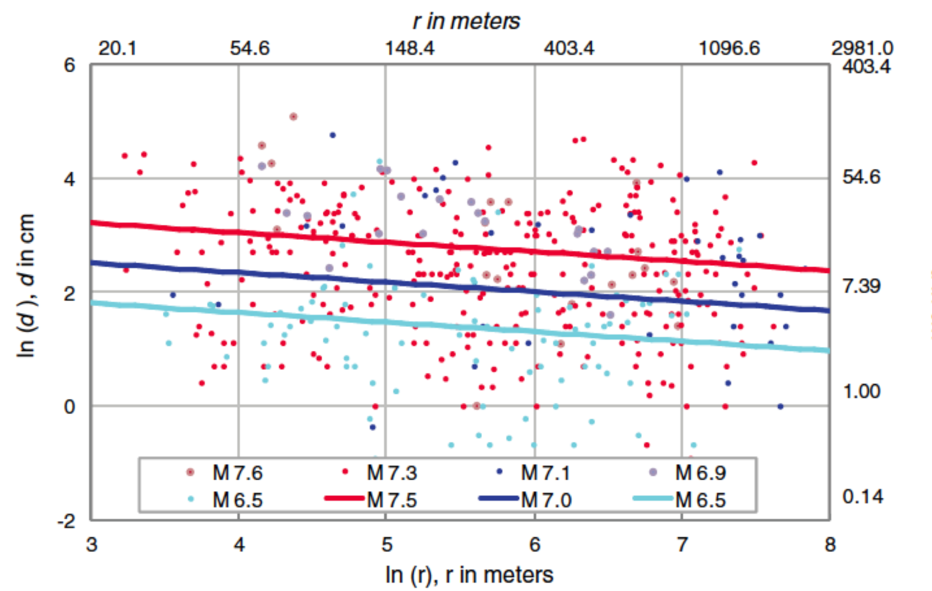
- Youngs et al. (2003), **Normal faulting**, Global data (Pezzopane and Dawson, 1996; Wells and Coppersmith, 1993)
- Petersen et al. (2011), **Strike Slip,** Global data, (Wesnousky, 2008, Wells and Coppersmith, 1993, others)
- Moss and Ross (2011), **Reverse faulting** (Global data from Lettis et al, 1997)
- Takao et al. (2013), **Reverse and strike slip,** Japanese earthquakes



For principal faults



For distributed faults



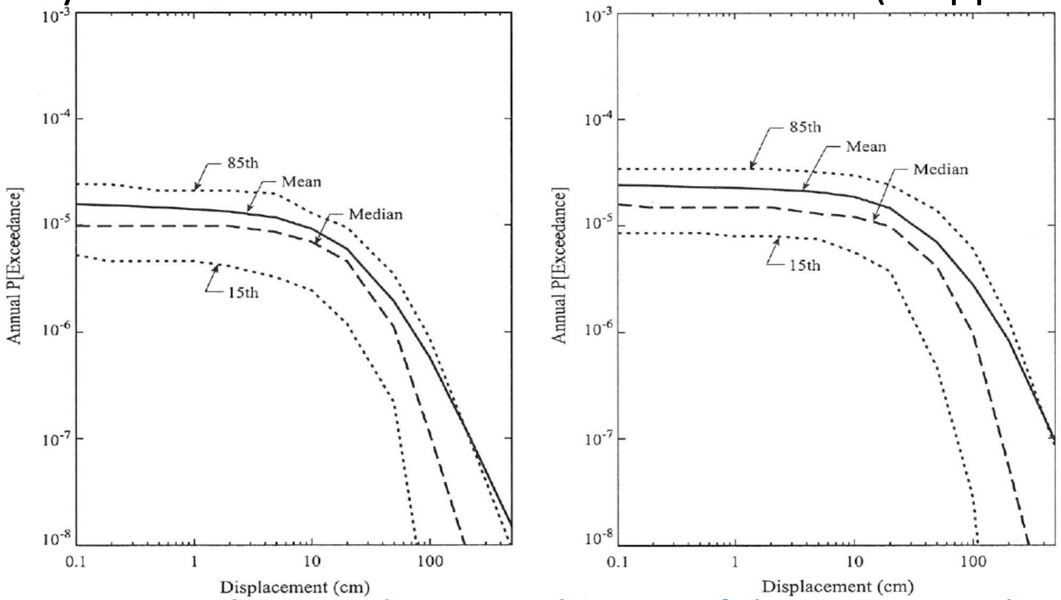
(Petersen et al., 2011)

Some site specific PFDHA related to Nuclear Installations

In all situations, the PFDHAs have been implemented using fully empirical approaches:

- **The Yucca Mountain case study:** pioneering PFDHA analyses performed in the mid-1990s for the proposed Yucca Mountain underground geologic repository. Use methodological approach in extensional tectonic domains (Stepp et al., 2001; Youngs et al., 2003)

Summary hazard curves at two different locations (Stepp et al., 2001)



- **The Diablo Canyon case study:** provides an application of the PFDHA methodology for distributed fault displacement hazard to a specific, safety-related engineered structure at an existing nuclear installation located away from the principal fault trace. The Diablo Canyon Nuclear Power Plant (Central California, USA) that is located in a zone dominated at regional scale by the San Andreas strike-slip fault. The applied methodology follows the general formulation of Petersen et al. (2011).

