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Mapping Submarine Bathymetry and Geological Structure Using the Lineament Analysis Method

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The Honam-Jeju, Korea-Japan, and Korea-China subsea tunnel construction projects have drawn significant attention since the early 2000s. These subsea tunnels are much deeper than most existing natural shallow sea tunnels linking coastal areas. Thus, the need for developing new technologies for the site selection and construction of deep subsea tunnels has recently emerged, with the launch of a research project titled "Development of Key Subsea Tunnelling Technology" in 2013. A component of this research, an analysis of deep subsea geological structure, is currently underway. A ground investigation, such as a borehole or geophysical investigation, is generally carried out for tunnel design. However, when investigating a potential site for a deep subsea tunnel, borehole drilling requires equipment at the scale of offshore oil drilling. The huge cost of such an undertaking has raised the urgent need for methods to indirectly assess the local geological structure as much as possible to limit the need for repeated borehole investigations. This study introduces an indirect approach for assessing the geological structure of the seafloor through a submarine bathymetry analysis. The ultimate goal here is to develop an automated approach to the analysis of submarine geological structures, which may prove useful in the selection of future deep subsea tunnel sites.

Key words: subsea tunnel, geological structure, tunnel design, indirect ground survey, lineament analysis method

Introduction

New and improved research methods are required to analyze the geological structure and integrity of a submarine region for potential tunnel locations using deep subsea bathymetric analyses. Available marine datasets, which include bathymetric and geological maps, as well as geophysical and borehole observations, provide a starting point for such an analysis. A relationship between seafloor lineaments and deeper geological structure can be derived from these datasets, allowing tectonic features to be inferred from bathymetric observations.

Geophysical surveys have been conducted to identify bathymetric and geological features in the ocean surrounding the Korean Peninsula. The resultant submarine geological maps provide constraints on bathymetry, sediment distribution and thickness, geological structure and isomagnetic intensity across the region. However, in contrast to the geological map of the Korean Peninsula, details on the geological structure of the submarine region are limited. Studies are currently ongoing to better constrain submarine geological structure via geophysical and borehole investigations.

Numerous studies have implemented the lineament analysis method for mapping geological structures since the 1990s. Kang et al. (1991) identified the lineament distribution across the entire Korean Peninsula, where the spatial distribution of fractures was identified and a

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statistical analysis of their directivity was performed to better understand regional tectonics. Kim et al. (1996) performed a analysis based on remote sensing data and a digital elevation model (DEM) of the Euiseong Area in the Kyungsang Province to map geological lineaments. An automatic lineament extraction algorithm has also been employed for lineament extraction (Kim et al., 1999). In the 2000s, Han et al. (2006) used remote sensing data to conduct a lineament analysis of the southeastern region of Korea to provide geological constraints for future construction projects.

In this study, the lineament elements of the Haenam Peninsula, Korea, have been identified and compared with its geological structure (Choi et al., 2002). After verifying that this lineament analysis method accurately captures the terrestrial geological structure of the region, this method is then applied the seafloor to analyze the submarine geological structure. This indirect method of inferring submarine bathymetric structure may serve as a means for assessing the feasibility of future subsea tunnel construction projects.

Lineament analysis method

A lineament refers to a topographic element with a straight or curved form. Lineaments are generally observed along the surface expressions of tectonic or lithologic boundaries, such as faults, fractured zones or fold axes (O'Leary et al., 1976; Wise et al., 1985; Kats et al., 1986). A shaded relief image is developed from satellite imagery that is converted to a DEM for the lineament analysis. The lineaments are then extracted from the DEM, and the final outcome is obtained by comparing the extracted lineament features with available field data and geological maps.

The automated extraction of lineaments from a DEM generally requires a filtering method that uses a simple boundary extraction filter. However, full automation is difficult, and manual filtering is often required to extract lineaments. Furthermore, errors in the shaded-relief DEMs used for lineament analysis reduce the accuracy of this approach. At scales of 1:1,000 and higher resolutions, the results from the shaded-relief approach are considered to be reliable. However, at scales of 1:25,000 and lower resolutions, lineament extraction from topographic maps provides more reliable results than from shaded-relief DEMs.

