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論文題目	Source Mechanism and Modeling of Seismic Events Causing Fault-Slip Rockbursts in Deep Mining（深層採鉱における断層すべり山はねを引き起こす誘発地震の発生メカニズムとモデリング）		

（論文内容の要旨）

This thesis systematically investigates the mechanisms of fault-slip rockbursts induced by deep mining activities, addressing critical challenges posed to underground safety and stability as mining operations advance to greater depths. By integrating 2-D and 3-D numerical modeling with dynamic rupture simulations and validating these methods with field data, this thesis provides a comprehensive framework for analyzing fault reactivation, coseismic slip, and the resulting seismic impacts. The thesis focuses on the key factors influencing fault instability, such as stress perturbations, fault geometry, and seismic wave propagation, offering both theoretical advancements and practical strategies for mitigating seismic hazards. The results emphasize the importance of dynamic processes in understanding fault-slip rockbursts and present practical guidance for safer mining designs and infrastructure protection.

Chapter 1 establishes the research context and motivation, highlighting the challenges posed by seismic events induced by deep mining. It identifies fault-slip rockbursts as a critical hazard driven by stress perturbations near geological faults, endangering safety and stability in mining operations. With increasing mining depths and scales, the risks have intensified, as evidenced by seismic events in mines like Yuejin and Yanzhou in China, revealing gaps in understanding fault reactivation mechanisms and the need for better prediction models. To address these gaps, the chapter proposes an integrated framework combining 2-D and 3-D numerical modeling with dynamic rupture simulations, providing insights and strategies for mitigating seismic hazards in deep mining.

Chapter 2 develops a 2-D plane-strain numerical model to evaluate fault reactivation mechanisms caused by mining activities, with a focus on the interaction between mining-induced stress perturbations and fault slip behavior. The analysis reveals that fault reactivation is predominantly driven by reductions in normal stress, rather than increases in shear stress, underscoring the critical role of effective stress changes in fault instability. Key parameters influencing coseismic slip, such as fault dip angle, mining distance, mining height, and background stress ratio, are identified. The study highlights that footwall mining poses higher seismic risks than hanging wall mining due to distinct stress redistribution patterns. A framework for determining the terminal mining line is also proposed to mitigate seismic risks near faults by controlling stress fields and mining distances. Validation of the model using data from the Yuejin coal mine demonstrates its accuracy in predicting coseismic slip patterns observed during the 2010 mining-induced earthquake, confirming the model’s reliability for assessing fault stability and providing practical guidance for safer mining operations.

Chapter 3 advances the work of Chapter 2 by introducing a 3-D numerical framework that incorporates complex fault geometries and far-field intermediate principal stress, providing a more detailed analysis of fault reactivation and coseismic slip mechanisms in deep mining scenarios. This chapter expands the investigation by evaluating the effects of panel length, panel orientation, and far-field stress directions on coseismic slip and stress redistribution. Key findings show that increasing the panel length significantly expands the coseismic slip area and intensifies stress disturbances, while panel orientations perpendicular to the fault strike effectively reduce coseismic slip and enhance fault stability. The inclusion of far-field intermediate principal stress allows for a more comprehensive understanding of three-dimensional stress interactions influencing fault slip. Validation with field data from the Yuejin coal mine, particularly the 2010 mining-induced earthquake, demonstrates its reliability in predicting coseismic slip patterns. These innovations provide practical strategies for optimizing mining layouts and mitigating seismic hazards in faulted deep mining environments.

Chapter 4 integrates static stress analysis with dynamic rupture simulations to comprehensively analyze fault-slip rockbursts and the propagation of seismic waves caused by fault slip at the Yuejin coal mine. The study demonstrates that fault-slip rockbursts are primarily triggered by mining-induced reductions in normal stress and increases in shear stress, leading to fault reactivation and significant seismic energy release. Through dynamic rupture simulations, which achieve a quantitative representation of rupture processes, rupture velocities of up to 1.7 km/s and peak slip rates of 3.4 m/s are revealed. The resulting seismic waves generate high peak particle velocity and peak particle acceleration zones, correlating closely with severe damage observed during the "8.11" coal burst accident. The simulations further validate the consistency between dynamic rupture results and static slip distributions, offering a robust framework for quantitatively analyzing fault-slip rockbursts. These findings highlight the critical importance of designing vibration-resistant support systems and optimizing mining layouts to mitigate seismic hazards and ensure structural resilience in deep mining environments.

