ANALYSIS OF A PARAMETRIC STUDY OF CONCRETE-LINED TUNNELS CROSSING ACTIVE FAULTS

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ABSTRACT
A challenge for municipal authorities of growing urban areas is to provide larger and faster transportation networks that are safe and resilient to significant disruptions after an earthquake event and other disasters. To allow cities to grow in recent decades, the construction of tunnels for individual traffic and mass transit through active fault zones became necessary despite knowing that large magnitude earthquakes can cause significant damage to tunnels in seismically active areas. In particular, large strains due to fault offsets and ground shaking lead to unacceptable stresses in tunnel linings, which can cause subsequent spalling and potential tunnel closure. Examining the seismic response of concrete lined tunnels built through active faults is critical to ensure resilient design and safe operation. A parametric study of a 2D concrete lined tunnel model with varying structural properties is performed. The effects of earthquake magnitude, geology, and structural properties are studied and assessed to develop novel tunnel design strategies to accommodate large fault motions and to minimize ensuing tunnel service disruptions.

KURZFASSUNG

Keywords: Seismic tunnel design, active fault offset, parametric study, numerical analysis
1. INTRODUCTION

A safe transportation network, which includes underground structures, provides one of the socio-economic backbones of an urban area. However, earthquake-induced large ground deformations, such as liquefaction, landslides, or fault displacements, have a great potential to permanently damage underground structures [1, 2, 3]. Recent events, such as the 1999 Kocaeli (M7.4) and Düzce (M7.1) earthquakes in Turkey and the 2008 Wenchuan earthquake (M7.9) in China, damaged several underground structures crossing active faults [4, 5, 6]. Although engineers have been developing methods to analyze earthquake-induced failures starting decades ago, much of the knowledge is limited to site-specific cases. In addition, primary design considerations are based on wave propagation and ground motion. However, ground shaking due to an earthquake event has contributed to lower incidents and damage when compared to severe damage from ground failure, such as fault rupture or subsequent landslides. Guidelines, like the technical manual for design and construction of road tunnels by the Federal Highways Administration (FHWA 2009) [7], suggest to analyze tunnels affected by permanent ground failure similar to pipelines, with a simplified beam-spring model.

To address the lack of a generalized interpretation framework of possible fault rupture influence on tunnel structures, we evaluate the response of tunnel structures with a parametric study. The purpose of the parametric study is to model simplified situations to predict the response of a proposed or an existing tunnel segment crossing the active strike-slip fault zone. Our objective is to investigate the tunnel deformations and internal stresses and strains in the reinforced concrete (RC) lining based on varying tunnel geometry, specifically the lining thickness, and surrounding rock type. The results show the variation of shear-offsets compared to tunnel strains in the reinforced concrete (RC) lining based on varying tunnel geometry, specifically the lining thickness, and surrounding rock type. The results compare positively to large-scale centrifuge tests of pipelines and similar fault rupture interactions performed by O’Rourke et al. (2015) [3].

2. MATERIALS AND METHODS

The numerical model in Figure 1a consists of a 300 m long two-dimensional (2D) beam-spring model representing the tunnel segment crossing the active strike-slip fault zone.

![Tunnel beam model in plan view.](image)

**Figure 1:** Problem definition: (a) Tunnel beam model with strike-slip like offset input in plan view. Springs are only shown on one side for graphical reasons, but modeled on both sides. (b) Schematic representation of section A-A: Defining parameters of the tunnel cross section embedded in rock with the discretized fiber section of the concrete lining. Road, structural fill, and vehicle are only shown schematically.

**Abbildung 1:** Beschreibung des Problems: (a) Tunnelmodell mit Blattverschiebung. Federn sind nur einseitig gezeigt, jedoch auf beiden Seiten modelliert. (b) Schematischer Querschnitt A-A des Tunnels mit Diskretisierung der Tunnelschale. Auffüllung, Strasse und Auto sind nur als Prinzipskizze angedeutet.

