DEVELOPMENT OF INSPECTION ROBOTS FOR HEADRACE TUNNELS

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SUMMARY

This paper describes an expert system with thinking and judgement abilities equivalent to human intelligence for use in developing an inspection robot for headrace tunnels. The significance of this system is that, based on data obtained by the inspection robot, it obtains the relationship between load conditions acting on the headrace tunnel and the stress that causes cracking in the lining concrete from the lining strength, and then judges the stability of the structure quantitatively.

1. HEADRACE TUNNEL INSPECTION SYSTEM

The inspection system described in this paper is able to balance the remaining life of the structure, the economic effect, and the cost of the inspection. For that purpose it is structured into two parts: the initial inspection and the detailed inspection.

Initial inspection means inspection and judgement with simple inspection tools (crack scale, hammer, etc.) and visual observation, while detailed inspection means adding the condition of the structure, the service environment, and service condition to these results of the initial inspection. (Figure 1 shows the overall procedure.)

2. INITIAL INSPECTION

Initial inspection should be quick and in depth. Care must be taken with inspection items that are structurally and functionally very important to the headrace tunnel, and it is necessary to provide as many qualitative judgement standards as possible so as to minimize differences in judgements between inspectors.

The inspection items and the inspection details were narrowed down as shown in the examples based on the results of investigation of the inspection examples and repair examples in the past were narrowed down as shown in Table 1. Tables 2 through 5 show the judgement standards and details by inspection item, taking cracking as an example.

3. DETAILED INSPECTION

The detailed inspection is based on the results of the initial inspection. A detailed inspection is carried out of items that are judged to be "level A" in terms of cracking, peeling and breaking away, and deformation and difference in level of the initial inspection items. (Scouring symptoms have little structural and functional effect on the tunnel, so judgement is based only on the initial inspection).

The yield strength of the headrace tunnel lining is affected by natural conditions including topography and geology, as well as design and constructional factors including the cross-section of the lining, its shape, rear cavities, the strength of the lining, and its thickness, etc., and although there are complex relationships between these factors, judgement during the detailed inspection is based on the load acting on the tunnel lining, the stress or yield strength of the lining based on geological data, the earth covering, the presence of cavities, the concrete strength, and the thickness of the lining.

Of these, rear cavities and the lining thickness take time and effort to elucidate, so it is important to mechanize inspections and carry them out regularly and efficiently. An inspection robot, or similar is an ideal way to do this.

The system developed here aims to offer quantitative judgement standards at the time of the detailed inspection. (Fig. 2 shows the overall procedure for the detailed inspection.)

Table 1 Details of inspection

Inspection item	Contents	Method by inspection	Remarks
Cracking	. Direction . Width . Length . Number	. Visual observation . Check by chipping . Cracking scale, . Clearance gauge	. Object in traversal and longitudinal directions with the width larger than 1 mm
Stripping and breaking away	. Area . Depth	. Visual observation . Scale, measure	. Object at arch and side walls
Abrasion and scouring	. Area . Depth	. Visual observation . Scale, measure	. Object at invert with the depth of more than 5 cm
Deformation and differential in level	Area Deformation amount	. Visual observation . Levelling . Collimation	. Object with cracking

Table 2 Inspection items and details

Inspection item	Contents
Width	1) Wider than 2 mm 2) Between 1 and 2 mm 3) Narrower than 1 mm
Length	1) Longer than 3 m 2) Shorter than 3 mm
Number	1) More than 3 2) Fewer than 2

Table 3 Details of judgement

Length, width	Longer than 2 mm	1 mm to 2 mm	Shorter than 1 mm
Wider than 3 mm	(A)	(B)	(D)
Wider than 3 mm	(B)	(C)	(D)

Table 4 Judgment standards

Number, area	(A)	(B)	(C)	(D)
More than 3	A	A	B	C
Fewer than 2	A	B	C	C

Table 5 Judgement results

Judgement level	Contents
A	Judgement as to whether detailed inspection is needed or not.
B	Judgement as to whether repair is needed or not
C	Leave it as it is.

(1) Geology

The problems presented by ground pressure, where loosened ground pressure, plastic pressure, etc., act on the tunnel lining, are that the unit strength of the bedrock, the physical properties of the bedrock (modulus of deformation, Poisson's ratio, cohesion, internal friction), etc., are greatly affected by it.

In this report, the relationship between geological conditions and primary ground pressure is classified according to the unit strength of the bedrock. And relative yield strength of the lining is evaluated based on a unit strength of bedrock of 2 as standard.

(Table 6 shows the relationship between bedrock strength ratio and yield strength of the lining with the tunnel configuration: D = H = 3.0 m, soil condition: C = 5 kgf/cm, ϕ = 30 as an example.)

