

# Performance of Concrete Tunnel Systems Subject to Fault Displacement

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## ABSTRACT

A Finite Element Analysis (FEA) investigation of concrete tunnel systems traversing seismic faults is carried out to determine how to effectively mitigate the stresses induced in the liner when subject to fault displacement. A parametric study of various fault parameters, both in the damage zone and competent rock, is carried out to determine the site conditions which induce the most stress on the tunnel liner system. Results indicate that friction angle, cohesion, and elastic modulus of fault zones have varying effects on the stresses induced on the liner. The width of damage zone and expected displacements are also investigated and it has been shown that even small displacements over narrow damage zones, around 10 m, can still result in significant damage to the concrete liner whereas in wider damage zones the effects of the displacement are more evident. The use of flexible joints in what is known as the articulated design method is investigated to mitigate the stresses induced by fault displacement and discussed. Several orientations, lengths and variations in relative stiffness of these flexible joints are investigated to determine their optimal effectiveness. Results show that this is an effective solution which can be used in design and repair of tunnels to mitigate the stresses and resulting damages to concrete tunnel liners subject to fault displacement.

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## INTRODUCTION

Tunneling is a large industry, from the underground construction of transportation tunnels to relieve surface congestion to lifeline systems required to provide essential utilities. Although avoided if possible, it becomes inevitable that some of these systems will cross faults in seismically active regions. This is a problem in areas such as the state of California which is a well-documented, seismically active area, namely due to the San Andreas Fault system in southern California. Tunnels in these regions are not only subject to dynamic loading from earthquakes, but those which cross active faults are also subject to a large degree of fault dislocation. Stability, strength and serviceability immediately become issues as the tunnel is forced to deform with the fault, which can cause major damage to the concrete tunnel liner.

Tunnels are constructed in a multitude of ground conditions varying from soft clays to hard rocks and the method of construction is highly dependent on these ground conditions as well as other factors, such as groundwater conditions, depth of tunnel and diameter of the tunnel.

### Cut & Cover Tunnels

The opening of America's first subway system – only two miles long – was achieved in 1897 due to the new technique at the time, known as cut and cover (Roach et al. 2017). In this method of tunnel construction, a trench is cut into the ground where the tunnel box is framed, and then covered which allows activities at the surface to continue while the final adjustments to the tunnel are made underground

### Immersed Tube Tunnels

In lieu of a bridge, or where bridge construction is not possible, an immersed tube tunnel construction method is a viable technique to cross rivers or other bodies of water. As the name implies, this method consists of floating prefabricated, water-tight, tunnel sections into place, and lowering each section into trenches that are dredged out of the river or seabed before being backfilled (Bickel et al. 1996).

### **Bored Tunnels**

Although the earliest forms of mechanized tunneling were developed throughout the 1800s, it was not until 1952 that modern tunneling techniques were realized when James Robbins completed the Oahe Dam diversion project in South Dakota with the use of his rock tunnel boring machine shown in Figure 1.5 (Roach et al. 2017). The further evolution of tunnel boring machines (TBMs) that propelled tunneling into the modern era was the development of rotating cutterheads and shields.

### **Faults & Faulting**

A fault is break in the rocks of the Earth's crust where there is relative movement on either side of the discontinuity. This movement can happen very slowly over time as rocks move and deform past one another or very suddenly when a fault ruptures and an earthquake ensues. In areas of repeated faulting, instead of a single discrete break, fault zones are formed and are composed of smaller regions of parallel or branching faults usually separating masses of broken rock (Davis et al. 2012). The wider the fault zone, the more displacement imposed on the zone, in general (Davis et al. 2012). The fault plane is the flat surface of the fault which defines the blocks on either side of the fault. Fault planes are typically not oriented 90 degrees to the horizontal plane, and the angle between these planes is defined as the dip.

