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Division III

DEVELOPMENT OF A PERFORMANCE EVALUATION METHOD FOR FAULT-CROSSING TUNNEL SUBJECTED TO FAULT DISPLACEMENT

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ABSTRACT

Although as per the new regulatory standards of nuclear agencies, important facilities should be established at locations where there is no possibility of an active fault to occur, there is a requirement for a quantitative assessment of these facilities when subjected to a fault displacement, from the standpoint of safety assessment and Probabilistic Reliability Analysis. The current study involves the development of method to quantitatively assess the influence of fault displacement on a fault-crossing tunnel. First, the finite element analysis method is validated by comparing the results with experimental data. Second, a parametric study is performed through finite element analysis of the tunnel by modelling the surrounding soil with soil spring elements and also as solid elements. The sensitivity of the parameters like the stiffness of surrounding soil, angle of fault incidence, material non-linearity etc., that influence the behaviour of the tunnel is investigated. Based on the findings of the current research, considering the functionality of the target structure, a method to evaluate the displacement based performance of tunnels is established.

INTRODUCTION

The Japanese Nuclear Power Plant regulatory standards forbids the construction of important structures, not only at location where seismic faults exists, but also at locations where there is a possibility of fault occurrence in the future. This can be attributed to the difficulty in verification of structural design of facilities affected by fault displacement and the lack of experimental/field data. Hence, there exists a need to understand the effects of fault displacement on such facilities.

From the stand point of seismic Probabilistic Risk Assessment (PRA) and beyond design basis event (BDBE) of nuclear structures, there is a possibility of a fault occurrence even at locations without a faulting history. In these cases too, there is a requirement to further research the effects of fault displacement on important nuclear facilities. Extensive research has been done in the past, with regard to analysis of underground structures subjected to seismic motion, and the results of these studies have been implemented in various design standards. For example, the manual published by the Japan Society of Civil Engineers (JSCE), specifies how to prepare analysis models, boundary conditions, input earthquake acceleration, etc., for a representative model of an important nuclear facility like the underground culvert, sea-water pump structure, etc.

Although the effects of acceleration input motion on underground structures has been studied in detail, there in insufficient research on the effects of fault displacement on underground structures, due to its low frequency of occurrence in the past.

Investigation reports of tunnels damaged due to seismic shaking are available aplenty, but past reports on fault-crossing tunnels damaged due to fault displacement are relatively scarce. The damages incurred by the Tanna tunnel during the Kita-Izu Earthquake (Ministry of Railways, 1934) and the Shioya Tanigawa Tunnel during the Hyogoken Nambu Earthquake (Sakurai, 1997) (Hanshin Earthquake Research committee, 1996). There also exists literature where, although not known for certain, there is a possibility of damage due to fault displacement, for example, the Tawarayama tunnel during the Kumamoto earthquake (Kokusho, 2016). The lack of site observations and experimental data makes it necessary to perform multiple numerical simulations to assess the performance of these structure with a certain degree of reliability.

When a tunnel is subjected to fault displacement, ring-like crack occurs around the tunnel cross section. This kind of damage mode does not usually occur when the tunnel is subjected to earthquake motion. The current study involves the development of a method to assess the performance of tunnel which traverses through a fault, and is subjected displacement along its fault boundary due to fault slippage. The performance is evaluated through numerical simulations of a RC tunnel subjected to fault displacement. The first part of this paper validates the ability of the numerical simulation method to simulate the damage modes of a fault-crossing tunnel subjected to displacement, for e.g., the occurrence of ring like cracks. The results from the numerical simulation are compared to the results from an experiment performed by Asakura et al. (2000), where a scaled tunnel model is subjected to fault-like displacement loading. The next part of the study involves a parametric study of a conventional RC tunnel where the surrounding soil is modelled using simple soil springs. The influence of surrounding soil stiffness and the angle of fault-crossing on the non-linear response of the tunnel is observed. Finally, the soil is modelled using non-linear solid elements to consider the influence of soil nonlinearity on the tunnel. Finally, once the structural integrity of the tunnel with respect to the fault displacement is established, a performance evaluation method is established. This method is based on the manual which provides seismic performance assessment guidelines for outdoor important nuclear power plant civil engineering structures published by the nuclear engineering committee, Japanese Society of Civil Engineers.

In the current study, the performance of the tunnel is assessed based on the displacement due to fault slippage, hence it is assumed that the fault displacement is a known parameter. In reality however, fault displacement is not easily determined. Fault displacement assessment also differs depending on whether it is a fault or sub-fault. For example, the fault displacement calculation for sub-fault depends on various parameters like distance from main fault, main fault displacement, and near-fault soil properties etc. These displacements can be obtained through the analysis of observation data of fault displacements (Akiyama 2011) or through large scale stochastic numerical simulations (Mitsuhashi et al. 2018).

