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The application of geomorphic indices in terrain analysis for ground engineering practice

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ABSTRACT

Terrain analysis studies for long linear engineering projects provide critical engineering geological and geomorphological data that inform project design options, route selection and construction methodologies. This paper introduces the use of geomorphic indices alongside methods of aerial photograph interpretation and remote sensing in the desk study phase of engineering terrain evaluations in the identification of landscape changes and geohazards in active tectonic regions. Three geomorphic indices (hypsometry, river long profile analysis and stream-length gradient index) are applied to freely available DEM data in order to develop the qualitative and quantitative (relative to study area) understanding of how the hillslope and river systems respond to the effects of tectonic activity and climate change. A hypothetical pre-feasibility study corridor (10 km width) located in the Sorbas Basin (SE Spain) is used to develop the methods of application, which could represent a proposed rail, road or pipeline routing. The results of the scaled indices approach, from catchment to reach (i.e. section of uninterrupted river channel) investigations, indicate a variable response of landscape processes. 'Active' erosional conditions are found in the central and northern limits of the basin relating to a known zone of tectonic deformation, the Infierno-Marchalico Lineament, and also to the effects of a river capture-related base-level lowering. 'Active' conditions are typically linked to an increased occurrence of landslides and badland formation. 'Stable' conditions are more common in the west and east of the basin where drainage channels are effectively coupled to base level. The combined results of geomorphic indices and aerial photograph interpretation are used in the identification of engineering constraints and geohazards as related to gully development, badland formation and the formation of landslides. A simple geohazard constraints map is produced which demonstrates ground related hazard to the wider project team and can be used to target field investigations and further inform construction methodologies and limitations.

1. Introduction

The early stages of large civil engineering projects for long linear infrastructure (e.g., highways, railways, oil and gas pipelines, etc.) often require rapid regional assessments to be made of the potential geological and geomorphological ground conditions that might be encountered, usually with limited information available. Results from these assessments can then be used to inform design options, route selection and construction methodologies, with lasting implications for the project. It is important that geology, geomorphology, geohazards information and other terrain-related geo-engineering issues can be determined along the proposed route corridor or alignment as accurately and as quickly as possible. In particular, the identification of landslides (both existing and potential first time failures), active erosional rivers and patterns of regional and local erosion are important (e.g., Lee et al., 2016).

An approach often used for oil and gas pipeline projects is Engineering Terrain Evaluation (e.g., Griffiths, 2001; Fookes et al., 2001, 2005; Shilston et al., 2005; Hearn, 2011; Hearn et al., 2012). This approach combines the knowledge and expertise of a project 'Geoteam' with regional remote sensing interpretation (e.g. satellite imagery, aerial photographs, etc.) and analysis of available mapping or digital datasets (e.g., digital elevation models, published maps of geology, topography, etc.) to derive engineering outputs (e.g., maps, drawings, tables, reports, etc.) that can be used to assist route selection, avoidance of geohazards and design of subsequent site investigations. The use of digital datasets, such as Digital Elevation Models (DEM), allows for the application of geomorphic indices. Geomorphic indices are quantitative analyses of topography that use DEM datasets in conjunction with Geographical Information System software. They are a long standing and rapidly expanding area of quantitative geomorphological analysis within academic research (e.g. Keller, 1986;

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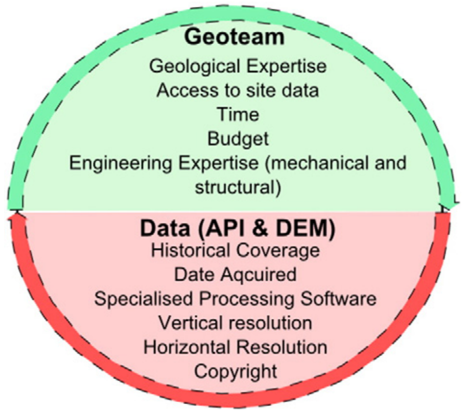

Fig. 1. Controlling factors in engineering studies for long linear infrastructure.

Lee and Tsai, 2010; Antón et al., 2014) yet to be widely realized by the engineering industry.

