Numerical seismic analysis of shield-driven tunnel crossing soil-rock interface under transverse excitation

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\textbf{Abstract.} When a tunnel crosses the interface between a soil stratum and a rock stratum, the seismic responses of two free-fields would cause discrepant reaction of the hosted tunnel. In order to analyse the seismic performance of this particular portion of the tunnel, a three-dimensional finite element (FE) model was established based on an actual construction in Nanjing. An artificial boundary was adopted to eliminate the reflection and refraction of seismic motion at the lateral boundary of the FE model. The soil was simulated using visco-elastic constitutive model, while the tunnel and the rock were assumed to be elastic. The lining was simplified into segmental equivalent rings by the principle of stiffness equivalence. Beam elements were used to imitate bolts placed between adjacent segments. Nanjing synthetic earthquake motion was inputted from the bottom of the model, and the shaking direction was perpendicular to the tunnel axis. The acceleration data were analysed to explain the discrepant seismic responses of the tunnel buried in different strata. The seismic performance of the tunnel was evaluated through three observed data: the sectional deformation, the extension of joints and axial force of bolts. Results indicate that: 1) the discrepant seismic responses of the tunnel buried in different strata are revealed by the acceleration data, and the acceleration responses of the tunnel is highly correlated to hosting medium; 2) there are noticeable localized behaviors of the tunnel observed near the interface of the two strata such as elevated bolt forces, great extensions of joints and huge sectional deformation; 3) the amplified areas of the seismic responses of the tunnel at the soil side and the rock side are 3 times and 1 time the tunnel diameter, respectively.

\textbf{Keywords:} Tunnel; Soil-rock interface; Earthquake; Numerical simulation; Seismic response

1. \textbf{Introduction}

A special issue regarding the seismic analysis of the tunnel project is that the extended structure is inevitably passing through different strata. The seismic response of the two free-fields would lead to the discrepant reaction of the hosted tunnel, indicating the high risk when experiencing an earthquake. The cases of seismic damage at the tunnel section near the interface of soft and hard strata are not rare \cite{1,2}. However, up till now, only a limited number of papers are published on this matter.

Conventional analytical methods for seismic responses of tunnels are mostly targeted at homogenous ground condition or transverse tunnel cross sections \cite{3}. Obviously, these solutions are not
suitable to solve problems such as tunnel crossing different strata. Thus, Yu et al. [4] filled the gap by developing an analytical solution considering the sharp transition in structural stiffness and ground properties. Due to the tunnel was assumed as Euler-Bernoulli beams, the attendant deficiency was that the detailed part of the tunnel could not be studied. Hence, the solution could only be utilized in the preliminary design stage.

Dynamic centrifuge tests and shaking table tests are conducted to study the soil-structure-interactions in seismic scenarios. He and Koizumi [5] conducted a series of shaking table test to analyze the seismic behavior in the longitudinal direction of shield tunnels located at irregular ground. The test results indicated that the direction of earthquake excitation had a great influence on seismic responses of tunnels in irregular ground and the secondary lining had a reinforcing effect for the segment under longitudinal excitation. Kawamata [6] investigated the seismic responses of shield-driven tunnel passing through soft and hard strata utilizing shaking table tests. Localized behavior such as tensile stress and sectional deformation were observed at the boundary of the ground layers. Shaking table tests were designed and carried out by Zhang et al. [7] to study seismic responses of shield-driven tunnel hosted in soft-hard stratum junction. Test data showed that the longitudinal strain of the tunnel was enlarged near the interface of the two strata. The enlarged region was distributed within 2.5-3.5 times of the tunnel diameter on both sides from the interface. Zou et al. [8] explored the seismic responses of a tunnel passing through vertical clay and sand. The relative displacements of the different strata caused the spinning, bending and twist-shearing of the tunnel. Although all the tests mentioned above considered the situation that the tunnel crosses soft-hard strata, there are some obvious limitation. 1) The scale effects could not be avoided. 2) The tunnel models are designed as continuous tubes, which could not reflect the actual discontinuous joints of segmental shield-driven tunnel. 3) Installation as many as hundreds of sensors is difficult in insufficient space on small-scale structure models and the number of measuring channels are limited.

Compared to the physical model test, numerical simulation is more flexible and could used to consider complicated structure and stratum condition. Numerical analyses can inherently describe the kinematic and inertial aspects of soil-structure interaction [9]. Three-dimensional (3-D) models have been widely used to predict the seismic behavior of tunnels. To effectively save the computing cost, Yu et al. [10,11] developed a multi-scale modelling approach to simulate the entire tunnel and take the structural details into account. Other researchers were devoted to developing different soil constitute models [12,13] or rational tuning of soil damping in the numerical analysis of tunnels [14]. However, the relevant numerical research considering tunnel buried in non-homogenous medium is scarce. Wang et al. [15] adopted a longitudinal equivalent stiffness model to simulate the seismic responses of shield-driven tunnel passing through soft-hard rock. The results showed that the internal forces of the tunnel increased evidently at the boundary of the different strata, and the affected areas on the soft ground side were four times larger than the tunnel’s diameter. In this circumstance, a three-dimensional finite element (FE) model considering the longitudinal joints was established to investigate the seismic responses of the shield-driven tunnel crossing soil-rock interface. The numerical model was based on an actual construction in Nanjing. The lining was simplified into segmental equivalent rings by the principle of stiffness equivalence. Beam elements were used to imitate bolts placed between adjacent segments. Nanjing synthetic earthquake motion was inputted from the bottom of the model, and the shaking direction was perpendicular to the tunnel axis. The acceleration data were analysed to explain the discrepant seismic responses of the tunnel buried in different strata. The seismic performances of the tunnel such as the sectional deformation, the extension of joints and the bolt forces were predicted and all the performances could be explained by the discrepant acceleration responses.

