

Seismogenic Potential of the Main Himalayan Thrust constrained by coupling segmentation and earthquake scaling

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1 Introduction

Most evaluations of the seismic potential of a region estimate how the deformation rate is apportioned amongst earthquakes of different magnitudes and recurrence intervals, using historical and instrumental seismic catalogs as a guide. Some models incorporate aspects of earthquake physics (e.g., Field et al., 2014; Shaw et al., 2018), but fault physics are not usually directly included. This is largely because physics-based models would significantly increase the computational time and power required to derive large scale earthquake hazard models such as for the entire Himalayan arc.

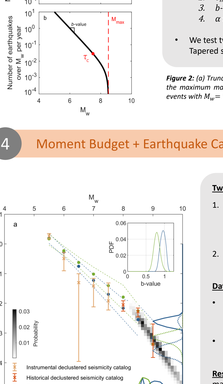
One particular missing ingredient in such estimates is the influence of the spatial distribution of locked/creeping sections of faults. On top of modulating the moment budget, **regions slipping aseismically influence the propagation and arrest of dynamic ruptures**, controlling the size and thus the magnitude of earthquakes.

We provide a computationally efficient method to evaluate the seismic potential of a region using four constraints:

1) The budget of moment along a fault
2) Instrumental and historical earthquake catalogs
3) Earthquake scaling laws
4) Effect of the fault frictional segmentation

We apply this methodology to the Himalayan region

2 Regional Setting



- Recent studies have shown that the Himalayan region is under the threat of earthquakes of magnitude 9 or larger (e.g. Stevens and Avouac, 2016).
- However, these studies did not account for physics of fault slip, specifically the **influence of frictional barriers on earthquake rupture dynamics**, which controls the extent and therefore the magnitude of large earthquakes.
- According to Dal Zilio et al. (2020), there are **3 potential frictional barriers** on the Main Himalayan Thrust (MHT)

***Figure 1**: Regional setting of the Main Himalayan Thrust (MHT) and interseismic coupling map along the MHT (Dal Zilio et al., 2020). Black dashed lines indicate the position of the potential barriers to earthquake propagation. The dots represent the microseismicity since 1995 from the ANSS catalog. Dark green dots are earthquakes selected for the seismic potential analysis (<200 km from the MHT trench). Thick green lines indicate the spatial extent of historical large earthquakes (Mw>7.5 since 1500; Bilham 2019). The thin solid blue line delimits the bottom extent of the coupled zone, based on a coupling threshold of 0.3. The bottom left inset shows the PDF of the moment deficit rate.*

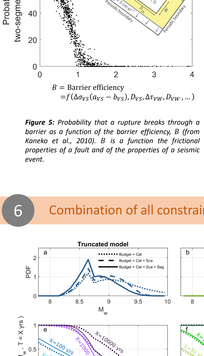
3 Overview of the Method



- We build a suite of long-term earthquake rate models and, for each model, evaluate its probability in light of the 4 constraints (see introduction).
- The models have 4 parameters:
  1. M_{max} : Maximum magnitude
  2. τ_{max} or τ_c : Recurrence time of event
  3. b-value : Relative distribution between small and large event
  4. α : Proportion of moment released by aftershocks + Postseismic => 25%
- We test two types of models: Truncated seismicity model (Fig 2.a) and the Tapered seismicity model (Fig 2.b)

***Figure 2**: (a) Truncated seismicity model. M_{max} and τ_{max} are the magnitude and recurrence time of the maximum magnitude earthquake. (b) Tapered seismicity models. τ_c is the recurrence time of events with $M_w = M_{max} - 1$.*

4 Moment Budget + Earthquake Catalogs Constraint



Two constraints:

1. We assume that on the long-term average, earthquakes and aseismic slip (represented by the seismicity model in Section 3) release a moment rate equal to the moment deficit rate estimated by the coupling map (i.e. the moment budget is balanced).
2. Earthquakes (excluding aftershocks) obey a power-law magnitude-frequency distribution (MFD) up to a maximum magnitude.

Data:

- Coupling model from Dal Zilio et al. (2020) which uses a Bayesian approach
  → Provides Moment Deficit Rate PDF (see inset of Figure 1)
- Instrumental (ANSS) and historical (Bilham, 2019) seismicity catalog
  → Provides constraint on the MFD

Results: For both truncated and tapered models, earthquakes of magnitude larger than 10 cannot be ruled out when scaling laws and segmentation of coupling are not accounted for.

