A PRACTICAL DYNAMIC CYCLE MODEL AS PART OF A PHYSICS-BASED SEISMIC HAZARD ANALYSIS FRAMEWORK

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Abstract

Physics-based approaches are increasingly being proposed as viable tools to be employed when computing seismic hazard. This is particularly true for the ground-motion characterization component of the analysis. However, although these ground-motion models have developed in their maturity, and physics-based considerations are also being employed within source-characterization studies, the characterization of rupture scenarios and their associated ground-motions remain uncoupled within hazard studies. In the context of ground-motion modelling, physics-based simulation methods have the potential to provide important site and region-specific information that are not explicitly captured in empirically-based models. For example, the models can reproduce effects due to particular fault geometries, rupture styles and off-fault plastification among others. In fact, it has been demonstrated that these rupture processes have a first-order influence on the surface motions, particularly in the frequency range relevant for earthquake engineering. On the other hand, while computational seismology is well established within the realm of scientific research, and there exist many advocates for these approaches, their use in practice remains limited. The present paper presents a simple, practical dynamic cycle model that can be used in order to simulate fault ruptures consistent with the requirements for hazard studies. The specificity of this multi-scale model is not to reproduce individual earthquake events but to simulate entire seismic cycles in order to generate complete synthetic catalogues of potential slip patterns which can be subsequently fed as input into existing ground motion models. A key objective of the work is to derive robust statistics about slip distributions over the entire spectrum of physically admissible source ruptures, and to link the underlying frictional characteristics that govern both rupture processes and ground motion generation. The two-dimensional lattice-grid fault model is based on stick-slip dynamics derived from the Burridge-Knopoff model [1], uses a regulated rate-and-state friction law and is embedded into an elastic and uniform half-space. Despite the limited number of parameters and simplification of the earthquake processes, the model has been validated for temporal and spatial characteristics, i.e. source time functions, which are consistent with observations and conventional dynamic rupture simulations. The results are independent of artificial initial conditions since the simulations naturally drive into self-organized critical stress states similar to actual tectonic slip processes. Further benefits are insights into regional seismicity patterns such as the potential of active seismicity, tremors and slow earthquakes. This paper presents the fundamental setup of the model including the parameter derivation from regional observations and sensitivity analysis of the rupture simulations and recurrence analysis with respect to the parameter. Advantages of a single-piece software to generate both ruptures and seismic cycle are demonstrated for the framework of seismic hazard analysis.

Keywords: source characterization; physics-based SHA; multi-scale modelling; computational seismology

1. Introduction

Seismic Hazard Analysis (SHA) plays a fundamental role in the design of infrastructure and as a component of seismic risk analyses that are used for risk management and mitigation plans. SHA is traditionally performed by combining two core components: the characterization of earthquake ruptures from a seismic source model; and ground-motion models (GMMs) that define the conditional distribution of levels of some intensity measure conditioned on each rupture. While the ground-motion models are conditioned upon the rupture scenario, this conditioning is relatively weak in that the connection relates to very simple macro descriptors of the source size (magnitude) and geometry. Ideally, a common set of underlying physical characteristics would be used to link these two components. GMMs used in practice are generally based upon the calibration of simple physically-motivated parametric models using ergodic datasets. As noted above, the independent variables used in these models are simple descriptors such as magnitude and distance, and cannot be readily related to physical characteristics of the local region.

Physics-based seismic hazard analysis (pb-SHA), i.e. the explicit modelling of the underlying physical processes, has the potential to complement and improve current hazard assessments. In particular, it should be possible to transfer apparent aleatory variability into epistemic uncertainty, and to then progressively reduce these epistemic uncertainties with data acquisition and refine theories. Current possibilities and methodologies for physics-based methods have been discussed by Field [2] and Hutchings et al. [3] respectively. Multiple attempts for regional models have been conducted such as the Cybershake [4] or RsqSim [5] project for southern California, in the Marmara Sea region [6] or the validation project for physics-based ground motion simulations the Canterbury region, New Zealand [7]. The advantages of physics-based models over conventional probabilistic SHA become particularly important for hazard studies in which the dominant rupture scenarios are those for which very limited empirical constraint exist. In such cases the extrapolations of GMMs are often based upon the choice of parametric functional forms rather than a underlying physical basis (although some exceptions to this exist).