EXPERIMENTAL VALIDATION

In order to understand the behaviour of a fault-crossing tunnel and damage modes it undergoes, Asakura et al. (2000), performed an experiment on a 1:30 scale tunnel (inner diameter 320mm). The experiment was setup such that displacement loading applied imitates the displacement caused due to fault slippage on a fault-crossing tunnel. The semi-circular tunnel is placed on an experiment table, with a set of 121 rubber springs on its outer surface that represent actual soil stiffness. The spring stiffness on either half on the tunnel is different in order represent soil stiffness variation along the length of the tunnel. The fault displacement is applied on the outer surface of the tunnel through radially placed bolts, where the flexible soil springs are located.

Analysis Model

The analysis model shown in Figure 1, comprises of a 3-D finite element model, where the tunnel is modelled using solid elements and the soil is modelled using soil springs along the tunnel outer surface.

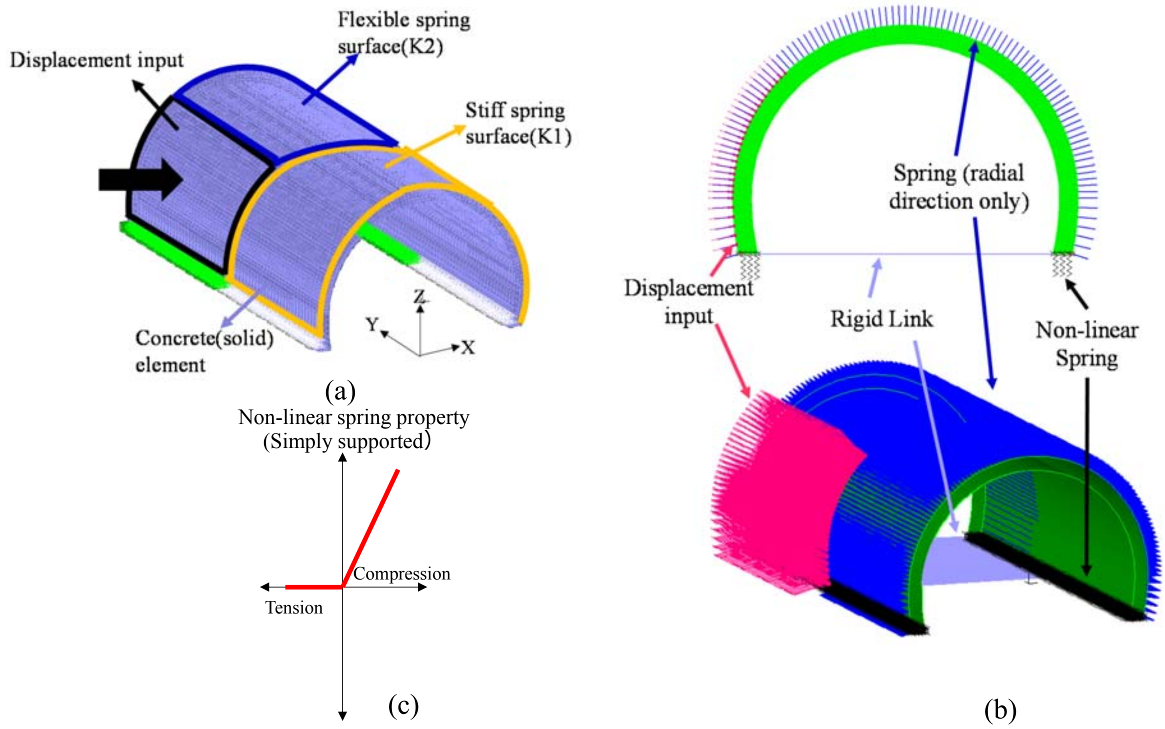


Figure 1. (a) Analysis model for experimental validation (b) Boundary conditions of the model
(c) Nonlinear spring property.

A concrete material model which exhibits non-linearity due to concrete cracking and compression failure is used to model the tunnel. The soil springs are linear and are oriented radially outwards. The material properties of the concrete soil elements and soil springs were set in accordance with the materials used during experimentation. In the experimentation, the tunnel was simple placed on an experiment table and in order to reproduce these effects on the numerical model, firstly, the inner edges of the loading half of the tunnel were connected by rigid springs, and secondly, the tunnel base consisted of compression-only spring with a high stiffness value. As observed in Figure 1(b), the soil springs connects the nodes on the outer surface of the tunnel, to the nodes where the boundary conditions are applied. The nodes connected to the tunnel-half with stiff springs are fixed and the input displacement is applied radially on the nodes connected to the other half. The response of the tunnel and the crack propagation results between the experiment and numerical simulation are compared.

