京都大学	博士（　工学　）	氏名	Zirui LU　（陸　紫瑞）
論文題目	Three-dimensional stress measurement technique based on electrical resistivity tomography （電気抵抗率トモグラフィーに基づく三次元応力計測技術）		

（論文内容の要旨）

Geo-stress plays a crucial role in the design and construction of underground excavations. It is a significant factor in designing slope protection, controlling settlement, and tunnel boring, as well as an essential safety indicator during construction. This study proposes a three-dimensional stress measurement technique capable of directly determining the stress tensor, which uses the electrical resistivity tomography (ERT) conductivity reconstruction technique, coupled with conductive rubber. ERT is a non-destructive technique that can infer the inner conductivity distribution from the voltage measurement conducted between the surface electrode. By applying the ERT conductivity reconstruction technique, conductive rubber that obeys the piezoresistive law can be used for pressure distribution measurement. When pressure is applied to the conductive rubber, the rubber deforms and its conductivity distribution changes; thus, the conductivity change could be monitored with ERT and converted to stress distribution based on the mechanical properties of conductive rubber. Experiments using the shield face visualization apparatus and centrifuge model test machine were performed to validify the applicability of the sensor.

Chapter 1: Introduction

The research background of geo-stress measurement and the motivation to develop the 3D stress sensor are introduced. The structure of thesis is briefly summarized.

Chapter 2: Literature Review

The development and current state of geo-stress measurement, electrical resistivity tomography and ERT-based stress sensor are reviewed.

Chapter 3: DEM simulation of cylindrical geo-sensing prototype

An electrical contact theory-based geo-sensing prototype is introduced. DEM simulation was performed to find out the relationship between mean stress distribution and contact area to verify its applicability.

Chapter 4: Electrical resistivity tomography

The physical model and algorithm of ERT conductivity reconstruction are presented. The data acquisition protocol for voltage measurement between the electrode is specified, and the process of transforming the voltage dataset into a conductivity distribution is introduced.

Chapter 5: Multi-directional stress sensor

The hardware of stress sensors is introduced, which possess wireless automatic and real-time measurement functions. The raspberry pi microcomputer is used to control the circuits and measure the voltage based on the stimulation and measurement pattern.

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Chapter 6: Preliminary experiments using planar rubber sensor

Preliminary tests using the planar rubber sensor were conducted to study the basic characteristics of the ERT-based rubber sensor. The ERT-based rubber sensor can effectively detect the loading area and location. The average conductivity of the rubber sheet is negatively correlated with the load and deformation. The time-dependent hysteresis is induced by the viscoelastic characteristics of the conductive rubber, and the hysteresis effect impacts the accuracy of the sensor.

Chapter 7: Stress measurement using hemispherical rubber sensor

The seventh chapter demonstrates the three-dimensional stress measuring ability of the hemispherical rubber sensor. Experiments are carried out using the shield face visualization apparatus with the hemispherical rubber sensor inside. The uniform water pressure test and uniform earth pressure test are conducted to reveal the relationships between the average conductivity and mean stress as the calibration method. Three prevalent projection methods between 2-dimension and 3-dimension are concluded, and an experiment is used to choose the most adequate projection method. The excavation experiments in the soil are performed to verify the stress measuring ability of the hemispherical rubber sensor. The relationship between peak value of average conductivity and shear strength of soil is discussed. Two stress tensor determination methods are presented.

Chapter 8: Stress measurement using cylindrical rubber sensor

The eighth chapter shows the test results of the cylindrical rubber sensor. The cylindrical rubber sensor is calibrated using uniaxial compression test. The centrifuge tests are conducted to confirm the stress measuring capacity of the cylindrical rubber sensor. A stress determination method is proposed to find the maximum and minimum principal stress.

Chapter 9: Conclusions

This study presents a novel approach to 3D stress measurement in geotechnical engineering, utilizing ERT-based conductive rubber sensors. While previous ERT-based sensors have primarily focused on planar pressure mapping, this research develops hemispherical and cylindrical conductive rubber sensors and corresponding 3D stress tensor determination methods. The reconstructed conductivity distribution image can provide distinct and intuitive stress magnitude and direction information. By the stress tensor determination methods, the comprehensive 3D stress tensor can be obtained using one device and one measurement which is not realized by the other sensors. The effectiveness of the ERT-based rubber sensors was experimentally validated in geotechnical experiments, demonstrating their capability in measuring the stress state. These sensors provide a comprehensive measurement scheme of the stress state and potentially increase reliability and safety in construction, design, and management.

Appendix A: Mathematical model, boundary condition and complete electrode model

Appendix B: Linearized inverse solution based on Gauss-Newton method

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（論文審査の結果の要旨）

本研究の目的は，電気比抵抗トモグラフィー（ERT: Electrical Resistivity Tomography)を用いて地盤・岩盤内の 3 次元応力場の測定を可能にする応力センサーを開発することである．3 次元応力場を精度よく計測することは従来困難であったが，これが可能となれば，地盤工学・岩盤工学分野における様々な工学的課題に適用可能であり，コスト削減やリスク低減につながることが期待される．

ERT は，表面電極から測定された電圧データを使用して，対象物内部の導電率やインピーダンスの分布を推定する非破壊の可視化技術である．導電性ゴムに圧力が加わると，変形に従って導電率が変化する性質を利用することで，作用する応力の大きさおよび方向を推定できる．本研究では，このような物理的背景に基づき，半球体型と円柱型の高導電性ゴム応力センサーを開発した．応力センサーの開発では，まず適切な導電性材料の選定を行い，その後，応力センサーの基本的な動作を確認するための複数の検証実験を実施した．

本研究で開発した，ERT を利用した半球体型および円柱型導電性ゴム応力センサーを用いて，デモンストレーション実験，一軸圧縮試験，割裂引張試験を実施し，外力の載荷方向と大きさを同時に測定できることを確認した．更に，トンネルボーリングマシン（TMB: Tunnel Boring Machine）チャンバー内の応力状態を把握するため，TBM 掘削を模擬する模型実験を実施した．実験では，半球型導電性ゴム応力センサーを用いて TBM チャンバー内の気泡混合土の応力状態を可視化する手法を提案し，その適用性を検証した．その結果，TBM チャンバー内の掘削土の応力状態と流動方向を直接測定できることを確認した．さらに，ステレオ投影による解析手法を用いることにより，3 次元応力テンソルを推定できることを示した．円柱型導電性ゴム応力センサーを用いた遠心模型実験では，応力センサーの導電率変化と平均土圧との強い相関関係が得られ，同センサーの土圧測定に対する有効性を確認できた．開発した応力センサーについては，載荷時と除荷時の導電率にヒステリシスが存在するという課題が確認できたが，様々な検証試験から，開発した応力センサーの有用性を十分に確認することができた．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５年８月２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．

なお，本論文は，京都大学学位規程第１４条第２項に該当するものと判断し，公表に際しては，当該論文の全文に代えてその内容を要約したものとすることを認める．

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