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Durability Evaluation System of Aged Water Supply Pipes

Système d'évaluation de la durabilité d'anciennes conduites d'eau

Ermittlung der Dauerhaftigkeit gealterter Wasserversorgungsleitungen

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SUMMARY
The durability of cast iron water supply pipes is affected not only by service duration, but also by corrosion environment, wheel loads due to traffics, etc. This paper proposes a two-step procedure to evaluate the durability of small diameter cast iron pipes for establishing reasonable replacement criterion. The first step uses fuzzy sets theory to combine expert knowledge with a statistical model. It can be used for the first screening of less durable pipe links. The second step is based on a series of investigation, analysis and experiment and can be used for detailed evaluation.

RÉSUMÉ
La durabilité des canalisations en fonte pour l'approvisionnement en eau est influencée non seulement par la durée d'utilisation, mais encore par l'atmosphère corrosive, les charges mobiles de véhicules du trafic routier, etc. Afin d'apprécier la durabilité des tubes de petit diamètre d'une conduite d'approvisionnement en eau, cet article propose un procédé en deux phases afin de fournir un critère raisonnable de remplacement. Dans la première phase, la connaissance d'experts est combinée à un modèle statique, à partir de la théorie des ensembles flous; ceci permet de découvrir les raccords de tubes laissant le plus à désirer. Pour une appréciation plus approfondie, la seconde phase se base sur des investigations en série, avec calculs et essais à l'appui.

ZUSAMMENFASSUNG
Die Dauerhaftigkeit gusseiserner Wasserversorgungsrohre ist nicht nur durch die Nutzungsdauer, sondern auch durch korrosive Atmosphäre, Verkehrsradlasten usw. beeinflusst. Der Beitrag schlägt zur Beurteilung der Dauerhaftigkeit von Rohren kleinen Durchmessers ein zweistufiges Vorgehen vor, mit dem sich ein vernünftiges Kriterium für den Auswechselbedarf aufstellen lässt. Im ersten Schritt wird mittels Fuzzy-Set-Theorie Expertenwissen mit einem statischen Modell verknüpft, um in einem ersten Durchgang die anfälligeren Rohverbindungen zu sichten. Für die genauereAuswertung werden in einem zweiten Schritt Reihenuntersuchungen mit Berechnungen und Experimenten vorgenommen.

1. INTRODUCTION

Water supply pipes (WSP) were first installed in Japan about a century ago and have extended about 8000 km even in Nagoya City, a major city with 2 million inhabitants. Especially in 1950s and 1960s large amounts of cast iron pipes were installed. The design life of these pipes was 38 years and quite a few breaks occurred in them recently. In order to ensure better serviceability it becomes urgent nowadays to replace them year by year based on their durability.

The durability of cast iron WSP is affected not only by service duration, but also by corrosion environment, wheel loads due to traffics etc., as shown in Fig.1. Unlike such structures as bridges, visual inspection is impossible when their durability is evaluated. In the past, mainly three approaches have been adopted in the evaluation, i.e. descriptive analysis, predictive analysis and physical analysis [1]. The descriptive analysis is to analyze the frequency and pattern of pipe breaks and it can hardly consider several influential factors simultaneously. The predictive analysis uses statistical method to build evaluation model, but it is not easy to determine the contributing factors and to obtain the corresponding data. The physical analysis employs engineering-based algorithm and it gives more reliable measure, provided that the failure mechanism is clearly understood and the related factors are easily evaluated.

