SAPIENZA
UNIVERSITÀ DI ROMA

PhD project proposal
XXXIX cycle

Unraveling dynamic rupture propagation of an earthquake rupture on an extended fault

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1. Introduction & state of the art

Earthquakes represent one of the greatest natural hazards facing humankind. The rapid increment of technological resources and computational power, as dense seismic networks, laboratory (fig.1a) or field experiments (fig.1c), and numerical simulations (fig.1b), allow the simulations of realistic scenarios and the study of the process scalability, contributing to progress in the understanding of earthquake physics.

Earthquakes are currently studied through kinematic and dynamic models. The former simulates earthquake waveforms and geophysical observation imposing the rupture history along extended fault planes where rupture propagates at assigned rupture speeds. The latter simulates the propagation of a rupture front by imposing dynamic parameters depending on the constitutive formulation adopted to prescribe the stress evolution with slip or slip rate and/or other parameters. A widespread framework for understanding earthquakes is the analogy with frictional ruptures along pre-existing faults[4]. Faults reactivation occurs at a critical shear stress value that depends on the friction coefficient of the slip surface and on the effective normal stress exerted on the fault, following:

$$\tau_p = \mu_s \, \sigma_n. \tag{1}$$

where r_p is the shear stress at failure (peak stress), μ_s is the static coefficient of friction and σ_n the normal stress. The simplest constitutive law is the linear slip-weakening (LSW)[5], shown in fig.2a. It consists of imposing the linear shear stress decrease with slip until a critical slip weakening distance (Dc), where the shear stress reaches its residual value r_r that depends on the dynamic friction coefficient (μ_d). The earthquake rupture likely involves different dynamic processes that have promoted in the literature the adoption of different constitutive laws. For example, fig.2b shows a more general representation of a slip weakening behavior, where an initial strength-hardening phase is included, fig.2c illustrates the exponential decay of the shear stress with slip that could be representative of the thermal weakening[6] during the co-seismic phase.

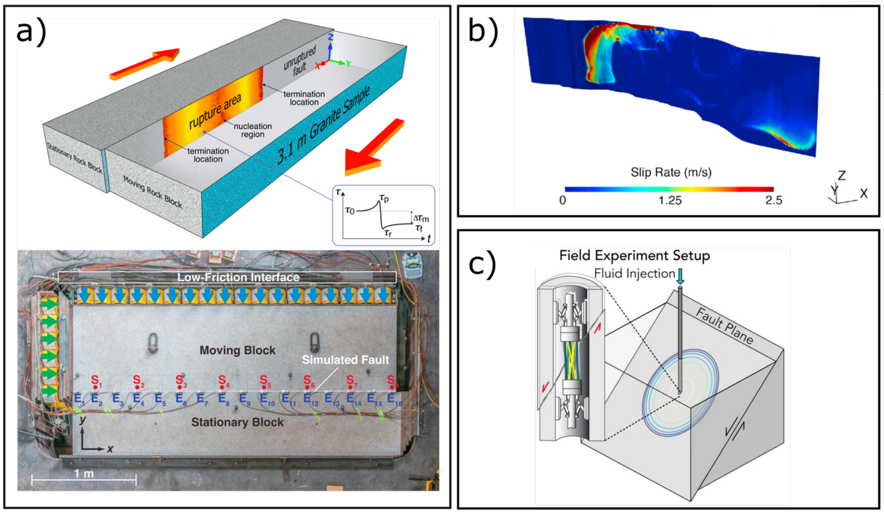

Figure 1. a) Illustration of 3m laboratory earthquake ruptures1, b) Slip rate of the Landers earthquake dynamic rupture simulation (Mw = 7.3)2, c) Sketch of a field fault reactivation experiment.

One of the crucial points for studying earthquake dynamics is understanding the energy budget. Discriminating how the energy is partitioned between on-fault dissipation, fracture energy and energy radiated in seismic waves is nowadays an open question. Defining the constitutive laws that are governing the rupture processes constrains the energy dissipated at the rupture front. The grey area below the three curves in fig.2 is representative of the energy dissipated to allow the advance of the rupture front (energy density), and it differs with the adopted constitutive relations. A crucial issue for investigating the energy budget emerges with the dichotomy between earthquakes propagation as crack or pulse-like ruptures[8]. In the first case the fault slides persistently during the propagation of the rupture front, while in the second case the fault slides during the propagation of a slip pulse moving with the rupture front. The involved physics could be strongly different[9,10,11], and to date there is not a clear view of which style of rupture (crack- versus pulse-like ruptures) is predominant.

