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SEISMIC ANALYSIS OF LONG TUNNEL: SIMPLIFIED OR UNIFIED

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Abstract. *Seismic analysis of long tunnel is important for safety evaluation of tunnel structure under earthquakes. Simplified models of long tunnel are commonly adopted in seismic analysis by structural engineers. Meanwhile, tunnel is usually modelled as a beam continuously supported by ground. Solving of the dynamic system is easy to get an overall response of tunnel structure. However, tunnels are not a tube with uniform cross-section. Road tunnel in mountain areas will be of varying section for emergence parking. Shield tunnel is assembled with segments to form a lining ring. Furthermore, the soil stratum, where a long tunnel is situated, is never at an identical geological condition. All of these would invoke non-uniform excitation if there be an earthquake. Tunnel engineers would like to know what it would be if a long tunnel subjects to earthquake, whether overall or locally, with the help of improved continuous-based or discrete-based dynamic analysis. This paper presents several examples to handle the seismic analysis with unified method, in comparison with simplified method. The proposed method developed a framework, with FDM and DEM, to compute both overall seismic responses of tunnel and damage in particular locations. A multi-domain analysis coupling discrete model and continuum model is proposed to reduce the computational cost and improve the accuracy, and a bridging scale term is introduced such that compatibility of dynamic behavior between the DEM-based and FDM-based models is enforced. To simulate the damage process of lining structure numerical method based on continuous mechanics and failure process by means of discrete method are hired to develop a coupled multi-scale method. Examples demonstrate the applicability.*

1 INTRODUCTION

Tunnels constitute a major part of civil infrastructure and serve as public transportation facilities, sanitation and irrigation utilities and storage places [1]. In seismically active areas, these tunnels are subject to earthquake induced risks. Recent events such as Kobe Earthquake in Japan (1995), Duzce Earthquake in Turkey (1999), Chi-Chi Earthquake in Taiwan (1999), Bam Earthquake in Iran (2003) and the Wenchuan Earthquake in China (2008) showed that tunnels are susceptible to receive irrecoverable damage due to seismic loading [2].

Dynamic behavior of tunnels subjected to seismic loading has been widely studied by a number of researchers [3-5]. There are two basic approaches in present seismic design and analysis of tunnel structures. The first approach is to carry out dynamic, nonlinear soil-structure interaction analysis using finite element methods. The excitation inputs in these analyses are time histories emulating design response spectra, and the excitations are applied to the boundaries of a “soil island” to represent vertically propagating shear waves. The second approach assumes that the seismic ground motions induce a pseudo-static loading condition on the structure. This approach allows the development of analytical relationships to evaluate the magnitude of seismically induced strains in tunnel structures [6-8]. These relationships are based on the premise that tunnel structures under seismic loading tend to deform with the surrounding ground, and thus the structure is designed to accommodate the free-field deformations without loss of its structural integrity.

The objective of this paper is to illustrate the seismic analysis of long tunnels with two different methods, i.e. simplified and unified. In the simplified method, multibody dynamics model and mass-spring-beam model for long tunnels are presented. The focus of the unified method is on the proposed multiscale method coupling both discrete model and continuum model to reduce the computational cost and improve the accuracy of the large soil-tunnel system. Examples are given to demonstrate the applicability of the proposed method.

2 CASES OF LONG TUNNEL

Three typical real-world long tunnels are described in this section, which will be used to demonstrate the simplified and unified methods presented in this study.

2.1 HZM immersed tunnel

HZM (Hong Kong-Zhuhai-Macau linkage) immersed tunnel, located at Lingding Sea, is under construction currently to connect Hong Kong, Zhuhai, and Macau, the cities around the Pear River. The length of the tunnel is more than 5,600 meters with 4-lane for highway, as shown in Figure 1. The immersed tunnel is made up of 33 concrete elements. Each element is 180m long, made up of 8 segments each 22.5 m long. The deep point of the seabed and the foundation level are approximately 30m and 45m below the mean sea level, respectively. The tunnel construction area is located in the seismic activity region, which is designed in accordance with the Chinese standards.