Chapter 5 discusses the broader implications of the findings, focusing on key aspects such as fault reactivation mechanisms, modeling approaches, and mitigation strategies. The study emphasizes the critical interplay between shear and normal stresses in driving fault–slip rockbursts, highlighting the importance of both static and dynamic stress factors. It underscores the limitations of static models alone and advocates for the incorporation of dynamic rupture processes to achieve more accurate seismic hazard assessments. Practical recommendations include optimizing mining layouts, such as orienting panels perpendicular to fault strikes, and designing adaptive support systems tailored to the characteristics of seismic waves to enhance safety and stability in deep mining environments.

Chapter 6 presents a summary of the key findings of this thesis and provides an outlook for future research directions.

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（論文審査の結果の要旨）

本論文は、採炭などの大深度地下資源採掘などの空間掘削により、採掘切羽近傍に存在する断層のすべりを誘発する条件を検討し、断層すべりが誘発された場合、断層すべりに起因して誘発される山はねの危険度評価に資することを目標に研究した成果についてまとめたものである。得られた主な成果は次のとおりである。

１．有限要素法(Code_Aster)を用い、２次元均質弾性媒質中において、既存逆断層に向かって採掘切羽が進んでいくことを想定し、採掘に伴う応力擾乱が断層に与える影響を評価した。その結果、下盤側からの採掘は断層上部にすべりを誘発し、上盤側からの掘削は断層下部にすべりを誘発することがわかった。まだ、断層すべりが安定から不安定に変化する臨界サイズの概念を導入し、採掘切羽がどこまで安全に断層に近づくことができるかの評価を行い、安全性指標の提案を行なった。

２．切羽面長の影響を考慮するため、有限要素法(Code_Aster)を用い、３次元均質弾性媒質中における近傍逆断層が再活動する条件を調べた。中間主応力の影響、切羽面長の影響、採掘方向の影響の評価を行った結果、切羽長はなるべく短くして断層に向かった採掘を行うことで、最も断層すべりを誘発させにくいことがわかった。この研究により、採掘スキームを検討する際の判断材料の提供が可能となった。

３．断層すべりによって生じる弾性波の切羽への影響を調べるため、有限要素法(Pylith)を用いた断層面における不安定すべり(誘発地震)の発生シミュレーションを行った。現実に近い地下構造モデルを用い、誘発地震から放出される弾性波の再現を行った。この弾性波動が採掘空洞面にどのような影響を与えるかを、採掘空洞面での振動の最大速度、最大加速度や卓越周波数、継続時間を推定することで評価した。その結果、断層下盤側から掘削が断層へ近づく場合、採掘空洞天井部分の切羽面に近い中心部が最も山はねを生じさせやすい場所であることが推定された。同様に、断層上盤側から採掘切羽が近づく場合は、採掘空洞床面において山はねが生じやすいことがわかった。これらの結果は、事前に山はね発生防止策を検討する際に役立つものと考えられる。

本論文は、大深度における採炭などの資源掘削において、既存断層の再活動を防ぎ、採掘を安全に進めるための条件を数値シミュレーションによって推定し、大深度掘削の安全性向上のための事前対策に寄与することが期待される。それにとどまらず、二酸化炭の地下貯蔵や放射性廃棄物の地層処分の安全性を検討する上でも重要な知見を提供することが期待され、学術上、実際上寄与するところが少なくない。よって、本論文は博士（工学）の学位論文として価値あるものと認める。また、令和６年１２月１６日、論文内容とそれに関連した事項について試問を行って、申請者が博士後期課程学位取得基準を満たしていることを確認し、合格と認めた。