Evaluating the cracks of Highway Tunnel Concrete Lining by Using a Fuzzy Inspection System

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Abstract

In the civil engineering, the prediction of cracks for tunnel lining is too hard because it depends by different factors for example concrete strength, tunnel operation conditions, stress and geological surroundings. The aim of this study is to design a Fuzzy inspect System (FIS) for evaluating the concrete cracks of tunnel lining. Fuzzy logic is a method to signify a type of uncertainty which is understandable for user. The system has been designed to meet permit crack formula that issued in "Highway Tunnel Design Specifications". When the maximal permit crack width as example is chosen as 0.7mm, 1.2mm and 3.3mm separately the fuzziness set accordingly is Minor , moderate and severe. The average error for the predicted crack (element sample) in FIS is 8.34%. The fuzzy evaluation model is based on the information of a real in-service PESHRAW highway tunnel, which reflects field status. Therefore, this evaluation is comfortable.

Key words: Tunnel inspection, crack width and fuzzy system

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تقيم الشقوق في بطانة انفاق الطرق الخرسانية باستخدام نظام المنطق الغيمي التسخيصي

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الخلاصة

في الهندسة المدنية ،ان التنبأ بالشقوق في بطانة الانفاق يعتبر صعب بسبب كونه يعتمد على عوامل مختلفة مثل مقاومة الكونكريت ، ظروف تشغيل الانفاق ،الاجهادات والطبيعية الجولوجية المحيطة بالنفق. ان الهدف من هذه الدراسة هو لتصميم نظام الغيمي التشخيصي من اجل تقيم الشق في بطانة النفق. المنطق الغيمي هو طريقة لامركزية تشير الى التشخيص والتي تكون مفهومة للمستخدم. صمم النظام ليقابل المتطلبات القياسية للشقوق وحسب مواصفات الانفاق. عندما يكون اكبر عرض للشق على سبيل المثال ،عند اختيار 0.7 ملم ، 1.2 ملم و 3.3 ملم على التوالي ستكون نتيجة البرنامج ضرر ثانوي ، متوسط وخطر. ان نسبة الخطاء للتنبأ بالشق في جزء من بطانة النفق هو 8.34 % . ان النظام المستخدم للتقيم قد بني على معلومات حقيقة اخذت من نفق بيشون والتي تعكس واقع الحال لذى يعتبر التقيم مطمئن.

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1. Introduction

There are not regularly countered for crack diagnosis cases at mega structures such as tunnels, dams and bridges. It needs to explain a choice of mechanisms by which cracks occur and evaluate the damaging effects, which these cracks inflict on these structures.

Conversely, it is known that many tunnels, for example in the US, which are more than 50 years old and have begun to illustrate symbols of deterioration, in particular due to water penetration [1]. For this purpose, the US Federal Highway Administration (FHWA) has established a Tunnel Operations, Maintenance, Inspection and Evaluation (TOMIE) Manual and a Highway and Rail Transit Tunnel Inspection Manual [1], [2]. There are various kinds of tunnel inspections: initial, usual, damage, in-depth and special inspections [1]. According to TOMIE, a team of inspectors, which consisting of registered professional engineers with expertise in civil/structural,

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mechanical, and electrical engineers, should always accomplish inspections and electrical engineers, as both structural elements and functional systems have to be assessed.

In current years, with the rapid progress of computer performance, the intelligent systems such as fuzzy logic, artificial neural network and genetic algorithm have been commonly used. The most significant application of the fuzzy system is in uncertain issues. A fuzzy logic has a suitable tool to deal with problems that have dynamic behavior. In the fuzzy theory, the evaluation of many complex systems, not only need to consider many factors which are fuzzy, but most of these factors are in different layers. That means a number of others determines these factors [3]. An accurate forecast of a tunnel deformation at the designing phase is very tricky even though computational methods are often used. This is due, to complex geological condition, changeability of rock material behavior and knowledge about the real ground condition resulting obviously into a type of uncertain prediction [4].

Fortunately, fuzzy set theory could be provided the practice such epistemic uncertainties connection with the many models based on FIS, which have been developed successfully in the field of tunnel, rock engineering and geo-mechanics [5]; [6]; [7]; [8]; [9]; [10] and [11].

In this study, fuzzy inspect system has developed to take into account factors mainly affect on cracks to activate safety critical systems which can be further built-in tunnel. For example, in the actual problem, the mostly factors that affect the maximal crack width (Wmax) are: loads, material strength, and resisting force analysis.