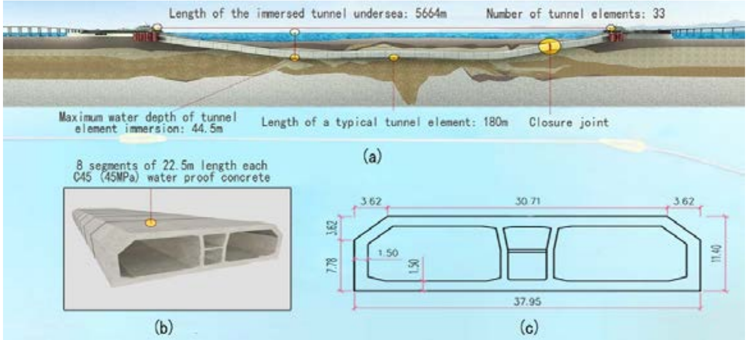


Figure 1: Layout of the HZM immersed tunnel

2.2 Qingcaosha water conveyer tunnel

The Qingcaosha water-conveyance tunnel is a double-line shield tunnel used for water supply in Shanghai, China. The tunnel has a total length of 14 km. Its layout can be divided into three segments: island, cross-river and land. The general layout and location of the shield tunnel are shown in Figure 2. Each ring consists of six segments, each with a length of 1.5 m. A stagger-jointed assembly is adopted between segments.

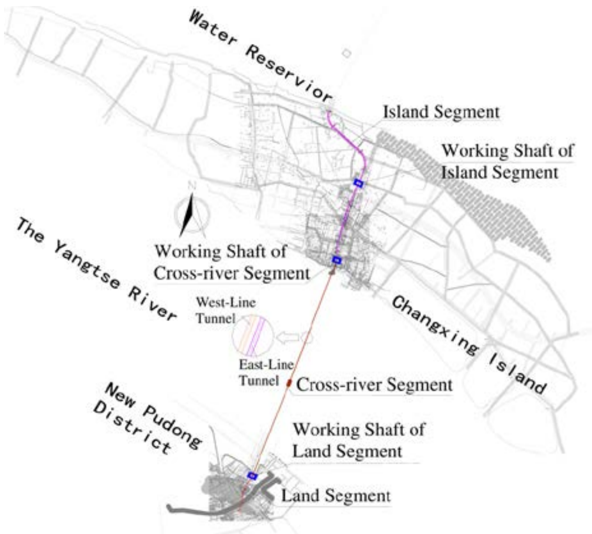


Figure 2: Map of the Qingcaosha tunnel

2.3 Road tunnel damaged during the Wenchuan earthquake

In western areas of China, a number of tunnels have suffered severe damage during the Wenchuan earthquake in 2008. For instance, the Longxi road tunnel, 2 kilometers far away from the epicenter of Wenchuan earthquake and at the faulted zone, suffered significant damage. The total length of the tunnel is 3,658 m, with a cross section composed of two parallel twin tunnels in two directions, 30m separated between axes. There were a number of cross sections where the liner was observed to be collapsed. Close to the fault the tunnel completely collapsed, as shown in Figure 3.

Figure 3: Collapse of the Longxi tunnel at the crossing of the fault.

3 SIMPLIFIED SEISMIC ANALYSIS OF TUNNEL

Two simplified models, i.e. multibody dynamics and mass-spring-beam, for seismic analysis of long tunnels are presented as follows.

3.1 Rigid model

Based on the modeling theory of MS-DT-TMM (discrete time transfer matrix method for multibody dynamics) and the structural characteristics of long tunnels, a chain of multi-system model for long tunnels is developed as a simplified method due to its high computational efficiency, as shown in Fig. 4. In this approach, a long tunnel is simplified and assumed as two types of components, rigid bodies and joints. Tunnel linings are considered as rigid bodies and the joints connecting each adjacent tunnel linings are assumed as elastic damping hinges. Soil-structure interaction is taken into account by damping joints. The procedure of implementing the multibody dynamics model (Figure 4) is illustrated as follows: all the bodies and joints are digitized as numbers; the mechanical properties of each element are expressed in matrix; then mathematical calculation is conducted for each body and the system, yielding the overall transfer matrices and the equations of the system simultaneously, and finally the dynamic response of the system are acquired according to boundary and initial conditions.

