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論文題目	Remote sensing-based detection and modeling of geo-environmental dynamics of the Red River Delta coastal zone (Northern Vietnam) （リモートセンシングによる紅河デルタ沿岸域（ベトナム北部）の地質環境動態の検出とモデリング）		
（論文内容の要旨） The coastal environment serves as a vital component of the broader geo-environment, fulfilling key roles in nutrient storage and dynamic cycling. It also functions as a natural filter, intercepting and reducing pollutants from inland sources, thereby maintaining ecological balance and sustainability. Understanding geo-environmental dynamics requires examining changes in sediment properties and pollutant concentrations. Tidal flats are dynamic coastal wetlands characterized by flat topography, formed by the deposition of fine-grained sediments like silt and clay transported by tidal currents. Variations in sediment properties such as moisture content, grain size, type, mineral and chemical composition, and organic matter, along with their spatial and temporal distributions, significantly influence the intertidal environment and the survival of marine organisms. The Red River Delta coastal zone hosts a diverse blend of natural, semi-natural, and agricultural vegetation, forming a dynamic and intricate ecosystem. Covering approximately 24,000 hectares, the mudflats within this zone experience seasonal transformations, serving as essential habitats for wetland biodiversity and providing critical protection for the surrounding marine environment. To achieve effective and sustainable management of this ecologically significant area, it is vital to develop dependable methods for monitoring and characterizing mudflat ecosystems. Coastal management approaches must utilize accurate, cost-efficient, and consistent techniques to track changes in sediment properties and the pollutants they harbor. Traditional sediment assessment methods are accurate but costly and time-consuming, limiting large-scale applications. Remote sensing offers a more efficient and scalable alternative for predicting sediment properties. However, intertidal mudflats present challenges due to a strong influence of water content on remote sensing signals. This interference complicates the estimation of sediment organic matter and grain size. Environmental factors such as tidal fluctuations and seasonal changes further affect spectral data interpretation. Reliable integration of hyperspectral data with satellite imagery requires precise calibration and validation. Overcoming these challenges is key to improving large-scale sediment monitoring. Based on those backgrounds, this research develops a framework for mapping and monitoring surface sediments in the Red River Delta’s tidal flats using remote sensing techniques. It links satellite-derived reflectance data with sediment properties composed of water content, grain size, and organic matter to			

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analyze sediment dynamics. Sentinel-2A imagery provides a cost-effective alternative to traditional field surveys, enhancing monitoring efficiency. The study refines spectral analysis techniques for estimating sediment organic matter. By examining the effects of sediment properties on reflectance spectra, it fills a gap in remote sensing applications for intertidal environments. Multivariate regression models and spectral analysis improve sediment property predictions. The high-resolution maps generated support sustainable coastal management in the Red River Delta. The thesis is composed of the following seven chapters: Chapter 1 delineates the background, research objectives, and structure of the dissertation. Moreover, it conducts a thorough assessment of prior studies related to the research topic, thereby enhancing insights into the existing body of knowledge in the field. Chapter 2 describes the study area and methodology. It outlines the natural characteristics of the Red River Delta coastal zone, including topography, climate, hydrology-oceanography, geological features, biodiversity, and socio-economic conditions. Additionally, this chapter details the methods employed, such as standard measurement techniques, image processing, and mapping approaches. Chapter 3 investigates the impact of water content on the reflectance spectra of intertidal flat sediment. Through a meticulous analysis, the correlation between laboratory reflectance spectra and water content is examined to ascertain the most effective method for estimating water content from reflectance spectra data. The surface sediment samples from the tidal flat were collected and measured their reflectance spectra and water content feature. Significant correlations were observed between the water content and Sentinel-2A band ratio. The reflectance spectra demonstrated a noticeable change with variations in water content, indicating that water content can be directly estimated using the Sentinel-2A band ratio. Regression models were developed using data from the initial samples to estimate water content. The best-performing model was chosen from the highest R^2 and lowest RMSE. Additionally, this chapter entails the generation of a water content map utilizing Sentinel 2A imagery, further enriching our understanding of sediment dynamics within the intertidal flat environment. Chapter 4 examines the relationship between the reflectance spectra and sediment grain size. All surface sediment samples collected and measured their reflectance spectra and grain size property. The characteristics of sediment types are thoroughly described, and multivariate regression analysis is applied to estimate grain size. Significant correlations were found between the D_{50} parameter and the band ratio Sentinel 2A, and the results highlighted the importance of considering water content for accurate D_{50} estimation. The most effective model was a linear multivariate model that incorporated the near-infrared and visible band ratio, the red band reflectance for sediment color differentiation, and water content to predict			