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The springs represent the surrounding rock and are modeled on both sides of the beam. The displacement-controlled tunnel offset is a static analysis and is placed at the east side of the tunnel segment, which is also east of the major fault plane. To impose a displacement onto the tunnel beam, simulating the fault offset, the amount of force that needs to be applied is back calculated. The tunnel cross-section in Figure 1b shows the reinforced concrete lining with a thickness $h$, which will vary, and an inner tunnel diameter of $D_i = 10$ m. The reinforcement ratio is 1.5% with inner and outer longitudinal steel of normal ductility and a strength of $f_y = 500$ MPa. The concrete is C25/30 with a Young’s Modulus, $E$, of 26,700 MPa. The inner and outer clear covers of 5 cm and 8 cm are given for weathered surfaces and in contact with the ground, respectively.

The model was established within the open source finite element software framework OpenSees [8]. The beam is fixed in three directions on the west end and fixed only in $x$-direction on the east end. The total length of 300 m was calibrated for the offset to have no influence on the fixed boundary conditions at the tunnel ends. For simplification, we assumed that no hydro-static pressure acts on the tunnel (i.e., a drained tunnel). The concrete and steel are modeled with non-linear constitutive relations. The rock springs are modeled with elastic parameters with no tension over the depth of the tunnel diameter, because the fault offset simulates a strike-slip fault. We assumed that the rock and the fault zone are homogeneous (i.e., no fault inhomogeneities are modeled). We specified uniaxial compressive strengths of 0.25 MPa for the fault gouge, 5 MPa for weak rock, and 50 MPa for medium strong rock [9, pg. 348]. The fault is simplified by a homogeneously damaged zone of 100 m width with a major fault plane on its east end, see Figure 1a, although other fault formations show multiple fault planes or damaged zones west and east of a fault plane [10]. The crossing angle of the tunnel beam to the fault plane was chosen to be 90°.

To understand tunnel displacements in terms of earthquake magnitudes, we use a correlation between surface rupture displacements and earthquake magnitudes for strike-slip faulting by Wells & Coppersmith [11]:

$$M = 6.81 + 0.78 \cdot \log(MD)$$

where $M$ is the moment magnitude of an earthquake and $MD$ is the maximum surface displacement in meters (m) at one location along the surface fault rupture.

3. NUMERICAL EXPERIMENTATION

3.1. Experimental setup

The numerical experimentation starts with a convergence analyses of mesh size and beam length. A proof of concept with verification to closed-form analytical solutions follows. We then perform a sensitivity analysis with respect to the tunnel geometry (by varying lining thicknesses, $h$) and the rock strength (by varying spring stiffnesses). The concrete and steel constitutive behaviors do not vary; they are implemented in the circular reinforced concrete cross-section. The computation consists of the fault offset input, which is inputted as displacement controlled loads. Following the computation, results for horizontal displacement and internal forces along the tunnel beam are drawn for visual interpretation. The horizontal displacement correlates directly to earthquake magnitudes. Results for internal forces, stresses and strains, and axial force-moment (N-M) interaction diagrams are interpreted using multiple limit states. Multiple limit states are defined as follows: (a) service limit state (SLS) at the beginning of yielding of steel at 0.25% tension steel strain, and (b) ultimate limit state (ULS) at 0.35% of peak compression concrete strain (after DIN 1045-1). Note that the computations, and therefore the results, do not contain any factor of safety. Reaching SLS is characterized by the steel taking on tension and results in cracking of concrete — either visible inside the tunnel or invisible below the road or on the outside of the tunnel, which is in contact with the rock. After ULS is reached, it is assumed that the concrete is spalling and crushing and therefore in a state of failure.
3.2. Calibration and verification

To model the system in a simplified but realistic manner, the numerical model beam element length and cross-sectional fibers were calibrated and compared to closed-form analytical solutions by Hetényi (1946) [12]. The tunnel was simplified as a 300 m long, fixed beam on elastic foundation, loaded at the center with a point-load. The subgrade modulus was modeled after Klar et al. (2005) [13]. The calibration and verification resulted in beam element lengths of 5 m, which coincides with other researchers, such as [14]. The discretization of the fiber cross-section was calibrated to 4 radial and 16 circumferential subdivisions, see Figure 1b. The numerical model compares well to closed-form analytical solutions in terms of displacements. The moments calculated with the analytical solution are higher compared to the numerical solution, although the values are on the same order of magnitude.