The physical model as well as the numerical implementations vary a great deal in pb-SHA applications and strongly depend on the specific aims of a project. Bradley et al. [8] present useful guidelines on the validation and verification process of physics-based models required to reproduce selected intensity measures (IMs). This project presents a simplified simulation tool that combines the seismic cycle model as well as the ground motion model required for SHA within a single physical model. The aim is to explore the benefits of the "one-piece" software to study fundamental correlations between fault characteristics and selected IMs, as well as to perform an initial attempt to generate ground motions with consistent variability (from the seismic cycle model) and potential use for SHA. The coupled model overcomes barriers present in existing physics-based approaches when merging earthquake recurrence simulations with independent rupture simulators. Hence the aim is not to replicate a single (past) event but rather generate complete synthetic databases over thousands of years with physically plausible events and use the latter to quantify uncertainties within the simulated ground motions relevant for a certain site of interest. As the model is physically based, it should be possible to calibrate the parameters for application in particular regions and to therefore generate region-specific rupture sequences and ground-motions.

The physical model is based upon the simple stick-slip block model initially presented by Burridge and Knopoff [1] and has been extended into a two-dimensional rupture simulator. The general slider-block model, including its potential and limitations, has been extensively studied in the past: Pelletier provides a broad overview [9] while specific magnitude frequency (MF) distributions have been studied in detail by Kawamura et al. [10] (and references therein), for one- and two-dimensional models and different friction laws. In [11, 12], the slider-block model is applied to successfully reproduce physically meaningful sequences of aftershocks. In addition, different stability regimes of the dynamic system have been studied and provide useful information about the potential to reproduce repeating earthquakes or tremors within the seismic cycle. The two-dimensional slider-block presented in this paper is then applied for the first time to replicate consistent seismic cycles for source-characterization studies and within the same model generate meaningful source slip distribution as input for GMMs. The slider-block model is a reasonable choice for the project inasmuch as only fundamental mechanisms are prescribed and hence allows determining basic relations valid for SHA. In addition, representing exact material and friction properties as well as the on-going physical processes require the specification of large numbers of highly uncertain parameters and also have significant computational burdens associated with them. Given the current stage of development of these methods, there is little to be gained from using significantly more complex rupture models as the large parametric cannot be reasonably reduced in the near future and the computational demands are practically inhibitive.

In this paper, the setup of the physical model will be presented and its assumptions discussed. The analysis then focuses on the validation and verification of the earthquake cycle analysis, which is fundamental for application in SHA. A sensitivity study of material and frictional parameters on earthquake recurrence metrics will be carried out and focuses on the magnitude frequency and aftershock distributions. The potential to simulate physically meaningful ground motions will be introduced and consequences for SHA discussed.

2. The physical model

The physical model used for this project is based on a Burridge-Knopoff spring-block model that has been extended into a two-dimensional coupled cycle and rupture simulator. A schematic of a one-dimensional slider-block is provided in Fig. 1 and displays the individual components of the basic model. The latter model is then extended in a second dimension in order to replicate a frictional interface that can be applied to all types of geological faults.

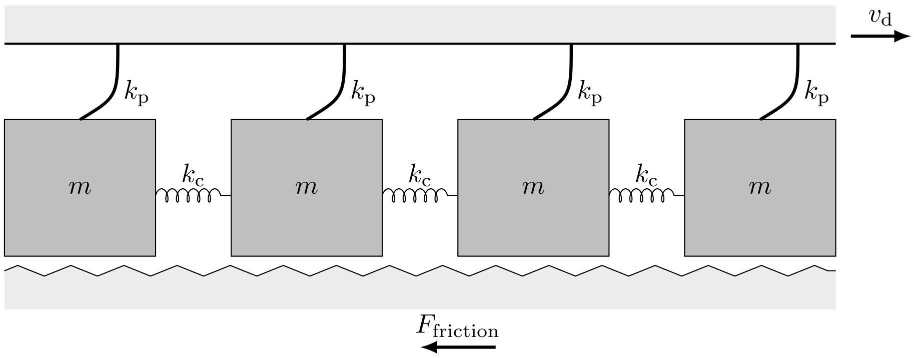

Fig. 1 – Schematic of the physical model of a one-dimensional slider-block model. The blocks of mass m are interconnected through springs with stiffness k_c and further connected to a driving plate via leaf springs with stiffness k_p. The latter plate is moving at a constant velocity v_d. A non-linear friction force $F_{friction}$ applied to each block governs the stick and slip motion

