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High dimensional model representation for reliability analyses of complex rock–soil slope stability

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ABSTRACT

The high-dimensional model representation (HDMR) and its modifications, the fractional HDMR (FHDMR) and hybrid HDMR (HHDMR), are new tools for calculating reliability indexes in stability analyses when several variables with large uncertainties are used to describe rock and soil behaviours. Plain HDMR utilises an inverse reliability analysis for the study of unknown design parameters associated with target reliability index values. This approach uses implicit response functions, named limit state functions, according to the response surface method (RSM). In this study, both the FHDMR and HHDMR are applied to the reliability index calculation of safety factors related to the stability analyses of sliding failure mechanisms in complex formations. These two methods improve the computational efficiency of the RSM in reliability index calculations compared to the HDMR. A case study of Carpathian Flysch rock–soil slopes is presented, and the efficiency of the reliability index calculation is estimated by comparing results with ones from neural network application.

1. Introduction

Since the 1960s, several numerical procedures have been developed to address uncertainty and variability in engineering geological applications, including first-order reliability method (FORM), second-order (SORM), Monte Carlo simulations, neural networks, fuzzy logic, and the response surface methods (RSM). The main goal of these procedures is to estimate the reliability index β related to designing parameters, such as the factor of safety (FoS) of slope stability problems. To this end, the RSM has been extensively applied [1]. The RSM method is efficient when applied to physical problems governed by few deterministic variables. In contrast, the computational effort increases rapidly and its efficiency reduces when more than four random variables are considered. Recently, [2] issued a review paper on response surface methods applied to perform the slope reliability analyses. The authors discussed four commonly-used RSMs in terms of computational efficiency and accuracy of four different types of soil slope reliability problems: (1) single-layered slope ignoring spatial variability, (2) single-layered slope considering spatial variability, (3) multiple-layered slope ignoring spatial variability, and (4) multiple-layered slope considering spatial variability.

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To overcome the limitations of the RSM, [3–7] proposed a new approach called the high-dimensional model representation (HDMR) method to address random variables characterised by large coefficients of variation (CoV). This method was developed for mathematics, physics and chemistry applications (e.g., [8–10]) and has recently been applied to civil engineering problems (e.g., [11,12]). Tunga and Demiralp [13,14] developed two modifications of HDMR in order to improve its efficiency: factorised HDMR (FHDMR) and hybrid HDMR (HHDMR).

In the present paper, the preceding modifications of the HDMR have been applied to the case study of rock–soil flysch slope located in the Polish part of the Carpathian Mountains. The geological structure of this area is complex due to the alternations of blocky rock masses and soil layers. Such a complex geological pattern of flysch slopes generated landslides elsewhere in Europe, such as in Germany, the Ingelsberg landslide [15] and the Draga Valley landslide near Rijeka city, Croatia [16]. The rock–soil flysch successions have been intensively fissured as a result of the geological history, weathering (precipitation and snowmelt) and long-term water retention, especially on surficial layers. Such a complex material is characterised by heterogeneous lithologies whose mechanical properties are largely uncertain. It was also confirmed by monitoring and controlling studies performed on large number of landslides [17]. The present study represents a contribution to improving the calculation of the factor of safety *FoS* against slope sliding instability performed in complex rock–soil settings in terms of reliability index β. The upper-bound value of *FoS* is searched and finally the two modifications of the HDMR are used to calculate β values.

2. Flysch complex formations in Carpathian Ranges

2.1. *Geological features*

The Polish portion of Carpathian Ranges is located in the southern region of the country and is part of the Carpathian thrust and fold range that belongs to the territory of Austria in the West; the Czech Republic, Slovakia, Poland, Ukraine in the North; and Romania and south east Serbia. The Polish Carpathians are dominated by Cretaceous to Tertiary flysch deposits consisting of sequential layers of shale and sandstone as a result of being deposited in the deep marine basin during the continental mountain building process. They are mainly composed of flysch rocks, where graded bedding features from turbidities are ubiquitous [18]. These rock–soil flysch formations are arranged in successions characterised by naps that are thrust one over the other and also over the Carpathian foredeep. Each succession reflects specific sedimentary conditions of particular basins. To simplify this rather complicated sedimentary pattern, the Polish flysch deposits are divided into three major groups [19]: (1) normal flysch, consisting of adjacent sandstone and shale beds of approximately equal thickness; (2) shale flysch, where shale beds are thicker than adjacent sandstone beds; and (3) sandstone flysch, where adjacent sandstone beds are thicker than shale beds. Thrusting and consequent folding of the greater part of the Southern Polish Carpathians caused fractures and folds within the flysch deposits, which often generate landslides along shale beds. Landslides occur in all types of flysch deposits, dipping both parallel and perpendicular to existing geologic structures.

Four morpho-dynamic zones can be detected in Carpathian Flysch slopes with different surficial deposits [20]: high and middle mountains, foreland and sub-mountain zones. The highest slopes are located above 1800 m in the moderate-cold and cold climatic zones. In this mountain sector, the slope inclination is often greater than 80°, and the slopes are typically free of any cover or exhibit residual thin weathered mantles.

Here, steep slopes are cracked, and mechanical weathering predominates. Most of the gravitational movement results in the fallen-out material collecting in gullies and at slope outlets and creates debris covers. The zones that are the most susceptible to displacement from debris flows are those prevalently constituted by loose material.

2.2. *Structural models of Carpathian Flysch sequences*

According to [20], the Carpathian Flysch formations can be grouped into five structural models, as shown in Fig. 1. They include prevalent hard rock blocks greater than 0.3 m (1.a) or less than 0.3 m (1.b) thick, sandstones and clay shale alternations (2.a, 2.b, 3.a, and 3.b) and a loose structure with sandstone layers consisting of a few sandstone blocks (4.a and 4.b).

The rocky slope stratigraphic settings observed by [20] in Carpathian Flysch involved in failure mechanisms are shown in Fig. 2a–f: strong rocky layers are joined by weaker lamina made of softer flysch soil. Thus, the slope can be modelled as a sequence of thin flysch soil and thick sandstone layers: soil strata are considered as boundary surfaces (characterised by random values of friction angle and cohesion) among rocky blocks (Fig. 2).

The variable and irregular structural settings shown in Figs. 1 and 2 is addressed hereafter by applying HDMR method: all the illustrated models but number 5 (Fig. 1) can be represented by the sequence of rocky and soil layers with variable thicknesses and mechanical properties. All the variables involved in a stability analysis can be considered as random fields. The case of sandstone bricks, which implies a three-dimensional structural model, is not investigated due to its irregular pattern.

The present study calculations are carried out for a 2D slope (Fig. 3) corresponding to the structural model 2.a (Fig. 1) and geological setting a (Fig. 2). In fact, in this ''apparently'' stable condition some typical geometric and geotechnical values involved in slope failure have been measured and reported in Table 1.

As shown in Fig. 2a, the assumption of rock layers dipping as in Fig. 3 is reasonable and can be considered as a safe case. The instability, then, can be due to the presence of random cracks and joints that intersect the flysch layers causing the progressive failure of the slope. This unstable case is then investigated according to a reliability-based approach. The mechanical behaviour of the rocky slope in Fig. 3 is described by a perfectly rigid plastic law following the Mohr–Coulomb