3.3. Input parameters and parametric study

The parametric study consists of 12 combinations and is conducted with 2 varying parameters:

1. Tunnel lining thickness, \( h \) varies from 0.25 m to 1.0 m. Successfully constructed circular or near circular tunnels tend to have a relatively narrow geometric ratio of lining thickness over inner tunnel diameter from 1/30 to 1/15. This study goes beyond this range and focuses on geometric ratios between 1/40 and 1/10.

2. Geology - Rock strength: The parameter of rock strength is a radial spring value \( k_s = (C \cdot E_g) / R \). This parameter depends on the modulus of elasticity of the ground \( E_g \), the radius of the tunnel, \( R \), and a factor \( C \) ranging between 0.5 and 3.0 [15, pg. 105]. The chosen \( k_s \)-values range from 1 000 MPa for weak rock as a lower bound, to 15 000 MPa for medium strong rock as an upper bound, with values for Young’s modulus based on [16].

3.4. Results

Shearing of the tunnel beam results in axial forces, \( N \), and moments, \( M \), along the tunnel alignment. These forces can be visualized in an axial force-moment (N-M) interaction diagram. The N-M-interaction diagram in Figure 2 illustrate the capacity of the tunnel cross-section with \( D_l = 10 \) m and \( h = 0.50 \) m at yielding of steel in yellow and at peak compression concrete strain in red.

![Figure 2: Axial force - moment interaction diagram for yielding steel and peak compression concrete strain. Abbildung 2: Normalkraft und Moment Interaktionsdiagramm für fließenden Stahl und für die maximale Betondehnung.](image)

The separate data points for weak and medium strong rock show the degree of capacity utilization of the tunnel beam after reaching each strain step. These data points are from the tunnel beam elements that reach the limit states first and are 1 to 5 m right of the major fault plane (cf. Figure 3). Figure 3 shows displacement and moment curves for a lining thickness of 50 cm, which corresponds to a geometric ratio of 1/20. The variation of lining thicknesses will be discussed in section 4.
Figure 3: (a) Displacements and (b) moments along the tunnel axis for baseline model with $D_i = 10$ m and $h = 0.50$ m for a 100 m wide fault zone, with varying geology outside the fault zone width.

Abbildung 3: (a) Deformation und (b) Momente entlang der Tunnelaxe für $D_i = 10$ m und $h = 0.50$ m mit einer 100 m weiten Scherzone mit variabler Geologie ausserhalb der Scherzone.

4. DISCUSSION

A localized area of strains in form of displacements and stresses in form of moments is between -50 m and +25 m, in total around 75 m. This is also the area of damage. The harder the rock, the more distinct and sharp is the offset with less possible displacement and a shorter area of damages computed. By doubling the tunnel lining thickness, e.g. from $h = 0.50$ m to 1.0 m, a 35 % increase in possible displacement can be achieved. Figure 4 illustrates the increase in displacements for increasing lining thicknesses, $h$. It also shows reduced displacements for conditions with higher rock strength.

Bending of a reinforced concrete beam above yielding of steel results in cracking of concrete. If these cracks grow at the outside of the tunnel in contact with the rock, it might result in new water ways. This will damage the concrete lining over time and reduce the lining thickness, resulting in reduced capacity. For practical reasons, a membrane with possible injection openings between the membrane and concrete lining might help concentrate the water ways to a minimum. Also, engineers and public authorities should discuss a doubling in reinforced concrete lining project specific, if it is worth 35 % increase of possible
displacements, considering a larger excavation diameter, increased material transport, increased disposal
needs, etc.