Analysis Results

Figure 2 shows the crack propagation pattern on the outer surface of the tunnel. The crack pattern when the input displacement is 0.1mm, 0.2mm, and 0.3mm are shown in Figure 2. In the initial stages of loading, cracks occur locally at the location of loading ((1)), along the boundary where the soil stiffness changes. As the tunnels is located on the same experimental table, similar cracks are observed on the radially opposite direction of the tunnels ((4)). The crack ((1)) further propagates creating a ring-like cracking pattern along the soil stiffness boundary, which curves into the tunnel-half with stiff soil at the top part of the tunnel. At an input displacement of 0.2mm, the crack on either radial side of the tunnel, ((1)) and ((4)) propagate and intersect at the top end of the tunnel. Also cracks begin to appear along the axial direction of the tunnel, along the nodes with input displacement ((2)). When the displacement increases to 0.3mm, there is no substantial difference in cracking pattern observed from during 0.2 mm input displacement.

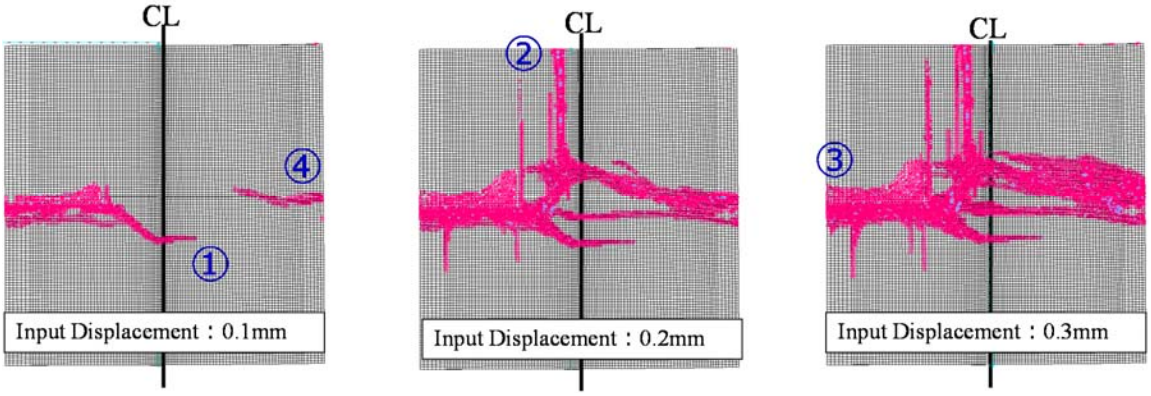


Figure 2. Analysis crack pattern with increase in fault displacement.

In the experiment performed by Asakura et al. (2000), the crack ((1)) is initially observed and crack ((4)) appears at a later stage and intersects ((1)) at the top end of the tunnel, whereas in the simulation, crack ((4)) appears at an earlier stage. These cracks are generated as the tunnel ends are on the same experiment table. Since rigid links are used in the numerical simulation the cracks appear instantaneously, where as in actuality the occurrence of cracks are slightly delayed. Other than the cracks that occur due to the difference in boundary conditions, good correlation was observed between the experimental and analysis results, which validates the usage of the current numerical tool for the parametric study of a fault-crossing tunnel.

STUDY USING SOIL SPRING MODEL

In order to study the effects of soil stiffness and fault-crossing angle on the tunnel, the soil is modelled using linear springs attached to the outer surface of the tunnel.

Analysis Model

Figure 3(a) shows the analysis model. For the parametric study a conventional RC tunnel is assumed. The RC tunnel diameter and lining thickness is assumed to be 5m and 0.5m respectively. The tunnel is modelled using non-linear concrete solid elements and the reinforcement is modelled using plane stress steel elements. Conventional material properties were used for the RC tunnel; concrete of compressive strength 23.5 MPa and reinforcement steel of yield strength 345MPa. The steel elements comprised of orthotropic material properties along the reinforcement direction and were located at reinforcement mesh location. The steel reinforcement in the concrete tunnel is assumed to be equal in the axial and circumferential direction with a reinforcement ratio of 0.00253 (25mm dia bars@200mm spacing).