2. Numerical Model

2.1. Engineering background
The highway tunnel project in Nanjing city, China was selected as the reference engineering. A large-scale shield-driven tunnel crosses the Yangtze River. The total length of the underground tunnel
section is approximately 4215m. The tunnel has an inner diameter of 13.3m and outer diameter of 14.5m. The buried depth of the research section is about 25 m.

According to the geological survey report, the main strata in the site are moderately weathered breccia and medium-coarse sand. This paper focuses on the critical region where the tunnel passes through the interface of the two strata. Since the prototype soil profile is multi-layered, it’s quite complicated to simulate the detailed layered soil profile. The prototype soil deposit is simplified and the strata with similar soil types and physical parameters are merged.

2.2. Overview of the numerical model
A FE model of 150m × 300m × 70m was established by ABAQUS, as shown in Figure 1. The strata model contains the soil layer (soil layer 2) and rock layer that the tunnel passing through and a layer of overlying soil (soil layer 1). The lining was simplified into segmental equivalent rings by the principle of stiffness equivalence [16]. Both the strata and the lining were discretized by solid element C3D8R. The interfaces between the tunnel linings and the strata were modelled by implementing a finite sliding hard contact model. The longitudinal bolts were simulated using beam elements and were embedded in adjacent segments. The bottom boundary of the numerical model is assumed as the rigid base and the acceleration time history is applied to the base of the numerical model.

![Figure 1. 3D numerical model: (a) Strata model; (b) Tunnel model (unit: m).](image)

2.3. Boundary condition and input earthquake motion
An artificial boundary [17] is introduced to eliminate the reflection and refraction of seismic motion at the lateral boundary of the FE model. In ABAQUS, the unbounded or infinite medium can be approximated by extending the finite element mesh to a far distance, where the influence of the surrounding medium on the region of interest is considered small enough to be neglected.

A Nanjing synthetic earthquake motion was adopted as the input signal for the numerical simulation. The acceleration time history and spectra are depicted in Figure 2. The motion was developed to predicted bedrock movements under the specific construction site [18]. Predominant frequency of the motion is 3 Hz and the shaking direction is along the transverse direction of the tunnel model.

![Figure 2. Input motion: (a) Time history; (b) Fourier spectra.](image)
2.4. Constitutive model
The seismic response of the ground under seismic excitation was simulated through a simplified visco-elastic material, following the equivalent linear approximation. Due to its easy complication, this approach is commonly implanted in design practice. One-dimension soil response analyses were conducted with the numerical code SHAKE 91 \cite{19}, using the \(G-\gamma-D\) curves, presented in Figure 3. The average shear moduli and damping calculated by iteration, estimated for each soil layer and shaking case, were then applied to the strata model. The damping was introduced in the form of the frequency dependent Rayleigh type with the mode damping ratio set as 0.05. It should be noted that the complicated yielding response of the soil does not fall within the scope of this work. A linear elastic model was implemented to simulate the tunnel lining and the rock response. The properties of materials applied to the numerical model were listed in Table 1.

![Figure 3](image)

**Figure 3.** Dynamic properties of soil layer: (a) \(G-\gamma\) curves; (b) \(D-\gamma\) curves.

| Material          | Density (kg/m\(^3\)) | Elastic modulus (GPa) | Poisson’s ration |
|-------------------|-----------------------|-----------------------|------------------|
| Soil layer 1      | 1970                  | 0.26                  | 0.35             |
| Soil layer 2      | 2110                  | 0.98                  | 0.35             |
| Rock              | 2550                  | 17.2                  | 0.2              |
| Lining            | 2600                  | 36                    | 0.2              |
| Longitudinal bolts| 7800                  | 206                   | 0.3              |

3. Results and discussion
Several critical profiles were selected, as shown in Figure 4, to better illustrate the instinct seismic responses of the tunnel section located near the soil-rock interface. The lining labelled as N75 is located at the interface of soil and rock, while the lining labelled as N20 and N130 are far away from the interface, which could be considered not to be affected by the interface. The acceleration response, sectional deformation, extension of joints and the bolts force were calculated and analysed in this section.