The data points on the N-M-interaction diagrams (cf. Figure 2) are at very low axial forces. To allow
higher moments, and therefore larger displacements, the axial forces need to be increased, e.g., through
prestressing of the cross-section a tunnel design strategy.

A correlation of tunnel displacements to earthquake magnitudes with equation (1) results in a range of
magnitudes from M5.3 for displacements of 0.01 m to M6.0 for displacements of 0.1 m, see Table 1. For
a 35 % increase in displacement by doubling the lining thickness, an increase of earthquake magnitude by
0.1 points is possible. The baseline model in weak rock with 0.50 m lining thickness results in 0.08 m
displacement, which correlates to M6.0. The same model with the thickest lining of 1.0 m results in
0.11 m displacement, which correlates to an earthquake with a magnitude M6.1. In any case, for tunnels
in medium strong rock, a smaller earthquake of M5.6 might result in concrete failure of the tunnel lining.
On the other hand, a tunnel in weak rock might be able to withstand a larger earthquake of up to M6.1,
before concrete failure occurs. Other tunnel equipment with less flexibility like telecommunications or
water/wastewater pipelines might be affected and need special considerations.

Table 1: Correlated earthquake magnitudes to strike-slip surface displacements [11].

<table>
<thead>
<tr>
<th>Displacement - Fault offset (m)</th>
<th>0.01</th>
<th>0.02</th>
<th>0.03</th>
<th>0.04</th>
<th>0.05</th>
<th>0.06</th>
<th>0.07</th>
<th>0.08</th>
<th>0.09</th>
<th>0.10</th>
<th>0.11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correlated Earthquake Magnitude</td>
<td>5.3</td>
<td>5.5</td>
<td>5.6</td>
<td>5.7</td>
<td>5.8</td>
<td>5.9</td>
<td>5.9</td>
<td>6.0</td>
<td>6.0</td>
<td>6.0</td>
<td>6.1</td>
</tr>
</tbody>
</table>

5. CONCLUSIONS

A parametric analysis of a 10 m inner diameter concrete-lined tunnel crossing active fault zones results in
the following conclusions:

(1) A doubling in lining thickness from 0.5 m to 1.0 m results in a 35 % increase in possible displacements.

(2) The length of tunnel with peak stresses and strains is about 75 m long and goes beyond the fault zone,
but in total, it is shorter than the 100 m fault zone width itself. The location of the major fault plane is
important.

(3) Tunnels in stronger rock affected by strike-slip faulting result in lower possible displacements for
concrete failure to occur. At the same time, tunnels in stronger rock will develop shorter lengths of
damaged area compared to tunnels in weaker rock.

In forethought to tunnel design strategies, there are two main methods: the resistance method to withstand
and the flexibility method to give way. The increase of the lining thickness is a resistance method. Another
resistance method might be to raise the axial force, N, with a prestressing of the tunnel cross-section
over the possibly affected area. Flexible strategies, like building larger cross-sections to create space
for the fault to move into and to be able to repair the tunnel while in service, or structural hinges or
cushion-material either inside the lining or outside as a replacement of rock, are additional approaches to
novel tunnel design strategies (cf. modular lining system of the Chienbergtunnel, [17]).

Future work needs to look at creep in combination with fault offset and also how earthquake waves interact
with the fault and influence the underground structure.

ACKNOWLEDGEMENT

Information provided by six different engineering consultancies specializing in tunnel design is gratefully
acknowledged. The authors would like to specifically thank Michael McRae for providing abundant
information and data. We appreciate talks with David Trejo, Edward Dever, Burkan Isgor, John Nabelek,
Eric Kirby, and Andrew Meigs, which greatly strengthened the work. This material is based upon work
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