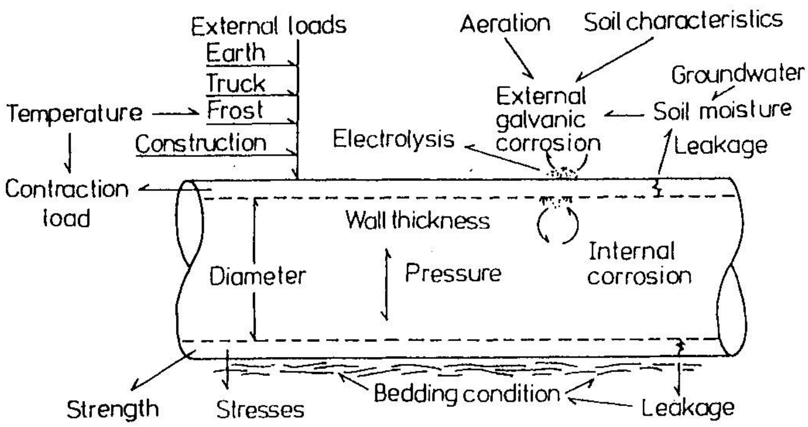

Fig.1 Conceptual model of structural condition of cast iron WSP [1]

This paper proposes a two-step procedure to evaluate the durability of small diameter (less than 400 mm) cast iron WSP. In the first step, fuzzy sets theory is applied to combine the experts' knowledge on corrosion environment factors with a statistical evaluation model. This step requires only qualitative information and can be used for the first screening of less durable pipe links. The second step uses the approach of physical analyses and is based on a series of sampling investigation, stress analysis and experiment. It can be used for detailed evaluation.

2. THE FIRST STEP - A PREDICTIVE MODEL USING FUZZY SETS THEORY

2.1 General

In 1984, the Japanese Ministry of Health and Welfare organized a nationwide sampling survey on aged WSP. An evaluation model called Model 4-7 was built from the data on 912 pipe links, half of which had not experienced breaking and the other half broke seemingly due to non-corrosion reasons [3]. The quantification theory was used to build the model and the objective was selected as whether a break has occurred in the pipe link. The factors included in the model are type of material and joint, diameter, depth of earth covering, traffic of large vehicles, maximum hydraulic pressure and service duration, and corrosion environment factors were excluded. The model showed a correct evaluation rate of 72.1 percent on the 912 sample pipe links.

In this step, first we assume that the influence of those factors can be evaluated by the Model 4-7, then we try to combine the influence of corrosion environment with it in order to obtain a general model. This approach is justified because we can avoid the expensive and difficult process to consider corrosion environment factors in a statistical model [3].

Through an extensive literature survey, we distinguished the environmental factors that influence the corrosion of small diameter cast iron WSP as shown in Fig.2 [4]. It is difficult to evaluate these factors quantitatively, but it seems possible for a site technician to evaluate them qualitatively by using specified vocabularies according to a guideline. Besides, the weight of 6 parallel factors (i.e. aeration difference along the pipe link, nonhomogeneity of backfill, stray current, bi-metallic corrosivity, concrete/soil corrosivity, corrosivity of water) may be evaluated by experts. In order to take advantage of this, we decided to use fuzzy sets theory.

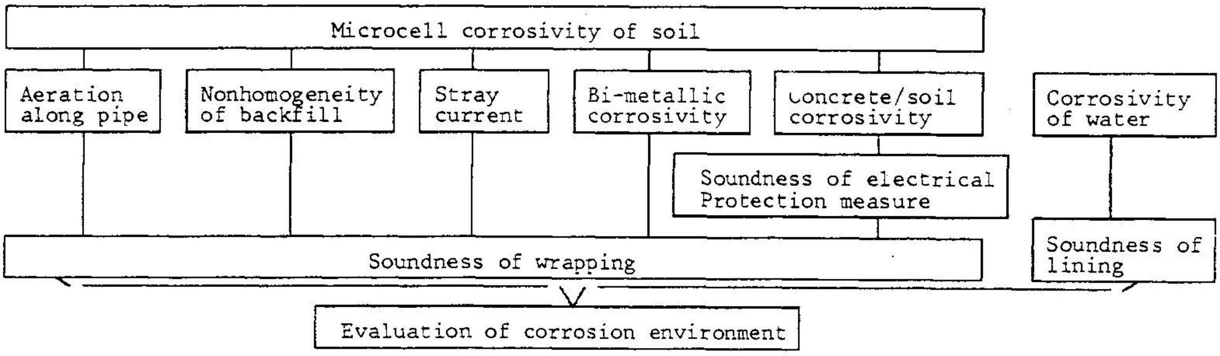

Fig.2 The conceptual structure of corrosion environment factors

In the study, engineers in Nagoya City Waterworks Bureau who had worked for 10 to 32 years with field work experience ranging from 2 to 24 years served as experts. The vocabularies used for evaluation were selected and their membership functions were evaluated as shown in Fig.3. Then the experts used