The evolution of the state in time and space for each block on the fault is defined by the differential equation in Eq. (1) that prescribes the elastic interactions for both the fault and surrounding medium through springs with stiffness k_p and k_c respectively. The variable $u_{i,j}$ corresponds to the relative displacement between each block and the driving plate. Each block has a mass m and is subjected to a driving force or plate motion at rate v_d. At the beginning of the simulations, all blocks are stationary and elastic forces between each block and the driving plate are building up while a static friction restrains all movement. This corresponds to the loading phase in the seismic cycle. Eventually, the elastic forces overcome the frictional forces and a first block starts to slide dynamically. This then corresponds to the nucleation phase or beginning of the seismic rupture. Depending on the amount of slip and level of interaction, the first sliding block can initiate the movement of neighbouring blocks and a fault rupture takes place. This model uses a rate-and-state friction force, which replicates well multiple rupture characteristics observed on real faults.

$$\rho_{surf}\ddot{u}_{i,j} = k_p(v_d t - u_{i,j}) + k_c(u_{i+1,j} + u_{i-1,j} + u_{i,j-1} + u_{i,j+1} - 4u_{i,j}) - \sigma_n\left[\tau_0 + a\log\left(\frac{\dot{u}_{i,j}}{v_0}\right) + b\log\left(\frac{v_0\theta}{D_c}\right)\right] \quad (1)$$

The evolution of the state variable θ follows the "aging" law in Eq. (2) formalized by Ruina [13]. A cut-off velocity v_0 regularizes the friction at low velocities during aseismic loading phases.

$$\dot{\theta}_{i,j} = 1 - \frac{\dot{u}_{i,j}\,\theta_{i,j}}{D_c} \quad (2)$$

The parameter set for the first parametric analysis has been derived from common material and friction properties and is detailed in Table 1. It is important to stress the direct link between some model parameters such as ρ_{surf}, k_p, k_c, τ_0 or σ_n and physical quantities that can be measured on the fault while other parameters such as D_c will be considered as tuning parameters for the model. The driving plate velocity v_d is expected to be of the order of a few cm/year. However the simulations use a 10^3 speed up which has been established to not affect the rupture process and maintain loading phases while reducing the computational costs. The initial sensitivity analysis then explores adjacent parametric spaces that result in physically meaningful recurrence and ground motion modelling. It is important to derive this standard set as a starting point for meaningful simulations as it is computationally unreasonable to explore the entire ten-dimensional parametric space in a single study. Finally, the initial model uses homogeneous parameters along the fault.

Table 1 – Derivation of model parameters

Symbol	**Parameter**	**Equation**	**Value**
e	Block dimension	-	0.8 [km]
A_{block}	Block area	$= e^2$	0.16 [km^2]
N_x, N_y	Number of blocks in x and y direction	-	20, 10 [-]
L_x, L_y	Fault length and depth	$= N_x \times e,\ N_x \times e$	16, 8 [km]
W	Lateral extent of the faulting zone	-	1 [km]
V_s	Minimum shear-wave velocity	-	2000 [m/s]
ρ_{vol}	Volumetric density	-	2.5×10^3 [kg/m^3]
ρ_{surf}	Surface density	$= \rho_{vol} \times W$	2.5 [kg/mm^2]
E	Elastic Modulus	-	6.5×10^4 [N/mm^2]
μ	Shear coefficient	$= E \times \nu/((1+\nu)(1-2\nu)),\ \nu = 0.25$	2.6×10^4 [N/mm^2]
k_c	Inter-block stiffness	$= (3\mu/(\rho_{surf}/\rho_{vol}))$	78 [N/mm^3]
k_p	Block-to-plate stiffness	$= A_{block}^{0.5}/V_s \times k_c$	16 [N/mm^3]
σ_n	Normal stress	$= \rho_{vol} \times g \times h$, $h \approx 8$ km (depth), $g = 9.81$ m/s^2 (gravity cst)	200 [N/mm^2]
τ_0	Static friction coefficient	-	0.6 [-]
D_c	Critical slip distance	-	0.004 [-]
a,b	Rate-and-state friction parameters	-	0.04, 0.06 [-]
v_0	Cut-off velocity	-	10^{-4} [m/s]
v_d	Driving plate velocity	-	10^{-6} [m/s]

Heterogeneous initial conditions are applied to the system in order to obtain the chaotic behaviour observed in earthquake processes. The initial conditions of each block's position, velocity and state are first derived from equilibrium equations before a dislocation is applied to a selected number of blocks, which will then initiate the motion during the first slip. The before-mentioned artificial kinematic conditions are only applied for numerical purposes to launch the model. After a few runs, the system will then naturally evolve towards self-critical stress states similar to actual tectonic slip processes. Given the current uncertainties in the quantifications of stress levels on real faults, this is a significant benefit of the slider-block model over more advanced models, which produce ground motions highly depending on the initial conditions.