Table 6 Relationship between unit strength of bedrock and yield strength of lining

G	2.0	1.0	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2
σrp	0	4.23	5.31	6.43	8.07	10.05	12.96	17.26	24.61	38.76
Loosened ground pressure	2.83									
Working load	2.8P	4.2P	5.3P	6.4P	8.1P	10.1P	13.0P	17.3P	24.6P	38.8P
Yield strength	1.0	0.67	0.53	0.44	0.35	0.28	0.22	0.16	0.11	0.07

1) Calculation of plastic ground pressure

$\sigma c/\sigma V = \sigma c/\gamma h = G$

where, σc: unconfined compression strength of core

σV: pressure due to earth covering

G: units strength of bedrock

$$\sigma rp = \frac{\sigma gd}{\varepsilon-1}\left[\left(\frac{r}{ra}\right)^{\varepsilon-1}-1\right]$$

$$ro = ra\left[\frac{2}{\varepsilon+1}\cdot\frac{P(\varepsilon-1)+\sigma gd}{\sigma gd}\right]^{1/\varepsilon-1}$$

$$\varepsilon = (1+\sin\phi)/(1-\sin\phi)$$

where, σrp: stress in the radial direction in plastic domain

ra: radius of tunnel

ro: distance of plastic domain and elastic domain from tunnel center

P: Primary stress

σgd: unconfined compression strength of bedrock

ε: passive earth pressure coefficient

2) Calculation of loosened ground pressure

$$R = 0.015(D+H)(6.0-v\frac{v}{V})^2 \quad : \text{in the case of blasting}$$

$$R = 0.006(D+H)(6.0-v\frac{v}{V})^2 \quad : \text{in the case of TBM}$$

$$R = 0.06(6.0-V\frac{v}{V}) \quad : \text{in the case of mechanical}$$

where, D: excavated width of tunnel (m)
H: excavated height of tunnel (m)
v: elastic wave velocity in bedrock (km/sec)
V: elastic wave velocity in sample (km/sec)

(2) Earth covering

Where the earth covering over the tunnel is shallow, the balance of the grand arch formed is broken, subjecting the tunnel to excessive load. To retain the balance of the internal stress within the bedrock, sufficient earth covering is required.

In this report, the extent of the plastic domain is assumed from the stress distribution around the tunnel, and this is used to derive the working load. The relative yield strength of the lining is derived by taking an earth covering of 5D as standard.

1) Calculation of plastic ground pressure

The relationship between elastic wave velocity and the loosened domain is obtained from the following equation: (Table 7 shows the relationship between earth covering and yield strength of the lining where D = H = 3.0 m, V = 4.2 km/sec, V/V1 = 0.6.)

$$R = \{0.3(D + H) + 3.0\} \times \sqrt{1.5 - X}$$

$$X = v\frac{V}{V_1}(\frac{1}{\text{Log } h})$$

where, D: excavated diameter of tunnel
H: excavated height of tunnel
V: elastic wave velocity shattered zone and soft rock (low velocity zone) in bedrock
V1: elastic wave velocity in sound bedrock surrounding shattered zone and soft rock (low velocity zone)
h: thickness of earth covering

Table 7 Relationship between earth covering and yield strength of lining:

Earth covering	2D	3D	4D	5D	6D	7D	8D	9D	10D	20D
Plastic domain	6.0m	9.0m	12.0m	3.6m	3.8m	3.9m	4.0m	4.1m	4.2m	4.5m
Working load	6.0γ	9.0γ	12.0γ	3.6γ	3.8γ	3.9γ	4.0γ	4.1γ	4.2γ	4.5γ
Yield strength	0.60	0.40	0.30	1.0	0.94	0.93	0.90	0.88	0.85	0.80

(3) Cavities behind lining

A cavity prevents the reaction force (passive earth pressure) being transmitted from the bedrock. Therefore, the reaction force differs depending on the size of the cavity, greatly affecting the stability of the tunnel.

In this report, the stress caused by this is derived under the conditions listed below (refer to Table 8). It is evaluated by obtaining the relative stress condition with regard to compression stress that affects the stability of the tunnel with the case where the cavity in the rear is most likely to occur from the viewpoint of lining work (Case F2) as standard.

(The results are shown in Table 9, and while Fig. 3 shows the conditions under which cracks are generated.)

(4) Concrete strength

The strength value of the lining concrete, though low in deteriorated sections, is based on the quality of the concrete as a whole.

The tensile strength of concrete can generally be judged by its compressive strength where it has been produced by appropriate methods. In this report compressive strength is evaluated as a relative tensile strength based on the yield strength ratio where a compressive strength of 180 kgf/cm^2 at the age of 28 days is taken as standard. (Refer to Table 10.)