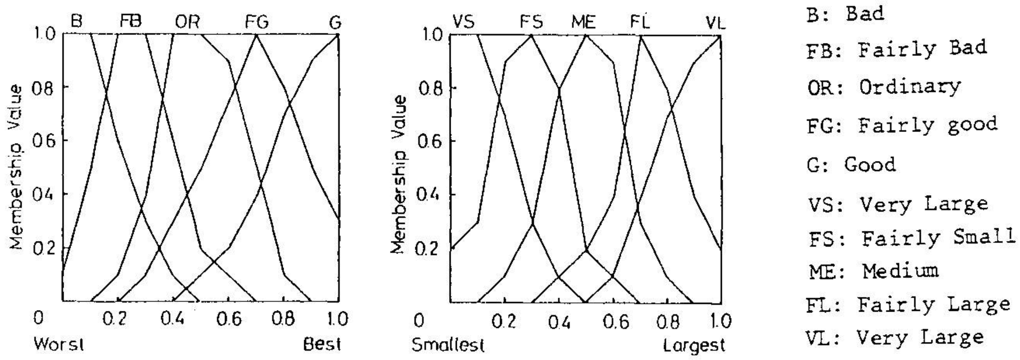

Fig.3 Membership functions of evaluation vacabularies

them to evaluate the weight of the six parallel factors. The results are shown in Fig.4.

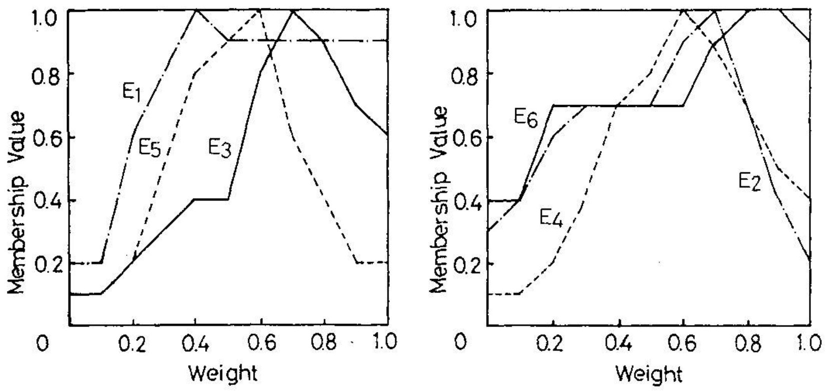

Fig.4 Weight of corrosion environment factors

2.2 The predictive model

In order to evaluate the severeness of corrosion environment of pipes based on Fig.2, the following equation is used.

$$P = P_a \oplus P_b \quad (1)$$

where

$$P_a = (\neg T_2) \cap \{ [\bigcup_{i=1}^{4} (S_i \cap E_i)] \cup [S_5 \cap E_5 \cap (\neg T_1)] \} \cap S_0$$

$$P_b = E_6 \cap S_6 \cap (\neg T_3)$$

The sizes S_0 to S_6, T_1 to T_3 and the weights E_1 to E_6 are explained in Table 1 and they are all fuzzy sets. The symbols $\neg$, $\cap$ and $\cup$ indicate supplement, interaction and union, respectively. The symbol $\oplus$ is the algebraic sum. The support of the fuzzy sets takes values of 0, 0.1, 0.2, to 1.