In this study, the tectolineament elements of the Haenam Peninsula was extracted from a combined analysis of available topographic and geological data. The satellite image and geological map in Fig. 1 highlight the tectolineament elements of the region. Primary NNE-trending lineaments and secondary SSE-trending lineaments delineate some of the major geological boundaries

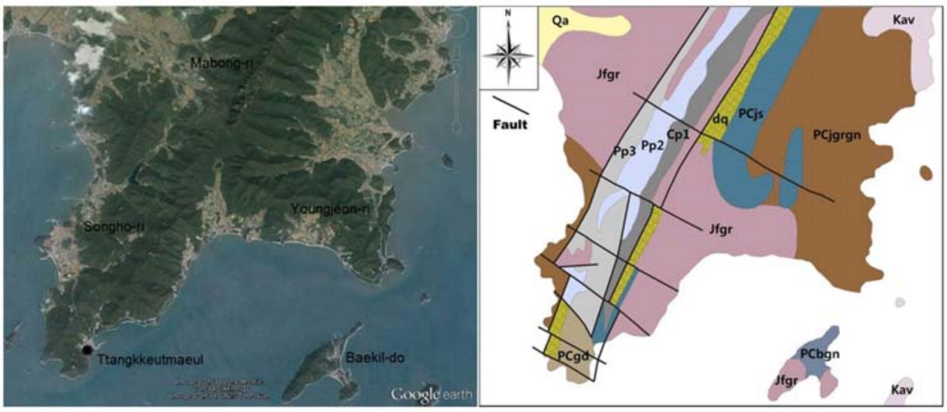

Fig. 1. Satellite image (Google Earth) and geological map (Choi et al., 2002) of the Haenam Peninsula, Korea. (PCbgn: biotite gneiss; PCjs: schist; PCjgrgn: granitic gneiss; PCgd: Precambrian sedimentary rocks; dq: Quartzite; Cp1, Pp2, Pp3: Carboniferous-Permian Pyeongan Group; Jfgr: foliated Jurassic granite; Kav: Cretaceous andesitic volcanics; Qa: Quaternary alluvial deposits)

of the peninsula (Choi et al., 2002). A shaded-relief image was then produced from the topographical map to evaluate the results from the lineament analysis method.

Lineament analysis using a digital map

A 1:25,000 digital topographic map of the Haenam Peninsula was used for the lineament analysis (Fig. 2). At this scale, many tectolineament features are visually unidentifiable on the map. Characteristics of the topographic contours were thus identified and grouped into four categories for the lineament analysis (Fig. 3).

The four categories of topographic contour characteristics are: (1) contour density (Fig. 3a); (2) topographic arrangement (Fig. 3b); (3) drainage system (Fig. 3c); and (4) mountain system (Fig. 3d). In Fig. 3a, the red line marks a sharp contrast in contour density between the right and left sides of the image. Fig. 3b shows a bilaterally symmetric structure, with the red line marking the

Fig. 2. Tectolineaments (red lines) marked on the digital topographic map of the Haenam Peninsula.

