# Slow-Slip Earthquakes in Costa Rica and their Potential Impact on Seismic Hazard Assessments

Mario Arroyo Solórzano[1,2], Fabrice Cotton[1,2], Graeme Weatherill[1], Jorge Jara[1] and Álvaro González[1,3]

[1]GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany; [2]University of Potsdam, Germany; [3]Centre de Recerca Matemàtica, Bellaterra, Barcelona, Spain

Contact author: marroyo@gfz-potsdam.de

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## 1. Introduction

- Costa Rica is located at a subduction margin in a complex boundary where four tectonic plates (Caribbean, Coco, Nazca, and Panama) interact (Fig. 1a).
- A Slow-Slip Earthquake (SSE) is a discontinuous event of fault slip that releases tectonic stress slowly, over a period of hours to months, and which may be accompanied by seismic tremor.
- SSEs play a very complex role in the seismic cycle, representing a crucial element to be considered in seismic hazard.
- SSEs are a common feature in subduction regimes and have been reported in most of the well geodetically instrumented subduction zones worldwide.
- In northern Costa Rica, shallow and deep SSEs have been identified at the Nicoya peninsula. Recently, shallow SSEs were also documented in the southern part of the country at the Osa peninsula (Fig.1b).
- Here, we present a synthesis and compilation of SSEs observations in Costa Rica based on an in-depth review of previous studies, aiming to explore potential implications and viable ways to incorporate them in seismic hazard assessments.

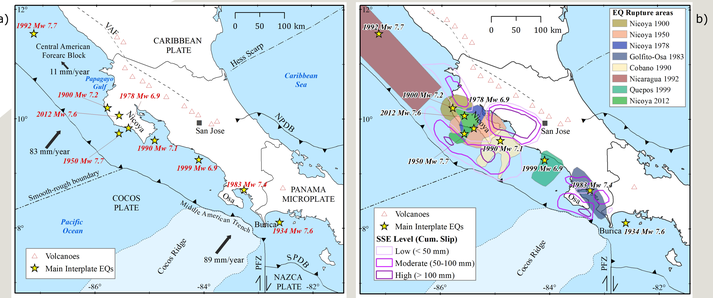



*Fig. 1. a) Tectonic framework of Costa Rica. b) SSEs and large interplate regular earthquakes. The dashed line represents the Volcanic Arc Faults (VAF), NPDB is the North Panama Deformed Belt, PFZ is the Panama Fracture Zone, and SPDB is the South Panama Deformed Belt.*

**SSE posible influence in Seismic Hazard**

1. In terms of triggering or not triggering of large earthquakes → ***Forecast***
2. In terms of seismic moment budget → ***Slip Rate quantification*** to assess seismic recurrence parameters used in PSHA.

## 2. Slow Slip Earthquakes in Costa Rica

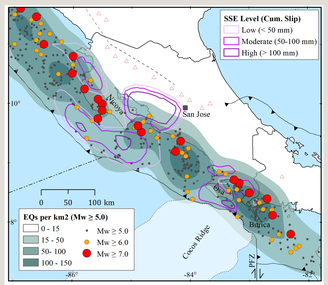



*Fig. 2. SSE and regular earthquakes in Costa Rica*

*Table 1. Summary of SSE activity in Costa Rica*

| Main features | Yes / No / Other | Comments / Seismic Hazard Implications |
|---|---|---|
| ***SSE magnitudes*** | Mw 6.5 – 7.2 | Seismic moment (energy) release |
| ***Foreshocks and SSE migration*** | Yes | Observed in Nicoya, before the 2012 Mw 7.6 |
| ***Shallow SSE*** | Yes | In Nicoya and Osa. Suggested that it limits the size of future EQs |
| ***Deep SSE*** | Yes | The most important recurrent patch in Nicoya |
| ***Swarms and Repeaters*** | Yes | In Nicoya very common. In Osa not well defined yet, but probably |
| ***SSE and Regular in the same area*** | Usually not | In Nicoya the patch of the largest EQs is outside SSE regions |
| ***Coupling in SSE region*** | Intermediate | When no SSE occurs, these regions can present intermediate or high coupling |
| ***Changes in Coulomb Stress (CFS)*** | Not enough | In Nicoya studies of the 2012 Mw 7.6 EQ concluded that the changes were not enough to correlate with SSE occurrence |
| ***b-value in SSE region*** | 0.69-1.10 (0.83 gen) | 0.83 is the general b-value for interplate earthquakes in CR. In the Nicoya segment stated as 0.69 and in Osa 0.84 |
| ***Seamounts presence*** | Yes | In Central and Southern Pacific of Costa Rica. Relevant for SSE in Osa and for the patch in the Nicoya Gulf |
| ***SSE role in seismic rupture*** | Yes | Has been stated as energy release processes and its limits the EQ size and tsunamigenic potential in Nicoya and Osa |
| ***Kinds of interaction*** | Not clear | Not well defined yet if there is a clear relationship SSE and big EQs |
| ***SSE recurrence period*** | 2 – 4 yrs | In Nicoya defined as 2yrs and in Osa 4 yrs (Mw>6.5) |