Table 1 Corrosion environment factors

No.	Factors	Weight	Size
1	Aeration difference along pipe link	E_1	S_1
2	Nonhomogeneity of backfill	E_2	S_2
3	Stray current	E_3	S_3
4	Bi-metallic corrosivity	E_4	S_4
5	Concrete/soil corrosivity	E_5	S_5
6	Corrosivity of water	E_6	S_6
7	Microcell Corrosivity of soil	-	S_0
8	Soundness of electrical corrosion protection measure	-	T_1
9	Soundness of wrapping	-	T_2
10	Soundness of lining	-	T_3

The result of durability evaluation Q that includes the influence of corrosion environment is computed by using fuzzy composition as follows.

$$Q = P \circ R \quad (2)$$

where R is the fuzzy relation obtained by trial-and-error method based on the result of a field survey that the experts took part in. In the field survey, 14 pipe links in various corrosion environment were selected, and the experts evaluated the corrosion environment factors and the durability rank of each pipe link. In the present model, R is adopted as shown in Table 2 and corresponds to the following meaning.

If P is very small, then Q is small;
If P is ordinary, then Q is medium;

If P is fairly large, then Q is large.
Q has the following form, and the values of Q as "small", "medium" and "large" were defined after Brown [5].

$$Q = a_1/L_o + a_2/(L_o-1) + a_3/(L_o-2) + a_4/(L_o-3) \quad (3)$$

where L_o is the rank obtained by using the Model 4-7.

Table 2 Fuzzy relation for cast iron WSP

	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
Lo	1	1	0.7	0.3	0.5	0.5	0.5	0.3	0.2	0.2	0.2
Lo-1	0.5	0.5	0.5	0.3	0.5	0.5	0.6	0.6	0.6	0.4	0.2
Lo-2	0.2	0.2	0.2	0.3	0.5	0.5	0.7	0.8	0.8	0.4	0.2
Lo-3	0	0	0.1	0.3	0.5	0.5	0.7	1	0.8	0.4	0.2

The durability rank is obtained by deffuzzifying Q using the gravity center method.

$$L = \left[\sum_{i=1}^{m} (L_o-i+1) \cdot \mu_Q(L_o-i+1)\right] \Big/ \left[\sum_{i=1}^{m} \mu_Q(L_o-i+1)\right] \quad (4)$$

where m equals to L_o if $L_o \le 4$, 4 otherwise.

The results of evaluation on the 14 pipe links by the Model 4-7 and the present model are shown in Table 3. The present model showed a different rank with the Model 4-7 and is closer to the average durability rank evaluated by the experts. Moreover, prediction by using each expert's evaluation on the corrosion environment factors varies within one rank.

Table 3 Durability rank of 14 pipe links

Item \ Sample No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Average evaluation by experts	4	3	3	3	2	2	3	3	4	4	3	3	3	3
Prediction by the Model 4-7	5	5	5	5	5	5	5	5	5	4	5	5	2	4
Prediction by average expert	3	4	3	3	3	3	4	3	4	3	3	3	2	2
Prediction by expert A	-	4	3	3	3	3	3	3	3	2	4	4	1	2
B	3	4	4	4	3	4	4	4	4	3	4	4	1	2
C	3	3	3	-	-	-	-	3	4	3	3	3	1	2
D	3	4	3	3	3	4	4	3	3	3	3	3	2	2
E	-	3	3	-	-	-	-	-	-	-	-	-	-	-

3. THE SECOND STEP - A PHYSICAL MODEL BASED ON FAILURE MECHANISM

3.1 The failure mechanism of small diameter cast iron WSP [6]

According to the break records in Nagoya City, about 91 percent of the breaks in small diameter cast iron WSP were due to circumferential cracks. In order to clarify the failure mechanism, we carried out a series of investigation, analysis and experiment as stated below.

(1) Sample investigation
Eighty nine pipe links in Nagoya City were randomly selected for detailed investigation. For each pipe link, a 1 m long sample pipe was excavated and a 15 cm long part of it was sand-blasted for the measurement of corrosion pits. The statistical theory of extreme values was used to compute the pipe length of having a through-wall pit [7].

