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Habilitation Thesis

"Numerical Simulation of Earthquake Rupture and Seismic Wave Propagation"

Presented by **Dr. Martin Galis**
Comenius University, Bratislava

Report and Evaluation by
Dr. Víctor M. Cruz-Atienza
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To whom it may concern,

Dr. Galis presents a vast and interesting habilitation thesis in which he introduces highly sophisticated physical-mathematical computational methods to explore different dynamic aspects of earthquakes, ranging from source instability to seismic radiation and its implication in strong ground motions. The discourse, consistent and well-structured, is composed of nine scientific articles/texts published between 2007 and 2019 in journals of high international prestige. While the contributions stem from collaborations with several (mostly prominent) scientists, the candidate shows leadership in most of them, as evidenced by his first authorship in five of the publications, and his second authorship in two others. Two things particularly stand out in the thesis: (1) the evolution of his scientific activity, in which he displays a remarkable methodological development (numerical and theoretical) during the initial investigations to later explore problems of great seismological importance, associated with the rupture of the seismic source and its implications in wave propagation and, (2) his ability to collaborate with expert scientists in different specialties and international academic institutions. In other words, Dr. Galis clearly possesses the maturity, capacity and motivation necessary for the development of original research projects and for the training of human resources at the highest academic level.

Trained in one of the world's most prestigious academic groups in the development of numerical methods for computational earthquake modeling at Comenius University in Bratislava, Dr. Galis was a major contributor to a monograph in the Acta Physica Slovaca (later published in its majority by Cambridge University Press), which is now an international bibliographical reference. In this monograph, the authors rigorously explore a vast number of finite difference (FD) and finite element (FE) numerical methods for dynamic modeling of seismic source and wave propagation in complex (i.e., viscoelastic and highly heterogeneous) media. Among other things, it is worth mentioning the implementation of a hybrid FD-FE method that allows simulating large-scale phenomena with high numerical efficiency and accuracy, including the dynamic rupture of non-planar faults and the presence of sedimentary basins at the surface.

The contribution of the candidate to the study of the seismic source is remarkable from a physical (i.e., dynamic) perspective. Thanks to the versatility of the traction-at-slip-node method he developed with adaptive spatial suppression of numerical noise in the FE domain of the mesh, Dr. Galis and coworkers performed a series of studies on the spontaneous propagation of the seismic source. Since the rupture initiation always responds to a user-imposed nucleation process (i.e., initial conditions and model parameterization) and this can have strong implications on the eventual evolution of the earthquake, they first conducted a parametric study of both the extension (and shape) of the nucleation zone and the initial prestress on the fault in order to determine the optimal (i.e., minimum sufficient) conditions that guarantee the rupture of the earthquake with the lowest initial conditioning. The most relevant contributions are that the 3D rupture initiation is mainly determined by the nucleation patch area as long as its geometry is quasi-circular, and the determination of the critical parameters of the patch for the case of low levels of prestress on the fault (i.e., $S>0.75$), which were determined from theoretical considerations of rupture mechanics.

Going deeper into earthquake initiation, the candidate and colleagues carried out a study of great interest for the international seismological community in which they analyze the initiation and propagation of earthquakes from an overpressured region (i.e., where the presence and evolution of pore pressure determines the effective stresses in the nucleation zone) in order to identify the factors that determine the spontaneous rupture and theoretical dimensions of earthquakes induced by fluid injection (in supercritical initial conditions), for example, and in the absence of mechanical barriers (i.e., frictional heterogeneities). The study concludes that the spontaneous arrest of rupture is mainly controlled by the integral of the pore pressure distribution in the nucleation region, which implies that the hydrological parameters determining the distribution (and evolution) of the effective pressure only affect the timing of seismic events. It is therefore the prestress and friction on the fault that mainly condition both the timing and the size of the self-arrested ruptures. It is shown that, in the absence of mechanical barriers on the fault, there is a theoretical relationship (consistent with observations at very different scales) that correlates the volume of fluid injected with the maximum expected magnitude of earthquakes.

Finally, Dr. Galis and coworkers explore the effect of elongated, overstressed regions on rupture initiation and dynamic instability, conditions expected in different tectonic/geologic environments. They found that except for a given range of the nuclation-patch aspect ratio for which rupture initiation is controlled by the patch area, the patch shortest dimension is the dominant parameter controlling nucleation. Regarding the rupture arrest, as expected, different regimes were identified depending either on the asperity aspect ratio or its area if rupture is dominated by 2D or 3D effects, respectively.

Dr. Galis also explores other interesting and potentially important factors of earthquake sources, such as fault surface geometry (i.e., its roughness) and strength variability, in the rupture moment magnitude, and found dramatic reductions in the size of earthquakes suggesting that the variability of stress drop in real events may be significantly smaller than believed. On the other hand, starting also from dynamic earthquake simulations, he studies the impact in the seismic radiation (i.e., in the spectral content of strong motions) of fault roughness to demonstrate that it is possible to generate effective kinematic parameters of the rupture in planar faults capable of simulating wavefields similar to those produced by realistic geometrical irregularities of the source. All of this has important implications for the seismic hazard assessment when conventional and computationally cheaper methods are used. Together with his colleagues, Dr. Galis finally analyzes the influence of stochastically generated crustal scatters on the amplitude of supershear mach waves, which theoretically may have large implications for strong motions at great distances from the fault, as demonstrated by several previous studies. Their results suggest that such medium heterogeneities together with source complexity could produce significant reductions of those conic waves amplitude.

For the reasons stated above, I am convinced that Dr. Martin Gális meets the required criteria and fully support awarding him the scientific-pedagogical title Docent (Associate Professor) after a successful defense of his Habilitation Thesis.

With kind regards,

Víctor M. Cruz-Atienza