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Timoshenko Flexocompression Beam Analogy Applied to the Calculation of Seismogenic Thickness and Cortical Rupture Prediction in the Sierra de Pie de Palo

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Abstract

This paper presents a deterministic geomechanical model to parameterize the spatial variability of seismogenic thickness (h) in basement thrust faults under flat-slab subduction regimes. We develop a physico-mathematical analogy by transforming the elemental elastic approximation into a variable cross-section Timoshenko beam model subjected to tectonic flexocompression. The governing differential equations are solved numerically over a regularized mesh using interseismic strain rates derived from GPS data. The lower seismogenic boundary (z_{max}) is formulated by coupling the effective stress tensor, deep dehydration-induced pore pressure, and rheological constitutive equations. The model is quantitatively calibrated and validated against hypocentral depths recorded by INPRES, and its integration into probabilistic seismic hazard assessment schemes is discussed.

1 Introduction

The classical analysis of seismic hazard in the Andean retroarc of San Juan ($27° - 33°$S) typically relies on statistical approximations or elastic dislocation models that assume a spatially homogeneous seismogenic thickness (h) [6]. However, phenomena such as the 1977 Caucete earthquake doublet ($M_w\,7.4$) demonstrate that the continental crust strongly coupled by the basal shearing of the flattened Nazca Plate experiences critical variations in its flexural rigidity and energy storage capacity [3].

In this paper, we formulate a structural analogy based on Timoshenko's beam theory with shear distortion. We calibrate its boundary variables using interseismic geodetic data and validate the depth of the elastic channel against high-resolution instrumental seismic catalogs.

2 Establishment of the Geomechanical Analogy

The cortical block of the Sierra de Pie de Palo is idealized as a beam with a rectangular cross-section of width b and an equivalent height corresponding to the variable seismogenic thickness $h(x, y, t)$. The physical variables are coupled under the following conditions:

1. **Axial Load and Stress Field:** The effective normal stress (σ_n) on the fault planes is derived from the resolution of the lithostatic stress tensor and the horizontal compressive force of the orogenic front (F_T).

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2. **Timoshenko Shear Deformation:** The effect of transverse shear stress coupled with section rotation is incorporated. This approach is ideal for modeling thick cortical blocks where geometric distortion is non-negligible and where Euler-Bernoulli approximations underestimate tangential stresses.

3 Mathematical Formulation of the Model

3.1 Projection of the Stress Tensor and Failure Criterion

To overcome scalar simplifications, the effective normal stress (σ_n) and the acting shear stress of tectonic origin (τ_{act}) are evaluated by projecting the local stress tensor onto the fault plane, characterized by a dip angle θ:

$$\sigma_n = \frac{\sigma_1 + \sigma_3}{2} + \left(\frac{\sigma_1 - \sigma_3}{2}\right)\cos(2\theta) - P_f \tag{1}$$

Where σ_1 is the horizontal maximum compressive principal stress (West-East), σ_3 is the vertical lithostatic stress ($\rho g z$), and P_f is the pore fluid pressure. The brittle failure threshold is governed by the modified Byerlee's law:

$$\tau_f = C + \mu \cdot \sigma_n \tag{2}$$

3.2 Modification by Timoshenko's Shear Shape Factor

The acting shear stress within the cortical beam is corrected using the shear shape factor k_s to account for the non-uniform distribution of distortions across thick sections. For a rectangular section, $k_s = 5/6$. Thus, the corrected tangential stress is defined as:

$$\tau_{act}(x, y, t) = \frac{1}{k_s} \cdot \frac{V(t) \cdot Q}{I \cdot b} \tag{3}$$

Where $I = (b \cdot h^3)/12$. The transverse tectonic shear force $V(t)$ is calculated exclusively at the interseismic time scale (multi-year elastic accumulation), without attempting to model dynamic coseismic rupture propagation (seconds). It is parameterized by integrating the shear strain rate ($\dot{\gamma}$) obtained geodesically via kinematic gradients from continuous GPS networks:

$$V(t) = \int G(x, y) \cdot \dot{\gamma} \cdot t \cdot b \, dx \tag{4}$$

Where G is the shear modulus of the crystalline basement. The spatial numerical integration of Eqs. (3) and (4) is performed by discretizing the cortical domain using a regularized mesh with a spatial cell resolution of 5 km × 5 km.

3.3 Thermomechanical-Hydraulic Coupling of h

The lower limit of the seismogenic zone (z_{max}) is intercepted at the Brittle-Ductile Transition (BDT). We introduce a dynamic pore pressure factor $\lambda(z)$ governed by the upward fluid flux (q_f) generated by metamorphic dehydration of the subducted oceanic plate and the matrix permeability (k_m) of the lower crust:

$$\lambda(z) = \frac{P_f(z)}{\sigma_3} = \frac{1}{\rho g z}\left[\int \left(\frac{q_f \cdot \eta}{k_m}\right) dz\right] \tag{5}$$

Where η is the dynamic fluid viscosity. Integrating the power-law creep rheological equations for an amphibolite and feldspar-rich gneiss basement, the thermomechanical equilibrium is formulated as:

$$C + \mu\sigma_n(z, \lambda) = \left(\frac{\dot{\epsilon}}{A}\right)^{1/n} \exp\left(\frac{Q_a}{nRT(z)}\right) \tag{6}$$

The temperature function $T(z)$ is parameterized by solving the transient thermal advection-conduction equation. For the basal boundary condition at the San Juan Moho, a uniform value of $z_{Moho} = 60$ km is fixed across the entire modeling area of the sierra. The thermal profile is calibrated adopting an average surface geothermal gradient of 22°C/km and a subcooled base ($T_{Moho} = 650$°C) due to the flat slab.

4 Validation Strategy and Parameter Sensitivity Analysis

4.1 Quantitative Validation against Hypocenters

To transform the mathematical framework into a calibrated predictive tool, the computed theoretical seismogenic thickness map ($h_{theoretical}(x, y)$) is directly validated against the maximum depth of background instrumental seismicity. We utilize the microseismicity catalog from the Instituto Nacional de Prevención Sísmica (INPRES) for the period 2000-2025 beneath the Sierra de Pie de Palo. A total of 1,247 events were selected ($M_L \geq 2.0$, $Err_z < 2$ km).

Table 1: Comparison of cortical thickness h with confidence intervals.

Sector	$h_{theoretical}$ **(km)**	h_{INPRES} **(km)**	**Error (%)**
North Pie de Palo	28.5 ± 1.8	27.2 ± 2.1	+4.7%
South Pie de Palo	32.1 ± 1.5	30.8 ± 1.9	+4.2%
Bermejo Valley	22.4 ± 2.2	24.1 ± 2.5	−7.0%

5 Discussion of Weaknesses and Limitations

The adoption of a static shear shape factor $k_s = 5/6$ is strictly rigorous only for homogeneous and isotropic prismatic sections. The actual crust of the Sierra de Pie de Palo exhibits marked anisotropy due to metamorphic foliation and pre-existing imbricated fault zones.

6 Conclusions

The formulation of the modified Timoshenko beam equation mitigates the understatement of shear stresses in thick cortical blocks. The statistical consistency and low error margins against the 1,247 filtered INPRES hypocenters validate the potential of the model.

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