(2) Stress analysis considering local soft and hard foundation
According to Takagi et al., the static strain in the axial direction of pipes

under wheel loads, which contributes to the circumferential crack, may be obtained by considering the pipe link as a beam on elastic foundation [8]. Using the method, we carried out a parametric analysis on a pipe link of 100 mm diameter to examine the static strains under various influential factors. In the analysis, local hard and soft foundation were considered; the former simulates a rock, concrete block or other cross pipes in the bedding, and the latter considers local washing caused by water leakage.

(3) Test of installed small diameter pipes under dynamic loading
The dynamic effect of wheel loading depends on many factors and it is very difficult to be evaluated analytically. In the study, we installed 100 mm diameter ductile iron pipes in a depth of 0.8 m and measured the strains under three modes of dynamic loading (normal rolling, braking and bumping), as well as under static loading of a dump truck. The dynamic effect on the strain of pipes were evaluated by the impact factor β defined as follows.

$$\beta = \varepsilon / \varepsilon_{st} \tag{5}$$

where ε_{st} is the strain under static loading and ε is the corresponding strain under dynamic loading. Both are the axial strain of pipes.

(4) Bending fatigue test of aged cast iron pipes
It was known from the above that the strain comparable to the ultimate strain of pipe material may occur only under the combination of extremely severe conditions for each influential factor. However, pipes that do not have such combination actually broke occasionally. So we suspect that fatigue is the cause of such failure. Thus we carried out bending fatigue tests on 13 aged pipes of 100 mm diameter, which were in service for 19 to 40 years. The test results were compared with the previous ones on the new material of pipes by Kusafuka et al. [9].

3.2 The physical model

Corresponding to the static failure and fatigue failure of small diameter cast iron WSP, two limit states may be defined, i.e. static limit state and fatigue limit state.

For the static limit state, we define a ratio D_1 as shown below.

$$D_1 = \varepsilon_{cs} / \varepsilon_s \tag{6}$$

where ε_{cs} is the static strength of cast iron WSP and ε_s the possible maximum strain in the pipe link. In this study, we use ε_{cs} as 1730 μ which is obtained by dividing the strength by the elastic modulus of cast iron.

For the fatigue limit state, we define a ratio D_2 as follows.

$$D_2 = \Delta\sigma_{cf} / (E \cdot \Delta\varepsilon_f) \tag{7}$$

where $\Delta\sigma_{cf}$ is the fatigue strength of cast iron WSP and $\Delta\varepsilon_f$ the possible maximum nominal strain range in the pipe link. In the above-mentioned experiment, we obtained the S-N diagram as shown in Fig.5. The fatigue strength corresponding to 2 million cycles is about 30 MPa with the average survice duration of 33 years. It is obvious that the slope of the S-N diagram is very small compared to that of structural steel. This phenomenon is also observed in the previous experiment on new pipe material. Based on these results, we adopt $\Delta\sigma_{cf}$ as the fatigue strength corresponding to 2 million cycles and assume that it varies with the service duration as shown in Fig.6, in which the influence of the stress concentration due to corrosion pits is included.

Although 2 million cycles are assumed, the pipes may fail after a much smaller number of cycles because of the small slope of S-N diagram and the scatter in fatigue strength.