## **LITERATURE REVIEW**

Russo et al. (2002) discusses fault crossing strategies for twin shield tunnels (specifically for the Bolu Tunnel project) crossing the Bakacak Fault and the Zekidađı Fault in Turkey. In 1999, after the Düzce earthquake ( $M_W = 7.2$ ), a detailed seismic reconnaissance of the area around the Bolu Tunnel project was carried out, allowing for a more accurate modeling of the two faults for the study. The Zekidađı Fault dips approximately 90 degrees with the tunnel crossing this fault over the length of 25 to 30 m (82 to 98 ft.) in both tubes.

Daller & Weigl (2011) investigated concepts for the new Semmering Base Tunnel in Austria to find a support and construction process which would provide tunnel displacements compatible with the fault system using FLAC2D. This tunnel was constructed through the Graßberg-Schlagl fault system and rock characteristics for this system were determined by triaxial compression tests from core samples.

Daller & Weigl (2011) also had access to cross-sections of this fault system from a railway project in May of the previous year and were able to generate a forecast model of the section of the fault under concern which consisted of six vertical rock bodies. This information also provided the strikes and dips of the faults although the authors decided to convert all of the fault planes to 90 degrees for simplification purposes. The authors conclude that an improvement to this study should include a three-dimensional analysis of an improved model of the geologic structure as well as more in-situ and laboratory testing of core fault material; however, the study does prove the shortcomings of the M-C model at large strains.

Wang et al. (2012) used FLAC3D to model tunnels crossing active faults subjected to a differential displacement across the fault. A fault zone, as opposed to a discrete fault plane, was modeled and the fault displacement was estimated to be 0.2 m.

To determine typical fault structures, specifically the width of damage zones, relevant literature was gathered and reviewed. The damage zone is typically a region of transition of fractured rock surrounded by competent rock that presents little to no deformation features associated to faulting (Mitchell & Faulkner, 2009). In a research study performed by Savage and Brodsky (2011) where they researched fracture densities in faults in the state of California in the United States, the authors documented typical widths of damage zones for the faults studied to be less than or equal to 100 m (364 ft) wide, however they can be as wide as few hundred meters (Cochran et al., 2009). Mitchell et al. (2011) investigated fault rocks along the Arima-Takatsuki Tectonic Line (ATTL), located in Japan.

This section will describe several aspects and methods of modeling tunnels and flexible joints for the purposes of accurately capturing tunnel-fault interaction necessary to develop the parametric relationships required for this research. This section is primarily organized from the simpler modeling of tunnels and joints to more detailed methods of modeling. The purpose of this methodology is to show the variety of approaches that have already been taken, and drawn from, to model tunnel structures and flexible joints.

Obrzud (2010) and Ohbo et al. (2000) both modeled their tunnel structures using beam elements, likely because their respective studies were more heavily focus on the modeling of the ground surrounding the tunnel and not the actual performance of the liner itself. Ding et al. (2006) modeled their tunnel using an eight-node hexahedron solid element in their modeling of the tunnel's response to seismic excitation.

## FINITE ELEMENT MODELING

Concrete behavior of the tunnel liner is represented using the Hognestad (1951) material model of unconfined concrete to account for the nonlinearity in the stress-strain behavior of concrete. Equations are included to also modify the behavior of plain concrete to represent the behavior of fiber-reinforced concrete. Effort is also made to account for the nonlinear, anisotropic, stress-dependent behavior of soil and rock included in this modeling.

The tunnel length chosen to be used in analyses is important because after the simulated fault dislocation, there should be negligible effects from dislocation at either end of the tunnel such that the total effect of fault displacement is captured in the model. A tunnel length of 100 m was chosen for the tunnel in creating the single fault plane model and the analyses remained computationally inexpensive with respect to time of analyses.

An effective mesh is important in this analysis to provide accurate results without becoming too computationally expensive. The Automatic Meshing feature within ANSYS resulted in an effective mesh meeting these criteria. The mesh used is a rectangular mesh for both the tunnel and ground with a mesh refinement value of 1 over the entire model.