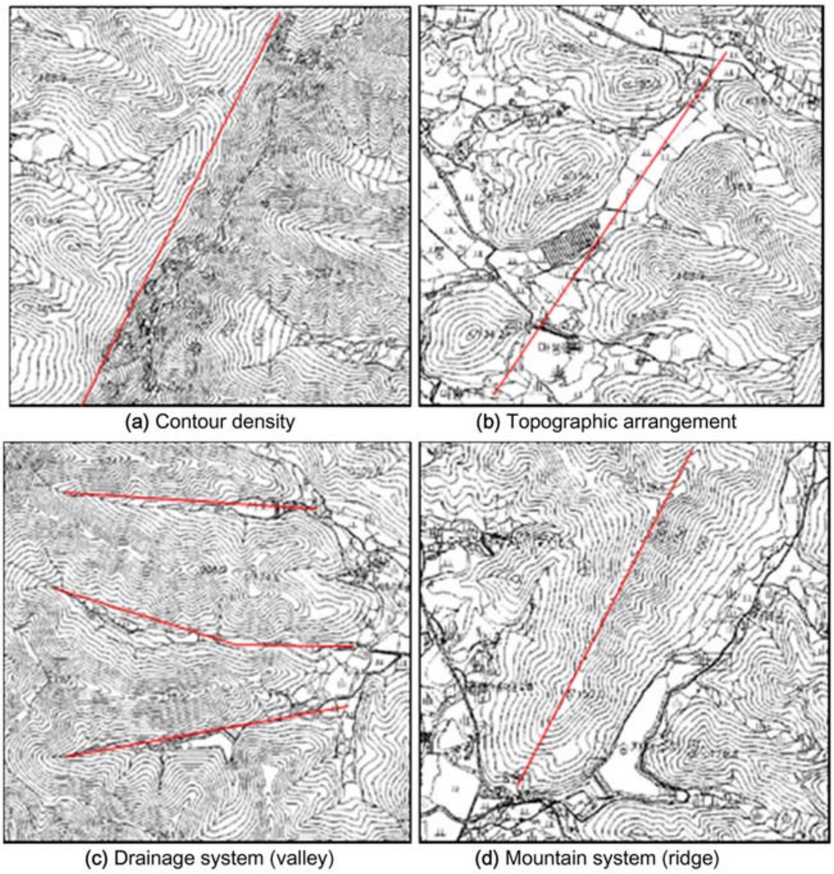

Fig. 3. Categories of topographic contour characteristics used in the lineament analysis.

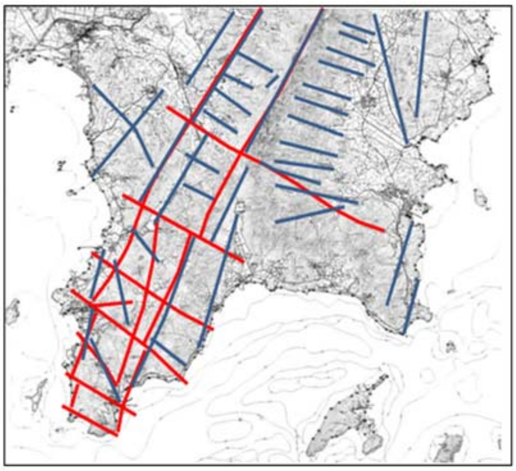

Fig. 4. Comparison of the lineament extraction elements of the Haenam Peninsula (blue lines) with geologically observed tectolineaments (red lines).

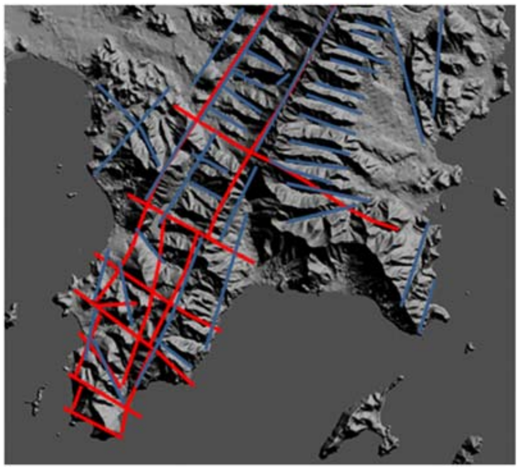

Fig. 5. Comparison between the shaded relief DEM and the lineament analysis results. Red and blue lines mark the geologically observed tectolineaments and lineament extraction elements, respectively.

3c and d highlight the linear characteristics of drainage and mountain systems, respectively. These characteristics highlight the main regions where significant elevation changes are observed, and are identified as lineament extraction elements. In this manner, the goal is to develop an automatic analysis that identifies geological structures by relating the contour characteristics of the topographic map to the lineament extraction elements.

The lineament extraction elements identified from the topographic map analysis were then correlated with the geological map of the region to determine how well this surficial analysis captures geological structures (Fig. 4). The red lines on Fig. 4 are the major geological structures identified from the geological map, whereas the blue lines are the geological structures obtained from lineament analysis using the 1:25,000 digital topographic map. The lineament analysis mapped most of the NNE-trending geological structures and boundaries; a number of small-scale geological structures were also identified from the lineament analysis method. These small-scale lineaments are considered to be minor geological structures related to the major NNE-trending geological structures of the region.

