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Research Paper

Finding a better shape: Morphological description of strain response envelopes using a Fourier series approximation method

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ABSTRACT

This paper introduces a new method for quantifying the morphological evolution of the strain response envelope (SRE). The Fourier series approximation was used to trace the morphological characteristics of SREs. Two SREs computed via numerical simulations using the Modified Cam Clay (MCC) model and three SREs obtained from stress-probing experiments on Chicago clay were used to validate the proposed method of Fourier series approximation. The results show that using a harmonic number of 1 or 2, the target shape of the SRE can be approximated within a 10% error.

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1. Introduction

When a stress path occurs in various directions, as is the case of excavation in complex downtown areas, it is very difficult to accurately predict the deformation of the ground. As a tool for analyzing the directional properties of soil, a response envelope has been being used. A response envelope is an envelope obtained by connecting output response points which emerge in different sizes depending on the radial direction when radially symmetrically applying an input probe of a certain amount at the origin. Lewin and Burland [1] analyzed the directional deformation properties of clay using stress increment as the input probe and strain increment as the output response. Bazant [2], Gudehus [3], Gudehus and Masin [4], and Gudehus [5] used the stiffness response envelope, which used stress rate as the input probe and strain rate as the output response. Tamagnini et al. [6] used finite strain increment as the input probe to introduce an incremental stress response envelope. Royis and Doanh [7], and Doanh [8] adopted stress increment and strain increment respectively as the input probe and output response to introduce an incremental strain response envelope (SRE). The directional responses as derived from experiments and various constitutive models have been compared. Costanzo et al. [9], and Masin et al. [10] used the strain increment acquired from stress-probing experiments to analyze the directional response of strain. Masin [11] used an incremental strain response envelope to compare the performances of constitutive models for structured clay. The response envelope dealt in this study is an incremental strain response envelope (SRE) acquired by using stress increment as the input probe and strain increment as the output response. Similar to what have been reviewed by Wu and Kolymbas [12] about the stiffness response envelope, the characteristic properties of the SRE can be summarized as below.

(1) The distance between the origin of incremental strain space to a point on the SRE is the secant compliance value for its corresponding stress probing direction.
(2) The SRE of elastic constitutive models is expressed as an ellipse with the initial strain in the center.
(3) The SRE of hypoplastic constitutive models is expressed as a translated ellipse.
(4) When the probing stress point approaches failure surface, the strain rate in the same direction rapidly increases, and the SRE becomes significantly extended.

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The response envelope is not exclusively used for the quantitative comparison between various constitutive models or the different behaviors of a material. For example, Wu and Kolymbas [13] showed the response envelope can be used to develop a hypoplastic constitutive equation. It is of interest that Jung and Cho [14], and Kim and Jung [15] found an elliptical SRE fitted for the SRE obtained from experimental data. They quantitatively investigated the characteristic directional behaviors of soil by tracing the translation of fitted ellipse and the changes in the rotation magnitude.

However, upon careful examination, several problems can be found in the fitted elliptical SRE suggested by Jung and Cho [14], and Kim and Jung [15]. For example, if a fitted ellipse with respect to an SRE which is peculiarly elongated to a specific direction due to excessive strain rate is found, the origin of incremental strain space can lie outside the fitted ellipse. In this case, the SRE expressed by the fitted ellipse completely misrepresents the deformation behaviors of soil during the unloading process. In the SRE with respect to the elastic-plastic constitutive models, a sharp turn occurs at the boundary where the elastic response transitions into the plastic response. If this is fitted to the ellipse, the sharp turn becomes rather blunt. The loss of valuable information included in the morphological texture of the SRE, which could look irregular and meaningless, obtained from experiments becomes clearly a limitation in expressing the shape of SRE as a simple ellipse. There would definitely exist an alternative theoretical equation which is capable of better expressing the SRE shape using the same number of parameters.

Fourier series can express a complex shape mathematically on a 2-dimensional space. As originally proposed by Cosgriff [16], the Fourier series can be used to analyze an arbitrary closed curve and has become a popular shape representation method in many research areas. In computer science, the Fourier series has been used for shape discrimination [17–19]. In powder technology, the Fourier series has been a popular tool for analyzing particle profiles [20–25]. In geotechnical engineering, Bowman et al. [26] used the Fourier series to analyze soil particle shape characterizations. Therefore, the Fourier series method can be used to effectively express a complex shape of the SRE as well.