While the initial setup uses homogeneous parameters among all blocks, boundary conditions and depth dependent profiles for the stick-slip model have been investigated. Given the simplifications in the model, the objective is not to add a surrounding layer but model the fundamental effect of interactions with the free surface or asthenosphere directly on the fault plane by modifying the values of k_p, a and b on the boundaries.

Finally, numerical implementations and optimizations have been studied in detail, as computational costs are particularly important for physics-based simulations. Combining both the seismic cycle and rupture model requires one to consider year-long time-spans of earthquake recurrence, to record individual ruptures at high frequencies (limited to 1 Hz in the current version) and to spatially discretize the faulting regions with sufficient detail for applications in pb-SHA. In addition, uncertainties are an intrinsic part of any hazard assessment and are often addressed using sampling methods or via parametric studies involving multiple runs of the numerical simulation. This is an important difference between software designed for engineering seismology and models developed for geophysical research. Good performances have been achieved using the numerical implementation presented by Lapusta et al. [14]. The numerical tolerances for the solver algorithms have been determined so to both limit numerical oscillations to a reasonable minimum and keep the computation times acceptable for the study. It is important to acknowledge the importance of chaotic behaviour in fractal dynamical system and its consequence for the accuracy and validity of the numerical simulations. An assessment based on the Lyapunov exponent has been carried out but the detail goes beyond the scope of this paper. The validity of the statistics and results presented in the following is satisfied by the shadowing theorem derived for numerical simulations of dynamical systems. Finally, Fig. 2 shows the dependence of the computation time on the number of blocks used in the model for a single earthquake cycle using the initially derived parameter set. Given the exponential relationship, computational optimizations such as domain parallelization will be required in order to run simulations for larger fault models or multi-fault systems.

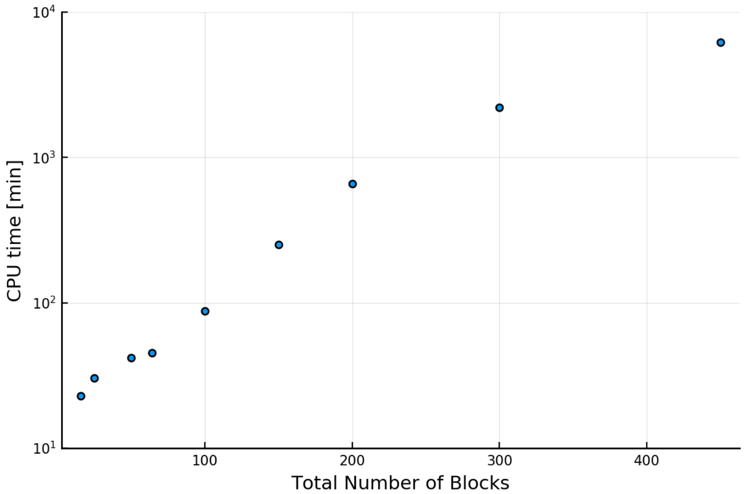

Fig. 2 – CPU time for a single rupture simulation for models using different number of blocks. Data is taken from simulations running on a single node Intel® Xeon® processor E5-2620 @ 2.00GHz