- **The Krško (Slovenia) case study:** provides a probabilistic perspective on an assessment of fault capability for two sites being considered for a future nuclear power plant.

Issues of empirical approaches for PFDHA

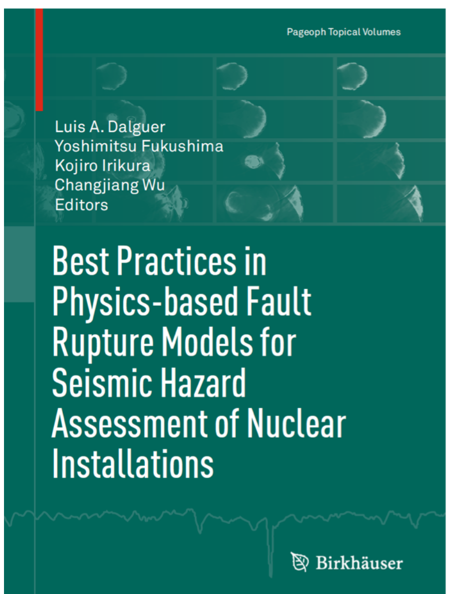
- In current practice, PFDHA is intrinsically a site specific study, because it is done for zones where capable faults have been identified.
- For a site specific, data is usually very limited, even more critical than ground motion database
- Due to data limitation at the site of study, the different components of PFDHA use empirical probability distribution models based in global data set (also limited).
- Therefore, current PFDHA relies on global empirical data, then assumes that the **ergodic** assumption in probability theory is valid for earthquake processes.
- But earthquake processes are not consistent with such ergodic assumption.
- The use of site-specific non-ergodic models can have a large effect on seismic hazard estimates (Abrahamson and Wooddell, 2018).

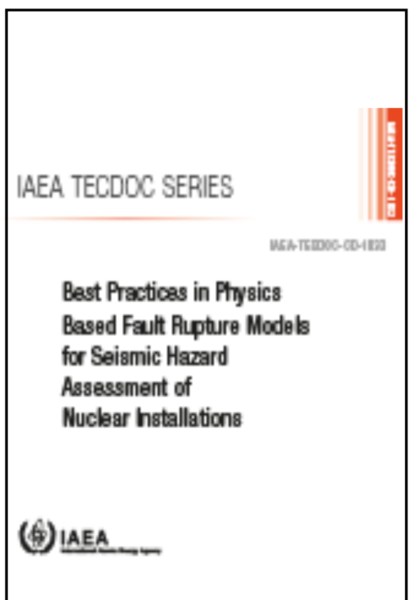
The role of physics-based rupture models in PFDHA

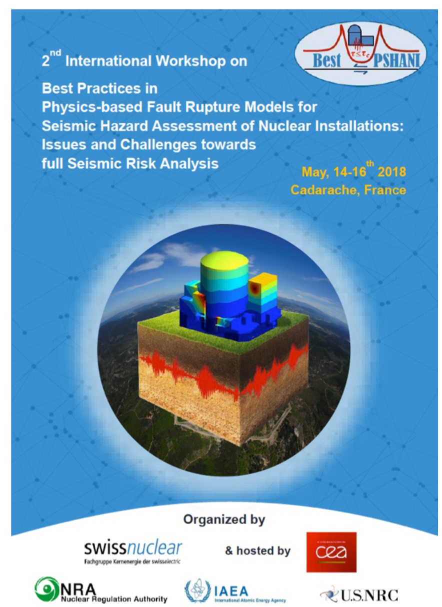
- 3-D physics-based dynamic rupture models are by construction site specifics models, because highly depend on the data of the site of interest. Therefore they are intrinsically non-ergodic models
- Capture details of the site of interest for fault displacement prediction
- Can complement the empirical models by filling the lack of data to improve the representation of the site of study and to be consistent with the non-ergodic process of natural earthquakes.
- Could provide insights on the likelihood of branching and degree of the partitioning of slip in different fault segments.