### Boundary Conditions & Contact Interfaces

To capture the effects due to fault dislocation in the immediate area of the fault, proper modeling of boundary conditions is essential. The plane of the foot wall opposite to the fault plane is fixed in space while the plane of the hanging wall opposite of the fault plane is modeled as a frictionless (roller) support, which allows the hanging wall to move freely in the y and z degrees of freedom. In preliminary analyses the effect of the proximity of the boundary condition on the behavior of the tunnel at the fault plane was studied and determined that 50 m (164 ft) is enough to negate any boundary effects on the stress induced by faulting.

## RESULTS

### Effects of Competent Rock Properties

Models run in this section show that the competent rock behaves linearly with the applied displacement of 1 m and although the stresses in the rock may change when nonlinear controls are turned on, the stresses induced in the nonlinear tunnel liner remain the same. The lowest reasonable value for elastic modulus in competent rock is about 2,000 MPa and for the damage zone the lowest reasonable value is about 50 MPa. Using a 10 m damage zone model where the elastic modulus of the damage zone and competent rock as described above along with 0.2 value for Poisson's Ratio was applied. From pertinent literature discussed in Sections 2.4 and 3.5, the lowest reasonable cohesion value for competent rocks is about 6.7 MPa which was also applied to the competent rock in the models. The initial inner friction angle in the competent rock and damage zone were set to 40° and 30°, respectively, typical values from literature. The ratios for residual friction angle and dilatancy angle to initial inner friction angle are set at 0.5 and 1.0 for both rocks. The range of cohesion values in damage zone rock ranges from 0.1 MPa up to 1.0 MPa and are also tested to prove linearity in competent rock. The ratio of residual cohesion to initial cohesion is 1.0 for both rocks as well. Table 4.1 presents the properties of the two models, NL1-1 and NL1-2, just described.

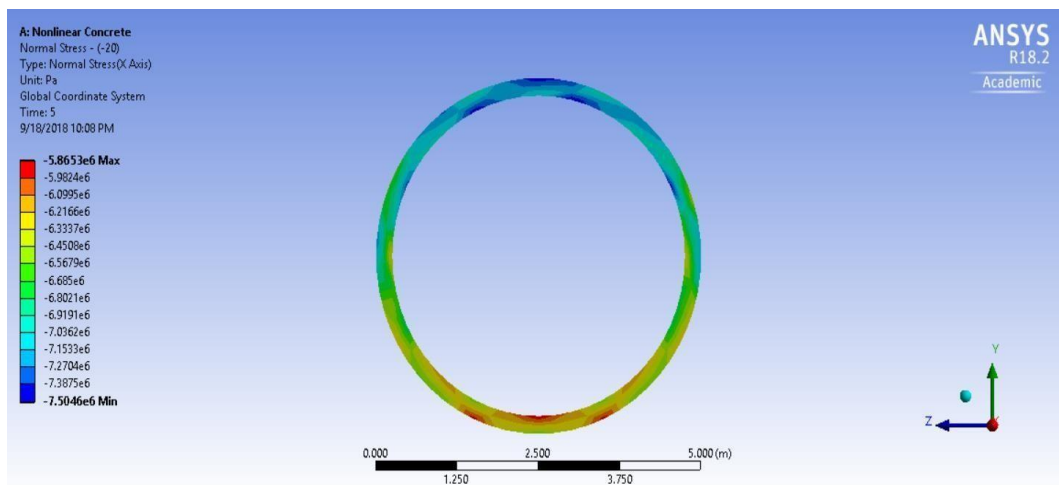


Figure 4.5: -20 m normal stress in the x-axis of the tunnel liner of model NL1-1.