2. Estimation Width of Crack

A crack is defined as a break without a complete separation of parts. In the other hand, a crack is a linear fracture in the concrete caused by tensile forces exceeding the tensile strength of the concrete. Cracks can occur during curing (non-structural shrinkage cracks) or thereafter from the external load (structural cracks). They may extend partially or completely through the concrete member.

The bond of concrete and reinforcement is a complex interaction to transfer stress and deformation. The former research achievements show that the interface characteristic will affect the concrete stress and the crack expansion. After cracks appear in the concrete lining, slip may even occur.

Yu and Qian, 1993 developed a concrete damage extent, which can be described by the following equation that is obtained from the tensile experiments: [12]:

$$D = 1 - \frac{\varepsilon_D \times (1 - A_T)}{\varepsilon} - \frac{A_T}{exp[B_T(\varepsilon - \varepsilon_D)]} \tag{1}$$

where D is the damage variable, which represents the material damage extent; ε is the first principal strain of the element; AT and BT are the curve fitting constants from the laboratory tests; AT ranges between 0.7 and 1.0 while BT ranges between 104 and 105; ε_D is the ultimate tensile strain of the concrete. D is calculated according to Eq. (1) when ε is more than ε_D; otherwise, D equals zero when ε is less than or equal to ε_D.

The load, which is jointly bear by concrete and reinforcement before cracks occur in lining, can be described by the following equation :

$$p = p_s + p_c = (E_s A_s + E_c A_c)\varepsilon_c = A_t(1 - \rho + \eta\rho)E_c\varepsilon_c \tag{2}$$

where Ps and Pc are the load bear by reinforcement and concrete respectively; η = (Es/Ec) is the ratio of elastic modulus between reinforcement and concrete; At = (As + Ac) is the area of reinforcement and concrete; ρ = (As/At) is the reinforcement ratio; ε_s and ε_c are the element strain of reinforcement and concrete, respectively.

The damage variable D is used to describe the change of material mechanical characteristic. When D is more than zero, the concrete will partly lose its force-bearing capacity, and the reinforcement will bear the other load. When cracks occur in lining, the load will be redistributed according to Eqs. (3a) and (3b), and the strain of reinforcement can be described as Eq. (3c).

$$p_c = E_c A_c (1 - D)/(E_c A_c \eta + E_s A_s D) \qquad (3a)$$

$$p_s = E_c A_c D/(E_c A_c \eta + E_s A_s D) \qquad (3b)$$

$$\varepsilon_s = D(1 - \rho + \eta\rho)\varepsilon_c/(\eta - \eta\rho + \eta\rho D) \qquad (3c)$$

$$\eta = 1 - D \qquad (3d)$$

In this paper, it is assumed that crack only occur in the element where the actual strain exceeds the ultimate tensile strain. It is known that the crack width has relation with the thickness of protection layer, the spacing and strain of reinforcement. The follow formula is often used to estimate the crack width (David and Scanlon, 1986),:

$$W = 4\varepsilon_s t_e \qquad (4)$$

where W is crack width; $t_e = 0.725\sqrt[3]{Ad}$; A = 2dr; d and εs are the thickness of protection layer and strain of reinforcement respectively; r is the spacing of reinforcement.

The final crack width of one lining element at tunnel could be described as following: [12]

$$w = \frac{2.9\sqrt[3]{dA}\,(1 - \rho + \eta\rho)D\varepsilon_c}{\eta - \eta\rho + \eta\rho D} \qquad (5)$$

3. Fuzzy Inference Systems (FIS)

The fuzzy logic permits a number or object to be a member of more than one set and most importantly it establishes the notion of partial membership. A degree of membership in a set is founded on a scale from 0 to 1 with 1 equivalent to complete membership and 0 meaning no membership [13].