Current IAEA effort to implement Physics-based model in PFDHA

- IAEA has already recognised this issue and currently is making the effort to implement the physics-based rupture modelling in practice for PFDHA. But also in PSHA.
- These efforts have been discussed through different international working group activities, being the most outstanding two international workshops on **Best** Practices in **P**hysics-based Fault Rupture Models for **S**eismic **H**azard **A**ssessment of **N**uclear **I**nstallations (BestPSHANI) in 2015 and 2018.
- Currently we are writing an IAEA-TECDOC (Technical Document) on Probabilistic Fault Displacement Hazard Analysis (PFDHA) in Site Evaluation for Existing Nuclear Installations. In this TECDOC we are explicitly describing the use of physics-based dynamic rupture models for PFDHA





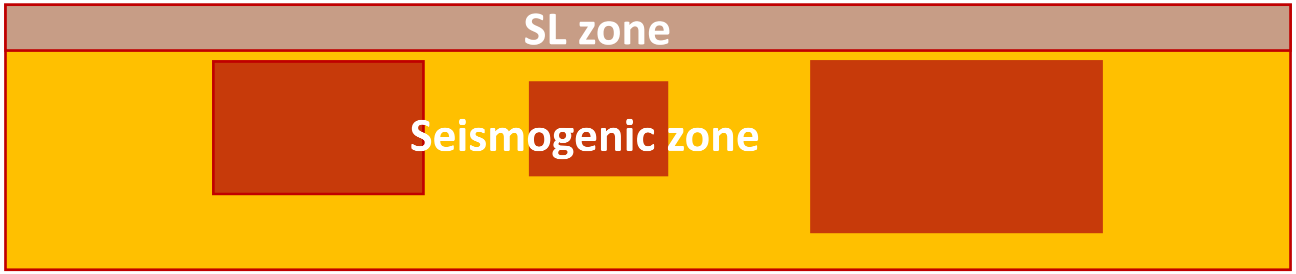


(In preparation)

Probabilistic Fault Displacement Hazard Analysis in Site Evaluation for Existing Nuclear Installations

Dynamic rupture model for fault displacement

- Need characterization of the shallow layer (SL) zone
- SL zone is assumed that rupture operates with an enhanced energy absorption mechanism (cracked, damaged zone).
- This makes the frictional properties of the shallow zone be distinct from those at seismogenic zone (e.g. Brune and Anooshehpoor, 1998; Day and Ely,2002)
- In dynamic rupture model with slip weakening friction: SL is dominated by zero or negative stress drop, and large critical slip distance (Dc)



(Dalguer et al., 2019, PAGEOPH)

Methodology

First step: Parameterization of the seismogenic zone.

- Calibrate initial stress drop to be consistent with a given target (could be kinematic slip model) and ground motion at distance larger than around 5-7km to be consistent with observed and/or empirical models.

Second step: Parameterization of the SL zone. Develop a dynamic rupture model including the SL zone for surface rupture.

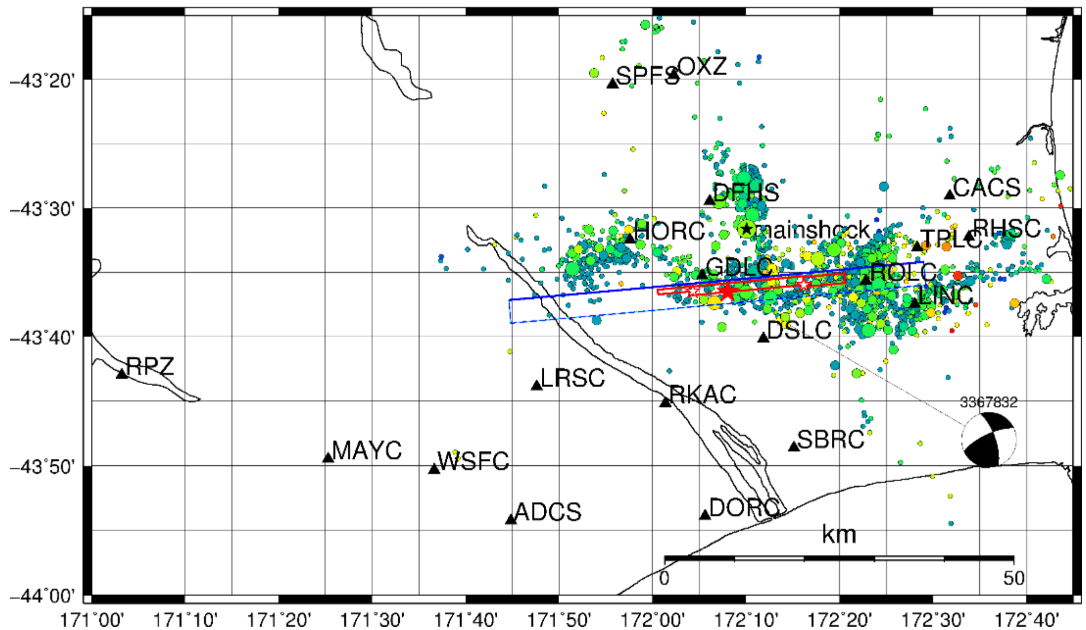
- Calibrate the stress drop at SL zone, keeping the same parameterization of the seismogenic zone developed in the first step, so that surface rupture be approximately consistent with the target (observed fault displacement).