The purpose of this study is to develop a new morphological model for the SRE based on the Fourier series, in order to effectively express an experimental SRE having a highly distorted shape. The shape of an SRE obtained from the results of the numerical analysis on the modified cam clay (MCC) constitutive model, and the shape of an SRE obtained by conducting stress-probing experiments on Chicago clay were approximated using the Fourier series method. The results show that SREs reconstructed by the Fourier series with a minimum number of variables is a good alternative to modeling elliptical SREs with shift and rotation.

2. Fourier series approximation

An SRE can be constructed by connecting the points of strain increments that result from input stress probes that radiate from the initial stress along the same length of the stress path (LSP). In

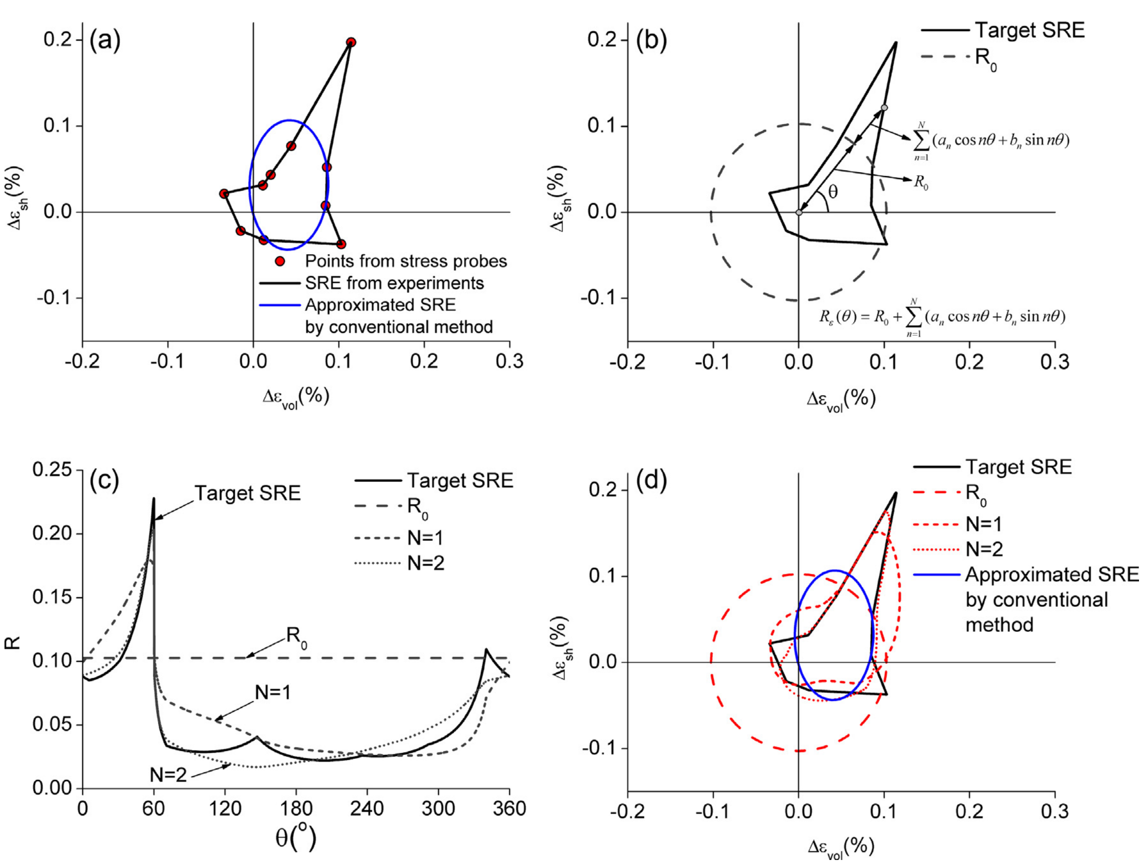

Fig. 1. Fourier series approximation of the strain response envelope (SRE): (a) target shape of an SRE; (b) measurement of R and θ; (c) Fourier series approximation; and (d) reconstructed SREs with different harmonic numbers.

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