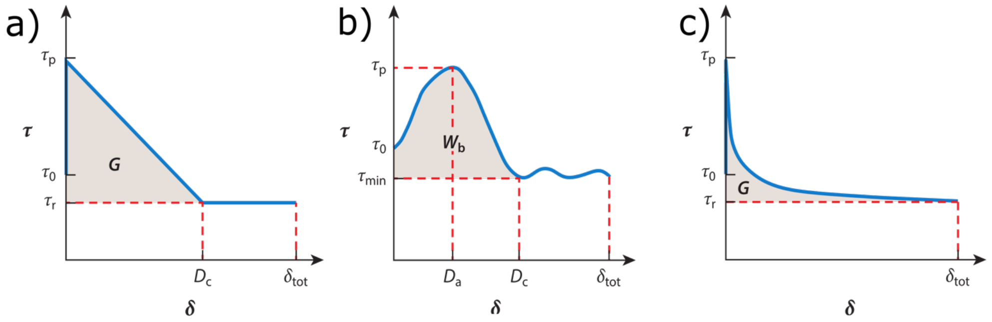

Figure 2. a) Classic slip-weakening model with residual stress independent of slip, b) General slip-weakening behavior with variable residual stress, c) Exponential decay law of the shear stress versus slip representative of the thermal weakening models. The gray area represents the energy contribution for the advance of the rupture front.

The estimated fracture energy density through geological, seismological and laboratory approaches is reported in fig.3. This figure shows that the fracture energy density scale with the slip[12], meaning that when the earthquake involves large dimensions the associated energy dissipation increases. However, inferred earthquake source parameters show a scale invariant behavior of stress drop[13]. This peculiarity seems to be still a paradox to be reconciled for the interpretation of the fracture energy scaling.

Understanding the earthquake dynamics, energy budget and rupture arrest has important implications also for the study of induced seismicity. The demand to mitigate the risk associated with anthropogenic activities and the on-fault fluid pressurization is growing[14], and an estimation of the maximum expected magnitude for the local specific conditions is required. The study of induced seismicity might foster progress for the understanding of earthquake dynamics depending on the discrepancy or analogy with the natural earthquakes.

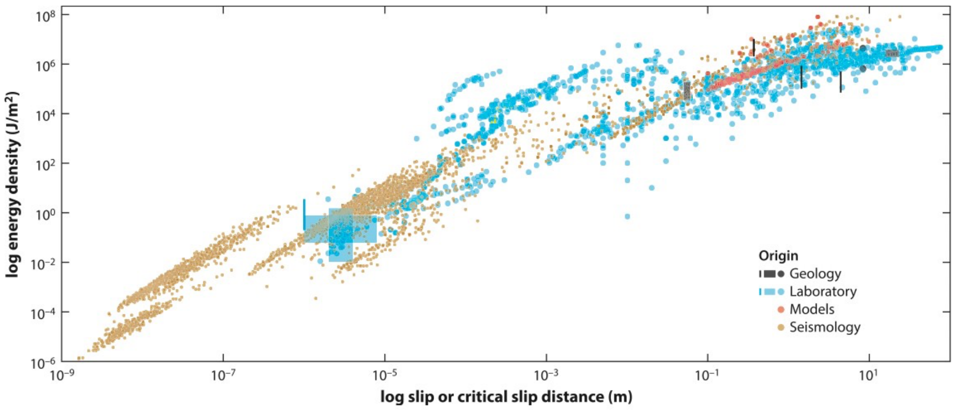

Figure 3. Scaling of fracture energy density with earthquake slip[12].

2. Research objectives

<u>General objective</u>: Modeling and constraining the dynamics of earthquake ruptures: nucleation, propagation and arrest on extended faults.

<u>Specific objective</u>: Modeling the dynamic rupture with physics-based approaches and High- Performance-Computing (HPC) of natural and fluid-induced earthquakes, focusing on:

1) Constraining the main physical parameters, constitutive relations and earthquake energy budget controlling dynamic rupture propagation from micro to large earthquake magnitudes.
2) Investigating dynamic weakening during earthquake nucleation, propagation and arrest to unravel the physical processes that control the earthquake occurrence and seismic wave generation.
3) Modeling near-fault observations of natural, induced and experimental faults.