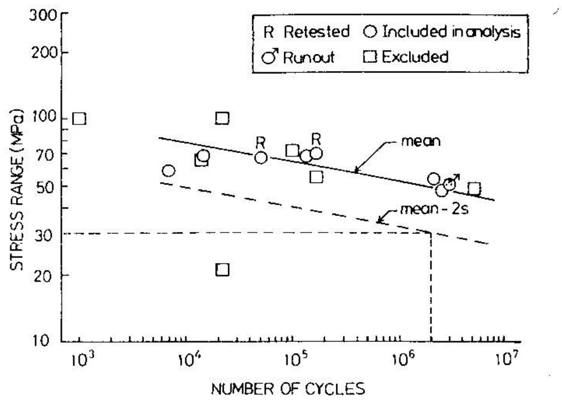

Fig.5 S-N diagram of 13 aged cast iron WSP

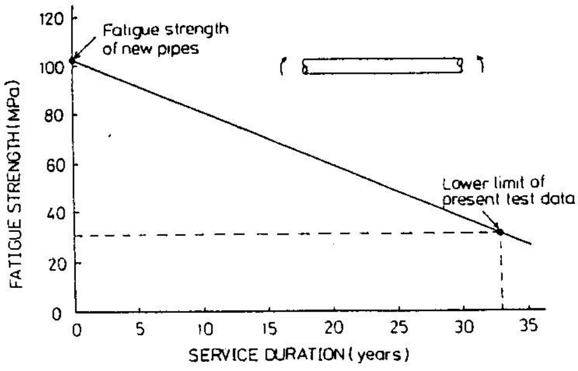

Fig.6 Assumed fatigue strength reduction of cast iron WSP with service duration

Here, ε_s and $\Delta\varepsilon_f$ can be computed as follows.

$$\varepsilon_s = \alpha(\beta \cdot \varepsilon_0 + \varepsilon_i) \quad (8)$$

$$\Delta\varepsilon_f = \beta \cdot \varepsilon_0 \quad (9)$$

where ε_i is the initial strain in the pipes due to installation and temperature change, ε_0 is the possible maximum static strain caused by wheel load, β is the impact factor, and α is the stress concentration factor caused by internal corrosion pits. By assuming that the internal corrosion pits have the shape of half sphere, which is conservative for most of the corrosion pits, α may be obtained [10].

The durability ratio D of the pipe link is assumed to be the smaller value between D_1 and D_2, i.e.

$$D = \min(D_1, D_2) \quad (10)$$

It is noted that the larger is D, the more durable is the pipe link, and that the pipe link is susceptible to failure when its D is smaller than 1.

The flow chart for using the physical model is shown in Fig.7. The major factors are evaluated by using the knowledge we obtained in the study.

4. EXAMPLES

4.1 Example of using the predictive model

A pipe link is in the condition as shown in Table 4. Its durability is evaluated by using the predictive model.

(1) Prediction by using the Model 4-7
The detail is described elsewhere [2]. We obtain L_0 = 5.

(2) Computation of P
The severeness of corrosion environment P is computed by using Eq.1, as shown in Table 5.

(3) Computation of the durability rank

By using Eq.2, we obtain the result of durability evaluation Q as a fuzzy set.

$$Q = 0.7/5 + 0.5/4 + 0.5/3 + 0.5/2$$

Then by using Eq.4, we get the durability rank L.

$$L = (5X0.7 + 4X0.5 + 3X0.5 + 2X0.5)/(0.7 + 0.5 + 0.5 + 0.5) = 4$$

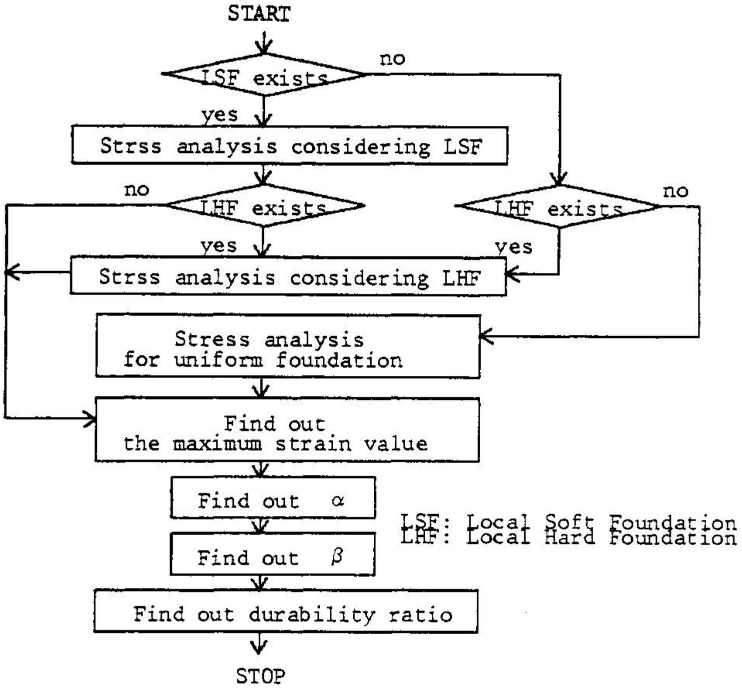

Fig.7 Flow chart for evaluating the durability of a pipe link using the physical model

