【Grant-in-Aid for Transformative Research Areas（B）】

Creation of digital twin for deep underground: Challenges in Prediction, Detection, and Control of Rock Mass properties

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Project Information	Project Number : 26B207	Project Period (FY) : 2026-2028
	Keywords : Multi-scale/physics processes within bedrock, Changes in bedrock structure/properties, Emulator, Observation and super-resolution	

Purpose and Background of the Research

● **Outline of the Research:** To build a society that achieves global environmental conservation, carbon neutrality, and a stable energy supply, it is essential to sustainably utilize not only the space above ground but also the vast underground space and its abundant resources. To achieve this, it is necessary to carry out various underground development projects in a sustainable manner that harmonizes with the surrounding environment. Furthermore, to meet these needs in a truly sustainable manner, it is essential to develop underground development support technologies that integrate prediction, control, and detection—specifically addressing (1) what will happen, (2) what has happened, and (3) how rock masses properties can be modified—within the 4D space of the deep rock masses where underground development takes place. However, such innovative technology represents uncharted territory in the history of underground development. The bottleneck lies in the multiscale characteristics of the complex phenomena occurring deep underground (Fig.1), and it is essential to develop a theoretical framework to elucidate them. In this research, we aim to establish a novel theoretical framework that seamlessly bridges coupled phenomena and physical properties across hierarchical scales, ranging from microscopic pore structures to large-scale actual rock masses. Building on this framework, we will undertake the ambitious challenge of creating a digital twin capable of predicting, detecting, and controlling the complex phenomena (multiscale/physics phenomena) occurring in deep underground and the rock mass properties changes.

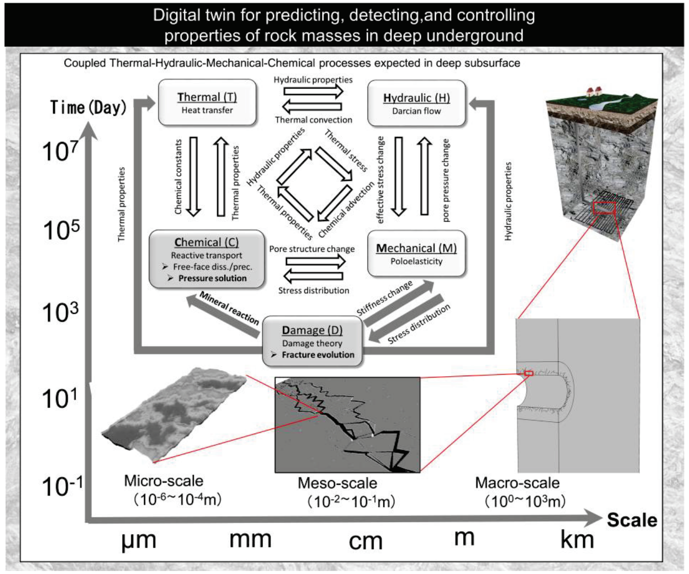

Figure 1. Conceptual diagram of digital twin for deep underground

Expected Research Achievements

● **Research Activities of Each Research Group**

Four groups (shown in Fig.2) will collaborate to achieve following three objectives.

Objective 1:Development of prediction and control technologies for changes in the pore structure and physical properties of rock masses in deep underground

Objective 2:Development of detection technologies for changes in the pore structure and physical properties of rock masses in deep underground

Objective 3:Development and field verification of a deep underground digital twin integrating prediction, detection, and control technologies

Group A01 (**Development of simulator for predicting/controlling rock mass properties**) In collaboration with Group A03, we will develop constitutive models capable of describing micro-scale coupled phenomena involving complex geochemical reactions, as well as the resulting spatiotemporal changes in fracture structure and permeability, using a novel approach that leverages interpretive machine learning capabilities. Furthermore, this model will be integrated with our multiscale, multi-physics numerical code to develop a prediction and control simulator for variations in fracture permeability within rock masses.

Group A02 (**Development of a method for detecting pore structure/permeability within rock masses from geophysical observation**) We will develop a method for indirectly detecting pore structures and hydraulic properties within rock masses using macroscopic geophysical observational data across different scales, thereby bridging the gap between field observations and prediction and numerical simulators.

Group A03 (Development and Integration of AI Platforms) In collaboration with Group A01, we will develop a machine learning-based model of coupled processes and establish an emulator to accelerate the prediction and simulator built by Group A01. Then, the emulator will be integrated into Group A04's digital twin platform.

Group A04 (Development of a digital twin platform utilizing observation and super-resolution techniques)

In collaboration with Group A03, we will perform super-resolution interpolation using PINNs (Physics-Informed Neural Networks) and other methods to reconstruct a high-density subsurface structural model. Subsequently, Group A03's high-speed emulator will be integrated into the digital twin platform established in Group A04, and create a bidirectional system that combines predictions in a virtual environment with the assimilation of observational data, which we will then apply in the field.

● **A ripple effect of this study**

This study is expected to create an entirely new academic discipline—digital twins focused on natural objects deep underground—within the academic field of digital twin , which has traditionally focused primarily on man-made objects on the ground.

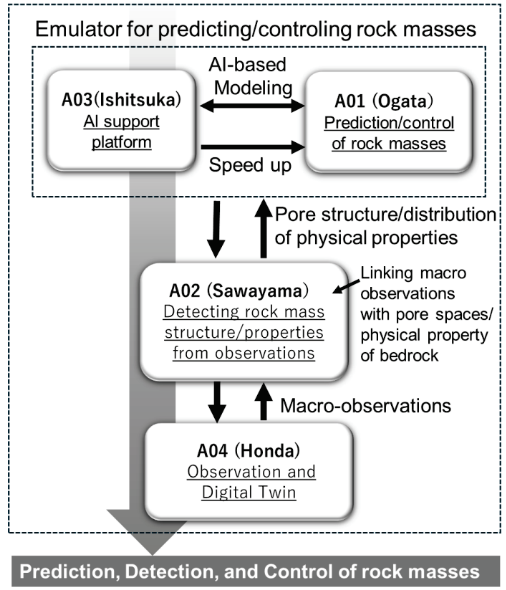

Figure 2. Cooperation among research groups

Website(s)	Under construction