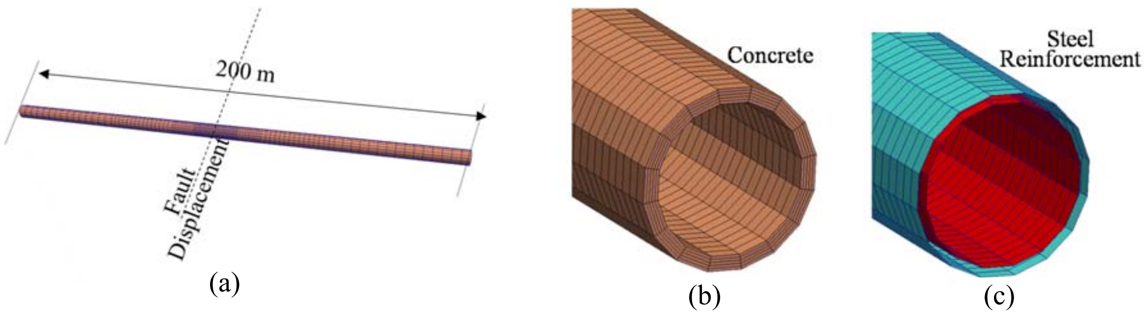


Figure 3. Tunnel model; (a) Overall model (b) Concrete solid elements (c) Steel plate elements

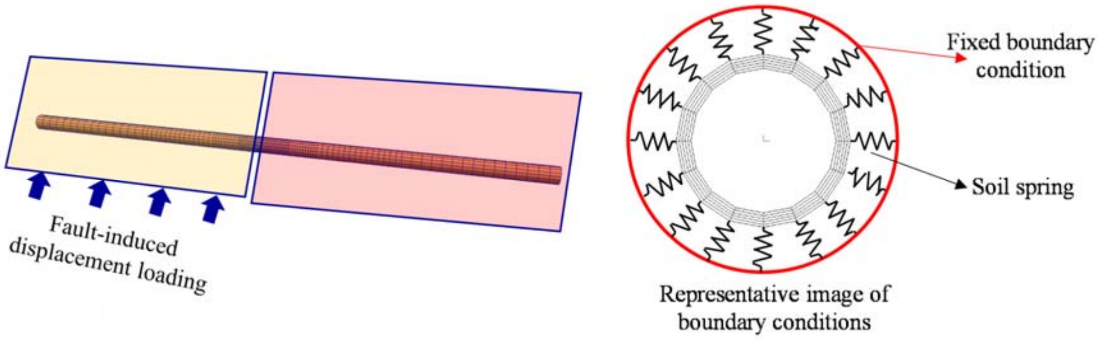
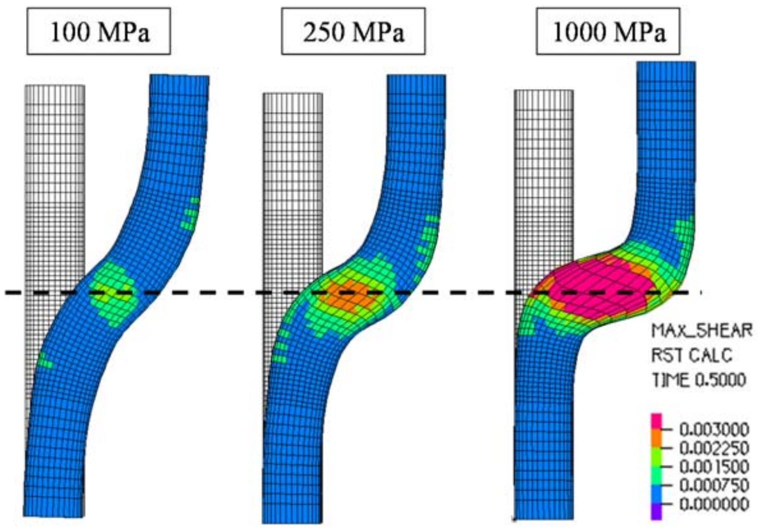


Figure 4. Boundary conditions; (a) Fault displacement input (b) soil spring and boundary nodes.

A non-linear smeared crack concrete model is used for the concrete, whereas a bi-linear constitutive relationship is used for the reinforcement. Soil springs oriented normally to tunnel surface, connect nodes present on the outer surface of the tunnel to boundary nodes as shown in Figure 4(b). The boundary conditions are applied on these boundary nodes. In the current study one half of the boundary nodes along the axial direction of the tunnel are fixed whereas a displacement input is given in the remaining boundary nodes. The soil spring stiffness per unit surface area was set such that the tunnel response is consistent with the tunnel response when the soil is modelled using solid elements, which will be explained in the next section. However the same spring stiffness was used for the springs along the radial and tangential direction.