The MS-DT-TMM based method is realized by using modern time integral approach at each discrete time in time domain. Compared with the finite element method, the MS-DT-TMM method is simple, high-efficiency and practical, which provides a powerful tool for dynamic response of long tunnels.

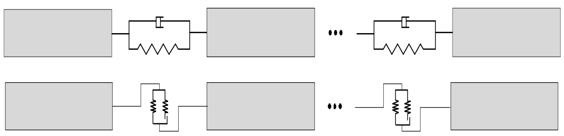


Figure 4: simplified multi-body dynamics model for long tunnels

3.2 Beam model

Another simplified method using mass-spring-beam model, as shown in Fig.5, is widely used in seismic design and analysis of long tunnels, especially for immersed tunnels. In this approach), a beam element is used to simulate tunnel linings or segments; a nonlinear spring element is used to simulate soil-structure or soil-soil interaction and tunnel joints; and a mass element is used for soil. For the immersed tunnel, the spring stiffness for tunnel joints is derived with the assumption that the GINA rubber is assumed as a spring with only the compression behavior.

Based on the equivalence theory, a new method, i.e. one-dimensional multiple-degree-of-freedom (MDOF) system, is developed in this study to represent the one-dimensional layered soil deposit. A series of one-dimensional MDOF system is further connected to constitute a two-dimensional mass-spring model for soil. The equivalent mass-spring model is then used for the longitudinal seismic analysis of long tunnels. The modal equivalent MDOF system has the distinction and advantage that it can characterize the exact properties of one-dimensional ground under shaking, such as natural frequency and hysteretic damping. By comparing the amplification function of the modal equivalent MDOF system with theoretical solution from one-dimensional wave propagation, it is concluded that an equivalent system of few degrees-of-freedom can provide accurate results.

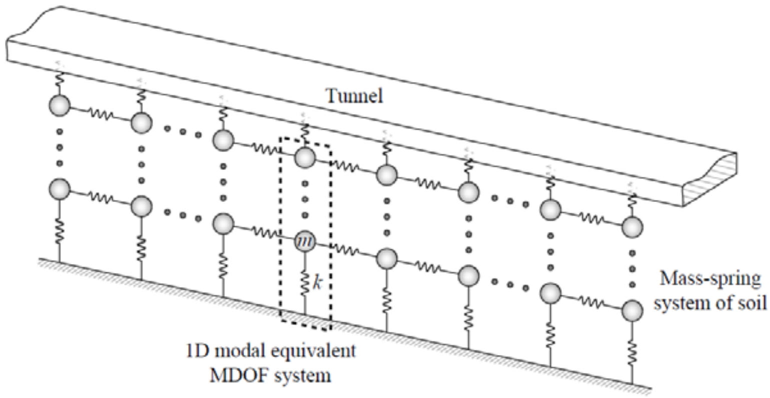


Figure 5: Mass-spring model for longitudinal seismic analysis of long tunnel

4 MULTISCALE MESHES FOR DETAILED SIMULATION

It should be pointed out that simplified seismic analysis may not be able to provide the overall understanding of the dynamic behavior of long tunnels subjected to seismic loadings. A multiscale approach is developed to investigate the dynamic properties of long tunnels described in Section 2.

4.1 Multiscale coupling approach

The multiscale approach combines the discrete element method (DEM) and the finite difference method (FDM). The DEM has been shown to be particularly suitable for capturing physical phenomena at small length scales where continuum mechanics is no longer applied. Its efficiency, however, is limited because of the computational intensity required. A multidomain analysis coupling DEM and FDM is thus proposed to reduce the computational cost. A bridging scale term is introduced such that the compatibility of dynamic behavior between the DEM-based and FDM-based models is enforced. The proposed method does not result in spurious wave reflections and does not need additional filtering or damping in the overlapping domain between the FDM meshes and the DEM particles. It starts with the discretization of the entire domain with finite difference meshes and discrete particles. The meshes are employed to capture dynamic response characteristics of the system, whereas the particles are used to describe the dynamic response at the mesoscale or microscale. In the overlapping domain as shown in Figure 6, the constraints between mesh and particle subdomains are imposed to the motion equations using Lagrange multipliers, which are developed in a consistent manner from the energy potential. This approach filters the high-frequency components at the interface.