(Dalguer et al., 2019, PAGEOPH)

The 2010 Mw 7.0 Darfield earthquake

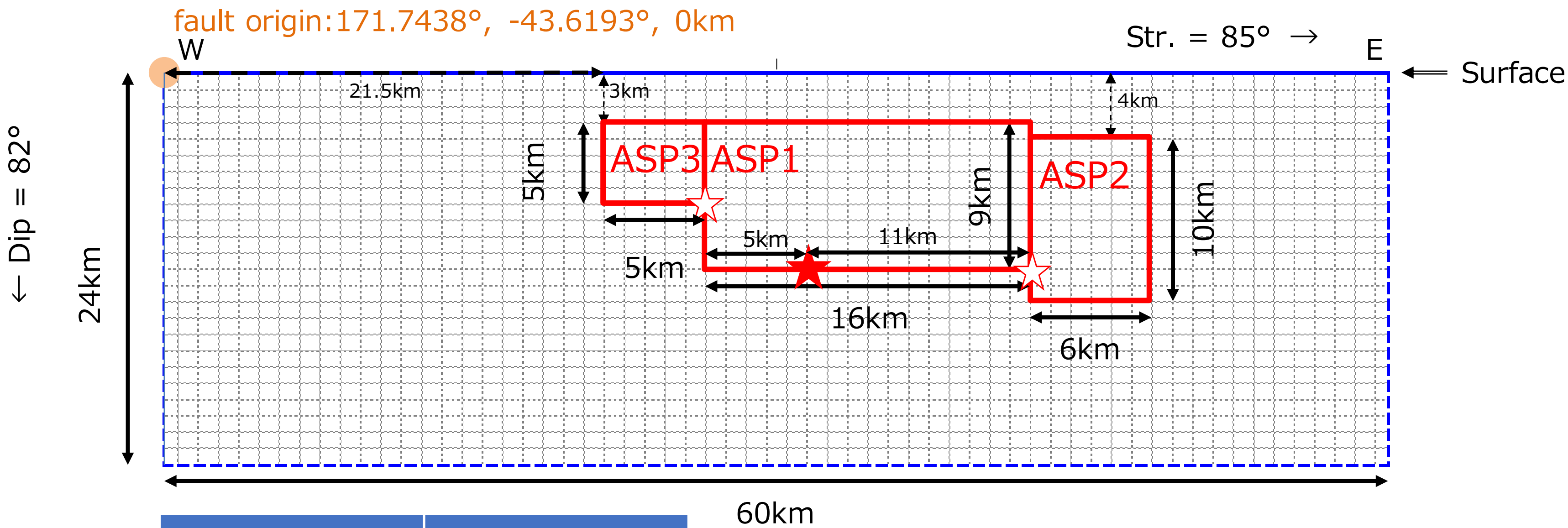
- Surface-rupturing was observed in several sites along the main fault with maximum values of 5.3m
- The fault geometry of this earthquake is complex with several fault segments, but a simplified strike slip single planar fault is assumed with a dip angle of 82 degree.

2010Darfield_H28_planer



Kinematic asperity model

- Simplified asperity model in a planar fault developed using Irikura's Recipe.