Fig. 5 compares the tectolineaments obtained using lineament extraction elements and using a shaded-relief DEM with a given lighting azimuth. Distinct shade contrasts on the shaded-relief DEM generally coincide with geological structures and the lineament extraction elements. However, the lineaments that were parallel to the lighting azimuth were difficult to identify on the DEM. Therefore, as previously mentioned, topographic contour analysis would be more accurate than a shade-contrast image analysis method when employing lower-resolution regional-scale imagery.

Application of the lineament analysis method to submarine bathymetry

An offshore section near the Haenam Peninsula, in an area linking Haenam Peninsula and Jeju Island, was chosen as a test region for applying the lineament analysis method to seafloor bathymetry (Fig. 6). Seafloor mapping from the 1980s indicates that depths of up to 145 m are reached in the southern region of Hwado. However, the coarse seafloor sampling of the region, where some lines were > 10 km apart, means that any interpolation of the data would greatly reduce the reliability of extracting meaningful lineament information in this region.

A multi-beam sonar survey was conducted in 2014 to produce a continuous high-resolution bathymetry map of the study area for lineament analysis. A Reson's Seabat 7125 SV2 multi-beam dual-frequency (200 kHz / 400

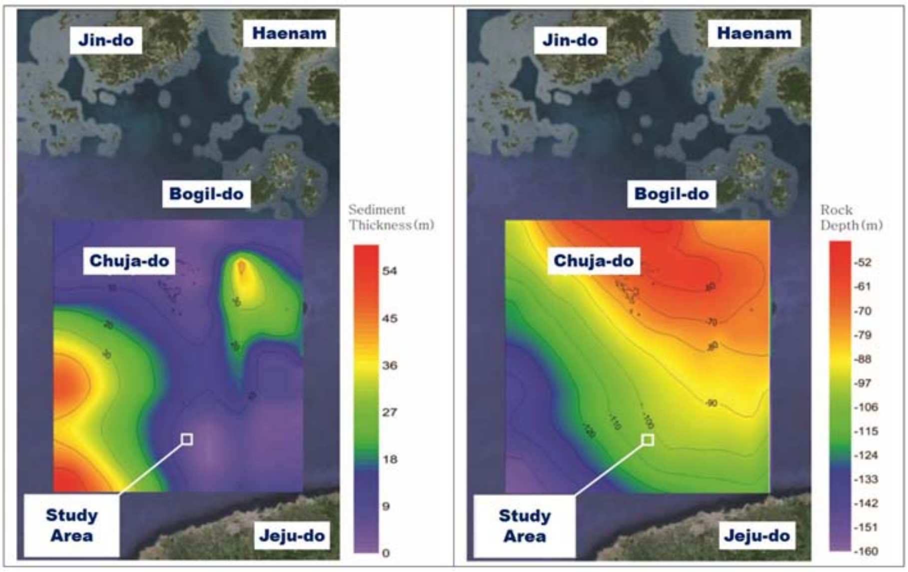

Fig. 6. Sediment layer depth and rock layer depth in the study area.

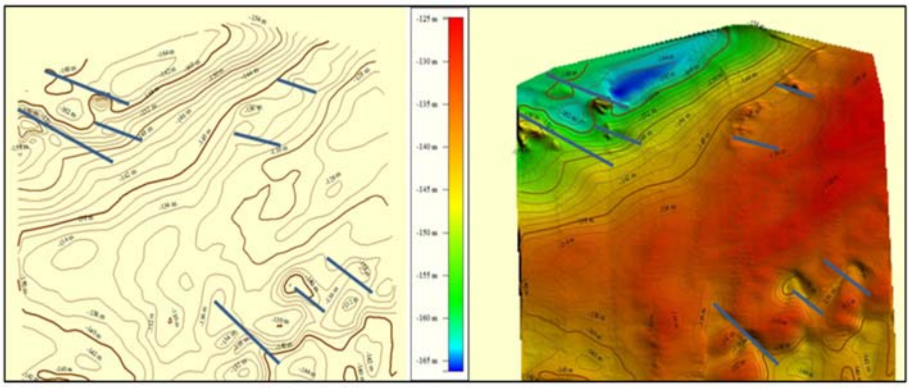

Fig. 7. Submarine topographic contour map and colored shaded relief image.