3. Analysis

The analysis presented in this section focuses on the validation of the seismic cycle and earthquake recurrence obtained from the slider block model as part of the seismic source characterization required for SHA applications. In order to study the recurrence of small and large magnitude earthquakes, a total time of more than 30000 years has been simulated and the statistics have been calculated using 5000 synthetic earthquakes with magnitude between 3.5 and 6. The detection algorithm for earthquakes within the catalogue is based on a moment rate threshold and as such all magnitudes are theoretically possible since they are derived from the overall amount of slip on the fault. Scaling relations have then been considered to define the before-mentioned magnitude boundaries as a function of the element and fault sizes. A fundamental metric for these studies is the relationship between the rate of occurrence and the magnitude of a given earthquake, which in case of real earthquakes is commonly described by the Gutenberg-Richter law [15]. The latter specifies a power-law relationship $(M > m) \propto M^{-b}$, where N is the rate of exceedance valid for any magnitude. The Burridge-Knopoff model has been extensively studied and "trained" to follow this distribution. A power-law relation is also observed in this version of the slider-block model and results are presented in Fig. 3. The limit in the maximum number of recorded earthquakes regularizes all cumulative curves in the low magnitude region. The analysis shown in Fig. 3 focuses on D_c, k_p, k_c and σ_n and their effect on both the b-value as well as the largest magnitudes observed in the synthetic catalogues. A power-law behaviour is consistently observed for a wide range of parameters. An increase in the characteristic length D_c of the rate-and-state friction law in the range [0.003,0.005] causes higher slip during the rupture and as a consequence an increased proportion of larger magnitude events. The conclusions on the influence of certain parameters are only valid within the ranges considered. The fault stiffness expressed by k_c has a central impact on the rupture. For low values relative to k_p, the model replicates a weak fault producing ruptures with few blocks. The range of observed magnitudes then gradually increases until a critical ratio dependent on both k_p and the fault size. At this level, the entire fault ruptures and characteristic behaviour appears in the recurrence analysis. While k_c controls the percentage of blocks that slip during a rupture, k_p influence the average amount of slip on the fault. Higher values of k_p imply an increased level of connectivity to the driving plate and subsequently less spread in the slip distribution. The magnitude frequency distribution shows that doubling k_p reduces the maximal observed magnitude by ≈ 0.8. Finally, the analysis of σ_n displays an increase in the b-value for higher values of normal stress. This trend is not supported in observations or laboratory test so that the influence of σ_n the rupture process has to be further analysed. In addition, the output of the magnitude-frequency relationship shows that for high values of k_p or σ_n, the fault starts to develop characteristic behaviour. It is therefore of interest to further analyse this observation in relation with the underlying physical parameters. Some parameter sets also contain a single large magnitude earthquake (with rate of exceedance equal to 10^0) and considerable deviations from a power law function are observed. These are then considered as artefacts due to the limited observation period and are not linked to a physical process.

The critical slip distance D_c used in the description of the rate-and-state friction law can hardly be observed in nature and the values used in numerical simulations vary significantly from experimental observations on rock samples in laboratories. Therefore D_c will be considered as a tuning parameter to calibrate the physical model. On the other hand, the inter-block springs as well as the applied normal stresses can directly be linked to material and stress properties on real faults. As such the simulations support fundamental correlations observed between geological observations and regional seismicity. Further studies are carried out in order to assess the impact of secondary parameters such as ρ_{surf}, v_0 and τ_0. Finally, size effects and model artefacts due to the finite grid have been considered and identified by varying the grid sizes during the sensitivity analyses. Limits of parametric domains can subsequently be derived based on a critical number of blocks that slip during a single rupture.

