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A pseudo-static method for seismic responses of underground frame structures subjected to increasing excitations

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ABSTRACT

The determinant factor for the seismic response of underground structures is the deformation of surrounding soil, which is different from above-ground structures. Considering that the existing deformation-based seismic design methods for underground structures are based on elastic hypotheses, this study proposes an improved Finite Element method called New Pseudo-Static Analysis (NewPSA) to predict the nonlinear behavior of underground frame structures subjected to increasing horizontal seismic excitations. A new method for one-dimensional(1-D) seismic analysis of soil layers is proposed to calculate the distributions of displacements and shear stresses along the depth in the free-field with increasing bedrock motions. Pseudo-static Finite Element analysis is then carried out by imposing the distributions of body forces derived from the 1-D analysis. A series of comparisons were made to validate the applicability of the proposed method. Its prediction capacity was also compared with that of a well-known method. The proposed method is able to predict the nonlinear performances of underground structures under horizontal earthquake loadings. Particularly, similar to the push-over analysis of above-ground structures, the method has the potential to predict the seismic capacity of underground frame structures subjected to design seismic loadings.

1. Introduction

Underground frame structures are widely used in urban construction such as subway stations, tunnels, underground parking lots and underground shopping malls. In earthquake-active areas, this form of construction should be designed to resist not only overburden gravity loads but also seismic loads. Underground structures were considered to be safe during earthquakes until the 1995 Hyogoken-Nanbu Earthquake in which subway stations in Kobe City suffered severe damage including failure of center columns and roof collapse (Kuroda, 1996; Iida et al., 1996).

There are basically two categories of approaches to analyze the seismic response of underground structures. One is to conduct a dynamic time-history analysis based on Finite Element Method (FEM) or Finite Difference Method (FDM). The complete model including underground structure and surrounding soil is built and then particular ground motion is input from boundaries to simulate seismic wave propagation in the discretized domain. In order to obtain the seismic capacity of a underground structure, a large number of analyses may be necessary, which makes the approaches too complex and time-consuming to be employed in the seismic design. The other, i.e., the pseudo-static approach, is more favorable for design purposes. The core idea of pseudo-static approach is to convert dynamic seismic actions into static equivalent seismic loads. The seismic collapse mechanism of underground structures is different from that of above-ground structures: in an earthquake, primary loads on underground structures come from the deformation of surrounding soil (Okamoto et al., 1973), while the lateral loads of above-ground structures are inertial forces. Deformation-based methods are therefore more appropriate for the seismic design of underground structures, and the key issue of pseudo-static seismic analysis is to compute the deformations and the internal forces of the underground structure from the peak deformation value of surrounding soil by means of soil-structure interaction.

A discrete number of previous studies on the pseudo-static analyses of underground structures has been found in history. St John and Zahrah (1987) imposed the free-field deformation given by Newmark (1967) on an elastic tunnel and obtained the analyt-

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ical solutions for the tunnel's curvature and axial strain caused by shear, compression and Rayleigh's waves. Kuribayashi et al. (1974) and Kiyomiya (1995) modified soil-structure interaction through shear and normal springs connecting the underground structure and the surrounding ground, and then imposed relative displacements to the boundaries to analyze the responses. Wang (1993) proposed an approach called Free-Field Racking Method to calculate the deformation of an underground structure from the shear deformation of free-field soil based on the ratio between soil and underground structure flexibilities. Penzien and Wu (1998) and Penzien (2000) developed Wang's method and presented an analytical procedure for evaluating the racking deformation of rectangular and circular tunnel linings caused by soil-structure interaction during a seismic event. Based on Wang and Penzien's work, Huo et al. (2005, 2006) and Bobet et al. (2008) proposed a more precise analytical solution approximating deep rectangular tunnel's deformation by far-field shear stress or strain, which takes more relevant variables into consideration. The US NCHRP (National Cooperative Highway Research Program, 2008) employed the Free-Field Racking Method modified from Wang's analytical solutions and gave the relationship between racking ratio and flexibility ratio. Katona (2010) simulated the seismic loading condition of underground structures by specifying quasi-static displacements at the peripheral boundaries of the soil envelope to produce a shear-racking distortion equivalent to the maximum free-field seismic shear strain from the design earthquake. Debiasi et al. (2013) compared the results obtained using Wang and Bobet's simplified approaches with those by nonlinear static soil–structure interaction analyses, accounting for the following effects: the frictional behavior of the soil–structure interface, the geometry of the box structure, the overburden depth, the maximum PGA, and the increasing soil stiffness with increasing depth.