Influence of soil stiffness

In order to evaluate the influence of surrounding soil stiffness on the tunnel response, three soil cases with varying soil modulus viz. 1000MPa, 250MPa, and, 100MPa, were considered. Figure 5 shows the comparison of the response between the three cases, in terms of the tunnel deformation and the maximum shear strain contour. The damage mode of the tunnel can be predominantly divided into (i) shear-like deformation across the tunnel cross section at the location of the fault displacement which causes ring like crack to occur around the tunnel, and, (ii) the overall beam-like bending mode of the tunnel along its length, which causes tensile bending cracking on the tunnel sides. As the soil becomes stiffer the shear-like damage mode has a greater influence on the tunnel which can be observed in Figure 5.



Young's Modulus (MPa)	Soil spring stiffness per unit area (MN/m/m²)
100	13
250	31
1000	165

Figure 5. Tunnel displacement and maximum shear strain contour with increasing soil stiffness

Influence of fault crossing angle

The influence of fault angle on the tunnel response was observed by changing the incident fault angle to 45°, and comparing the response to the results obtained in the previous section, where the fault plane was orthogonal to the tunnel axial direction. For comparison, except the incident fault-angle, all the analysis conditions including soil stiffness (100MPa), was assumed to be the same. There are two kinds of 45°slip displacement possible namely (i) the left-lateral slip, where the tunnel is being compressed along the fault plane, and (ii) the right-lateral slip, where the tunnel is in tension along the fault plane. Figure 6 shows the response comparison of these three cases in terms of the tunnel deformation and the maximum shear strain contour when the fault displacement is 10cm. Strain values observed when the fault is orthogonal, are larger when compared to the 45°cases. In the right-lateral case, the tunnel is subjected to tensile stress at an early stage of loading, resulting is large cracking and yielding of reinforcement at a much earlier stage. In the left-lateral case, the tunnel is predominantly in compression, which leads to lesser cracks, smaller strains and delay in the yielding of steel reinforcement. However, since the left-lateral case is predominantly in compression, it undergoes sudden brittle compressive failure.

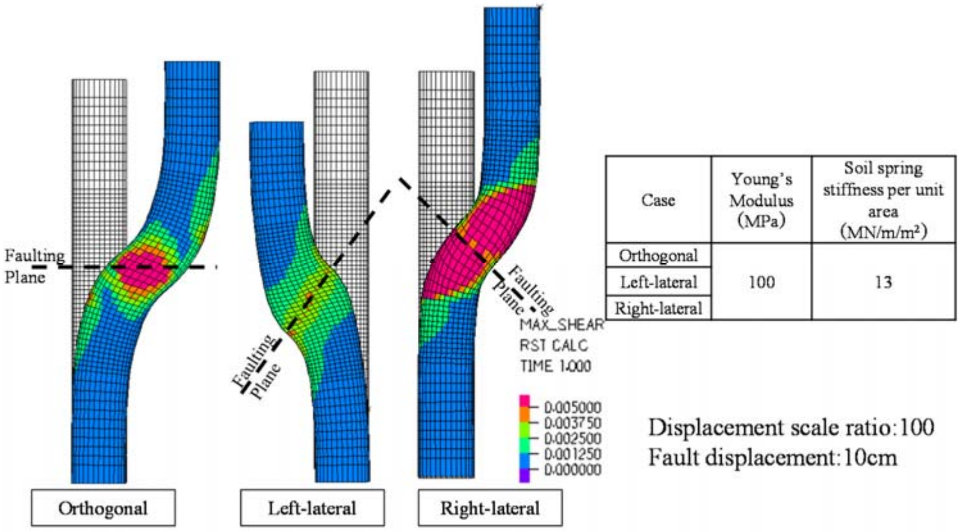


Figure 6. Tunnel displacement and maximum shear strain contour with change in faulting angle

Fault displacement and maximum shear strain relationship

In the numerical simulation, an incremental displacement is applied along the fault plane. Figure 7 shows the plot between the input displacement and the maximum shear strain in the tunnel for all the aforementioned cases. The figure also shows the instance when the reinforcement steel has started yielding, using red points whose shape represent steel yielding in different direction on the inner and outer edge of the tunnel lining. Comparing the response of 100 MPa and 1000 MPa, the reduction in tunnel response with respect to the soil stiffness is observed, as the strain incurred in the tunnel is more when the soil is stiffer for the same fault displacement. Although the strain in the orthogonal case tends to be larger than the diagonal cases, the steel tends to yield faster in the right lateral case. Also, as the input displacement increase, the strain in left-lateral case suddenly increases owing to the softening of concrete model due to compression failure. In summary, a parametric study is performed, where the Young's modulus of the soil and the fault crossing angle are used as parameters. As the soil modulus increases the damage tends to localise at the fault-tunnel intersection causing ring like cracks. Damage is more predominant when the fault is orthogonal, but, at large fault displacements, the tunnel passing through a left-lateral fault, fails suddenly owing to the compressive failure of concrete.