3. Implications & applications

The research planned for my PhD has several aspects of unicity and innovation. A wide and systematic characterization of the dynamic parameters for micro-earthquakes in an extended fault will ensure progress in understanding earthquake dynamics. Detailed description of the processes involved during the rupture from micro to moderate size allows me to open new horizons in earthquake physics.
The results obtained will have implications in different areas of interest:

- Scientific impact: increase the knowledge of the earthquake physics by studying unique dataset.
- Economic impact: possibility to provide innovative understanding for renewable energy industries to address at the induced seismicity hazard.

4. Work plan

During my PhD I will participate in the research activities of the FEAR (Fault Activation and Earthquake Ruptures) project (ERC Synergy grant) contributing to the modeling working group and having accessto the data collected during the stimulation experiments. The project will use controlled fluid injections to reactivate a fault in the Bedretto tunnel (Switzerland) and induce $M_w < 1$ earthquakes. Theavailability of high-resolution data collected through on-fault instrumentations and a deep knowledgeof subsurface geology, will allow the availability of new and unique observations and the possibility tovalidate the dynamic models I am currently use. The study of induced micro-earthquakes with this unprecedented detail might be helpful to constrain the scaling relations of source parameters and toprogress in the understanding of the earthquake dynamics.
Data of frictional sliding on experimental faults performed at the lab scale using BIAX 2 in Sapienza and MEERA at the INGV (both bi-axial machines) with the Bedretto rock samples, will be analyzed andadopted in my models to reproduce the laboratory conditions and compare results with theoretical predictions.
I am also going to analyze data from natural earthquakes from micro to moderate magnitude size.The research plan foresees activities following two different directions (fig.4), as follows:

- <u>Dynamic rupture simulations (forward modeling)</u>: I will use *SeisSol*, an opensource software optimized for high performance computing (HPC), which simulates the earthquake dynamic rupture and the generated seismic waves. As already experienced during my master thesis, a distributed multi-GPU SeisSol implementation will be used, coupled with the compilation of packages to optimize the parallel computing. During the PhD I will use the numerical simulations to analyze the dynamic rupture propagation under different scenarios:
  Induced condition: I will try to provide reliable models and expected magnitudes for the induced target fault of the project considering the geological heterogeneities, fault structural complexities, laboratory/in-situ constrained stress and friction conditions and different pore pressure profiles. Simulating the 3D seismic waves propagation will also allow me to measure the expected peak ground motion (e.g. PGV) associated to micro fluid induced earthquakes, aiming to reproduce the principal seismic recorded phases arrival.
  Natural earthquake: I will model micro to moderate earthquakes ($0 < M_w < 5$) on extendedfault occurred in natural stress conditions to fill the gap in the estimates of dynamic parameters, to study their dynamic consistency with induced earthquakes and to unravelon the scaling of parameter with the large events.
  - <u>Inversion of seismic source parameters</u>: I will use a seismological inversion approach on well recorded seismic signals close to the fault to obtain the kinematic and dynamic source parameters. In particular, I will use the displacement amplitude spectral inversion coupled with a probabilistic

approach through which is possible to compute statistical indicators (mean, variance and correlation coefficient) of the source parameters (e.g., corner frequency, stress drop and radius) and anelastic waves attenuation[15]. The inversion will be applied both in the induced seismicity and natural earthquakes to have a more comprehensive and complete view of the process. The possibility to access at the FEAR data, with this unusual close distance to the fault, and with unusual high resolution, will allow me to directly compare the inferred source parameters with observations and the on-fault processes. During all the PhD period the simulations will be performed in collaboration with the CINECA infrastructures (I will annually submit a project) which provide the use of super-computeradopting HPC optimization technique.