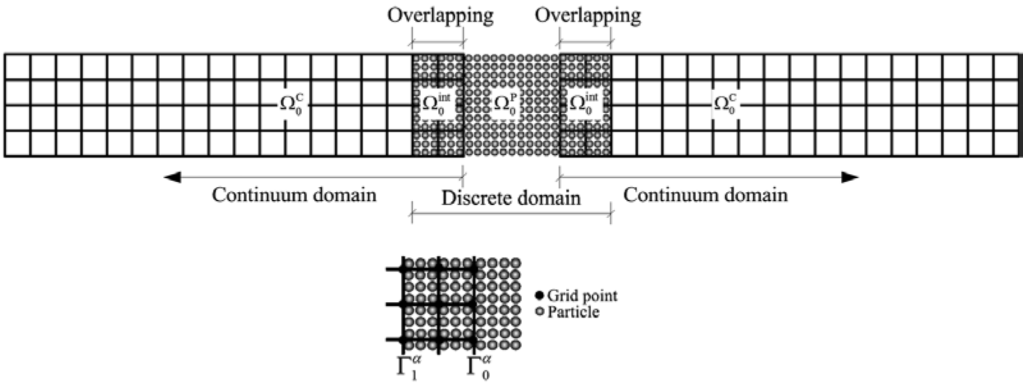


Figure 6: Bridging domain coupling discrete and continuum regions

The equations of motion for the coupling method including Lagrange multipliers are [9]

$$\bar{M}_J \ddot{\mathbf{u}}_J = \mathbf{f}_J^{\text{ext C}} - \mathbf{f}_J^{\text{int C}} - \mathbf{f}_J^{\text{LC}}, \text{ in } \Omega_0^{\text{C}} \tag{1}$$

$$\bar{m}_I \ddot{\mathbf{d}}_I = \mathbf{f}_I^{\text{ext P}} - \mathbf{f}_I^{\text{int P}} - \mathbf{f}_I^{\text{LP}}, \text{ in } \Omega_0^{\text{P}} \tag{2}$$

where $\bar{M}_J$ and $\bar{m}_I$ are the lumped mass of node J and particle I, respectively; $\mathbf{f}_J^{\text{ext C}}$ and $\mathbf{f}_I^{\text{ext P}}$ are the external node force and particle force, respectively; and $\mathbf{f}_J^{\text{int C}}$ and $\mathbf{f}_I^{\text{int P}}$ are the internal node force and particle force, respectively.

The forces $\mathbf{f}_J^{\text{LC}}$ and $\mathbf{f}_I^{\text{LP}}$ are caused by the constraints, enforced by Lagrange multipliers, and given by [9]

$$\mathbf{f}_J^{\text{LC}} = \sum_K \boldsymbol{\lambda}_K \frac{\partial \mathbf{g}_K}{\partial \mathbf{u}_J} = \sum_K \boldsymbol{\lambda}_K \mathbf{G}_{KJ}^{C} \tag{3}$$

$$\mathbf{f}_I^{\text{LP}} = \sum_K \boldsymbol{\lambda}_K \frac{\partial \mathbf{g}_K}{\partial \mathbf{u}_I} = \sum_K \boldsymbol{\lambda}_K \mathbf{G}_{KI}^{\text{P}} \tag{4}$$

where $\boldsymbol{\lambda}_K$ is a vector of Lagrange multipliers, and $\mathbf{g}_K$ is the representation of the kinematic constraints in the overlapping domain satisfying

$$\mathbf{G}_{KJ}^{\mathrm{C}} = \left[\frac{\partial \mathbf{g}_K}{\partial \mathbf{u}_J}\right] = \left[N_{JK}\mathbf{I}\right],\ \mathbf{G}_{KI}^{\mathrm{P}} = \left[\frac{\partial \mathbf{g}_K}{\partial \mathbf{u}_I}\right] = \left[-\delta_{IK}\mathbf{I}\right] \tag{5}$$

in which $N_{IK} = N_I\left(\mathbf{X}_K\right)$ is the interpolation function.

