Tunnelling and Underground Space Technology 68 (2017) 58–73

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

# Implementation of the modified cross-section racking deformation method using explicit FDM program: A critical assessment

Chih-Chieh Lu[a,*], Jin-Hung Hwang[b]

[a] National Center for Research on Earthquake Engineering, No. 200, Sec. 3, Xinhai Rd., Taipei 10668, Taiwan, ROC

[b] Department of Civil Engineering, National Central University, No. 300, Jhongda Rd., Jhongli City, Taoyuan County 32001, Taiwan, ROC

ARTICLE INFO

*Keywords:*
Performance-based design
Seismic capacity
Tunnel
FDM

ABSTRACT

The modified cross-section racking deformation (MCSRD) method can accurately derive the vulnerability and the deformation of underground structures resulting from different magnitudes of earthquakes; while the nonlinear soil-structure interaction can be determined by numerical calculation. Compared with dynamic analysis, the MCSRD method is a more efficient and simpler way of achieving the seismic performance-based design (SPBD) for underground structures. To better apply the method using FLAD2D, the research includes several numerical examples, which study critical numerical points of the approach. The framework of the MCSRD method to assess the seismic capacity of underground structures will be demonstrated with an example.

## 1. Introduction

Seismic performance-based design (SPBD) of surface structures is commonly required in seismically active areas. In practice, the nonlinear static pushover analysis is used to derive the seismic performance of a structure. By gradually applying a seismic inertial force on the structure, pushover analysis can accurately quantify the seismic deformation of the structure, as well as identify its vulnerability when subject to different magnitudes of earthquakes. Conversely, the SPBD of underground structures has largely been ignored because it was thought that underground structures had better seismic resistance and were therefore less susceptible to damage from earthquakes than surface structures (Okamoto, 1973). However, this viewpoint has gradually changed due to an increase in incidents of damaged tunnels caused by catastrophic earthquake events such as the 1923 Kanto earthquake, 1995 Kobe earthquake, 1999 Chi-Chi earthquake, and 2008 Wenchuan earthquake (Okamoto, 1973; Asakura and Sato, 1996; Wang et al., 2000; Hwang and Lu, 2007; Wang and Zhang, 2013; Shen et al., 2014). As demonstrated by historical evidence, underground structures are still at a high risk of damage from compression by the surrounding ground, triggered by strong shaking. Therefore, the assessment of seismic capacities of underground structures in seismically active areas becomes an important issue to tunnel engineers, and there are several references providing an overview of design work regarding the seismic issues of underground structures such as FHWA (2009), ISO 23469 (2005), and Hashash et al. (2001). In design work, the earthquake-induced ground shaking and ground failures such as liquefaction, fault displacement, and slope instability should be carefully identified and evaluated. Among these causes of structural damage, the study discussed in this paper focuses on ground shaking.

In contrast to surface structures, the seismic response of underground structures is not dominated by inertial force but instead, by the surrounding ground response because of the confinement provided by the rock mass. This seismic mechanism of underground structures was observed and demonstrated by the field measurements of Okamoto et al. (1973). The focus of underground seismic design, therefore, is on the free-field deformation of the ground and its interaction with the structure. This finding led to the development of the cross-section racking deformation (CSRD) method (SFBART, 1960). The approach was first proposed by the San Francisco Bay Area Transit (SFBART) District in the late 1950s, and was used to evaluate the seismic response of a rectangular tunnel structure. The method assumes that the amount of racking imposed on the structure is equal to the free-field shear distortions of the surrounding medium, and directly applies the free-field deformation on the structure shown in Fig. 1. Since the CSRD method ignores the interaction between the underground structure and the surrounding ground, the structural deformations may be overestimated or underestimated depending on the rigidity of the structure relative to the ground. In order to further consider the variable of stiffness for the underground structure system in the CSRD method, some researchers derived analytical solutions, using some assumptions, to simply evaluate the seismic response of underground structures. (Wang, 1993; Penzien, 2000; Huo et al., 2006; Park et al., 2009). Note that the evaluated soil-structure interaction can be accurate only while

* Corresponding author.
*E-mail addresses:* chchlu@ncree.narl.org.tw (C.-C. Lu), hwangjin@cc.ncu.edu.tw (J.-H. Hwang).

http://dx.doi.org/10.1016/j.tust.2017.05.014
Received 18 November 2016; Received in revised form 24 March 2017; Accepted 17 May 2017