Delimitation of SSE areas based on references of previous observations of SSE in Costa Rica. The SSE level was defined as:

- High (>100 cm)
- Moderate (50-100 cm)
- Low (<50 cm)

| | *Nicoya peninsula* | *Osa peninsula* |
|---|---|---|
| **Period for cumulative slip estimation** | 6 yrs (2007-2012 and 2014-2019) (Dixon *et al.*, 2014; Xie *et al.*, 2020) | 6 yrs (2018-2023) (Perry *et al.*, 2023) |
| **Magnitude threshold (Mw range)** | Mw 6.5 (Mw 6.6-7.2) | Mw 6.5 (Mw 6.5-6.7) |
| **Recurrence period and year of first observation** | 21.7 months (2003) | 4 to 5 yrs (2013) |

## 3. Data and Methods

### 3.1. Seismic Slip Rate Approach

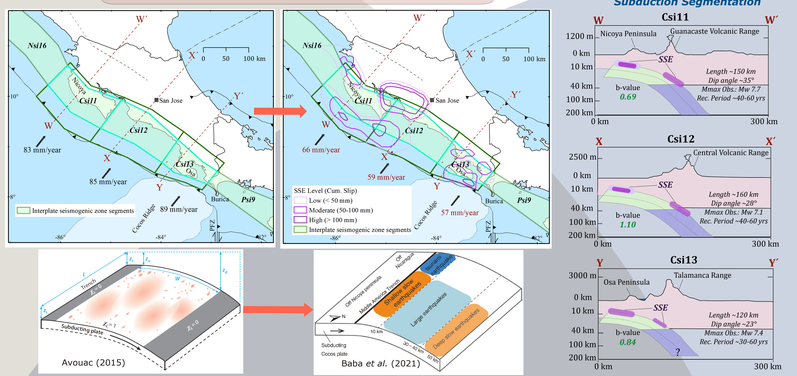
Based on the SSE regions definition (Fig. 2) and according to the subduction interface seismogenic segmentation for Costa Rica (Fig. 3) from Protti *et al.* (1994) and Alvarado *et al.* (2017), we estimated the seismic slip rate from slip deficit inferences using the steps presented by Radiguet *et al.* (2012) and based on the DeMets *et al.* (2010) MORVEL model, as follows:

**(1)** ***Total (cumulative) slip*** = Plate convergence. Rate * 6 yrs

**(2)** ***Cumulative seismic slip in SSE areas*** = (Cumulative Slip No SSE) – Slip SSE

**(3)** ***Seismic slip rate in SSE areas*** = (Cumulative Slip in SSE areas) / 6 yrs

**(4)** ***New seismic slip rate per segment*** = [Average of cumulative seismic slip in SSE areas and non SSE areas (locked and unlocked regions)] / [6 yrs (observation period)]










***Subduction Segmentation***




*Fig. 3. Schema for the approach of new seismic slip rates in subduction segments considering SSEs in Costa Rica*

### 3.2. Moment Budget and Earthquake Rate Estimations

The seismic potential is represented by the total rate of earthquakes ($\dot{N}min$) and the cumulative rate of seismic moment ($\dot{M}oSegment$) for the magnitude range between the minimum and maximum magnitude [Mmin, Mmax].

$$\dot{M}oSegment = SR \cdot \mu \cdot A$$

*Seismic Slip Rate segment* · *Shear modulus (30 GPa)* · *Seismogenic segment area*

→ ***($\dot{N}min$)= Average of Anderson and Luco (1986) and Youngs and Coppersmith (1985) models***

***Models Dependencies:***

- It is assumed a Gutenberg-Richter Magnitude Frequency Distribution
  - Length/width ratio
  - Slip/length ratio
  - Shear modulus
  - Slip Rate
  - b-value

*Mmin*= **4.5**

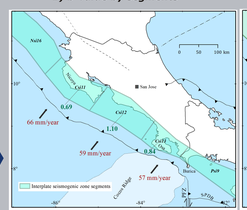
*Mmax inferred*

| *Csi11* | *Csi12* | *Csi13* |
|---|---|---|
| **Mw 7.9** | **Mw 7.4** | **Mw 7.6** |