Fuzzy system models established relationships between input and output variables of a system by using fuzzy sets in a collection of IF-THEN rules. A generalized fuzzy inference structure has shown in Fig. 1. [14].
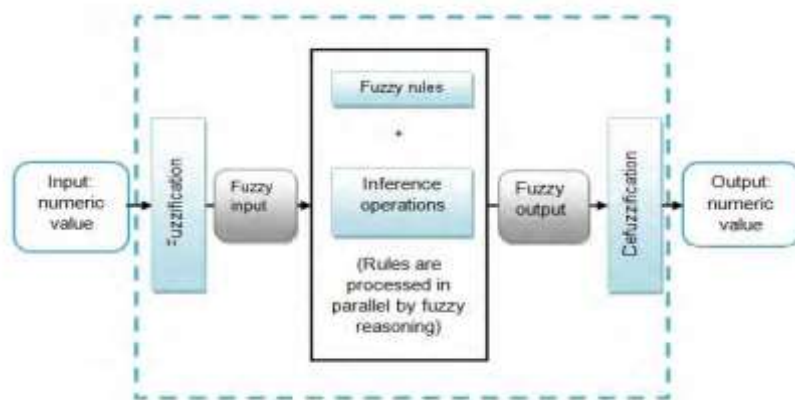

Figure (1): General design of a (FIS) structure [14].

The function of a fuzzy maximal permit crack width shows half trapezoidal distribution as follows:

$$u(w_{max}) = \begin{cases} 1 & w_{max} \leq 0.8 \\ \dfrac{w_{max} - 0.8}{3.21 - 0.8} & 0.8 < w_{max} < 3.21 \\ 0 & w_{max} \geq 3.21 \end{cases} \qquad (6)$$

The main idea of this research is based on two powerful resources: first, the rules and principles (specification) of Highway Tunnel Design manual to determine the maximum crack width of concrete tunnel lining and second, the inspections' crack data for PESHRAW Tunnel.

For this study, there are six inputs and one output according to the 1-5 equations, which used to determine the crack width. After that, designing the membership functions of all the variables will be started. For example, this output (crack width) takes quantities from [0.8, 3.2] mm. This field has been divided into three fuzzy sets such as: "Minor", "moderate" and "severe". The membership functions of "Minor" and "severe" sets are trapezoidal and the membership function of "moderate", set is triangular. These fuzzy sets are shown in Table 1. The membership functions of the crack width field are shown in Fig.2.

Table (1) Classification of crack width

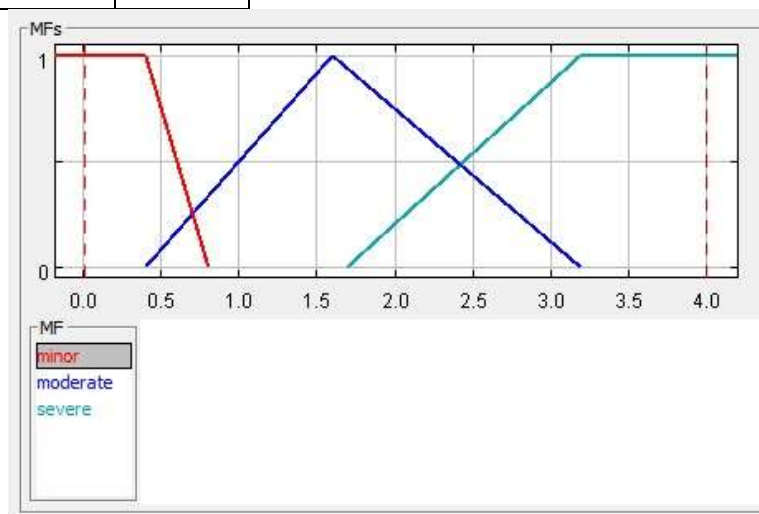| Field	Range (mm)	Fuzzy set
Crack width	<0.8	Minor
	0.8-3.2	Moderate
	3.2>	Severe

Figure (2) Member ship function of crack width.

4.Case study:

The PESHRAW tunnel was built in 2004; it's a separated tunnel, which belongs to Sulaymaniyah High way at the north of Iraq as shown in Figure 3. The length of tunnel is 2389m. The thickness of lining was 45 cm and fc=17.55mpa and the elastic modulus of concrete was 25 mpa, while the ultimate strength of the concrete was 30 Mpa. The static analysis of parameters that used to estimate crack width would be noted at table2.

The inspection of PESHRAW tunnel was to fix crack positions, length and width; therefore the inspectors divided the tunnel to many stations and elements. Cracks at tunnel are categorized to horizontal, vertical and diagonal cracks as shown in table 3.