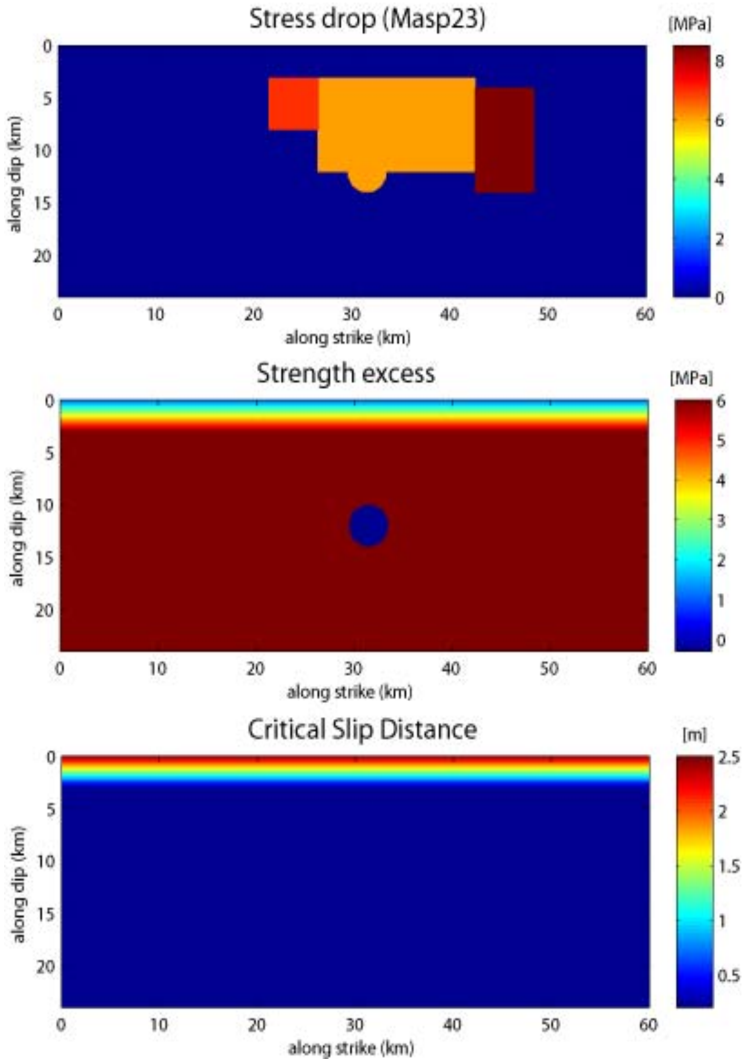


Asperity	Slip (m)
ASP1	2.5
ASP2	2.5
ASP3	2.0

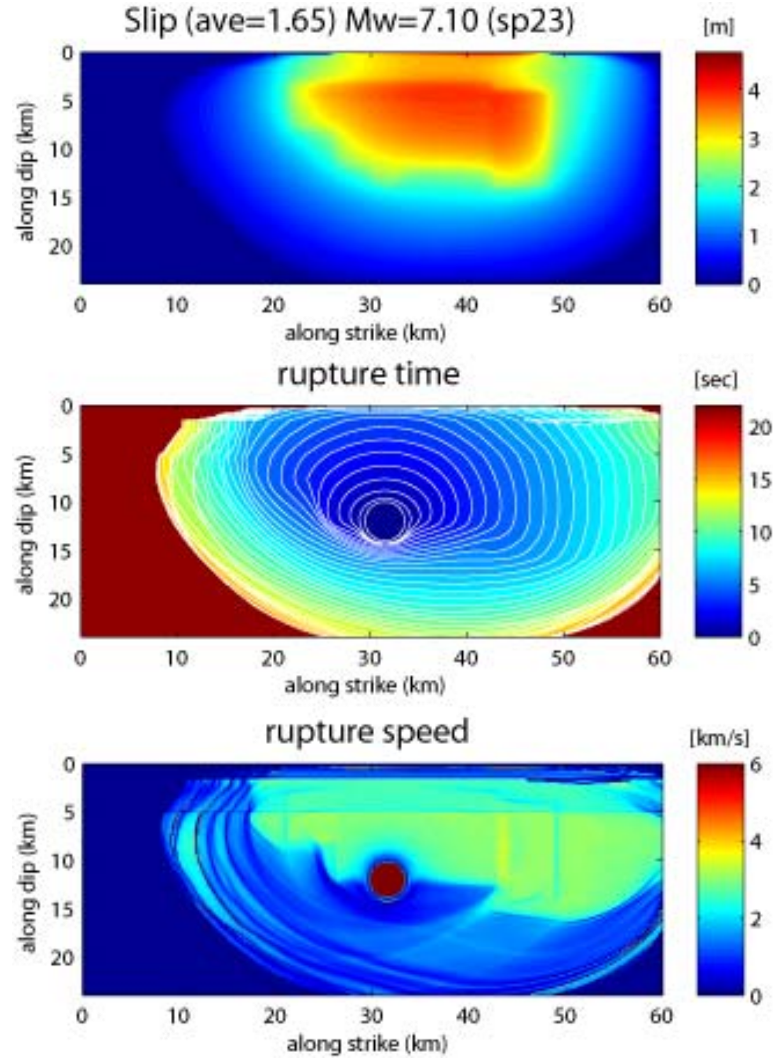
(Dalguer et al., 2019, PAGEOPH)

Dynamic asperity model

Stress Parameterization



Dynamic rupture solution

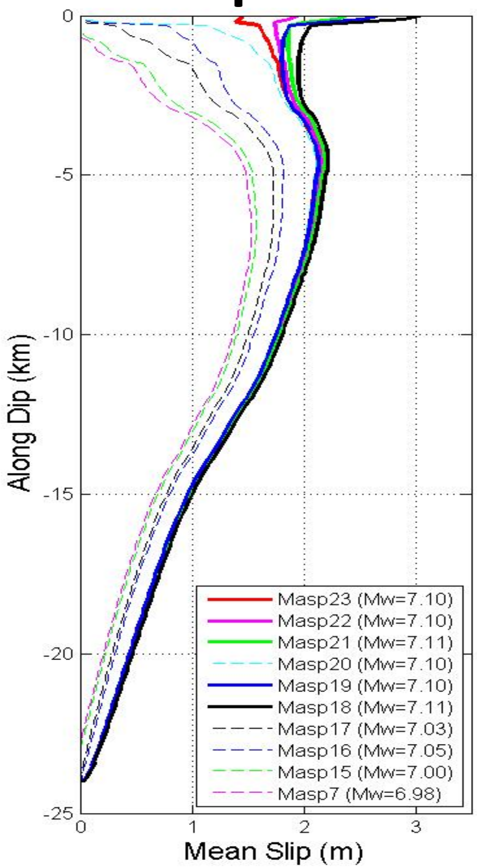


(Dalguer et al., 2019, PAGEOPH)