Table 4 Condition of a pipe link

Item	Value	Item	Value	Item	Value
Type of material and joint	CIP-M*	S_0	Medium	S_6	Fairly Small
Diameter (mm)	75	S_1	Fairly Small	T_1	Trivial
Depth of earth covering (m)	1.2	S_2	〃	T_2	Bad
Traffic of large vehicles	None	S_3	Trivial	T_3	Ordinary
Maximum hydraulic pressure (N/cm^2)	34.3	S_4	Very Small		
Service duration (years)	19	S_5	Very Small		

* CIP-M indicates cast iron pipes with mechnical joints

4.2 Examples of using the physical model

Seven pipe links in Nagoya City are evaluated by using the physical model. The conditions for evaluation and the evaluation process are shown in Table 6. The resulted durability ratio is between 0.55 and 1.81 depending on the severeness of static and fatigue loading condition, and the combination of various factors jointly affected the durability.

This model should be further verified by comparing the evaluation results with the reality. However, the influential factors considered here seems to be plausible in the detailed evaluation on the durability of small diameter cast iron WSP.

Table 5 Computation of P

Item \ SM*	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	Note
S_1	0.2	0.3	0.9	1	0.8	0.2	0.1	0	0	0	0	FS
E_1	0.2	0.2	0.6	0.8	1	0.9	0.9	0.9	0.9	0.9	0.9	
$P_1=S_1\cap E_1$	0.2	0.2	0.6	0.8	0.8	0.2	0.1	0	0	0	0	
S_2	0.2	0.3	0.9	1	0.8	0.2	0.1	0	0	0	0	FS
E_2	0.3	0.4	0.6	0.7	0.7	0.7	0.9	1	0.7	0.4	0.2	
$P_2=S_2\cap E_2$	0.2	0.3	0.6	0.7	0.7	0.2	0.1	0	0	0	0	
S_3	0	0	0	0	0	0	0	0	0	0	0	TR
E_3	0.1	0.1	0.2	0.3	0.4	0.4	0.8	1	0.9	0.7	0.6	
$P_3=S_3\cap E_3$	0	0	0	0	0	0	0	0	0	0	0	
S_4	1	1	0.7	0.3	0.1	0	0	0	0	0	0	VS
E_4	0.1	0.1	0.2	0.3	0.4	0.4	0.8	1	0.9	0.7	0.6	
$P_4=S_4\cap E_4$	0.1	0.1	0.2	0.3	0.1	0	0	0	0	0	0	
S_5	1	1	0.7	0.3	0.1	0	0	0	0	0	0	VS
E_5	0.1	0.1	0.2	0.5	0.8	0.9	1	0.6	0.4	0.2	0.2	
$\neg T_1$	1	1	1	1	1	1	1	1	1	1	1	$\neg$TR
$P_5=S_5\cap E_5\cap(\neg T_1)$	0.1	0.1	0.2	0.3	0.1	0	0	0	0	0	0	
S_0	0	0	0.1	0.3	0.8	1	0.9	0.3	0.1	0	0	M
$P_0=S_0\cap(\cup P_i)$	0	0	0.1	0.3	0.8	0.2	0.1	0	0	0	0	
$\neg T_2$	0	0	0.4	0.7	0.9	1	1	1	1	1	1	$\neg$B
$P_a=P_0\cap(\neg T_2)$	0	0	0.1	0.3	0.8	0.2	0.1	0	0	0	0	
S_6	0.2	0.3	0.9	1	0.8	0.2	0.1	0	0	0	0	FS
E_6	0.4	0.4	0.7	0.7	0.7	0.7	0.7	0.9	1	1	0.9	
$\neg T_3$	1	1	0.9	0.6	0	0	0.1	0.7	0.9	1	1	$\neg$OR
$P_b=S_6\cap E_6\cap(\neg T_3)$	0.2	0.3	0.7	0.7	0.2	0	0.1	0	0	0	0	
$P=P_a\oplus P_b$	0.2	0.3	0.7	0.8	0.8	0.2	0.2	0	0	0	0	

* SM indicates support of membership function.