Previous pseudo-static analysis approaches for underground structure design are mostly built on elastic hypotheses. The underground structures and surrounding soil are assumed to be linear-elastic or equivalent linear-elastic. These approaches are applicable for the responses of underground structures under small earthquake loading. However, as the amplitude of ground motion increases, plastic deformations exist in both the underground structure and soil. Hence, the elastic approaches are not suitable to predict the inelastic behavior of underground structures subjected to strong ground motion. It is therefore necessary to establish a new elastoplastic pseudo-static seismic design method to determine nonlinear performances and failure characteristics of underground structures under strong earthquake loadings.

Recently, pushover analysis has become a widespread approach for nonlinear pseudo-static seismic design of above-ground structures. ATC-40 (Applied Technology Council, 1996) and FEMA-356 (Federal Emergency Management Agency, 2000) both recommended pushover analysis as a standard Performance-Based seismic assessment method for building structures. In pushover analysis, seismic inertial forces are distributed on a building structure in various forms (uniform, inverted triangular or determined by vibration modes). Likewise, pushover analysis may be introduced into the nonlinear pseudo-static seismic design of underground structures. Liu et al. (2014) proposed a pushover analysis method for underground structures, which imposes inertial forces derived from inverted triangular distributed accelerations in the soil-structure system. The influences of inhomogeneous soil layers and seismic wave propagation are neglected. However, differently from above-ground structures, the distribution of inertial accelerations in the ground is not simply inverted triangular but determined by the properties of soil layers and ground motions. In addition, properties of soil layers change continuously owing to inelastic soil deformations under strong earthquake loading, leading to the alteration of inertial acceleration distribution.

The main objective of this study is to develop an improved pseudo-static method for the seismic design of underground frame structures based on pushover analysis, taking inelastic deformations of both soil layers and underground structures into consideration. The subsequent presentation is organized as follows. First, the nonlinear constitutive models of soil and underground structures are introduced, which are essential for the pseudo-static analysis. Second, an improved 1-D seismic analysis method of soil layers is proposed to calculate the continuously varying distributions of displacements and shear stresses in the soil deposit with increasing seismic excitations. Third, the distributions of body forces derived from free-field shear stresses are imposed in the complete soil-structure interaction model to carry out static pushover analysis. For the verification of the proposed method, the predicted results are compared with those from shaking table tests and dynamic time-history analyses.

2. Methodology of new pseudo-static analysis

2.1. Nonlinear constitutive models for soil and underground structures

In the common practice of soil dynamics, nonlinear shear behavior of soil is described by a shear stress-strain backbone curve (Kramer, 1996). The backbone curve can be approximated by the hyperbolic formula (Hardin and Drnevich, 1972):

$$\tau = G_r\gamma/(1+\gamma/\gamma_r) \tag{1}$$

where τ and γ are the octahedral shear stress and strain, respectively; G_r is the elastic shear modulus of soil at low-strain; γ_r is the reference shear strain, and γ_r is equal to τ_{max}/G_r, in which τ_{max} is the maximum shear stress when $\gamma\to\infty$. Regarding seismic events as variable transverse motions, stress-strain relationship of soil under cyclic loading is constructed according to the Massing's rules.

In order to expand the 1-D shear stress-strain relationship in Eq. (1) to 2-D and 3-D problems, a range of progressive yield surfaces are created in the deviatoric plane according to Prevost's theory (1985). The yield function follows von Mises Criterion:

$$f_i = J_2 - \tau_i^2 = \boldsymbol{s_i} : \boldsymbol{s_i} - \tau_i^2 = 0 \tag{2}$$

where $\boldsymbol{s_i}$ and τ_i are respectively the deviatoric stress tensor and the octahedral shear stress of yield surface i. Therefore the nonlinear constitutive model of soil in the principal stress space is established by combining the hyperbolic backbone curve and the Massing's rules relating the octahedral shear stress-strain through Prevost's multi-yield-surface theory.

As reinforced concrete structures, underground frame structures can be modeled in bidimensional through plane elements or beam-column elements and in tridimensional through solid elements or shell-lining elements. In the present cross-sectional seismic design of underground structures, which can be simplified into a 2-D plane strain problem, a fiber beam-column element proposed by Taucer et al. (1991) is selected. The cross-section of a beam-column element can be divided into a few subregions of simple shapes (quadrilateral, circular or triangular) called patches. In addition, layers of steel bars can also be specified as fibers. If the uniaxial constitutive relationships of concrete and steel bars are given, the nonlinear force-deformation behavior of beam-column element can be determined by the Gauss-Lobato integration scheme. In this study, Kent-Scott-Park model (1982) is adopted to describe the concrete constitutive relation, and a bilinear model with kinematic hardening is adopted to describe the steel reinforcement.