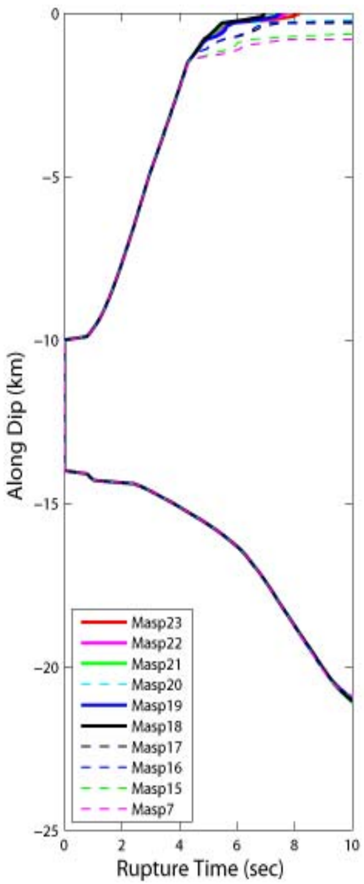
Buried vs surface rupturing (source)

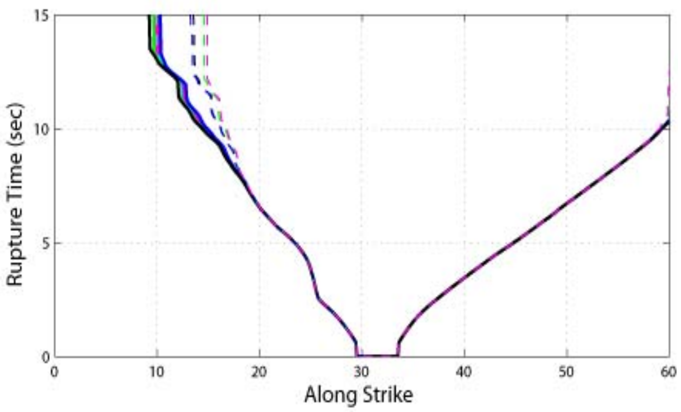
- Final slip increases due to surface rupture effect
- Rupture time at the seismogenic zone are nearly identical between buried and surface rupturing models