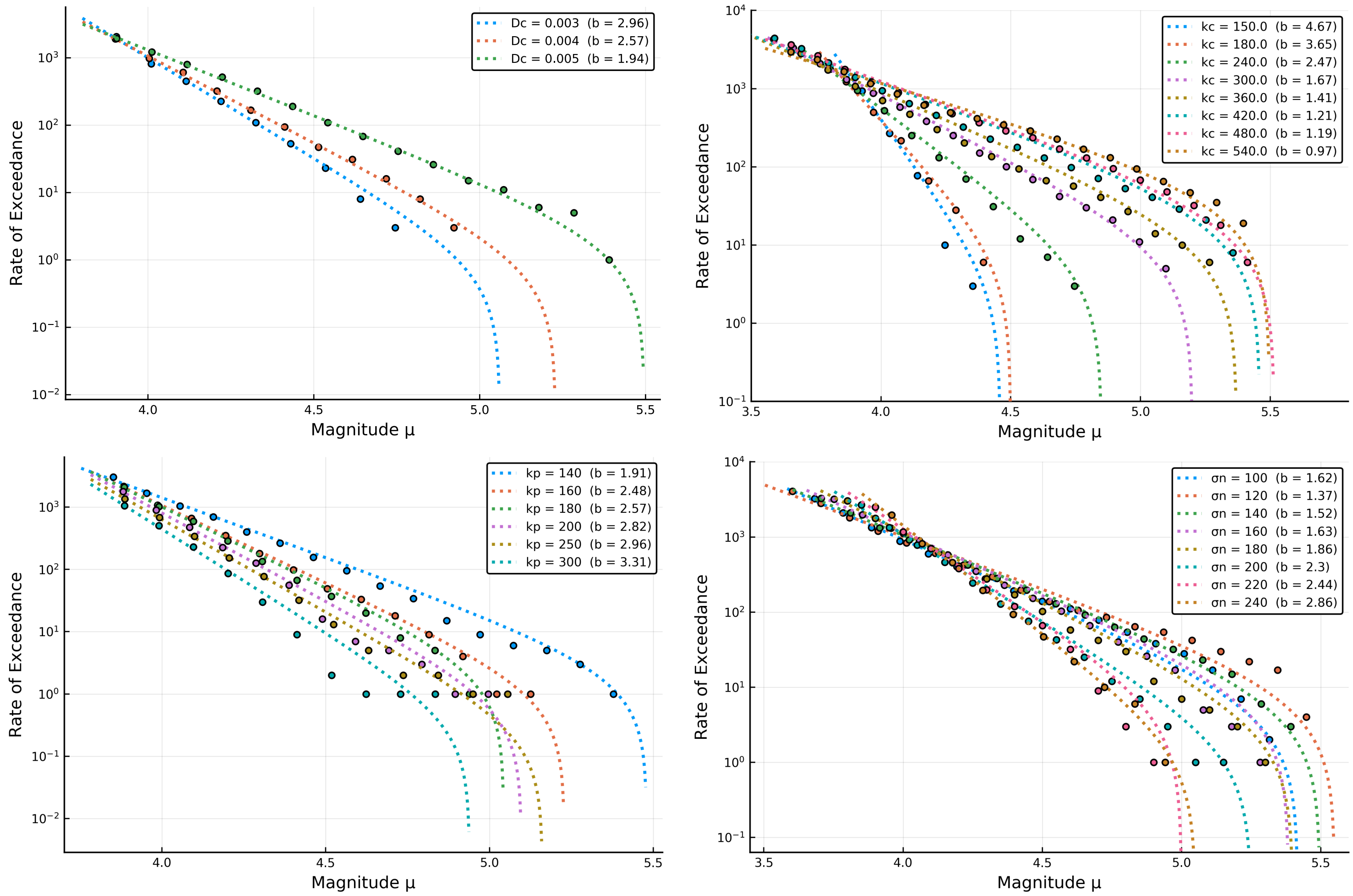

Fig. 3 – Rate of exceedance as a function of the magnitude represented for various values of parameters D_c [-], k_c [Mpa], k_p [Mpa] and σ_n [Mpa]. b-value from a maximum likelihood estimation of a power law is provided in for each simulation.

The initial observations regarding the relationship between constitutive parameters and seismicity have motivated further specific analysis such as the propagation of uncertainties in the b-value due to the variability of a given input parameter. The b-value in the simulations can certainly be matched to a value close to one as observed in nature though it should be considered that in the current setup, it only expresses the seismicity of a single fault with free boundary conditions and not of a final region-specific model. Seismicity studies due to the parameters a and b from the rate and state friction law have been extensively discussed in the literature and are therefore not included in this paper.

The recurrence analysis based on the magnitude frequency relationship provides robust statistics that underline the capabilities of the modified Burridge-Knopoff model to reproduce physically meaningful seismic cycles. A further requirement is to generate physically plausible fore- and aftershocks sequences. For this study, the rate of occurrence is analysed as a function of the time elapsed since the mainshock. The synthetic recordings are then compared against the modified Omori law [16] which states a power law relationship $N(t)=\frac{K}{(t+c)^p}$ where N is the number of aftershocks at a time t after the mainshock and K, c and p are constant values. Metrics have been defined to extract the mainshocks from the synthetic catalogues while the processing of aftershock data follows Ogata [17]. In order to extend the range of possible stress redistributions, a 10 × 30 block grid has been used for the aftershock analysis. In the simulations, the occurrence of aftershocks qualitatively follows a power law despite a considerable variability from one mainshock to another. A wide range of simulations shows features of power law decay while only few display a constant rate of occurrence immediately after the mainshock (c > 0), as shown in Fig. 4 for a specific simulation using altered values for k_p = 250 MPa and σ_n = 120 MPa.