The success of any terrain evaluation is governed by a number of factors (Fig. 1). The ability of the Geoteam (i.e. collective of experienced project personnel from a range of related disciplines such as geologists, geotechnical engineers and mechanical engineers) to accurately qualify and quantify landscape attributes is strongly influenced by their combined experience in the geological/geomorphic environment and their ability to analyze landscape data over a range of temporal and spatial scales (Lee and Charman, 2005; Hart et al., 2009). The landscape data used in long linear infrastructure projects aim to support interpretations of landscape stability (i.e. state of a landscape and its propensity to change) which are important when defining route suitability (Mollard et al., 2008). Aerial photograph interpretation (API) is a routine mapping approach for assessing morphology and rates of landscape change over set time intervals. API is widely applied in engineering projects and is supported by the increased usage of freeware such as Google Earth (e.g. Mather et al., 2015). The definition of key landscape attributes from publically available terrestrial DEMs (e.g. SRTM), such as slope angle and length, has also become increasingly useful in pipeline, road or rail routing studies (Mollard et al., 2008). However, these techniques provide little insight into relative landscape activity, with key elements of slope incision, stream channel migration or formation of larger landscape instabilities unaccounted for.

Geomorphic indices extract a combination of height, distance, area and slope data for input into simple equations. Index approaches are low-cost and rapid, allowing engineers to qualify and quantify landscape activity attributes such as rates of gully erosion, headwall retreat or river erosion, which depending on location/setting, are key geohazards for linear infrastructure investigations (Table 1) (Charman et al., 2005). The quantitative assessment of geohazards is important in many stages of engineering design, including river crossings (Veldman, 2008) or routings through steep/mountainous terrain (Hearn, 2011), where observations from API can be limited by data coverage, shadows, distortions or image quality. In such settings, index approaches can be employed to produce map derivatives that allow for clear comparisons with other geological and geomorphological datasets, such as landslide density derived from API. These data form vital baseline inputs for routing studies and can be input into engineering constraints maps in order to develop geohazard related project risks

Table 1
Terrain constraints and geohazards affecting pipeline routings from Charman et al. (2005). Hazards highlighted in bold are investigated herein by means of Geomorphic indices.

Geohazard	Description	Operation & maintenance risks	Geotechnical mitigation options		
			Investigation	Routing	Design & construction
Earthquakes – fault ruptures	Movement likely along pre-existing fault lines during earthquake activity.	Displacement, deformation, rupture, uncontrolled spillage. Can be trigger for landslides and ground collapse.	Locate fault zones. Assess earthquake history.	Detailed alignment control in fault zones.	Special trench design.
Earthquakes - liquefaction	Ground shaking causes liquefaction or loose fine, granular and metastable soils.	Loss of support, displacement, Deformation, rupture, uncontrolled spillage.	Locate and classify material types and soil structure.	Avoid susceptible soils by lateral realignment or deepening.	Soil improvement
Volcanoes	Dome eruption, lava flows, ejected material, lahars	Displacement, deformation, rupture, loading, uncontrolled spillage	Locate existing domes and flow channels	Avoid and local alignment control to negotiate existing flow channel	
Landslides	Slow or rapid ground displacement caused by change in geometry, ground water level or Seismicity, includes rock fall, shallow soil slides, deep rotational slides, debris and mud flows to significant distance from source.	Loss of support, displacement, deformation, rupture, loading, uncontrolled spillage	Locate existing landslide-landslide prone terrain and extent of sidelong ground	Detailed alignment control to avoid existing landsides. Minimize potential unstable sideling ground	Careful earthwork, design, spoil handling measures and reinstatement.
Karst-Limestone	Limestone that has been or continues to dissolve in groundwater resulting in a network of sinkholes, caves, etc. Prone to sudden collapse.	Loss of support, displacement, deformation, rupture, uncontrolled spillage into groundwater system.	Assess and classify extent of karstification.	Avoid, minimize, detailed alignment control	Ground improvement measures
Karst-Gypsum	Gypsum or other sulphate enriched soils and rocks that have been or continue to dissolve in groundwater resulting in a network of sink holes. Caves, etc. Prone to sudden collapse.	Loss of support, displacement, deformation, rupture, uncontrolled spillage into groundwater system.	Assess and classify extent of karstification	Avoid, minimize, detailed alignment control	Ground improvement measures
River channel migration	River channels migrate across wide valley floors and sudden changes in location can occur under flood conditions	Loss of support, displacement, deformation, rupture, uncontrolled spillage into river system.	Map valley floor Assess catchment and hydrological history.	Minimize crossing length.	Pipe bridges or maintain sufficient depth of burial, river control.
Gullying and soil erosion	Removal of soil by water action across and adjacent to the pipeline. Existing gullies prone to enlargement by erosion and scour of banks and headwall	Loss of support, displacement, deformation, rupture, loading, uncontrolled spillage	Assess extent of sidelong ground, locate gullies and assess catchment	Minimize sidelong ground and avoid areas of active erosion.	Careful design of earthworks, cross drainage and erosion protection measures.