Slip



Rupture time

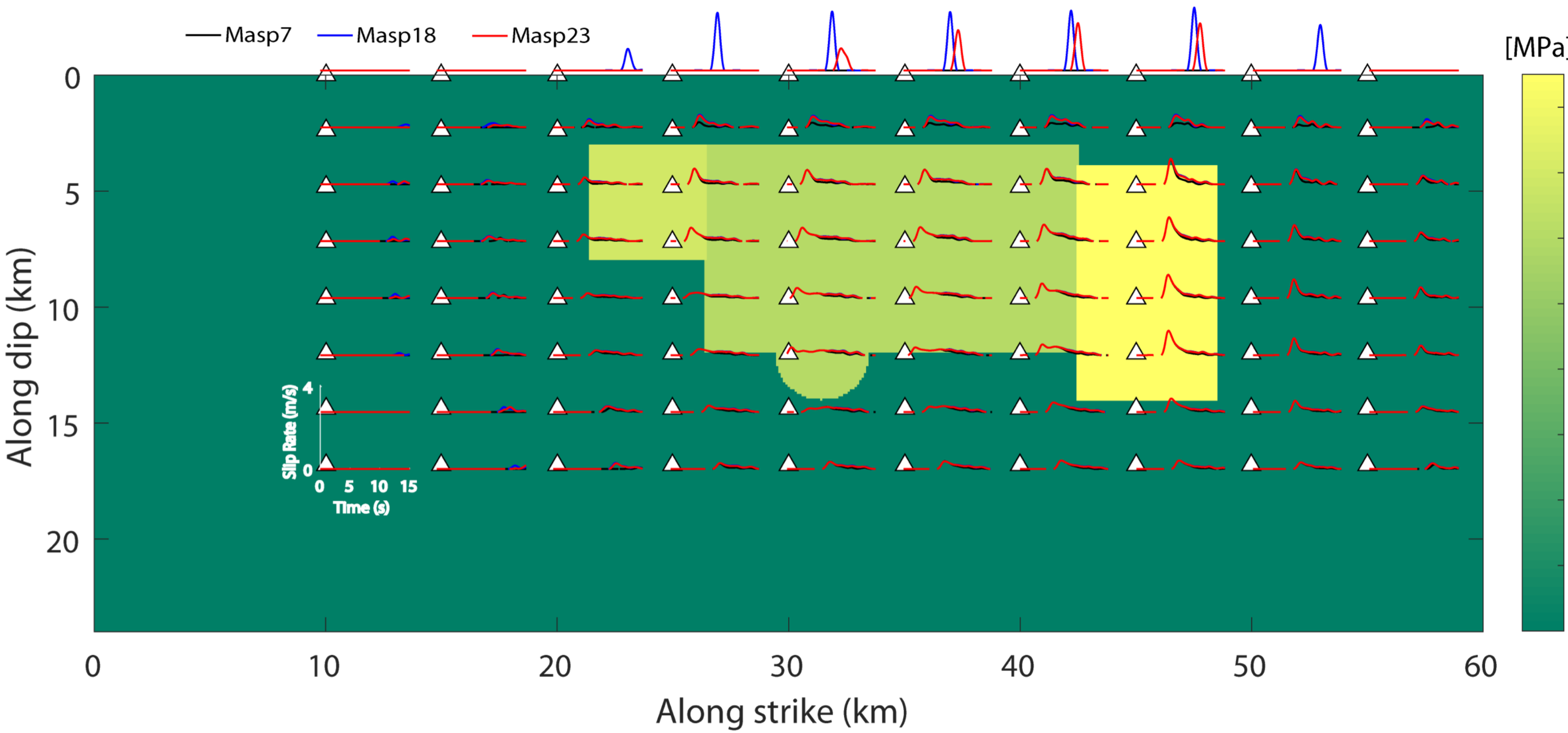




(Dalguer et al., 2019, PAGEOPH)

Buried vs surface rupturing (source)

- Slip velocity functions at the seismogenic zone are nearly identical between buried and surface rupturing models

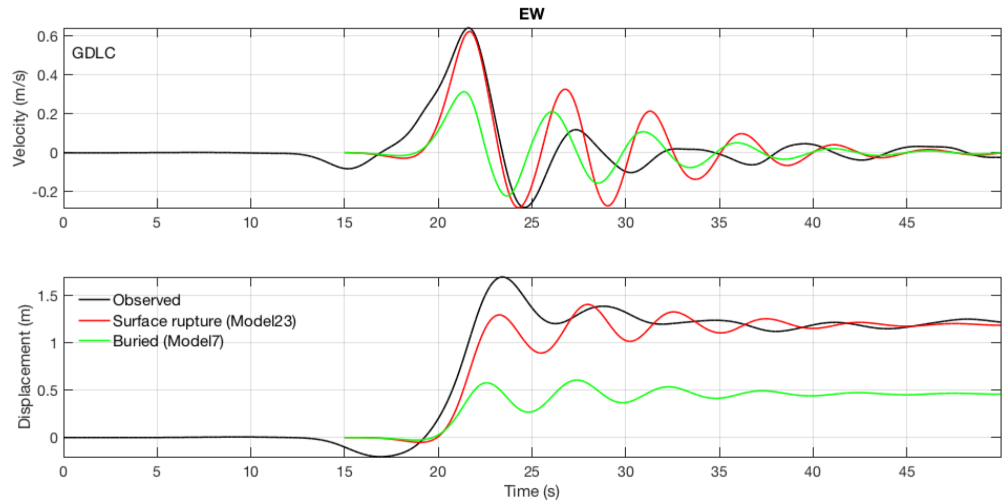


(Dalguer et al., 2019, PAGEOPH)

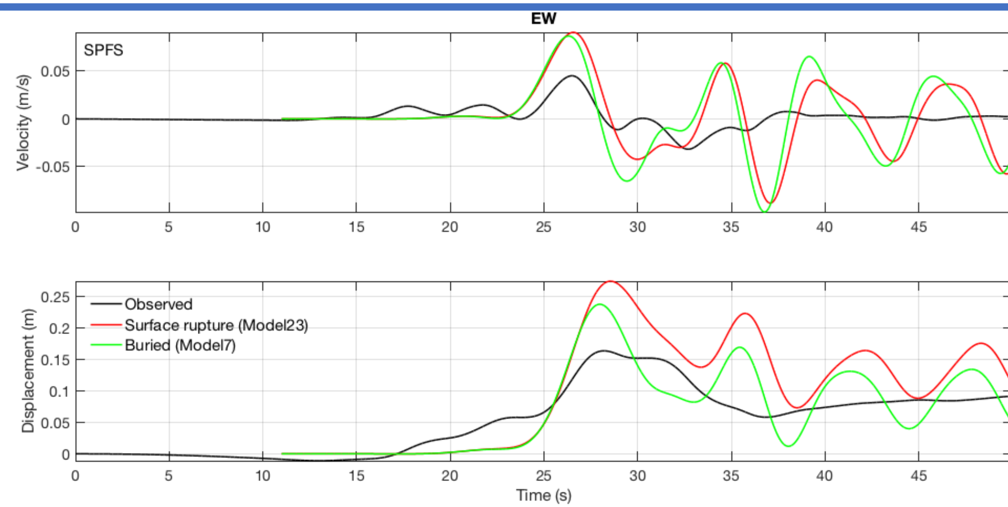
Buried vs surface rupturing (ground motion)