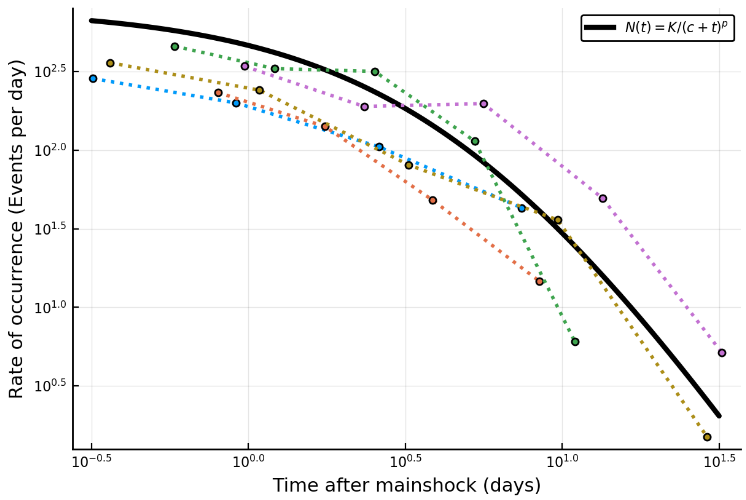

Fig. 4 – Rate of aftershock occurrence as a function of the time elapsed since the mainshock. The aftershock data is provided for the five largest mainshocks in a simulation using k_p = 250 MPa and σ_n = 120 MPa. The data is compared against an Omori law using parameters K= 105, c = 3 and p = 2.

In addition, it can be noted that the variability is quite significant from one mainshock to another for the same parametric setup. This observation is characteristic for simulations with weak interactions (small values of k_c) and eventually leads to chaotic aftershock sequences without significant decay in the number of occurrences. Finally, numerous simulations qualitatively reproduce the known distributions but the fitted model use constants (K, c and p) outside the ranges of commonly observed values for real earthquakes. For instance, the aftershock sequences in Fig. 3 are compared to a power law with exponent p = 2 while in reality, values from 0.9-1.4 are generally observed. Unlike in the latter model setup, many simulations cannot be qualitatively compared to a single curve describing the modified Omori law. Their more complex aftershock sequencing is caused by the presence of individual aftershocks with high magnitude, which add additional local power-law decays to the sequence. For a range of parameters, the simulations do not satisfy Båth law and contain aftershocks that cause important deviation from a modified Omori law and make the fitting to a single curve unrealistic. These characteristics in addition to the fractal decay are nevertheless occasionally observed in real earthquakes, such as the aftershock sequence of the Amatrice-Norcia (2016-2017) earthquake. For the aftershock study as well as the previous magnitude frequency analysis, it is of interest to understand the effect of a parameter set on the output in order to subsequently model regional cases (including their complexity) rather than to explicitly map the model to either a modified Omori law or Gutenberg-Richter law.

Beside the ability to reproduce seismic cycles, the model is expected to generate physically meaningful rupture sequences as input for applications in SHA. Very little research has so far focused on event-specific properties of individual slip patterns generated with the slider-block model and the analysis part of this project has asserted a high potential also for source rupture simulations. For an initial validation, the synthetic ruptures are qualitatively compared to observed properties of real rupture processes. The analysis therefore focuses on the kinematic characteristics on the fault as they exclude additional variability due to path and site effects present in surface motions. The stick-slip model is in itself just a source model and expected to generate physically meaningful slip patterns which can subsequently be fed into existing kinematic ground motion models in order to obtain the displacements off the fault. Regarding the validation, the assessment is based on robust metrics including the Fourier spectrum of the moment rate function. The moment rate is a reliable measure inasmuch as discretization effects due the individual blocks tend to be smoothened out in the calculation of the moment rate. Fig. 5 displays the spectral decay of the moment rate of the same mainshocks used previously for the aftershock study. The simulated earthquakes qualitatively show good agreements with characteristics observed in real earthquakes including a nearly constant rate at low frequencies and a smooth transition towards the ω^{-2} decay for higher frequency ranges. While the spectral decay is observed for larger earthquakes and generally mainshocks, the simulations produce, particularly for lower k_p-values a significant amount of slow slip events involving only few blocks.