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D_{50} values. The findings are presented through a distribution map of sediment grain size. Chapter 5 explores the impact of sediment organic matter on reflectance spectra, offering valuable insights into its influence on spectral signatures. Leveraging in-laboratory hyperspectral data, the chapter endeavors to develop a robust methodology for estimating organic matter content, thereby enhancing our ability to characterize and monitor environmental factors within the study area. Hyperspectral reflectance measurements of sediment samples revealed key correlations with sediment organic matter. The hydroxyl absorption near 2200 nm was identified as a reliable indicator for quantification. To reduce measurement noise, a novel estimation model was proposed based on the difference between these ranges of reflectance spectra. Chapter 6 presents an application of the developed algorithmic models to multi-temporal Sentinel-2 satellite images, revealing the spatial and temporal evolution of sedimentary parameters as water content and grain size and providing insights into the dynamic changes in the coastal geological environment of the Red River Delta coastal zone. Vegetated flats are expanding due to sediment deposition and mangrove growth, whereas un-vegetated flats are shrinking and fragmenting. This reflects natural succession and sediment stabilization processes. Sediment water content has changed, with higher moisture zones indicating shifts in transport and grain size dynamics. Estuarine areas are accumulating more fine sand and silt, whereas clay-dominated zones are decreasing. These trends suggest evolving hydrodynamic conditions driven by tidal currents and river flows. This trend highlights the combined effects of natural forces and anthropogenic activities, including sediment trapping and land use changes. Chapter 7 represents the synthesis of this dissertation's findings, encapsulating the key insights derived from the research. Furthermore, it offers forward-looking recommendations for future studies, identifying potential areas for further investigation and suggesting pathways for continued progress in the field.			

(論文審査の結果の要旨)

河口デルタに広がる干潟には豊富な生態系が形成されており，その環境の保全は世界的に重要である。紅河デルタ沿岸域は生物多様性を育む場所として，ベトナムで初めてラムサール条約に登録された湿地であるが，近年環境の悪化が顕在化しており，長期にわたる沿岸域全体の環境モニタリングと環境変化の要因の特定が急務の課題になっている。これに対して本研究ではリモートセンシング技術を応用し，原位置と実験室で干潟試料の測定・分析を行い，これから得られた反射スペクトルと物性との回帰モデルを衛星画像に適用することで地質環境の時空間変化を明らかにできた高度な環境地質学研究である。測定・分析の対象は，50 地点から採取した干潟試料の含水率，中央粒径 (D_{50})，有機物含有率，および可視域から短波長赤外域 (350～2500 nm) の分光反射率である。 D_{50} は土質区分に適用できる。主な成果は次の 4 点に纏められる。

- 1) 試料の含水率は 0～40 % の範囲にあり，反射率は含水率の増加とともに水分子や水酸基による電磁波吸収で低下し，その低下は短波長赤外域で大きく現れることが確かめられた。短波長赤外域でも 1610 nm と 2190 nm での反射率の比が反射率低下を最も大きく表し，その比を用いた回帰モデルで含水率を高精度で推定できる（決定係数 $R^2 = 0.93$ ）ことを明らかにした。
- 2) 32 試料の D_{50} は 31～135 μm の範囲にあり，近赤外域と可視域緑での反射率比，可視域赤の反射率，および含水率を線形に組み合わせた多変量回帰モデルと最も強い相関性が得られた ($R^2 = 0.85$)。その反射率比との相関は，堆積物の粒径が大きくなるほど一般に空隙が増加して電磁波の光路長が長くなり反射電磁波の減衰が増大し，それによる反射率の差が近赤外域と可視域で顕著になるという従来知見に対応した。また，干潟堆積物は酸化鉄の含有により赤みを帯びているため， D_{50} 推定に可視域赤の反射率も寄与することがわかった。
- 3) 有機物の反射率は可視域で波長とともに急増し，それよりも長波長側ではほぼ一定になった。0.57～25 % の範囲にある 50 試料の有機物含有率は，可視域赤と青での反射率差の対数と最も相関が強く ($R^2 = 0.95$)，これを用いた回帰モデルで従来よりも高い推定精度が得られた。これは，有機物含有率が高いほど可視域赤と青での反射率の差が増加するためと解釈できた。
- 4) 得られた回帰モデルを Sentinel-2A 衛星画像に適用し，対象沿岸における 2017～2022 年の間の含水率，土質，有機物含有率の変化を求めた。その結果，干潟域とマングローブ生育による植生域が増加し，含水率および細粒砂とシルトの分布も増加したことなどが見出され，これらは干潟と潮流，河川流出の相互作用および環境修復活動の効果によると解釈できた。

以上，本論文でのリモートセンシング技術に基づく開発手法の有効性は高く，本対

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象域に限らず世界各地の沿岸域における地質環境動態の検出とモデリングに応用できることが示されたので、学術上、實際上、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 7 年 2 月 21 日、論文内容とそれに関連した事項について試問を行い、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。

また、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。