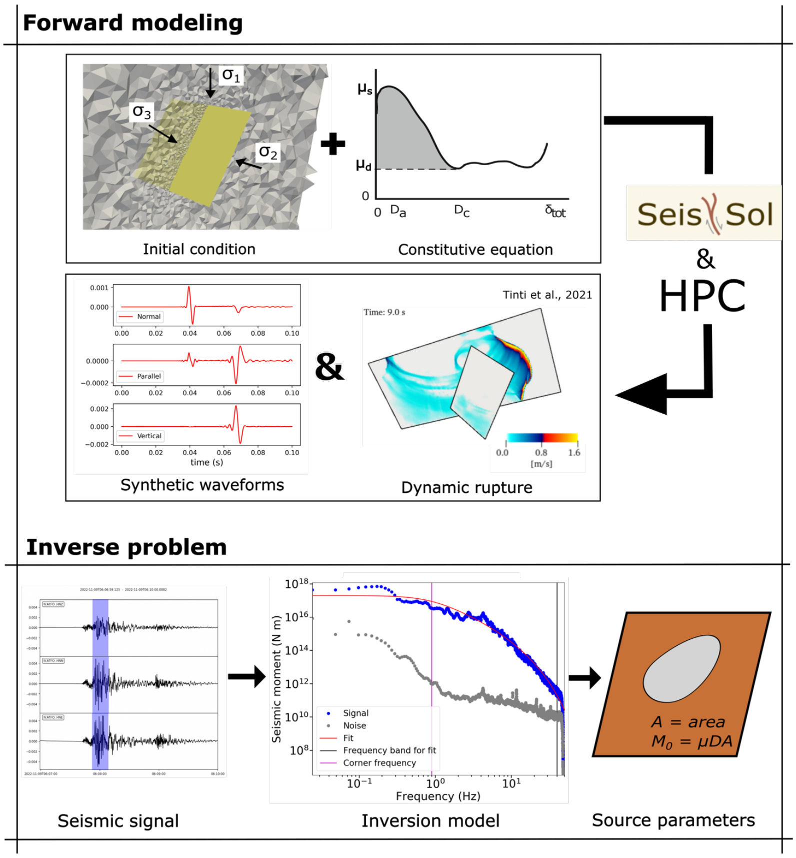

Figure 4. Summary key steps of the PhD project.

5. Milestones

The PhD will result in the publication of at least one scientific paper in an ISI journal for each of the following milestones: a) Dynamic modeling of micro-earthquakes induced by fluid injection; b) Characterization and scaling of the dynamic parameters for different earthquakes size; c) Dynamic consistency between natural and induced earthquakes; d) Energy dissipation during the co-seismic phase.

6. Dissemination plan of the results

I will actively share the results of my research participating in major geoscience and seismology conferences, such as EGU, AGU, GNGTS and SSA. During these gatherings, I intend to present my findings to a diverse audience comprising experts and fellow researchers. Furthermore, my objective is to publish influential scientific articles in esteemed peer-reviewed journals.

7. Training activities

During my PhD I will attend:

- Courses provided by the Earth Sciences PhD course of La Sapienza University (All 3 years)
- Courses on Python programming (1 year)
- Summer School on Parallel Computing held by CINECA
- ERC Tectonics weekly seminars (All 3 years)

8. International mobility

A period of formation abroad: 12 months in the University of California San Diego (UCSD) in the Institute of Geophysics and Planetary Physics where I will interact with the seismology group lead by Prof. Alice Gabriel (with whom I already have an active collaboration), conduct and planning numerical simulations on *SeisSol software* and improving my coding skills (second year).

Other activities will be evaluated during the PhD.

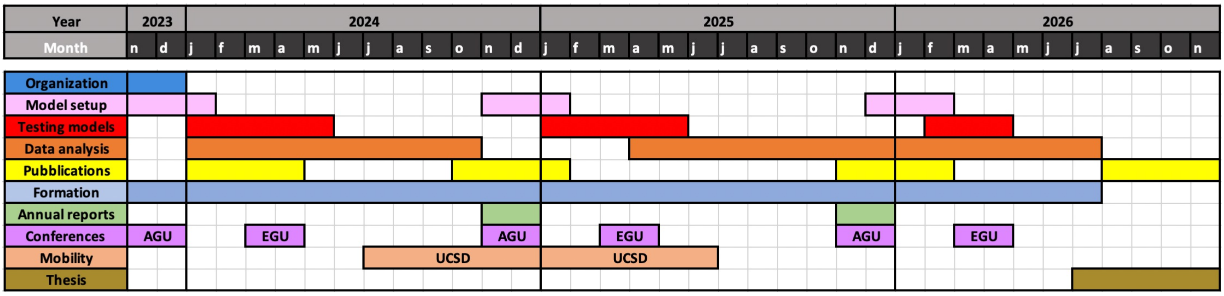

Figure 5. Gant chart of the PhD Project

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