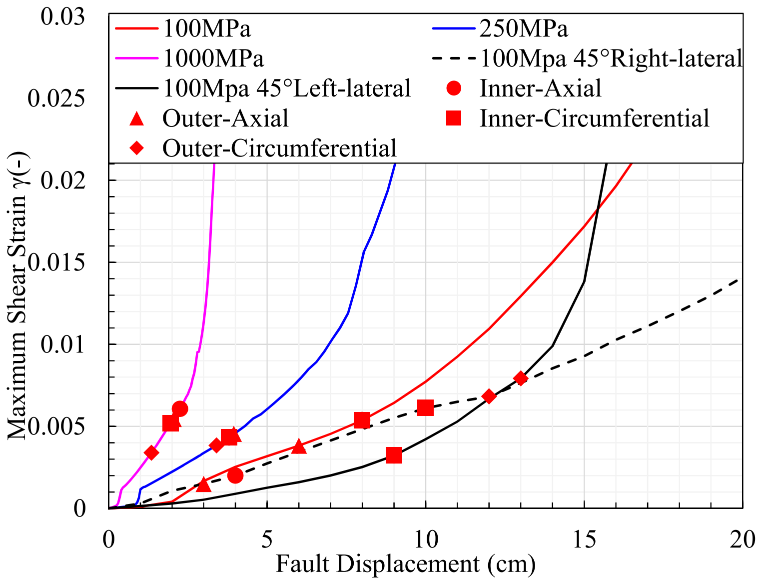


Figure 7. Fault displacement-Tunnel maximum shear strain relationship for all cases

STUDY USING NON-LINEAR SOIL SOLID ELEMENTS

The previous parametric study was focused on the non-linear tunnel behaviour, therefore the soil was modelled using linear soil springs. In order to understand the effects of soil-nonlinearity on the tunnel, the next study involves the soil being modelled using non-linear solid elements.

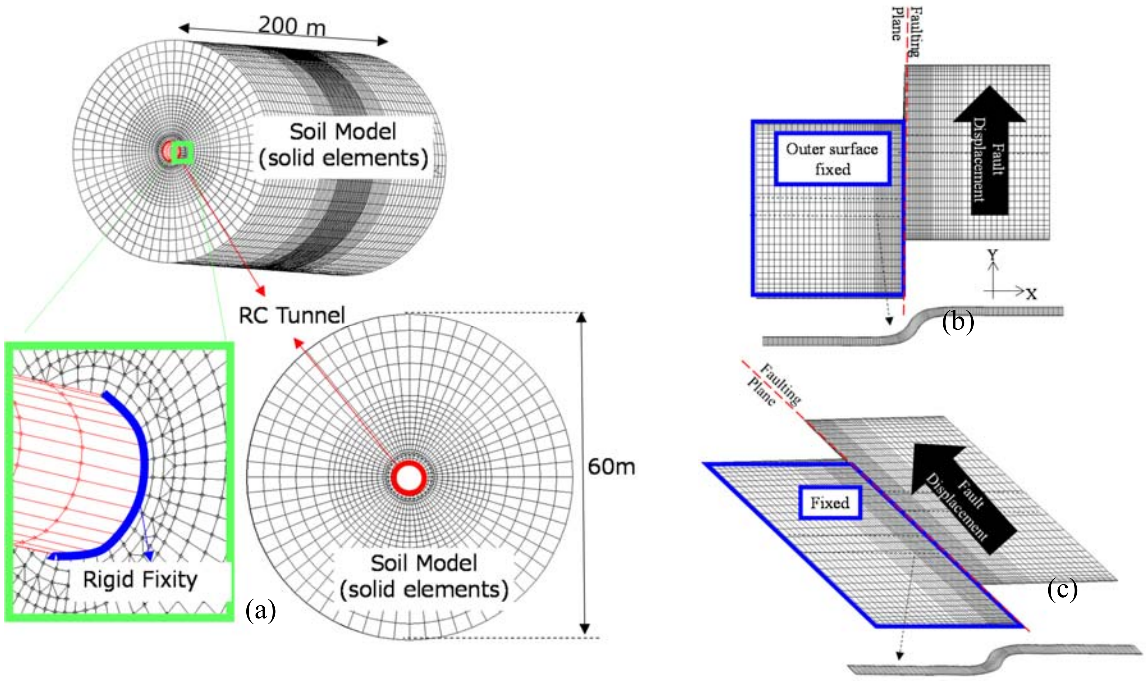


Figure 8. Analysis model- (a) Overall model (b) orthogonal faulting boundary conditions
(c) 45 ° left lateral faulting boundary condition

Analysis Model

Figure 8(a) shows the analysis model used for the current study. The solid elements used to model soil used non-linear plasticity model with a Mohr-Coulomb failure criteria. The boundary conditions were applied on the outer surface of the soil elements, fixing one half of the model and applying displacement on the other half, as shown in Figure 8(b) and Figure 8(c). For the current study, although the tunnel and soil elements were connected by rigid links, the tensile soil failure at the tunnel-soil interface is captured by the Mohr-Coulomb failure criteria. In reality, the interface behaviour depends on the kind of construction practice adopted, which is not within the scope of the current study. From the previous section, the two critical cases viz. the orthogonal fault and the 45° left-lateral fault cases are considered for analysis. The Young's modulus of the soil was assumed to be 100 MPa and its cohesive strength to be 100 kPa. A confining pressure was set such that the tunnel is assumed to be 10m below ground level.

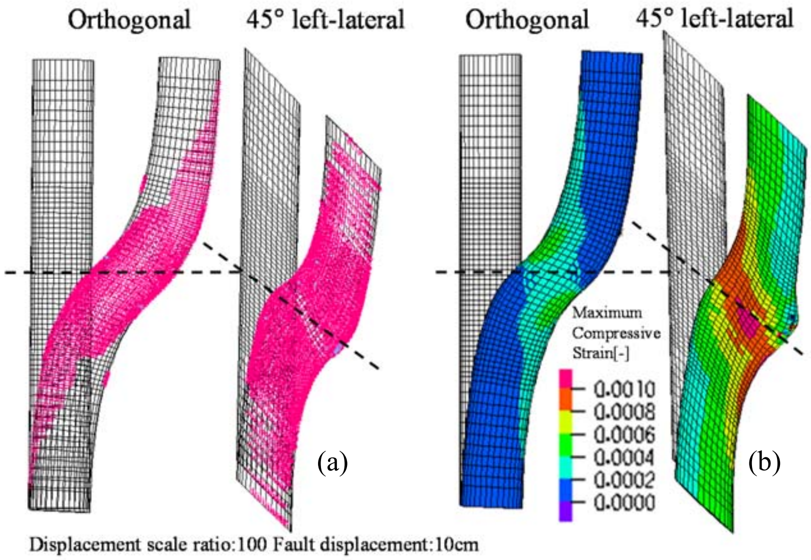


Figure 9. (a)Cracking pattern and (b) maximum compressive shear strain contour

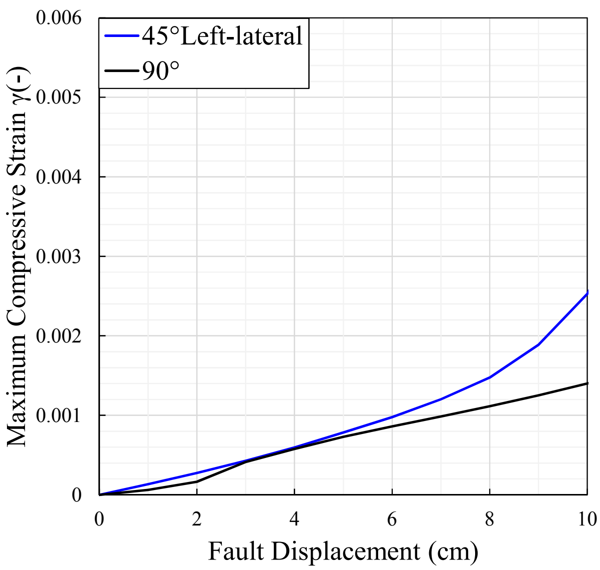


Figure 10. Fault displacement-Tunnel maximum compressive strain relationship

Analysis Results

Figure 9(a) and Figure 9(b) shows the cracking pattern and maximum compressive strain contour respectively. In both the cases maximum compressive strain is observed to be larger at the fault-tunnel intersection. In the orthogonal case the strain are large at the side walls of the tunnel due to the compression created by the S-like bending mode of the tunnel. Similar patterns are also in the 45° left-lateral fault case, but since in general the tunnel is in compression, the compressive strains are larger when compared to the orthogonal fault case. Figure 10 shows the plot between the input displacement and the maximum compressive strain in the tunnel for the two cases. From figure 10 it is observed that at the initial stages the maximum compressive strain is similar for both cases, however, there is rapid increase in the strain in the 45° left-lateral fault case due to compressive failure of concrete.

EVALUATING TUNNEL PERFORMANCE THROUGH ANALYSIS

In nuclear power plants the underground utility tunnels can be broadly classified based on its utility into, tunnels used as services vault for cables, equipment, piping etc., and tunnels used for water conduit. In the case of service vaults, the displacement requirement from the equipment inside the tunnel during fault slippage can be obtained through the simulations performed in the current study, therefore, there is no requirement to explicitly model the equipment. In the case of water conduit, the requirement is that there should be no hindrance to the flow of water, like the possibility debris from concrete spalling or large change in cross-section of the tunnel. Also, for both kinds of tunnels, the ultimate state is the collapse of the tunnel lining. There exists various studies on methods for performance evaluation using 3-D numerical simulation, however the current study refers to performance criteria set by the manual published by the nuclear agencies (Nuclear Civil Engineering Committee, 2018), where the damage criteria is judged based on past research and site investigations. Since the fault displacement is predominantly a static phenomenon, we have performed static non-linear simulations in the current study. The manual provides guidelines for the maximum allowable concrete compressive strain obtained through 3-D finite element method (FEM) simulation of an underground tunnel. The critical compressive strain value depends of the mesh size (Figure 11), which is expressed through the characteristic length of the mesh, lr. Since the general size of the mesh near the fault is 500mmx500mmx100mm, the representative length (lr) =714mm. From the equation given in the manual, the maximum allowable compressive strain εcu=0.006 is obtained (Figure 11). Considering the results obtained in the previous section (Figure 10), the compressive strain in the tunnel is well within its service limit at a fault displacement of 10cm, even after considering the recommended factor of safety of 1.2. Although the current assessment is restricted to the current analysis conditions, multiple case scenarios can be considered to get a comprehensive performance evaluation of the tunnel.

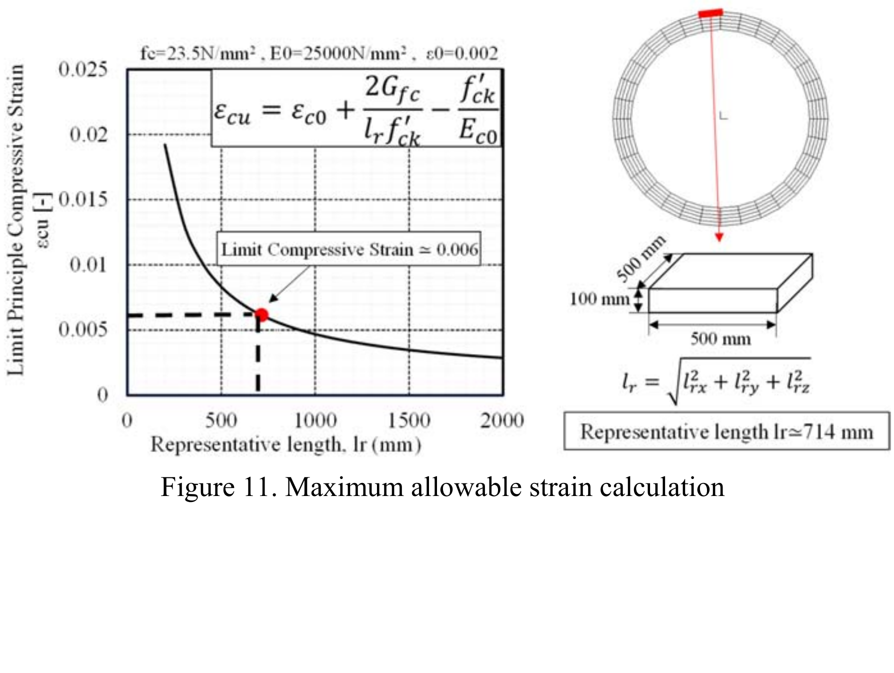


Figure 11. Maximum allowable strain calculation

CONCLUSION

A performance based evaluation method for a fault crossing tunnel, based on 3-D FEM analysis has been established. The displacement across the tunnel cross section due to fault slippage is used as the performance indicator.

The tunnel strain and fault displacement plot gives a good picture of the demand and response tunnel, for a particular analysis condition. Based on the parametric studies, the following points can be concluded (i) when the surrounding soil stiffness increases the damage is more localised near the fault leading to larger response values (ii) up to a certain tunnel displacement limit, the strain is larger when the fault is orthogonal to the tunnel, but when the displacement is large, there is sudden increase in strain response when the tunnel is left lateral and inclined to the tunnel at 45°, due to concrete compression failure (iii) when considering the soil non-linearity, the soil failure mode can be broadly classified into shear failure and tensile failure, in the current scenario, the effects of the tensile failure of soil is more predominant.

The manual used by nuclear agencies enlists the performance requirement through the maximum compressive strain in the tunnel obtained through 3-D simulation. In the current study, the fault displacement – tunnel strain relationship is used as a performance indicator, to gauge the structural integrity of a fault crossing tunnel subjected to displacement due to fault slippage. In the future, the current research will be extended, by comparing the performance evaluation method with actual site investigation.

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