Not all prospective cracks are actually cracks. Elements causing confusion include construction layers, an artificial mark, noise, or a blot. In this paper, has been used the quantum for the length and width of the crack. The widths of points composing each area were calculated when the region was formed from the edge. Fig.4 show example of cracks that extracted from the PESHRAW tunnel lining.
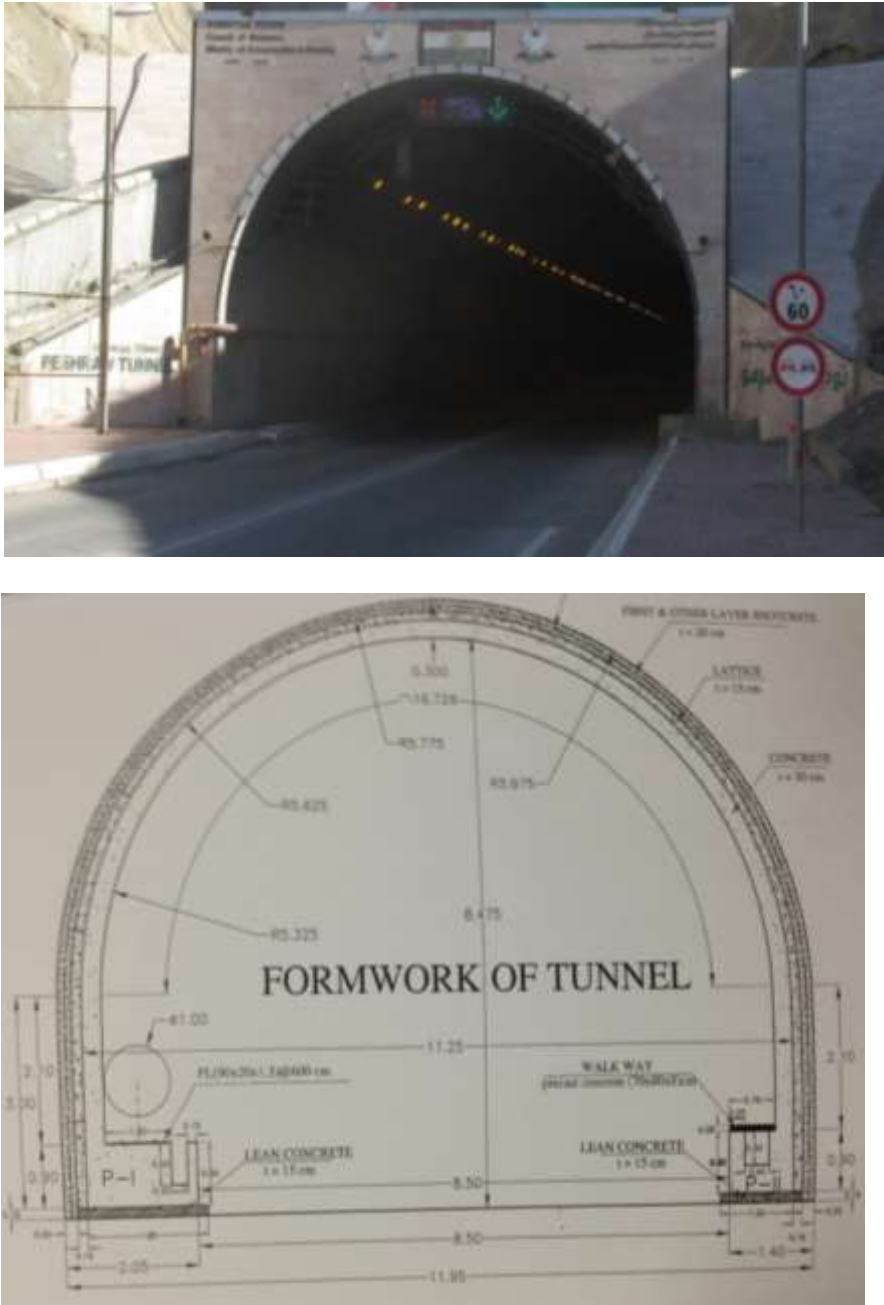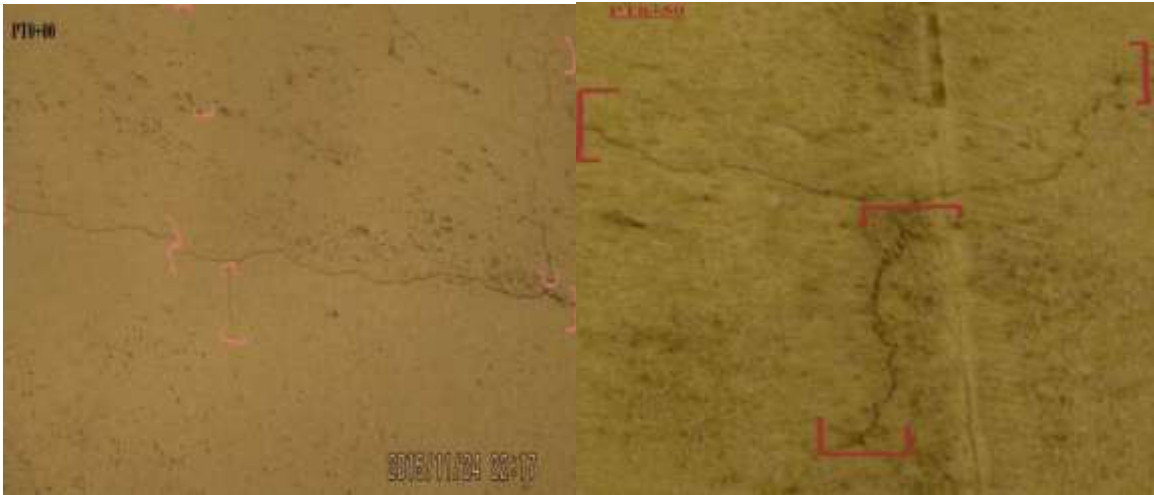
Figure (3) PESHRAW Tunnel