To solve the coupled dynamic system with the Lagrange multiplier method, an explicit algorithm is developed based on the central difference method. In this approach, displacements and velocities are assumed to be known at time steps n and n+1/2. First, a set of displacements and velocities are initialized by neglecting the constraints. Second, Lagrangian multipliers are obtained to satisfy the constraints. Finally, displacements and velocities are updated.

4.2 Implementation

In the proposed multiscale method, the FDM subdomain is employed to capture seismic response characteristics of the integral system, whereas the DEM subdomain describes in detail the dynamic response in locations with potential damage. This multiscale method couples two 2D commercial packages. The DEM computations are performed using Particle Flow Code (PFC) v4.0 and the FDM computations utilize Fast Lagrangian Analysis of Continua (FLAC) v5.0. Although data exchange at each time step, using different codes, is inconveniency, it should be noted that, both of these two codes are developed by Itasca software firm and share the same dynamic explicit algorithm. They have TCP/IP socket connection ability, which means that data can be exchanged rapidly on the same machine or on separate machines with a network connection. The data transmission between the two codes is invoked by FISH functions that allow large arrays of data to be exchanged with single function call [9].

The proposed multiscale method enforcing velocity continuity at the interface is adopted to handle FDM and DEM. The aim is to enforce the energy compatibility at the interface, and to ensure that energy can propagate through interface without spurious reflection.

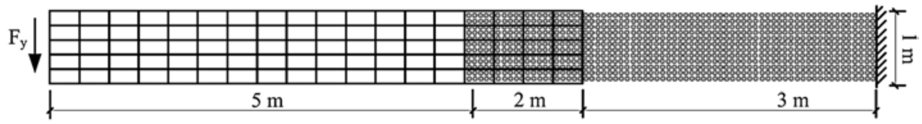
5 UNIFIED SIMULATION OF DAMAGE PROCESS

5.1 Model description

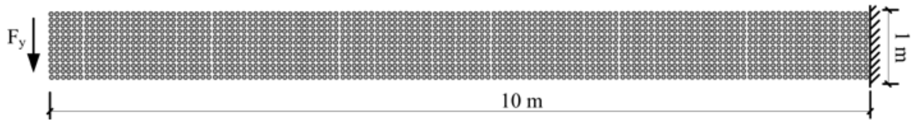
To validate the proposed multiscale coupling method for damage simulation, a 2D beam model, with dimensions of 1 m in height and 10 m in length beams as shown in Figure 7, is simulated by two different approaches, i.e. DEM and the multiscale coupling method. The radius for each particle is 0.09615 m, and the mesh size in both coupling and full continuum models is the same, i.e. 0.25 m×0.5 m. The overlapping zone is 2 m long and composed of 131 particles and 30 grid points. The right end of the model is fixed and the left end is subjected to dynamic bending loads in the vertical direction. The applied dynamic loading is described in Equation (6), where the circular frequency is *f*=50 Hz.

$$F_y = \begin{cases} 5.0e6 * \sin(2\pi ft) & t \le 0.01s \\ 0.0 & t > 0.01s \end{cases} \quad Unit: N \tag{6}$$

The parameters used in the continuum and the discrete model can be found in detail in [9].



(a) Coupling method



(b) DEM

Figure 7: The cantilever beam model subjected to dynamic bending loads

5.2 Results and analysis

Cracks form between bonded particles and each subsequent bond-break event will result in a crack in the tunnel. The geometry and location of each crack are determined by the sizes and current locations of the two parent particles from which the crack originated.

Figure 8 (a) shows particle force chains calculated by DEM at time t=0.028 seconds. It can be observed that the maximum force chain between particles is 1,388 kN, but no crack is observed on the beam at this time. With the time increasing, cracks are observed at the fixed end of the beam and the maximum particle force chain increases to 8,611 kN at time t=0.032 s, as shown in Figure 8 (b). Figure 8 (c) illustrates the results obtained by the multiscale coupling method at the same time t=0.032 s. From the comparison between Figure 8 (b) and (c), it can be observed that cracking is observed at the same location (i.e. at the fixed end of the beam) and the difference of the maximum particle force chain is less than 1.2 percent.

