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Robust geotechnical design of shield-driven tunnels

Wenping Gong [a,b], Lei Wang [a], C. Hsein Juang [a,c,*], Jie Zhang [b], Hongwei Huang [b]

[a] Glenn Department of Civil Engineering, Clemson University, Clemson, SC 29634-0911, USA
[b] Department of Geotechnical Engineering, Tongji University, Shanghai 200092, China
[c] Department of Civil Engineering, National Central University, Jhongli City, Taoyuan County 32001, Taiwan

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ABSTRACT

This paper presents a fuzzy set-based robust geotechnical design (RGD) methodology for the design of shield-driven tunnels. Here, uncertain geotechnical parameters required for analysis of tunnel *performance* (referred to herein as the structure safety and serviceability performance of tunnel cross section) are represented as fuzzy sets. Given fuzzy input parameters, the performance of a shield-driven tunnel will be uncertain, which is expressed in this study as a fuzzy factor of safety, according to the analysis of vertex method. Then, the fuzzy factor of safety for a given design is used to evaluate the failure probability and design robustness, which are, in turn, employed in the proposed RGD framework. Note that a design is considered *robust* if the performance of the shield-driven tunnel is insensitive to the variation of its uncertain geotechnical parameters. Within the RGD framework, each candidate design in the design space is analyzed for its safety state (in terms of failure probability), design robustness, and cost. The goal of the RGD of a shield-driven tunnel is to bring the safety state to an acceptable level, while maximizing the robustness and cost efficiency simultaneously. To this end, a multi-objective optimization is performed and a Pareto front is obtained, which provides a trade-off that may be used to select the most preferred design. Through an illustrative case, the effectiveness and significance of this new robust design methodology is demonstrated.

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1. Introduction

Benefiting from the advances of shield-driven machines and tunneling technologies, shield-driven tunneling has gained a world-wide popularity in the construction of tunnels in urban areas [1,22]. Because of the inherent variability, testing error and transformation error, geotechnical parameters for design of shield tunnels are often hard to characterize with certainty [29]. To compensate for such uncertainties, a conservative estimate of geotechnical parameters is generally taken in the design. To further ensure safety, the computed factor of safety (Fs) for a feasible design is required to be greater than the *allowable* Fs, a value derived from past experience. Thus, the "true" safety level of a design is generally unknown, as the uncertainties are only implicitly considered.

To overcome the shortcoming of the above deterministic design method, probabilistic approaches that consider uncertainties *explicitly* have also been sought [18,20,26,34]. The uncertain geotechnical parameters are generally treated as random variables, and the outcome of the analysis of a design, referred to herein as the system response, is generally expressed as a reliability index or a probability of failure. In the practice of geotechnical engineering, the site-specific data is often limited, thus an accurate statistical characterization of the uncertain variables is indeed a challenging prerequisite for adopting probabilistic approaches. The value of a probabilistic analysis could be greatly undermined if the adopted joint distribution of input geotechnical parameters cannot be reliably determined.

Recently, the robust geotechnical design (RGD) methodology has been developed for analysis and design of geotechnical systems with uncertain input parameters [14,15,35]. In the context of robust design, a design is considered *robust* if the performance of the system is insensitive to the variation of uncertain geotechnical parameters. Within the RGD framework, the design robustness is sought along with safety and cost efficiency. The cost is primarily a function of *design parameters*, those that are "easy-to-control" by the designer, such as the geometry and dimensions of the system. Safety and robustness are, however, a function of the design parameters as well as the "hard-to-control" parameters, such as uncertain geotechnical parameters. In the context of the RGD, these hard-to-control parameters are termed "*noise factors*." The primary goal of RGD is to derive an optimal design (represented by a set of design parameters), in which the system response is robust against, or insensitive to, the variation of noise factors, while the requirements of safety and cost efficiency are also

* Corresponding author. Address: Department of Civil Engineering, Clemson University, Clemson, SC 29634-0911, USA. Tel.: 1 864 656 3322.
E-mail address: hsein@clemson.edu (C.H. Juang).

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satisfied. The RGD provides a new perspective for designing geotechnical systems under an uncertain environment. Although applications of the RGD methodology in various geotechnical problems have been explored [11,14,15,35], it is based on probability theory which requires the probability density function of the uncertain variables. Moreover, it is based on repetitive reliability analysis and could be computationally intensive within the RGD framework.

When a fully statistical characterization of geotechnical parameter is difficult, the uncertain parameter can be alternatively modeled using the fuzzy set theory [38]. In the fuzzy set theory, an uncertain variable can be modeled with only knowledge of its highest conceivable value (HCV) and lowest conceivable value (LCV), which are generally easy to determine even with limited data [6]. The application of fuzzy sets theory indeed has a track record in geotechnical engineering particularly when the site-specific data is limited [12,13,21,27,33]. As will be seen later in this paper, the response of a system with fuzzy input data can be evaluated accurately and efficiently through the vertex method. Thus, the fuzzy set theory appears to be an effective and efficient means for representing and processing uncertain information in geotechnical engineering, and suitable for inclusion in the intended RGD framework for design of geotechnical systems.