Figure (4) Image of cracks at PESHRAW Tunnel lining

Table (2) Statistical parameter of variable factor

Random variable	Probability distribution	Ratio of average value and normal value	Coefficient of variation
ε_D is the ultimate tensile strain of the concrete	normal	1.00	0.02
Ps is the load bear by reinforcement.	normal	1.06	0.03
ŋ = (Es/Ec) is the ratio of elastic modulus between reinforcement and concrete	normal	1.03	0.1
At = (As + Ac) is the area of reinforcement and concrete;	normal	1.04	0.3
d is the thickness of protection layer	normal	1.01	0.01
ρ = (As/At) is the reinforcement ratio	normal	1.05	0.02
εs is strain of reinforcement	normal	1.04	0.2
r is the spacing of reinforcement.	normal	1.00	0.3
ε_c is the element strain of concrete.	normal	1.06	0.2
Pc is the load bear by concrete	normal	1.02	0.3

5. System result

The user of fuzzy system interacts with the system through fuzzy sets that simplifies communication and hides much of the complexity, such as the internal structure of the rule base. FIS system interfaces employ a variety of user styles, including range of data, menu-driven, or graphics interfaces.The final decision on the system is a compromise between user needs and the requirements of specification.

The tested designed system has been shown in Table4 for specific element of tunnel. The obtained results have been compared with the results of Field data. The FIS result was based on FHWA. The average error for the predicted crack width (element sample) in FIS is 8.34%.

Table (3) Example of investigation crack data in PESHRAW tunnel.

I.D	Max.Crack width from field results	Cracks width from system results
Element PT0	2.45	2.03
Element PT10	1.67	2.9
Element PT15	1.56	1.12
Element PT30	3.5	2.3

Table(4) RESULTS OF FIS TESTING

ID	CLASS	Length(mm)	Width (mm)	Positions	
				Start st.	End st.
1	Diagonal	66.7	0.3	PT0+00.00	PT0+50.00
2	Horizontal	134.2	0.8	PT0+00.00	PT0+50.00
3	Horizontal	132.7	1.2	PT0+50.00	PT0+100.00
4	Vertical	190.1	2.1	PT0+00.00	PT0+50.00
5	Vertical	247.9	2.9	PT0+50.00	PT0+100.00

6. Conclusions

Based on the maximal permit crack formula issued in "Highway Tunnel Design Specifications", the fuzziness analysis is carried out to the crack width; the following conclusions could be drawn:

1. The permit section for maximal crack width (Wmax) with clearly boundary should be considered from ordinary set to fuzziness set, that is, the middle transition state should be expanded from gradual change to sudden change which is between inefficiency and reliability.

2. When the maximal permit crack width as example is chosen as 0.7mm, 1.2mm and 3.3mm separately the fuzziness set accordingly is Minor , moderate and severe.

3. In this built fuzzy evaluation model, the assessment parameters are based on the information of a real in-service PESHRAW highway tunnel, which reflect its field status. therefore, this evaluation is comfortable.

4. In this fuzzy evaluation model, the membership function and membership value of each single factor attach great importance to results. It also needs to improve in engineering application for achieving more reasonable and reliable evaluation results.

Acknowledgment

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