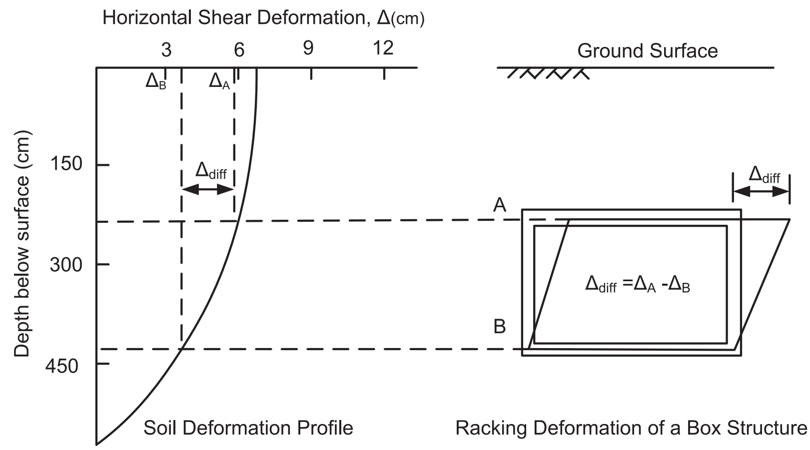


**Fig. 1.** Free-field racking deformation imposed on a buried rectangular frame (St. John and Zahrah, 1987).

the surrounding ground is homogenous and elastic and while the shape of the underground structure is not complex. Due to these restraints, the use of the CSRD method is limited in practice, and the recommended application of the CSRD method is to provide an initial seismic performance estimate for an underground structure. More detailed analyses, such as the MCSRD method or dynamic time history analysis, are needed to better understand the seismic interaction response between an underground structure and the surrounding ground (Hashash et al., 2001, 2005; Anastasopoulos et al., 2007; Abate and Massimino, 2017).

The modified cross-section deformation (MCSRD) method, comparatively, discards the direct application of the free-field seismic shear-strain on the structure and instead imposes a prescribed seismic shear-strain to the boundaries of a ground domain wherein an underground structure has been constructed, as shown in Fig. 2. This method can better simulate seismic loading acting on the underground structures due to its increased consideration of complicated soil-structure interactions. Furthermore, the calculation time of the MCSRD method is relatively short compared to that of dynamic time history analysis. Similar to the pushover analysis, by gradually applying seismic deformation on the structure, the MCSRD method can accurately quantify the seismic deformation of an underground structure and identify the vulnerability of the structure when subject to different magnitudes of earthquake. Moreover, the nonlinear deformation of the underground structure system can also be identified if the nonlinear properties of the structure and soil materials are defined.

The MCSRD method has been applied by several researchers for specific applications, and the feasibility of the MCSRD method has been proven by their studies. Among them, Wang (1993) used the FLAC2D program to perform the MCSRD analysis by applying shear force on the boundary of the model in order to observe the ovaling effect of a circular tunnel lining and validate his proposed simplified design method. Nishioka and Unjoh (2002) focused on the shear-strain transmission characteristics from the surrounding ground to the underground structure. Gil et al. (2001) conducted the MCSRD method to evaluate the seismic internal forces of the tunnel lining by imposing ground deformation in both vertical and shear modes, which correspond to seismic P and S waves, respectively, on the boundary. Besides, there are several case studies using the MCSRD to assess the performance of the tunnels subject to their corresponding earthquakes. Hwang and Lu (2007) employed the MCSRD method to assess the seismic capacity of the old Sanyi railway tunnel. Lu and Hwang (2008) used the method to ascertain the failure mechanism of the new Sanyi railway tunnel during the 1999 Chi-Chi earthquake. Kontoe et al. (2008) used the MCSRD method to evaluate the Bolu highway twin tunnels subject to the 1999 Duzce earthquake in Turkey.

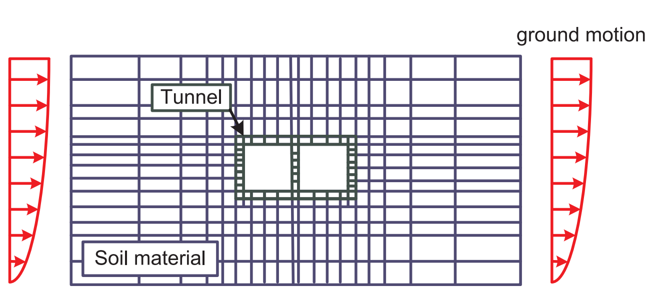


**Fig. 2.** Numerical model of modified cross-section racking deformation method.

Although there are many cases in the literature that cite the MCSRD method, few have carefully studied the numerical details while implementing this method, which could influence the results of analysis. As such, the main objective of this paper is to study these variables in detail. At the beginning of this paper, the procedure for conducting the MCSRD method for assessing seismic capacity of underground structures will be briefly introduced. Then, a comparison will be made between the analytical and numerical solutions of an elastic problem to validate the numerical program. After that, several numerical studies will be performed that address the following areas of analysis, and some suggestions regarding the use of the MCSRD method will be concluded for reference.

1. The simulation of nonlinear behavior of structural elements in FLAC2D.
2. The influence of the constitutive models of geotechnical materials.
3. The suitable boundary distance to the structure
4. The types of imposed shear-strain on boundary and shear-strain rate.
5. The effect of the interface between soil and tunnel lining.

The final part of the study uses a sample case to demonstrate the procedure of the MCSRD method. The seismic capacity in terms of peak ground velocity (PGV) and intensity scale, as well as the vulnerability of the structure in the demonstrated example will be expressed.

## 2. The modified cross-section racking deformation method

The procedure of the modified cross-section racking deformation method is to apply the prescribed shear deformation on the soil-structure boundaries of the model and let the associated numerical program consider the soil-structure interaction effect. Since the soil-structure interaction has been automatically considered by numerical calculation, the derived results are more reasonable than those obtained by the original CSRD method, and therefore the MCSRD method is the preferred method for seismic design. The computational steps of the MCSRD method are summarized in Fig. 3 and described below: