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Tunnel Rehabilitation in Fault Zone Using Sequential Joints Method-Case Study: Karaj Water Conveyance Tunnel

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ABSTRACT

The lining structure of Tunnel Boring Machine (TBM) excavated tunnels is composed of a series of precast Reinforced Concrete (RC) pieces called segments. In this paper, a novel method is introduced for seismic retrofitting of segmental tunnels located in active fault zones in rock environment, on a case study of the Amirkabir dam - Tehran water Transfer Tunnel (Karaj Tunnel). The main design concept in this method is based on stiffness degradation of the tunnel structure, intersecting with central fault zone. . Even strong structures do not tolerate the faults displacement, and will ultimately fail. Therefore, the logical solution for stiffness degradation is providing life safety operational limit. Stiffness degradation develops due to the creation of sequential joints in segments intersecting with central fault zone; so, it is called sequential joints method. In this method, a joint is considered between each or multiple rings to synchronize the tunnel structure with the tunnel displacements during the faulting process, and to avoid the global failure of the tunnel structure. This method is currently applied on the second part of the Karaj water transfer tunnel (Part K"-BR).

Keywords : *Fault, Segment, Mechanized tunneling, Seismic retrofitting*

1. Introduction

Nowadays, construction and application of mechanized tunneling by TBM is widely used. Designing and undergoing seismic loads are considered as the effective problems of such tunnels [1-3]. Although comprehensive studies have been carried out [4, 5] such as Hashash et al. [1], the relevant studies on proper solutions for intersection of faults and segmental tunnel are limited [6, 7]. Displacement of faults initiates significant displacement in a limited length of the tunnel. Current researches on structural design of tunnels intersecting the faults represent application of different methods [7].

Existing methods generally concentrate on non-segmental tunnels.

1) Application of extra excavation in fault zone filled with weak and ductile materials [8]; the tunnel structure will be composed of two covers in which the exterior cover will be damaged under displacement of the fault, but the interior cover will not be affected by fault displacement. This method was used on the Gavoshan tunnel intersection with the Morvarid fault [8]. This water transfer tunnel is a horseshoe tunnel having diameter of 4.2 m.
2) Application of flexible joints in multiple points of the tunnel in fault zone [7]: In fact, these joints act as structural fuses and restrain the propagation of damages due to displacement of faults to other parts of the tunnel structure. This method was applied in the Koohrang-III tunnel intersecting the fault zones [7]. This water transfer tunnel is circular tunnel having diameter of 4 m.
3) Providing ductility in the segment structure and application of opening control joints [9]: The previous methods are used in non-segmental tunnels. Regular and sequential joints are closely available between rings along the tunnel (the distance for the Karaj tunnel is 1.3 m). These joints cause stiffness degradation along the tunnel, and allow displacement of the tunnel structure intersecting the fault zone, and they tolerate lower loads compared to non-segmental tunnels.

The Coronado twin tunnels in California are outstanding examples of designing segmental tunnel intersecting a fault zone [9]. The final diameter of this road tunnel is 9.9 m and the maximum horizontal and vertical displacement of the fault is 29.8 and 55.8 cm, respectively. The plastic deformations in this fault reduce the loads, absorbing by the tunnel structure and assure the total stability of the tunnel if the segment structure is capable to undergo inelastic deformations. A special connection is used to connect the rings and control the opening. This connection is the conventional bolt connection but the seismic isolation washer is used behind the nuts. This washer is made of elastomer materials and opens the rings without any significant load in bolt. Liu et al [10] simulated displacements of a normal fault with different dip angles in loose strata over an active normal fault. They found out that for tunnels under similar conditions, it is important to restrict the movements of a normal fault through designing a lining support system, including determining the weak parts and following reasonable structural parameters. Kiani et al [11, 12] proposed an experimental approach to evaluate shallow segmental tunnels in alluvial deposits subjected to normal surface faulting. They did not consider any seismic retrofit in tunnel lining.

In the current paper, the status of the Pourkan–Verdij fault is geologically investigated and the structural solutions required for the tunnel-intersecting fault are evaluated. In the first part, the solutions related to defining the location of the fault based on tunneling parameters and geological mapping are presented. In the second part, the structural performance of the tunnel adjacent to the fault, conventional solutions for the tunnel and fault intersection conditions are presented. Finally, considering the type of permanent support of the tunnel (i.e. precast RC segmental lining) and the excavation method

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(TBM full mechanized method), the proposed method was investigated to reduce the destructive effects of the fault.

2. Determination of fault zone location

2.1. General characteristics of fault zone

According to Fig. 1, the Pourkan–Verdij fault that has a thrust mechanism extends along northwest to southeast. This fault is located in the vicinity of the north Tehran fault zone. It passes the Verdij village and terminates to the mountains from the northern part of the Pourkan village in Chaloos road, Iran.

Fig. 1. View of Pourkan–Verdij fault along the tunnel.

The faulting can be observed as collapsed surfaces in hanging wall and footwall. The tunnel and fault intersection angle is 70 degrees in vertical plane. The displacement of the fault is in vertical direction, so the intersection angle in vertical plane attracts the main importance. The TBM performance generally depends on geotechnical conditions of the tunnel path. Various equations and experimental models have been proposed to predict the performance of the TBM [2]. Based on geotechnical conditions of the tunnel path, the performance of the TBM is predictable by using such models. It is clear that these models can be inversely used and the geotechnical conditions of the tunnel can be found based on real performance parameters of the TBM. This can be especially appropriate for tunnels excavated by a double shield TBM. In this study, considering ambiguities, especially about the location of the Pourkan–Verdij fault, it was aimed to investigate the real performance of the TBM adjacent to the fault to find the accurate location of the fault zone.

2.2. Classification of rock mass excavatability

One of the recent classifications of rock mass excavatability is the study if Hassanpour et al. on different national projects, such as the first part of the Karaj water transfer tunnel and other international projects [14]. In this method, the rock mass is divided into six different categories, as shown in Fig. 2 and Table 1, based on the excavatability properties (strength of rock materials and structure of rock mass). Here, the excavatability of the rock mass is defined based on difficulties or conveniences of excavation by disc cutters installed on the TBM cutter head. The variation of defined class from "0" to "B" improves the excavatability of the rock mass, and its stability condition around the tunnel wall is worsened from B to IV. In this method, the relation between the Field Penetration Index (FPI) parameter and geological characteristics of the rock mass are used to classify the ground excavatability.

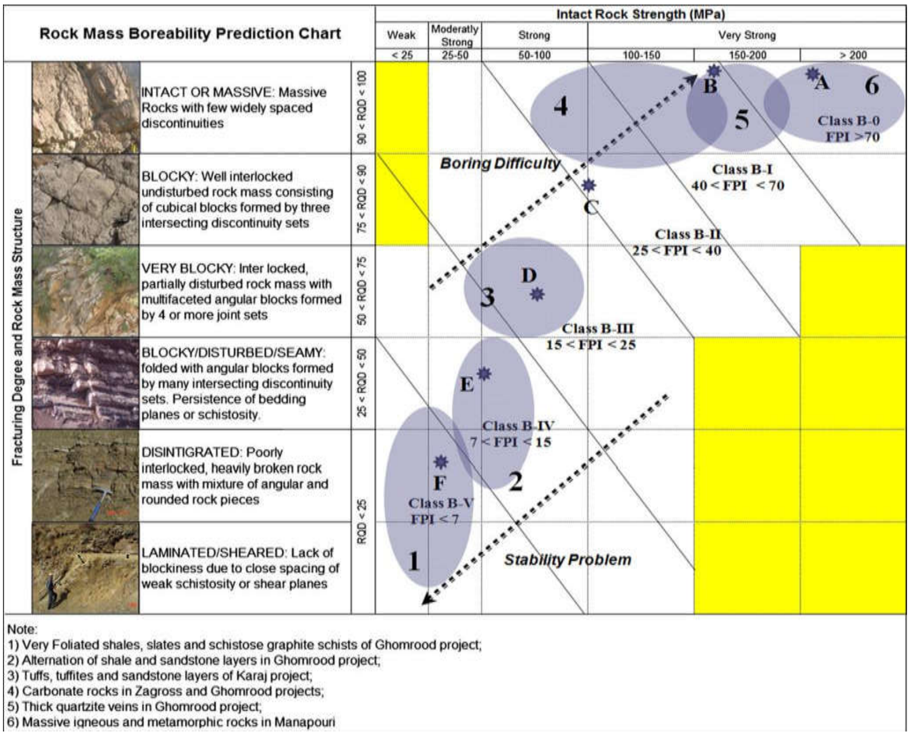


Fig. 2. Rock mass boreability prediction chart with actual FPI range for different geological units in the database [14].

Table 1. Summary of ground conditions for B-III, B-IV and B-V boreability classes [14].

Boreability class	FPI range	Rock mass boreability	Stability condition	TBM excavatability
B-III	12-25	Good	Only local structural instability	Very good
B-IV	7-15	Very good	Some major instability	Good
B-V	<7	Excellent	Collapse, gripper problems, squeeze, etc.	May be problematic

FPI is a hybrid parameter that is calculated based on other parameters related to machine such as thrust, revolutions per minute (RPM) and the TBM penetration rate.

$$FPI = \frac{60\ F_n\ RPM}{1000\ ROP} \quad (1)$$

Where, ROP is the TBM penetration rate (m/h), RPM is the TBM revolutions per minute, F_n is the cutter head thrust (kN/cutter).

2.3. Determination of fault location based on performance of TBM

The FPI parameter was calculated at each progress courses based on the acquired data from the PLC (Programmable Logic Controller). The variation along this part of the tunnel is plotted in Fig. 3 to investigate the geological characteristics of the tunnel in the section close to the Pourkan–Verdij fault [13]. This part of the tunnel was classified into three categories, B-III, B-IV and B-V based on the ground excavatability classification. The analysis results revealed that the FPI parameter in 400 meters of the tunnel was low and was classified into the B-V category that was equal to the crushed rock mass and the fault zones. In addition to the low value of the above index (FPI), an increase in water seepage in the tunnel approved the existence of a crushed zone having a thickness equal to 400 meters in this part of the tunnel (see Fig. 3).

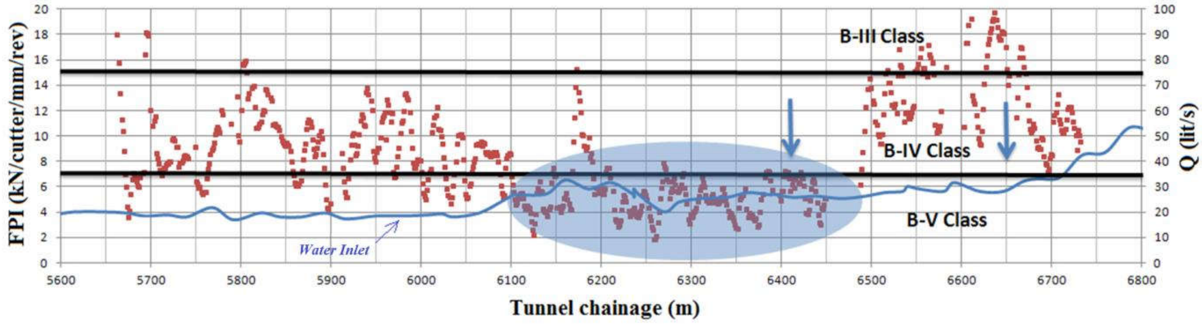


Fig. 3. FPI parameter and ground excavatability classification of the Karaj water transfer tunnel near the Pourkan-Verdij fault. Variation of water inlet is included.

The location of the Pourkan–Verdij fault has attracted a high degree of importance. Moreover, on the abovementioned evaluation, a complementary field investigation was conducted at the exaction time. As-built findings revealed the geological unit E_5^{SS} located near unit E_3^{SS1} in the fault location (Fig. 4). It was an evidence for determination of the fault location. Besides, considering the ground observations, the main core of the fault (extremely crushed zone) is detected approximately 32 m, as illustrated in Fig. 5. The geometrical properties and related parameters of the Pourkan–Verdij fault are shown in Fig. 4 and Table 2.

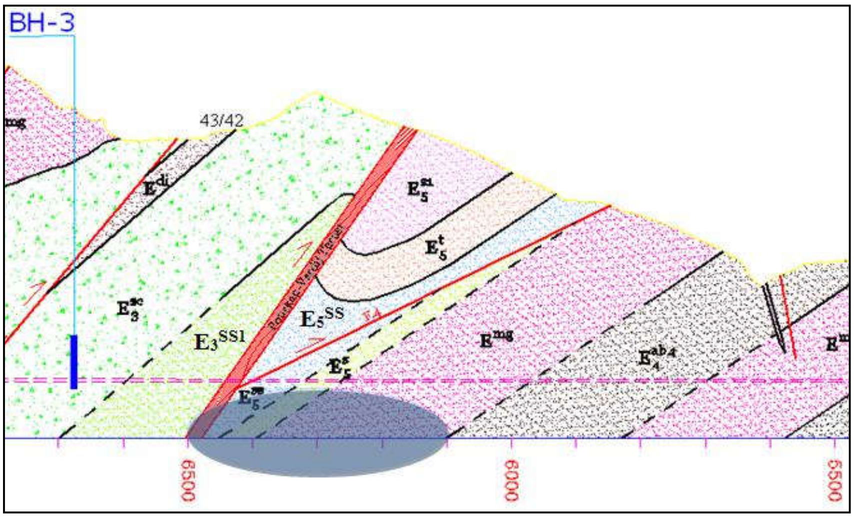


Fig. 4. Geological profile of the tunnel in close section to the Pourkan–Verdij fault.

Table 2. Engineering properties of the Pourkan–Verdij fault.

Maximum acceleration				Maximum displacement of the fault	Magnitude of probable earthquake	Thickness of main zone of displacement	Thickness of affected zone to the fault	Fault length	Degree of activity	Fault mechanism
in tunnel entrance (BR)		In portal K"								
V	H	V	H							
0.476	0.573	0.32	0.432	1.15 m	6.7	32 m	450 m	44 km	active	inverse

H: Horizontal, V: Vertical

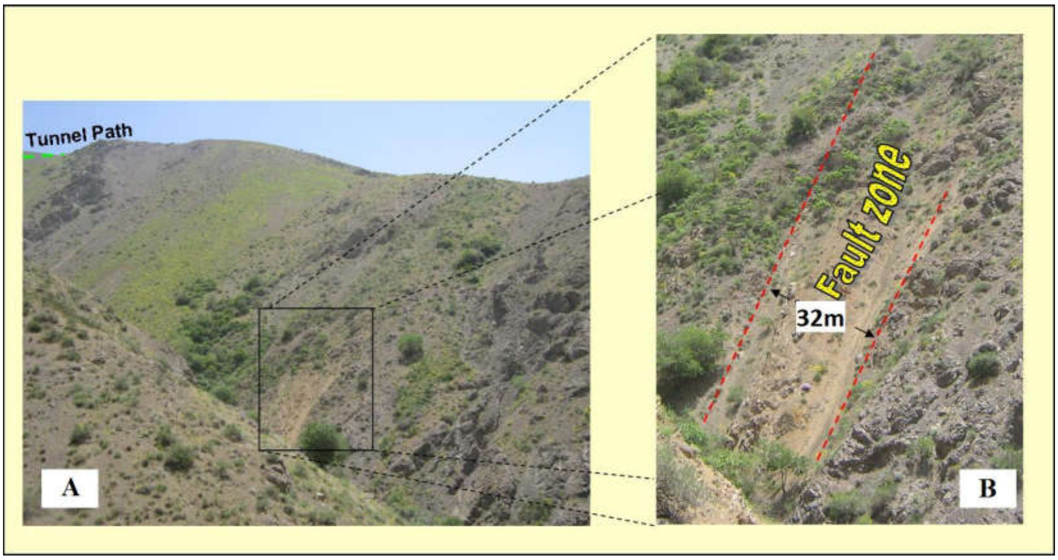


Fig. 5. A) Extremely crushed zone of the Pourkan–Verdij fault, B) Close view of extremely crushed zone.

3. General concept of sequential joints method

The sequential joints method, which is introduced for the first time in this research, is used to attenuate the fault effects on the tunnel structure. It is assumed that some openings are considered in regular distances along the tunnel with limited opening width as depicted in Fig. 6. Shahidi and Vafaeian [7] proposed this concept for seismic retrofitting of the Koohrang-III tunnel intersecting the Zarab fault. The method used by these researchers is different from the method used in the current paper, but they have an identical design concept. In presence of joints, the tunnel structure is allowed to be opened or closed during a large displacement in the fault. This process makes the tunnel structure to have the minimum resistance under applied displacements of the faults. Therefore, the load demand (i.e. internal forces due to faulting) reduction is provided instead of increasing the required strength of the tunnel structure. The similar concept is found in the seismic design of the above-ground structures (such as buildings) where the seismic loads (i.e. inertia loads) are not directly applied to the structures. In such cases, application of active or passive control instruments (structural fuses) can reduce the seismic loads [18, 19]. Structural joins on a tunnel structure can reduce the attracted loads to the structure while the displacements are directly applied to the tunnel structure.

The sequential joints can be inserted in favorable distances and the opening width of the joint will be changed by variation in the distance of joints. Based on the analytical concept of this method, application of joints with low spacing is more efficient to handle large fault displacements. Thus, three different assumptions including inserting joints between one, two or three rings were evaluated in this research.

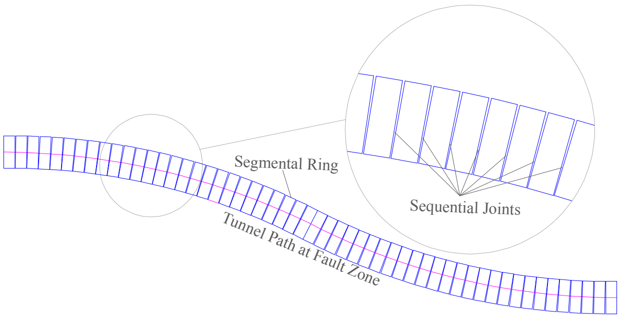


Fig. 6. The sequential joints method.

4. Structural analysis of the tunnel under fault displacements

4.1. Analysis method

According to a recently published technical manual by FHWA for the design and construction of road tunnels [15], application of similar equations for pipelines has been proposed as the principle method for structural analysis of tunnels intersecting faults. The manual introduces three conventional methods for pipelines: 1) Newmark-Hall's method, 2) Kennedy et al.'s method, 3) Finite element method.

The above-mentioned methods have been also introduced and illustrated in the ASCE (American society of civil engineering) standard. The first two methods are the closed form solutions, which are mainly based on the generalized behavior of beams on elastic foundations. Various equations such as the bearing capacity of strip foundations are used in accordance with the host ground properties and conditions that are often related to the ground environment with a limited embedded depth (depth of embedded structure). Application of these two methods was not appropriate on the present research due to the high depth of the tunnel and the surrounding rock environment. The finite element method was used for the tunnel structure of the present project. According to Fig. 7, the loads in the tunnel structure were calculated in the finite element method assuming a continuous displacement in the critical region (i.e. fault zone).

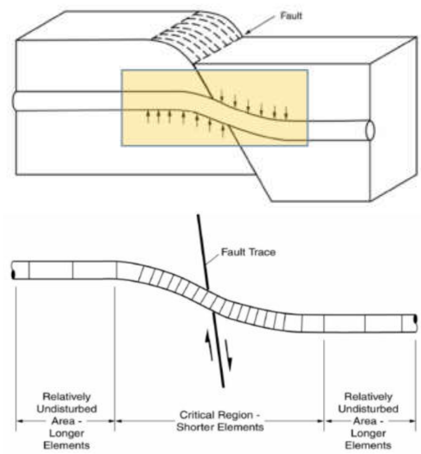


Fig. 7. Displacement 7.

Due to the fault displacement, the internal forces of the segmental lining could be calculated if the deformation function of the surrounding rock mass was predictable.

Although this method has been introduced as the most appropriate approach compared to the other two closed form solutions according to FHWA code, no detailed description on calculation of the critical zone deformations has been presented. One of the best and most probable patterns for deformation of the tunnel structure in the fault zone can be chosen as a displacement pattern such as a tow fixed end structure.

4.2. Numerical modeling of segmental ring in fault zones

As discussed in the previous section, the tunnel structure was modeled as a two fixed end structure in the SAP2000 structural analysis package [16]. A settlement equal to half of the probable fault displacement was imposed to each fixed end. As the Pourkan–Verdij fault does not intersect any quaternary deposits, so determining the fault displacement was impossible using the paleoseismology method [22]. The fault displacement was measured by empirical formulas [22] and 115 cm fault displacement was considered as the total fault displacement [22]. Therefore, a displacement equal to 57.5 cm was applied at both ends with different directions. The deformation function of the tunnel at the fault zone was obtained applying the structural properties of the tunnel. More details could be found in reference [21].

The corresponding loads and displacements can be calculated after applying the deformation to the tunnel structure with the desirable properties.

General seismic analysis of the tunnel structure was conducted based on the Hashash et al's [1] methodology (endorsed by International Tunneling Association) assuming two major deformations: longitudinal bending and ovaling (racking) deformations. For the current case study, this analysis has been done elsewhere [17] and is not included here.

In the analytical method, the fault displacement was applied to the tunnel structure due to imposing a probable load pattern. After that, in order to achieve the displacement pattern of the target fault, a modification factor was applied to the loading pattern. Assuming a continuous displacement, the tunnel structure and the considered joints in the model experienced a fault displacement. The structural model for three different assumptions are depicted in Figs. 7 to 9. The joints were modeled and the middle support was only considered for stability of the finite element solution. The reaction of this support was obtained zero (the joints are characterized by the Gap in Figs. 7 to 9).

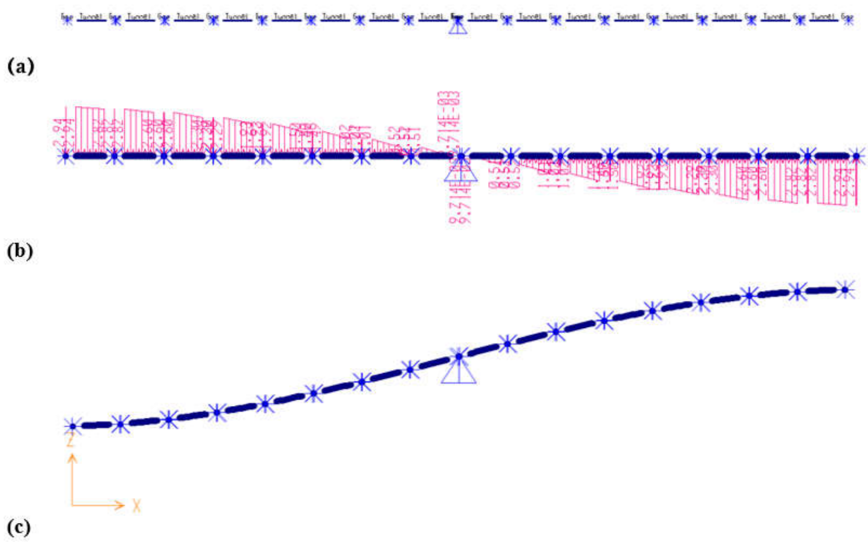


Fig. 7. Modeling of joints between each ring, a) modeling of tunnel and joints, b) application of base loading (kN-m), c) results of displacements.

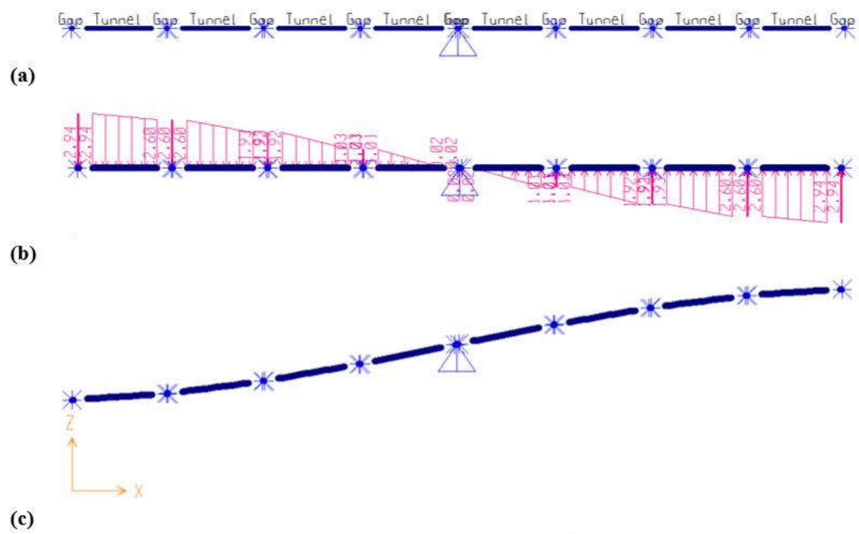


Fig. 8. Modeling of joints between every two rings, a) modeling of tunnel and joints, b) application of base loading (kN-m), c) results of displacements

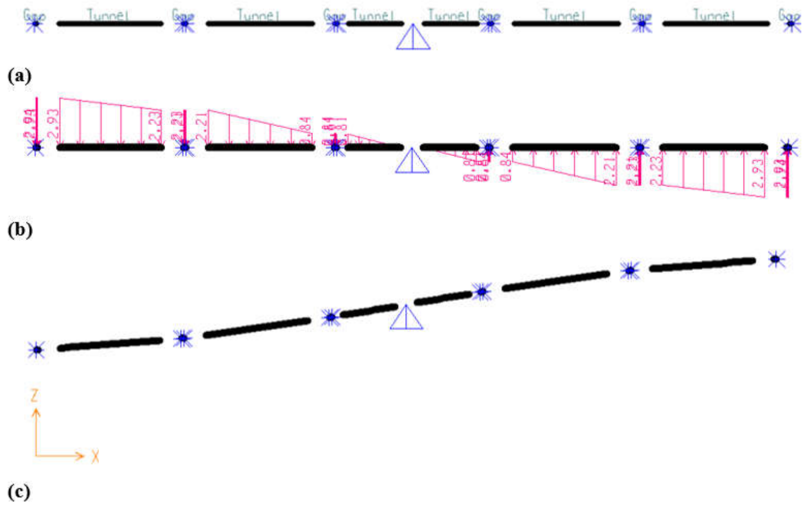


Fig. 9. Modeling of joints between every three rings, a) modeling of tunnel and joints, b) application of base loading (kN-m), c) results of displacements.

4.3. Calculation of required opening width

The main result of numerical modeling was determining the deformation pattern of the tunnel structure in the fault zone, considering the sequential joints effect. According to Figs. 7 to 9, the angle difference can be calculated between every two sequential sections. As depicted in Fig. 10, the required opening width at each joint was equal to multiplication of "angle between two adjacent rings of the joint", to "radius of the tunnel". The results of the required opening based on calculations for each assumption is presented as follows:

The joint between each ring: 30 mm; Joint between every two rings: 54 mm; Joint between every three rings: 70 mm.

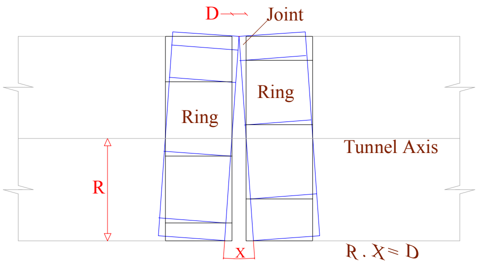


Fig. 10. Calculation of required opening width for each joint.

Considering the uncertainties, a safety factor of 1.3 was applied in calculations. The structural solutions in the Pourkan-Verdij fault are summarized in Table 3.

5. Discussion

As observed in Table 3, a bigger spacing of joints leads to a bigger required opening width. Fault zone medium is usually an unstable crashed zone and a wide opening may not guarantee the general stability of surrounding rock mass. In opposite, a smaller joint spacing (i.e. more numbers of joint) reduces the structural indeterminacy, and a higher joint spacing is preferred based on the structural analysis viewpoint [20]. Evaluation of two mentioned requirements finally was condcted based on the stability analysis of the surrounding rock as well as the engineering judgment. Taking into account the medium stability as well as the structural indeterminacy, it was finally decided to select a two-ring spacing. Nonetheless, a complementary research is required on this case. While a segmental lining comprising the precast RC pieces having a width equal to 1.3 m is used as tunnel lining, application of predefined joints (gaps) between rings can be considered instead of cutting the sequential joints. These gaps could be prepared using some temporary plywood layers or any disposable materials in the joints location. After installation of rings in the fault area, the disposable materials will be removed. In this way, no ring cutting is required. In many cases, such as the Karaj water conveyance tunnel, execution of joints after excavation of the tunnel and installation of the segments is unavoidable, as the exact location of the fault was not clear before excavation. In such cases, in order to provide the maximum structural integrity, it is recommended to cut the joints in a way that the segment reinforcements (steel bars) not be damaged during the cutting process. For safety assurance, it is necessary to insert joints in a greater length of the tunnel path if the location of the crushed zone (the core of the fault) is not clearly defined. In addition, it is required that all of the connecting instruments located out of the joint area (used for connecting the segments to each other) be fully tightened prior to the creation of joints. Steel banana bolts were used as connectors, in segments of the Karaj water conveyance tunnel.

Table 3. Summary of joint solutions applying safety factor equal to 1.3.

Spacing of joints (ring)	*Opening size (cm)*	*Descriptions*
1	3.9	All ring to ring connection bolts shall be permanently opened. All segment to segment connection bolts in each ring shall be tightened.*
2	7	The ring to ring connection bolts shall be permanently opened only in joints. The ring to ring connection bolts in other sections shall be tightened. All segment to segment connection bolts in each ring shall be tightened.*
3	9	The ring to ring connection bolts shall be permanently opened only in joints. The ring to ring connection bolts in other sections shall be tightened. All segment to segment connection bolts in each ring shall be tightened.*

* The above-mentioned considerations related to construction and sealing shall be observed.

The connection bolts of two sequential rings with joints are permanently tightened in the operational period of the tunnel. All of the displacements for the Pourkan–Verdij fault were calculated only in the fault core, a length equal to 32 m. Thus, the sequential joints are only applied in the fault core. The specially designed segments (including extra steel reinforcement) were used in fault zones [21]. Fig. 11 illustrates sequential joint method during execution in the Karaj water conveyance tunnel (Second Part of the tunnel: K"-BR). Core drilling was used to create the joints.

6. Details of sealing in joints

Cutting the width of openings in the joints, the conventional sealing of the segments that were provided by installed gaskets was removed. Therefore, it was required to apply new details of sealing. Specifications of two proposed sealing methodology are illustrated in Fig. 12. Both details are recommendable for sealing purpose. For the current case study, the backfill grout was injected before cutting the joints, so there was no threat for the pea gravel rush from the joint opening into the tunnel. As a result, the second one was selected (Fig. 12, detail number 2). In cases that the backfill grout injection is not conducted before the joint cutting, the first details are recommended.

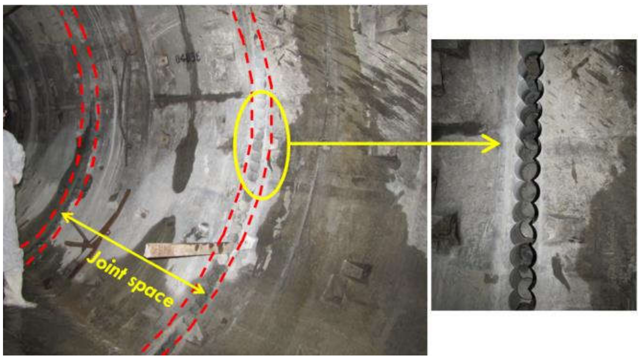
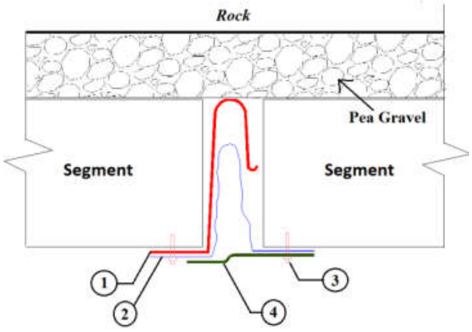
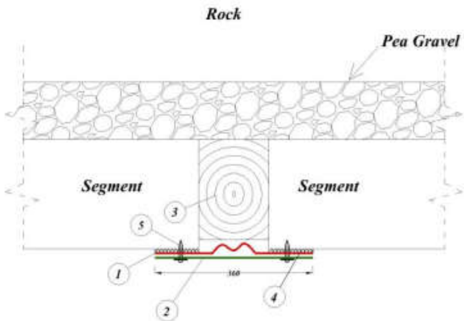


Fig. 11: Sequential joint method during execution, the Karaj water conveyance tunnel, (Second Part of tunnel: K"-BR).



Details of joint (1)

1. **Galvanized steel plate to avoid entering the pea gravel;**
2. **Geomembrane sheet to provide sealing;**
3. **Bolt or pin for installation;**
4. **Galvanized steel plate to cover the opening width.**



Details of joint (2)

1. **Geomembrane sheet to provide sealing;**
2. **Galvanized steel plate to cover the opening width;**
3. **Injection of Polyurethane;**
4. **Epoxy paste;**
5. **Bolt and pin for installation.**

Fig. 12. Specifications for sealing in joints.

6.1. Geo-membrane sheet to provide sealing

It was required to apply the new details of the sealing, as the conventional gaskets had been removed in the joint cutting process. So, the geo-membrane sheet was used to provide the sealing in joints. This flexible sheet is made of a high-density polyethylene (HDPE) that was precisely and symmetrically located all over the surface of the opening. The thickness of the sheet was 2 mm and the width was considered approximately 40 cm to properly cover the opening. This sheet was bent on both sides of the opening joint with a length of 10 cm and was pasted to the surface of the segment.

6.2. Aluminum cover plate

In order to protect the geo-membrane sheets from environmental attacks, an aluminum cover plate was installed on the inner surface of the tunnel, in the location of joints. Moreover, this plate with a thickness of 3 mm, a width of 360 mm and a length of nearly 1000 mm provided a smooth surface in the joint to avoid hydraulic problems.

6.3. Bolt or pin for installation

The bolts were installed on the galvanized plate and the aluminum plate to seal the geo-membrane sheet to the tunnel lining. The applied load to these stainless steel bolts was not considerable. The bolts are implanted in locations where the segment reinforcements (steel bars) are not presented.

6.4. Galvanized steel plate

In order to maintain the pea gravel behind the joint, a galvanized steel plate was installed before the geo-membrane sheet (detail number one, Fig. 12).

6.5. Injection of Polyurethane

Finally, after installation of the galvanized plate, hydrophilic polyurethane foams were used to fill the opening between two segments. This was carried out by foam injection with a special pump. The high flexibility of foam allows displacement and variation of opening width and keeps the integrity of the rings.

6.6. Epoxy Paste

The PVC (Polyvinyl chloride) or epoxy paste can be properly used to paste the geo-membrane sheets to the surface of the segment. The process requires a proper epoxy paste to attach items 1 and 2 to provide a full sealing. The type of epoxy should be properly adapted to provide an appropriate sealing and durability in accordance with the function of the tunnel.

7. Comparison of sequential joints method with other methods

Existing structural considerations on fault-tunnel intersection are categorized in three general methodologies; 1) Providing an extra excavation in the fault zone that are filled with weak and ductile materials [8]. 2) Application of flexible joints in multiple points of the tunnel in a fault zone [7]. 3) Using the opening control connectors [9]. The first two abovementioned methods are applicable only for conventionally mined tunnels (non-segmental). The third way is advised just for small fault displacements. There is no registered method for structural considerations in a segmental lining experiencing a considerable fault displacement. A distinguished feature of the proposed method in the current research is the applicability for large fault displacements in mechanized tunneling (segmental lined tunnels).

8. Conclusions

In the present paper, a new method was introduced for seismic retrofitting of segmental tunnels intersecting an active fault zone in a rock environment. This method was applied in the second part of the Karaj water conveyance tunnel. The main results are summarized as follows:

1) Estimating the length of the fault zone and probable displacement of the fault are the significantly important input parameters.
2) The methodology in the current research was proposed for the first time and the in situ measurements are required for validation. It is recommended to use the instrumentations (strain gauges, pressure cells, etc.) on segmental rings to perform the structural health monitoring during the service

life of the tunnel, as well as preparing the in situ data.

3) Between two presented details for sealing the joints, the second detail is more appropriate if the backfill grout injection is carried out and field observations show that the pea gravel materials do not slide to the inside due to cutting the segments. Otherwise, the first detail should be applied.
4) An appropriate device should be adapted to create the joints to prevent any damages to the segment structure. For instance, the application of the demolition hammer such as the jackhammer is not rather appropriate. The required opening can be cut from one or two rings to create the joints and it depends on the convenience of the construction method.
5) To carry out the sequential joints method, if the fault location is obviously determined, it is recommended to install the segmental rings with a predefined joint at the fault zone.

In the current engineering practice, no perfect method was available for structural considerations of the segmental tunnels intersecting fault zones. The proposed model in this paper can be an appropriate research basis, and a validation by field instrumentations is still required.

Acknowledgments

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