***Figure 3**: Seismic potential analysis using only the moment budget and the seismicity catalog as constraints. The blue and green elements in the figure are associated to the truncated and tapered MFD models, respectively. The dots indicate the mean of the marginal PDF of the seismicity models. The dashed lines indicate the spread of the 1% best seismicity models. Red and orange crosses and error bars indicate the rate of occurrence of historical earthquakes and earthquakes occurring over the instrumental period, respectively. The gray shaded distribution indicates the marginal probability of the maximum magnitude earthquake and its rate. The solid lines on the M_w axis indicate the marginal probability of M_{max}, $P_{M_{max}}$. The blue solid line on the earthquake frequency axis indicate the probability of M_{max} frequency, assuming that M_{max} is equal to the mode of $P_{M_{max}}$, M_{Mode}, for the truncated model: $P(\tau_{max} \mid M_{max} = M_{Mode})$. The dashed lines on the earthquake frequency axis indicate the probability of having an event of magnitude $M_w = M_{max}$ at a certain rate, τ: $P(\tau \mid M_w = M_{Mode})$. $P(\tau \mid M_w = M_{Mode})$ considers all magnitudes in the seismicity models, while $P(\tau_{max} \mid M_{max} = M_{Mode})$ considers only the recurrence rate of M_{max}. The top-right inset shows the marginal probability of the b-value. Note that the seismicity MFDs in the figure are not cumulative.*

5 Fault Segmentation and Earthquake Scaling Constraints

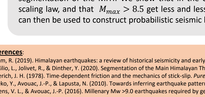


***Figure 4**: Moment-Area scaling law. Black dots represent the data from Ye et al., 2016. The red line is the data linear regression, fixing the slope at 3/2, for which the equation is shown at the bottom right of the figure.*

***Figure 5**: Probability that a rupture breaks through a barrier as a function of the barrier efficiency, B (from Kaneko et al., 2010). B is a function the frictional properties of a fault and of the properties of a seismic event.*

Two constraints:

1. Considering the moment-area scaling law, earthquakes of a certain size are only plausible if they can fit within the seismogenic area.
2. We consider the effect of aseismic barriers on rupture propagation based on rate and state friction law (Dietrich, 1978). Kaneko et al. (2010) provides a relationship between the frictional properties of a fault, the properties of a seismic event, and the probability of this event to pass a frictional barrier (Figure 5).

Data:

- Coupling model from Dal Zilio et al. (2020)
  → Provides area of the seismogenic zone
  → Location and size of the barriers
- Magnitude and area of earthquake catalog from Ye et al., 2016
- The properties of the fault and potential seismic events, and their uncertainties, can either be estimated from the coupling model or from other published studies.

Method: We sample the space of magnitudes, compute the corresponding spatial extent of ruptures and evaluate their probability considering the scaling and their probability to cross barriers.

Results:

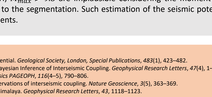


***Figure 6**: PDF (expressed in counts) of earthquakes considering the moment-area scaling law and the MHT segmentation, from 408'500 events uniformly sampled between M_w6 and 10. The pink histogram shows the PDF of earthquakes considering only the moment-area scaling law while the yellow histogram considers both the scaling law and the coupling segmentation into account. The black line is the ratio between the yellow and pink histograms, representative the effect of the segmentation, alone.*

6 Combination of all constraints

***Figure 7**: (a) show the evolution of the marginal PDF of the maximum magnitude for an earthquake when progressively adding constraints, for the case of truncated MFDs. Dotted lines indicate the marginal PDFs for the moment budget analysis, the dashed lines indicate marginal PDFs when adding the earthquake scaling constraint and the continuous line indicate the marginal PDFs with all constraints. (e) shows the probability of occurrence of earthquakes of magnitude larger than Mw over a period of X yrs for the case of truncated MFDs. Dashed lines indicate the PDF considering only the moment budget analysis while continuous lines show the PDF including all observational and physics-based constraints. We show the probability of occurrence of such events for 4 time periods, 30, 100, 1e3 and 1e4 yrs. (b) and (f) are the same as (a) and (e) for the case of tapered MFDs. (g) Marginal probability of rupture extent for a M_w9 earthquake. This PDF directly derives from our PDF of seismic models accounting for all observational and physics-based constraints. K and D stand for Kathmandu and Delhi. (d) Cumulative PDF of a M_w9 source distance from Kathmandu and Delhi.*

In conclusion, our study shows how the seismic potential of a fault can be evaluated taking into account first-order physics of fault slip and all sources of uncertainties. We introduce constraints by considering global scaling laws and the frictional segmentation of the MHT. We show that in the case of the MHT, $M_{max} > 9.5$ are implausible considering the moment-area scaling law, and that $M_{max} > 8.5$ get less and less probable due to the segmentation. Such estimation of the seismic potential can then be used to construct probabilistic seismic hazard assessments.

References

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