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## Physics-Based Estimates of the Maximum Magnitude of Induced Earthquakes in the Groningen Gas Field

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The induced seismicity in the Groningen gas field, The Netherlands, has led to intense public concerns and comprehensive investigations. One of the main challenges for assessing future seismic hazard in the Groningen gas field is to estimate the maximum possible earthquake magnitude ( $M_{\max}$ ) that could be induced by gas extraction. Previous methods are strongly rooted in empirical and statistical approaches that are inherently limited by the scarcity of data. Here, we combine a physics-based dynamic rupture model based on the 3D theory of fracture mechanics with field-based and lab-based constraints to estimate  $M_{\max}$  in the Groningen gas field. If earthquakes in the reservoir have a rupture depth extension constrained by the reservoir thickness, the largest earthquakes should develop a large aspect ratio (longer horizontally than vertically). The model is thus an extension of the 3D theoretical rupture model on long faults with uniform stress and strength developed by Weng & Ampuero (2019), in which we have incorporated spatial heterogeneities, such as along-strike variable fault width, depth-dependent initial stresses and friction properties. The essential parameters that control rupture propagation and earthquake magnitude are the stored elastic energy and the fracture energy. Our method requires estimates of the stored elastic energy on reservoir faults as a result of the stresses induced by differential reservoir compaction during depletion. The fracture energy is constrained by laboratory experiments and theoretical frictional models. Coupling physics-based rupture models with field and lab observations provides an estimate of  $M_{\max}$  in the Groningen gas field and serves as a practical step toward physics-based seismic hazard assessment for other gas fields in the world.

Citation:

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