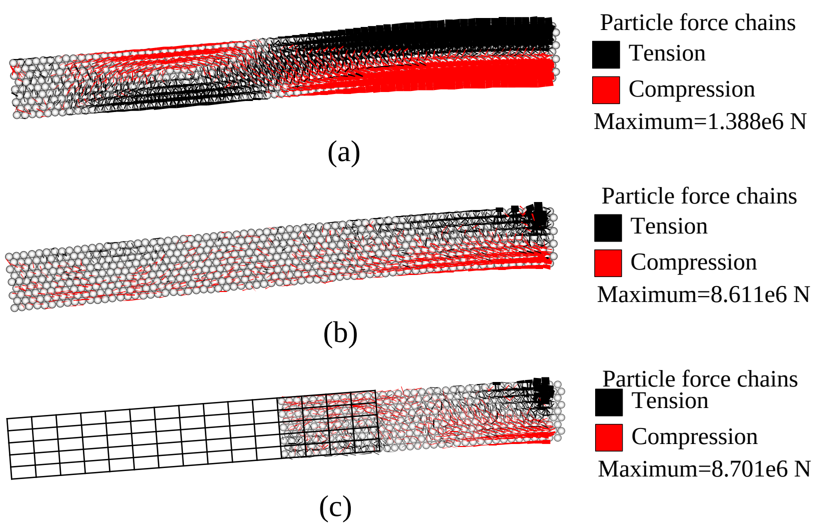


Figure 8: Particle force chains at time: (a) t=0.028 s by DEM, (b) t=0.032 s by DEM, and (c) t=0.032 s by the multiscale coupling method.

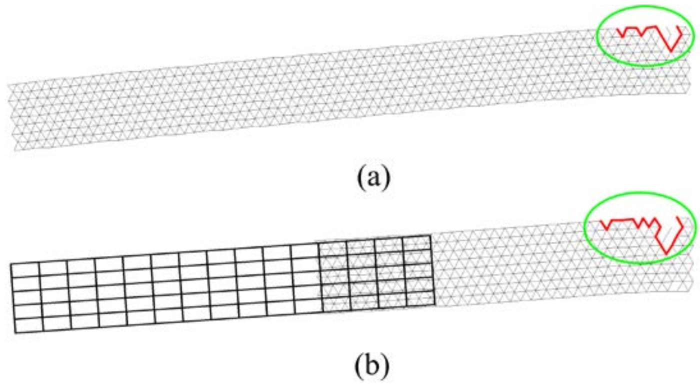


Figure 9: Particle contact bonds at time t=0.032 s. (a) DEM , (b) the multiscale coupling method.

Figure 9 (a) and (b) show the contact bonds of particles calculated by DEM and the multiscale method at time t=0.032 s, respectively. It can be seen from the figures that both the location and shape of the cracks are similar with the two methods.

6 CLOSING REMARKS

Two different methods, simplified method and unified method, are fully introduced to be used in seismic analysis of long tunnels. The simplified method using the rigid model or beam model can be an effective tool for practitioners. They allow readily identification of the variables controlling the magnitude of the distortions and thus provide an insight into the behavior of the structure. However, the simplified method fails to address in detail the structural response and damage process in positions of potential failure due to the simplified assumption of tunnel structure and soil-tunnel interaction.

Thus, a novel and reliable multiscale coupling method is proposed to solve the problem. Two distinguished numerical methods: continuum-based FDM and discrete-based DEM are coupled in the proposed method. An overlapping domain is created between the finite difference meshes and the discrete particles and a bridging scale term is introduced to ensure the compatibility of energy in the overlapping domain. The bridging domain coupling method is implemented to minimize, or at least reduce, spurious wave reflections at the continuum-discrete interface. The multiscale coupling governing equations are derived between the FDM and DEM, and the user-defined subroutines are developed based on two commercial packages, FLAC and PFC. The advantage of the multiscale continuum-discrete coupling approach is that it allows modeling of local physical phenomenon occurring at meso- or micro-scope scales in very large systems. An example is used to validate the proposed multiscale coupling method for damage simulation and hence demonstrate the applicability of the multiscale method in seismic analysis of long tunnels.

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