The objective of this paper is thus to create and demonstrate a fuzzy set-based RGD methodology for design of complex geotechnical systems such as shield-driven tunnels. This paper is organized as follows. First, a deterministic model for design of shield-driven tunnels is introduced. Then, the vertex method to process fuzzy input data in this deterministic model for tunnel performance analysis is presented, followed by a probabilistic procedure to interpret the results of fuzzy set-based analysis. Thereafter, the fuzzy set-based RGD methodology is introduced and explained. Finally, a shield-driven tunnel design example is studied to illustrate the effectiveness and significance of the proposed design methodology.

2. Deterministic model for shield-driven tunnel performance analysis

As a slender structure embedded underground, the performance of tunnel cross section with respect to the limit states of segment strength (ULS) and serviceability (SLS) is the major concern in the design of a shield-driven tunnel [3,9,10,25], although the effect of tunnel longitudinal differential settlement should also be considered in cases [8,19]. The focus of this paper is on the performance of non-staggering shield-driven tunnels, and no differential settlement of shield-driven tunnels is included. Before presenting the fuzzy set-based RGD, the adopted deterministic model for assessing the performance of shield-driven tunnels is first introduced.

2.1. Analytical solution of jointed tunnel internal forces and deformation

Among various existing approaches to analyze the internal forces and convergence deformation of jointed shield-driven tunnels [16,17,36], the model by Lee et al. [17] is adopted herein for its simplicity and wide acceptance. Fig. 1 depicts the possible loads acting on a shield tunnel, including the earth pressure, water pressure, dead load, ground surface surcharge, and subgrade reaction. Detailed formulation of the load conditions in this model is listed in Appendix A.

As will be shown later, the segment thickness (t), segment steel reinforcement ratio (ρ) and diameter of joint bolt (D_j) are the key design parameters that affect the tunnel performance. The stiffness

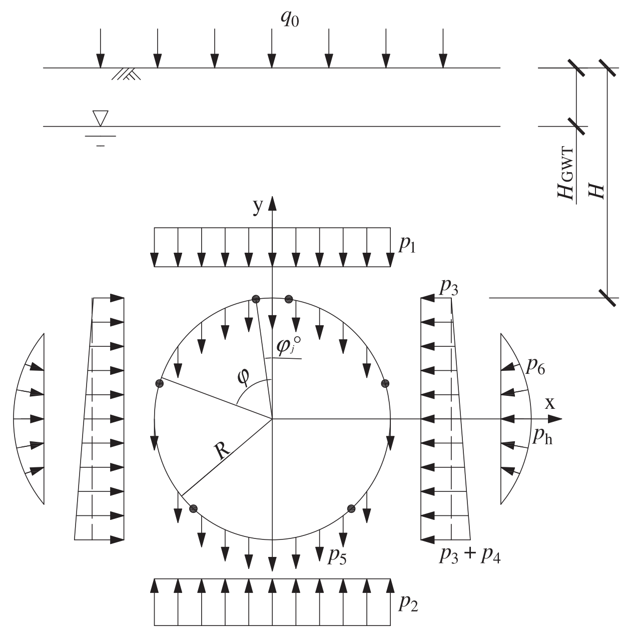

Fig. 1. Schematic diagram of loads on a shield-driven tunnel cross-section.

of segment is determined by the segment thickness and reinforcement ratio, while the stiffness of the joint is dependent on the diameter of joint bolt and segment thickness. The stiffness of tunnel segment, E_cI_e, is calculated as (referred to Appendix B):

$$E_cI_e = E_c\left[\frac{1}{12}bt^3 + 2(bt\rho)\frac{E_s}{E_c}\left(\frac{t}{2}-a\right)^2\right] \quad (1)$$

where E_c = the elastic modulus of concrete, E_s = the elastic modulus of steel bar, b = the width of tunnel ring, t = the thickness of tunnel segment, and, a = the concrete thickness of protective cover for steel bar. With the assumptions that (a) all the tension is beard by the bolts at joints; (b) no pre-stress is applied to the bolts; and (c) the adjacent tunnel segments are initially contacted, the joint stiffness, K_j, when subjected to the positive bending moment (i.e., the inside surface of tunnel segment is subjected to tension), can be estimated as (referred to Appendix B):

$$K_j = \frac{E_cbx^2(t-h-x/3)}{2l_b} \quad (2)$$

where l_b = the length of joint bolt, B_s = the cross sectional area of the bolts at concerned joint, h = the position of the bolts center measured from the inside surface of the tunnel segment, and, x is defined as:

$$x = \sqrt{\frac{2E_sB_s}{E_cb}(t-h) + \left(\frac{E_sB_s}{E_cb}\right)^2} - \frac{E_sB_s}{E_cb} \quad (3)$$

For simplicity, the joint stiffness that subjected to negative bending moment is assumed to be equal to that subjected to positive bending moment.

With the computed load and stiffness of the tunnel lining, the internal forces and convergence deformation of tunnel cross section are readily calculated through the existing model [17]. The resulting internal forces and deformation can be used to assess the segment structure safety (based on ULS) and serviceability (based on SLS) of tunnel cross section.

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