- Differences are evident very near to the fault
- Far to fault, ground motions are similar

Very near to fault



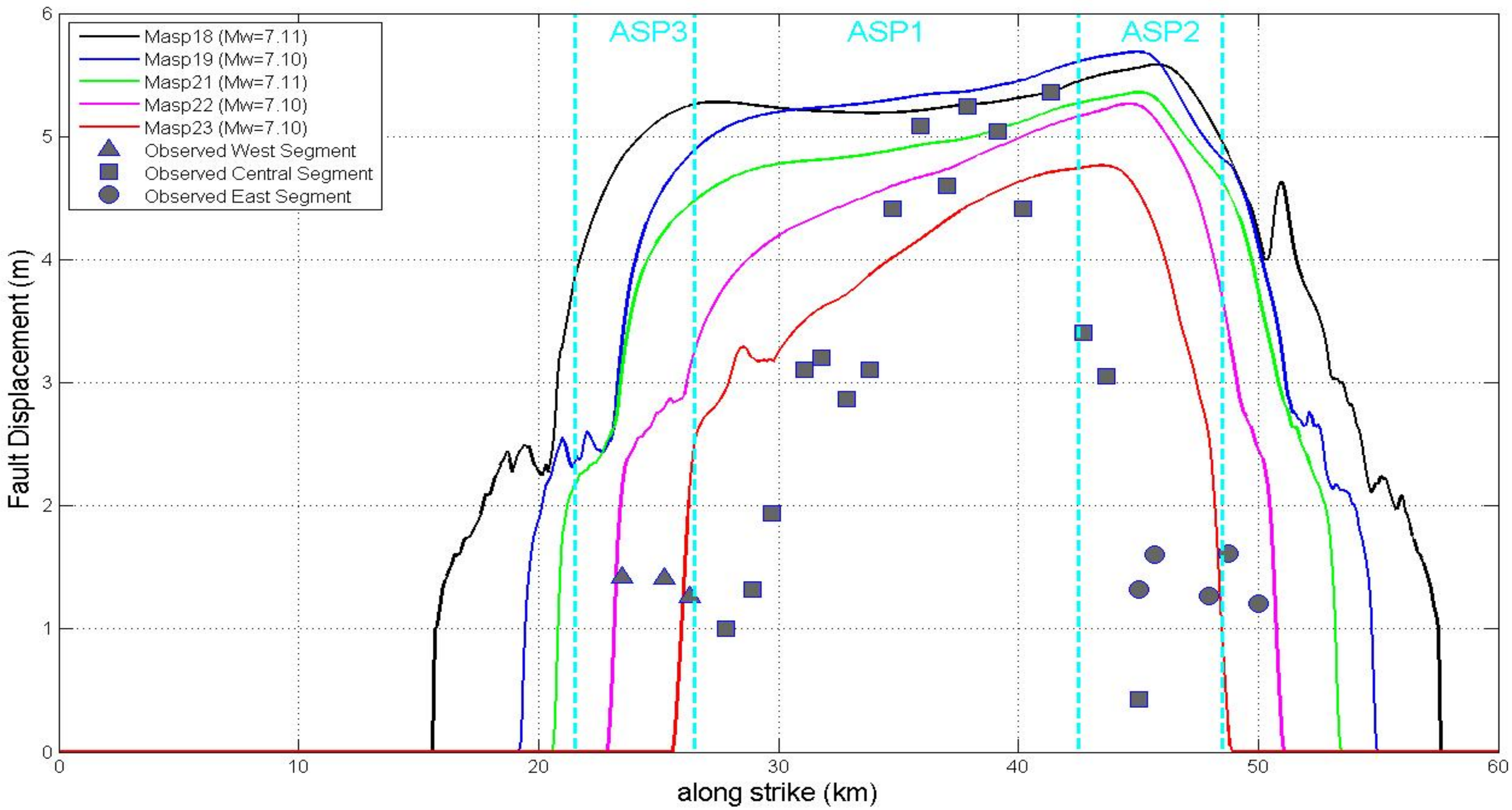
Relative far from fault



(Dalguer et al., 2019, PAGEOPH)

Fault displacement

- All surface rupture models predicts very similar ground motion
- Differences are only on surface rupture offset dur to different SL zone parameterization



(Dalguer et al., 2019, PAGEOPH)

Conclusions

- There is a concern in the IAEA member states for the safety of existing nuclear installations against fault displacement
- Current site specific PFDHA relies on global empirical data. It is a big issue because of lack of data and the assumption of ergodic models.
- 3-D physics-based dynamic rupture models can complement the empirical models by filling the lack of data to improve the representation of the site of study and to be consistent with the non-ergodic process of natural earthquakes.
- The IAEA is making an effort to implement physics-based rupture models in PHDHA and PSHA to strengthening nuclear safety.