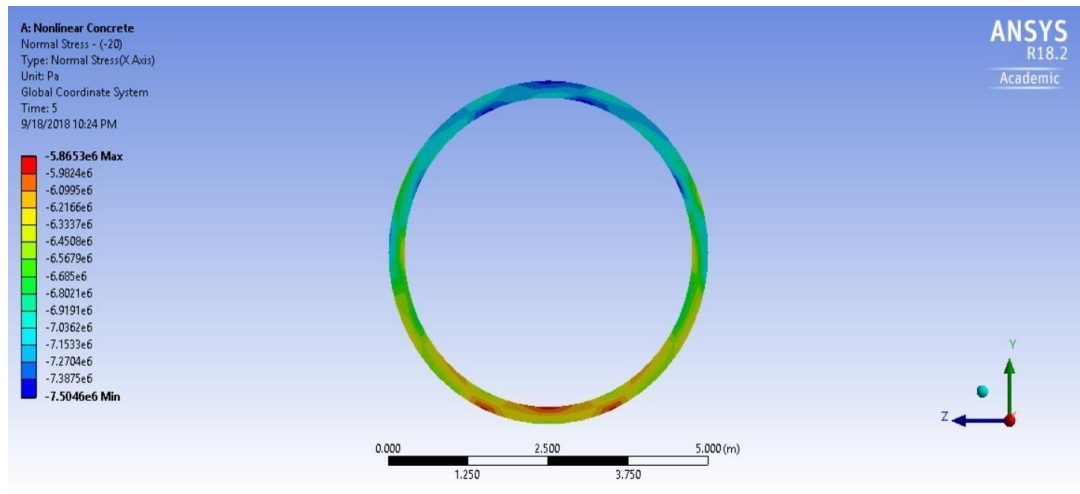


Figure 4.6: -20 m normal stress in the x-axis of the tunnel liner of model NL1-2.

### Elastic Modulus of Competent Rock

The elastic modulus of competent rock was then investigated, and results are presented in Figures 4.27-4.30. All properties for the models described, NL1-6 & NL1-7, can be found in Table 4.4. Similar to the plots shown above, the distribution of Von-Mises and normal longitudinal stresses displayed in these graphs plot on top of one another which indicates that the competent rock still behaves linearly even when the elastic modulus is increased to a high value as determined from literature. This also means that its behavior is still controlled by the defined value of initial cohesion.

### Elastic Modulus of Damage Zone

In determining the 10 m damaged zone elastic modulus critical to the models, initial cohesion of 0.1 MPa and initial inner friction angle of 30° are used as the M-C properties in the damage zone. In investigating the effects of varying initial cohesion in models where the damage zone and competent rock elastic moduli are 50 MPa and 100,000 MPa, respectively, the effect of elastic modulus in the competent rock overtakes the effects of varying cohesion and friction angle in the competent rock.

## SUMMARY & CONCLUSIONS

In this thesis a FEA investigation of tunnels traversing seismic fault zones is reported. Parameters of competent rock and damage zone rock properties were studied to observe their effects on tunnel liner damage. The use of articulated tunnel liners to mitigate liner damage was also evaluated. A literature review was completed to determine appropriate ranges of material properties and fault displacements.

Results show that competent rock can be modeled as linear-elastic using only the elastic properties for up to 1.0 m fault displacement investigated, and for the properties gained from literature review. It was also determined the M-C properties of the damage zones have effects of varying degrees. In 10 m damage zones subject to 1 m of fault displacement, surrounded by softer competent rock ( $E = 2,000$  MPa), the effects of the cohesion and friction angle of the faulted rock are evident in the stress distribution of the tunnel liner outside of the damage zone into the competent rock though full yielding of the liner in the damage zone was observed for all cases. Higher friction angle and lower cohesion result in the highest stress values in the competent rock section of the tunnel. The results of this research can be used to focus a design approach when specific information about fault width, expected dislocation and ground properties are known. Details of links in an articulated design could be engineered to match the moment curvature relationships assumed in these models.

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