![Figure 4](image)

**Figure 4.** Layout of measuring points of the numerical model (unit: m).
3.1. Acceleration responses of the tunnel

Since the shaking direction is perpendicular to the tunnel axis, all the acceleration responses analysed following are the same as the shaking direction. The time history and Fourier spectra of N20, N75 and N130 are shown in Figure 5. The acceleration responses of the crown and bottom of the lining are depicted by a red line and black line, respectively. Acceleration data of the crown and bottom are almost identical at the lining labelled N20, which is totally buried in rock strata. However, the lining in the soft strata showed discrepant responses at the crown and bottom. Comparing the Fourier spectra of the N20 and N130, the lower frequency component (0-2.5Hz) is significantly amplified at the N130, while the higher frequency component (5-10Hz) is enlarged at the N20. The amplification effect is relevant to the properties of the hosting medium. It is commonly known that the soft soil would magnify the lower frequency component of the propagating seismic motion. The lining closed to the interface, namely N75, presents double predominant frequencies, which is also observed in Zhang’s shaking table test [7].

The peak accelerations (PA) of the tunnel are depicted in Figure 6. The PA of the crown is bigger than that of the haunch, as well as the bottom of the lining. The PA curves show a decreasing trend coming close to the interface. There are manifestations of the discrepant responses of the tunnel buried in distinct strata.

![Figure 5. Acceleration time history and Fourier spectra of the tunnel model at N20, N75 and N130.](image-url)
3.2. Sectional deformation of the tunnel

Figure 7 illustrates the distribution of the maximum sectional deformation along the longitudinal axis of the tunnel. The values of sectional deformation in horizontal (0-degree) and vertical (90-degree) direction are ten times smaller than that in 45-degree direction. This means that the circular tunnel deforms mainly along with the shear deformation of the ground under transverse excitation, which agrees with the conclusion put forward by Hashash [20]. The linings hosted in rock strata are hardly deformed, while the linings buried in soft soil strata show large sectional deformation. This phenomenon could be explained by the acceleration responses of the lining. Since the lining located at rock strata has similar responses at the crown and bottom, imply that it only has translational displacement along with the strata. The distinction of acceleration responses at the crown and bottom of the lining in the soil layer causes large deformation. There is an abrupt change of sectional deformation at the lining labelled as N80 and N85. Large dislocation of segments could arise at this location, which should be paying much attention to during the seismic design.

3.3. Maximum extension of joints

Extensions of joints are one of the most concerning features in tunnel engineering. The bending of the tunnel axis would cause joints to open longitudinally, even if the excitation direction is along the transverse direction. As shown in Figure 8, the maximum extensions of joints distributed along the tunnel axis are collected. The extension at the haunch is much larger than that at the crown and bottom of the lining, and the maximum value appears near the interface of soil and rock strata (N75). This means that the tunnel curves primarily in the horizontal direction. Of course, the maximum curvature point is close to the interface and on the side of the soft strata. The acceleration responses of lining near the interface are distinctly different from that in soil and rock strata. Then, the horizontal differential motion is the major cause of the curve of the tunnel. Extensions of joints at the crown and bottom of the lining indicate that the tunnel is also curved in the vertical direction. This conclusion was confirmed in Kawamata [6] and Liang’s [21] shaking table tests. Given the width of a single ring is
2m, the amplified areas of the extension of joints at the soil side and the rock side are 44m (22 rings) and 10m (5 rings), which approximately equal to 3 times and 1 time the tunnel diameter, respectively.

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\text{Maximum extension of joints (mm)}
\]

**Figure 8. Maximum extension of joints.**

### 3.4. Bolt forces

The longitudinal tensile forces of the shield-driven tunnel are mainly born by bolts. Maximum bolt forces of the measured points are plotted in Figure 9. Like the extension of joints curves in Figure 8, the maximum bolt forces have a similar tendency of declination. It is anticipated that the bolt force is related to the extension of joints at the corresponding position. The bolts near the soil-rock interface tend to undertake larger tension than that in the uniform soil strata or rock strata. For a single lining, the bolts located at the haunch bore larger tension. All the evidence, i.e., the elevated bolt force and the large extension of joints, indicated that the tunnels crossing the soft-hard strata interface are vulnerable to earthquake damage.

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\text{Maximum bolt force (kN)}
\]

**Figure 9. Maximum bolt forces.**

### 4. Conclusions

A three-dimensional finite element (FE) model was established to investigate the seismic responses of shield-driven tunnel crossing soil-rock interface. The main conclusions can be outlined as follows:

1. The discrepant seismic responses (i.e., the sectional deformation, the extension of joints and bolt forces) of the tunnel buried in different strata are revealed by the acceleration data, and the acceleration responses of the tunnel are highly correlated to hosting medium.

2. There are noticeable localized behaviors of the tunnel observed near the interface of the two strata such as elevated bolt forces, great extensions of joints and huge sectional deformation.

3. According to the distribution of the maximum extension of joints and the bolt forces, the amplified areas of the seismic responses of the tunnel at the soil side and the rock side are 3 times and 1 time the tunnel diameter, respectively.

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