(Arroyo-Solórzano and Linkimer 2021)

***Three different approaches to assess earthquake rates from seismic slip rates for the characterisation of interplate seismic sources***

***1) b-value by segments***




***2) General interplate b-value for Costa Rica in each segment***


***3) Without segmentation using the general interplate b-value for Costa Rica***

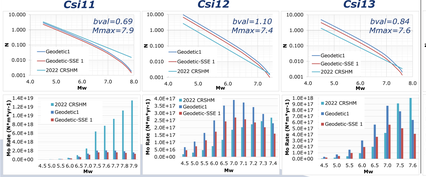

### 3.3. Seismic Hazard Calculation

- We used the Costa Rica Seismic Hazard Model 2022 (CRSHM 2022) with its respective ground motion models and seismic source characterisation (Hidalgo-Leiva *et al.*, 2022), except for the SSEs regions.
- Calculation of Peak Ground Acceleration (PGA) for a return period of 475 years.
- Ground shear-wave velocity (VS30) of 760 m/s (rock conditions).
- 6 truncation levels (epsilon=6).
- Assesments considering and without considering SSEs.
- Quantification of the differences when SSEs are incorporated.
- Comparison of the Geodetic approach considering SSEs with the CRSHM 2022.

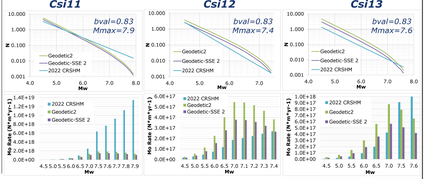
## 4. Results

### 4.1. Seismic Source Model Characterisation from Geodetic data

***1) b-value by segments (see section 3.2)***




***2) Interplate b-value for Costa Rica (see section 3.2)***




### 4.2. SSE impact in PSHA for Costa Rica

*We defined a logic tree from the three Geodetic approaches (section 3.2) considering SSEs or not (Figs 4a and 4b).*

***PSHA for Costa Rica from seismic slip rates for the subduction interface zone***

- 0.5 → 1) b-value by segments.
- 0.4 → 2) General interplate b-value for Costa Rica in each segment.
- 0.1 → 3) Without segmentation using the general interplate b-value for Costa Rica.

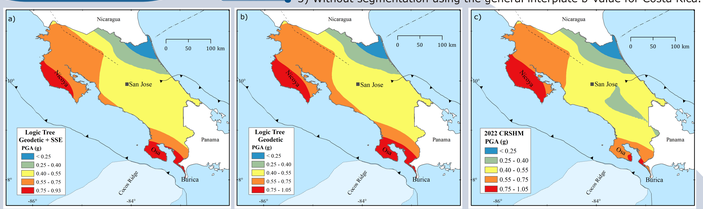



*Fig. 4. Seismic Hazard for Costa Rica (475 yrs return period). a) considering SSEs and b) without SSEs; c) The CRSHM 2022 (Hidalgo-Leiva et al., 2022).*

***Geodetic/Geological approaches comparison***

***Considering SSE / Without considering SSE*** =

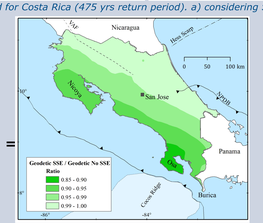



*Fig. 5. Ratio map geodetic approach considering SSEs / without considering SSE.*

***Seismic Slip Rates (SSEs) Vs Classical seismic catalog***

***Geological/Geodetic considering SSE / CRSHM 2022*** =

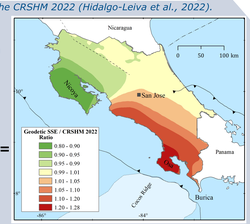



*Fig. 6. Ratio map Seismic Hazard from geodetic approach considering SSE / CRSHM 2022.*

## 5. Final Remarks

- PSHA calculations using geodetic data reflect that disregarding SSEs overestimates the seismic hazard (Figs 4 and 5).
- The classical PSHA used in the CRSHM 2022 overestimated (in Nicoya) or underestimated (in the Central Pacific and Osa Peninsula) the hazard, compared to this new assessment using geological/geodetic data and considering SSEs (Fig. 6).
- To further refine the geological/geodetic approach presented here, we plan to revisit the determination of the seismic recurrence parameters (b-value and Mmax, taken from the CRSHM 2022).
- Assessing long-term earthquake rates from the moment rate budget is crucial for the final results. So different approaches could be eventually considered to evaluate its consistency.
- To consider epistemic uncertainties in PSHA for subduction zones, we propose using logic trees with one branch for the classical approach (based on earthquake catalogs) and another for the geological/geodetic approach considering SSEs.

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