Table 6 Examples of using the physical model

Item \ Sample No.	1	2	3	4	5	6	7
· Diameter (mm)	100	100	100	100	100	100	100
· Joint type	S	S	S	S	S	S	S
· Depth (m)	0.7	0.9	1.3	0.7	0.8	0.7	0.9
· Service duration (years)	36	29	28	30	28	30	32
· t_e (years)	36	12	20	18	19	21	27
1) t (mm)	7.5	9.0	9.0	7.5	7.5	7.5	7.5
Pipe length (m)	4.0	4.0	4.0	4.0	4.0	4.0	4.0
2) Soil type	sand	sand	sand	sand	silt	silt	silt
N value	28	1	4	15	4	3	2
Reaction coefficient (N/cm^3)	186.2	9.8	33.3	105.8	33.3	25.5	17.7
3) Length of LSF (m)	0	0	0	0	0	3.0	0
4) Length of LHF (m)	0.2	0.2	0.2	0.2	0.2	0.2	0.2
5) Road condition	VN	P	VR	P	VN	VN	VR
6) Maximum weight of trucks (kN)	196	196	196	196	196	196	196
· ε_1 (μ)	400	400	400	400	400	400	400
· ε_0 (μ)	83	114	56	83	103	305	116
· $b/t = 0.83 \cdot t_e^{0.56}$	0.83	0.37	0.49	0.56	0.57	0.61	0.71
· α	3.0	2.1	2.1	1.0	2.2	2.2	2.4
· β	2.0	2.0	1.0	3.0	1.0	2.0	3.0
· $\varepsilon_s = \alpha(\beta \cdot \varepsilon_0 + \varepsilon_1)$ (μ)	1689	1318	957	1427	1106	2323	1795
· $\Delta\varepsilon_f = \beta \cdot \varepsilon_0$ (μ)	166	228	56	249	103	610	348
· $\Delta\sigma_{cf}$ (MPa)	29.4	35.8	37.2	36.3	37.2	36.3	33.3
$D_1 = \varepsilon_{cs}/\varepsilon_s$	1.02	1.31	1.81	1.21	1.56	0.75	0.96
$D_2 = \Delta\sigma_{cf}/(E \cdot \Delta\varepsilon_f)$	1.64	1.46	6.17	1.35	3.35	0.55	0.89
D (Durability ratio)	1.02	1.31	1.81	1.21	1.56	0.55	0.89

Note. S: socket joint VN: no repair of pavement VR: repaired pavement P: pedestrian t_e: duration before lining t: nominal wall thickness E = 10.8 N/cm^2

5. SUMMARY

In the study, the authors proposed a two-step procedure for evaluating the durability of small diameter cast iron WSP based on a series of investigation, analysis and experiment. The following summarizes the main findings.

1) As the first step, a predictive model that combines a statistical evaluation model and experts' knowledge was proposed. This model makes it easy to include the corrosion environment factors and can be used for the first screening of the pipe links that are less durable.

2) Small diameter cast iron WSP break mainly as a result of static failure or fatigue failure. The major influential factors are service duration, bedding condition, surface condition of road, wheel loads, stress concentration caused by internal corrosion pit, reduction in fatigue strength, etc.

3) As the second step, a physical model based on static limit state and the fatigue limit state was proposed. This model includes the knowledge that we obtained from a series of investigation, analysis and experiment, and can be used for detailed evaluation on the durability of small diameter cast iron WSP.

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