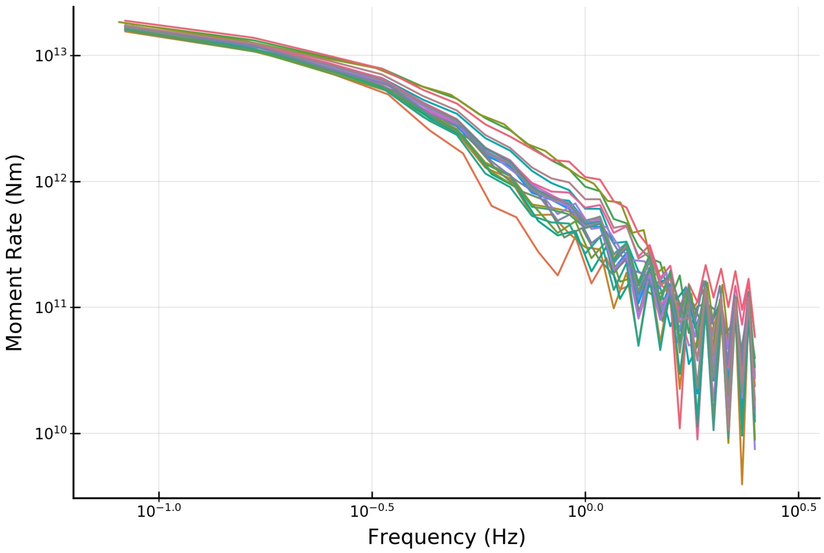

Fig. 5 – Spectrum of the moment rate function observed in the selected simulation using k_p = 250 MPa and σ_n = 120 MPa in addition to the standard parameter set. Each colored curve corresponds to the moment rate of a different mainshock observed during the overall simulation time.

The trend of the moment rate spectrum generated by the slider-block model then gives rise to further studies and validations to determine the influence of material and friction parameters as well as geometric effects on the location of observed corner frequencies. With regard to engineering applications, the simulations allow to specify higher sampling rates and refined mesh sizes in order to obtain more precise information on the high frequency content.

In addition to the temporal evolution of the individual ruptures on the fault, the spatial complexity of the slip distribution has been investigated statistically. The average radial slip spectrum decay has been studied for this purpose and a physically plausible power spectrum has been observed in the wavenumber domain. Given the relatively coarse discretization of the model, the validity of the observed fractal distribution has to be examined first in order to avoid potential numerical artefacts or finite size effects.

4. Conclusions

The analysis in the previous section outlines the ability of the modified slider-block model to replicate both fundamental properties of long-term seismicity and rupture characteristics of individual events. Some of these properties have been studied previously and much research has focused on the relationship between the magnitude and frequency of occurrence of earthquakes. This paper then emphasizes on the potential of the slider-block model to be used as a coupled source and ground motion simulator to support studies in engineering seismology. From this perspective, the slider-block model presents the key benefit that its parameters can be tuned to a particular region and simultaneously provide specific information on the source characterization as well as region-specific properties that influence the ground-motion modelling. As such, the model has important application in SHA and should enable some unrealistic combinations of source and ground-motion characterizations logic-trees to be removed. In fact, the seismic source and ground motions are currently considered independently. As the overall analysis derives from a single set of parameters, influence of model and parameter uncertainties can be studied systematically and the confidence in the final hazard consistently quantified. Furthermore, the model provides a basic physical model to study the influence of observable material and frictional properties on seismicity and rupture patterns.

First, a seismicity study has been performed in order to characterize the seismic source. Overall earthquake recurrence studies as well as an aftershock study for specific events demonstrate the potential of the slider-block model to provide physically meaningful results. The modified stick-slip model presented in this paper reproduces observed statistics such as the Gutenberg-Richter law or the modified Omori law. These results are supported by many previous publications on this specific topic. The sensitivity analysis then highlights first-order effect of model parameters on seismicity statistics and enables the model to be adapted to specific regional cases.

The second part of the analysis demonstrates that the slider-block model, together with the same parametric setup, is equally capable of reproducing physically meaningful fault ruptures. To this extent, the evolution in time has been analysed based on the moment rate spectrum and the spatial distribution of slip along the fault studied based on its spatial spectrum. Given the present variability in the output, future studies will focus on the statistical description of the rupture properties and capture the relationship between material and friction properties and the rupture dynamics in the slider-block model.

Finally, the efficient numerical implementation and the simplification of the physical processes allow for quick computations, which facilitates further parametric studies, uncertainty analyses and extensions of the fault size and geometry. Hence, these performances enable further developments of the current model as required for real application in SHA and in engineering seismology.

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