kHz) sonar was used, receiving 256 and 528 beams (for the two frequencies) across a swath approximately four times wider than the water depth. The vessel primarily travelled in a north-south direction at a 300-m line spacing during the survey. A sound velocity profile was obtained with a sound velocimeter for velocity corrections, tidal observations were made for the ride correction, and continuous global positioning system (GPS) measurements for the vessel and sonar were made to locate the bathymetric observations with high precision.

The PDS2000 data acquisition program was used to collect the sonar data. It displayed the approximate depth in real-time, using the GPS and motion sensor information and simple data processing in a bid to enhance the data accuracy. The acquired data were then subjected to position error removal, noise removal, sound velocity correction and tidal correction, using the CARIS HIPS & SIPS 7.1 post-processing program. This resulted in a map of seafloor bathymetry across the study area at a spatial resolution of 10 m and a depth resolution of < 1 m (Fig. 7).

The lineament analysis method was applied to the submarine contour map produced from the multi-beam sounding survey. The blue lines in Fig. 7 highlight the primary geological structures identified by the lineament analysis; ESE-trending geological structures are observed across the study area. The central region possesses a broad and gentle bathymetry, attributable to the thick sediment layer, which reduces the bathymetric features related to the submarine geological structures that were identified from the lineament analysis. It is thus necessary to employ other geophysical methods to characterize this sediment cover and produce a bedrock map that will capture the extent of these observed lineaments across the study area.

Review of automated lineament analysis methods

Two theoretical methodologies that automate the lineament analysis for identifying geological structures were evaluated. The DEM analysis and image processing technique employs the digital image processing of a DEM for the lineament analysis. The spatial statistic visualization analysis technique employs a statistical approach to extract lineament elements.

The DEM analysis and image processing technique uses the available topographic and geological data to produce a regional DEM. After identifying the horizontal and vertical curvatures from the DEM, it is converted to the regular DEM by applying Delaunay triangulation and piecewise quadric polynomial interpolation. Then it identifies the digital model to horizontal curvature (Kh) and vertical curvature (Ky) from the regular DEM according to the Evans-Young method (Florinsky, 1998; Schmidt et al., 2003). Finally, the lineament elements are automatically extracted from the digital map after the digital image processing (Haralick, 1983; Koenderink and van Doorn, 1993; Eberly et al., 1994; Rieger, 1997; López et al., 1998), where the degree of contrast is visually chosen to guide the lineament extraction.

The spatial statistic visualization analysis technique is a new methodology that determines the statistical significance of each location from the topographic map in relation to a regional value by applying the moving-window concept. Lineaments are then determined through visualization analysis of the spatial statistics. The criteria that define a lineament are then set (critical value), and the lineament elements are automatically extracted from the statistical analysis of the regional topography.

To develop an effective technique that will automatically extract the geological structure from submarine bathymetry, it is necessary to compare different methodologies of automatic lineament analysis applied to similar cases and datasets. It is also necessary to develop a method for determining how well the tectolineament extraction elements relate to key geological structures.

Conclusion

The lineament analysis method was employed to characterize the geological structure of the Haenam Peninsula, Korea, and then applied to recent submarine bathymetry data to determine how well these surficial analyses capture key geological structures. Lineaments were first identified from the available topographic data and then related to known geological structures. Both primary and secondary geological structures were identified across the Haenam Peninsula by the lineament analysis method. Discontinuous geological structures were also identified across the submarine study area; however, the presence of sediment cover across the central portion of the study area made it difficult to map the continuity of these geological structures across the entire area.

Future studies include: (1) a detailed study that highlights the advantages and limitations of the lineament analysis method where the geological structure is well known; (2) verification of the applicability of this method to various geological conditions; (3) the collection of topographic and geological data in areas surrounding existing tunnels to ascertain the applicability of this method in selecting future tunnel locations; and (4) further development of an automated lineament extraction module.

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