$\sigma ca \leqq ftk/7 \leqq 3 kgf/cm^2$
$\sigma ca \leqq fck/80$

(5) Lining thickness

As the relative size of lining thickness determines the magnitude of stress caused, it greatly affects the yield strength of lining. In this paper the evaluation is performed with the relative lining thickness against the standard lining thickness (refer to Table 11) as a yield strength.

Table 8 Studied cases on cavities behind lining

1. Structural conditions
   1) 2R horse shoe type
   2) Thickness of concrete arch and side wall sections (0.3 m)
   3) Thickness of concrete invert section (0.5 m)
   4) Side wall and invert are joined by pins on each side

2. Load conditions
   1) Arch and invert section (10 t/m^2)
   2) Side wall section (5 t/m^2)

Table 9 Stress intensity ratio for cavities

	Case	M(max) :tm/m	N(max) :t/m	σ(max):kg/cm^2 Outside	σ(max):kg/cm^2 Inside	Stress intensity ratio Outside	Stress intensity ratio Inside
Arch section	F1	6.519 -7.107	- 7.757 -16.753	46.1 -41.8	-40.9 53.0	0.48	0.54
	F2	2.898 -3.687	- 8.085 -12.482	22.0 -20.4	-16.6 28.8	1.00	1.00
	F3	2.130 -2.569	-10.361 -13.495	17.7 -12.6	-10.7 21.6	1.24	1.33
	F4	2.941 -3.564	- 8.980 -13.370	22.6 -19.3	-16.6 28.3	0.97	1.02
	F5	9.148 -6.480	- 1.052 -11.451	61.4 -39.5	-60.6 47.1	0.36	0.61
	F6	5.981 -8.315	- 4.876 -14.359	41.5 -50.6	-38.3 60.2	0.53	0.48
	F7	6.390 -8.900	- 3.821 -13.981	43.9 -54.6	-41.3 64.0	0.50	0.45
	F8	4.010 -3.184	- 1.599 - 6.408	27.2 -19.1	-26.2 23.3	0.81	1.24
Side wall section	F1	5.512 -4.304	- 8.537 -14.840	39.5 -23.8	-33.9 33.6	0.56	0.86
	F2	2.829	- 8.199	21.6	-16.2	1.02	
	F3	2.296	-13.259	-10.9	19.7		1.46
	F4	-3.564	-13.308	-19.4	28.2		1.02
	F5	8.333 -1.483	- 1.770 - 8.076	56.2 -7.2	-55.0 12.6	0.39	2.29
	F6	3.209 -6.608	- 6.826 -13.131	23.7 -39.7	-19.1 48.5	0.93	0.59
	F7	1.941 -7.875	- 6.875 -13.181	15.2 -48.1	-10.6 56.9	1.45	0.51
	F8	4.010	- 1.645	27.2	-26.2	0.81	

Table 10 Concrete and yield strength of lining

Design strength: f ck	50	100	150	180	210	240	270	300
Bending tensile strength: f tk	4.4	8.8	13.1	15.8	18.4	21.0	23.6	26.3
Yield strength	0.28	0.56	0.83	1.0	1.17	1.33	1.50	1.67

Table 11 Standard lining thickness

Arch and side wall	Invert	Geological conditions
1/20D≧15	1/20D≧15	Fresh rock with little cracking
1/20D≧20	1/20D≧15	Somewhat weathered rock with cracking
1/15D≧20	1/15D≧20	Weathered rock, shattered zone, hard rock
H/12D≧20	1/15D≧20	Remarkably weathered rock, shattered fault zone, soft gravel

(D: diameter of tunnel inner section)

4. CONSIDERATIONS

The factors affecting the stability of a headrace tunnel are extremely uncertain, and include the physical properties of the bedrock, the environment conditions, etc. To complicate matters, they all have complex relationships to each other. The characteristics caused in the headrace tunnel that were made clear this time are shown below.

1) Cracking in longitudinal in side wall section

a) Where there is a cavity near the tunnel crown and lateral pressure acts.
b) Where the side wall is straight and the lining is thin.
c) Where the tunnel is located in a shattered zone etc., and a large lateral pressure acts.

2) Cracking in longitudinal direction due to lifting of the tunnel crown

a) Where the crown has lifted as a result of inward deformation of the side-wall section.
b) Where the lining of the arch section is thin.

3) Cracking due to slippage of construction joints

a) Slippage in the transverse direction: the load acts as a partial pressure in the transverse direction.

4) Cracking due to shear breaking

a) Where the lining pressure suddenly changes.

5) Cracking in oblique direction due to compressive shear breaking

a) Although the cavities are small, the whole of lining is subject to external pressure

If rear cavities and the thickness of the headrace tunnel lining can be inspected mechanically, the uniform quantitative inspection standards thus introduced will mean more rational and economic judgements can be made.

This has been a basic consideration of such judgement, and it is considered necessary to verify the judgement standards, details of judgement, and other issues using actual data in the future.

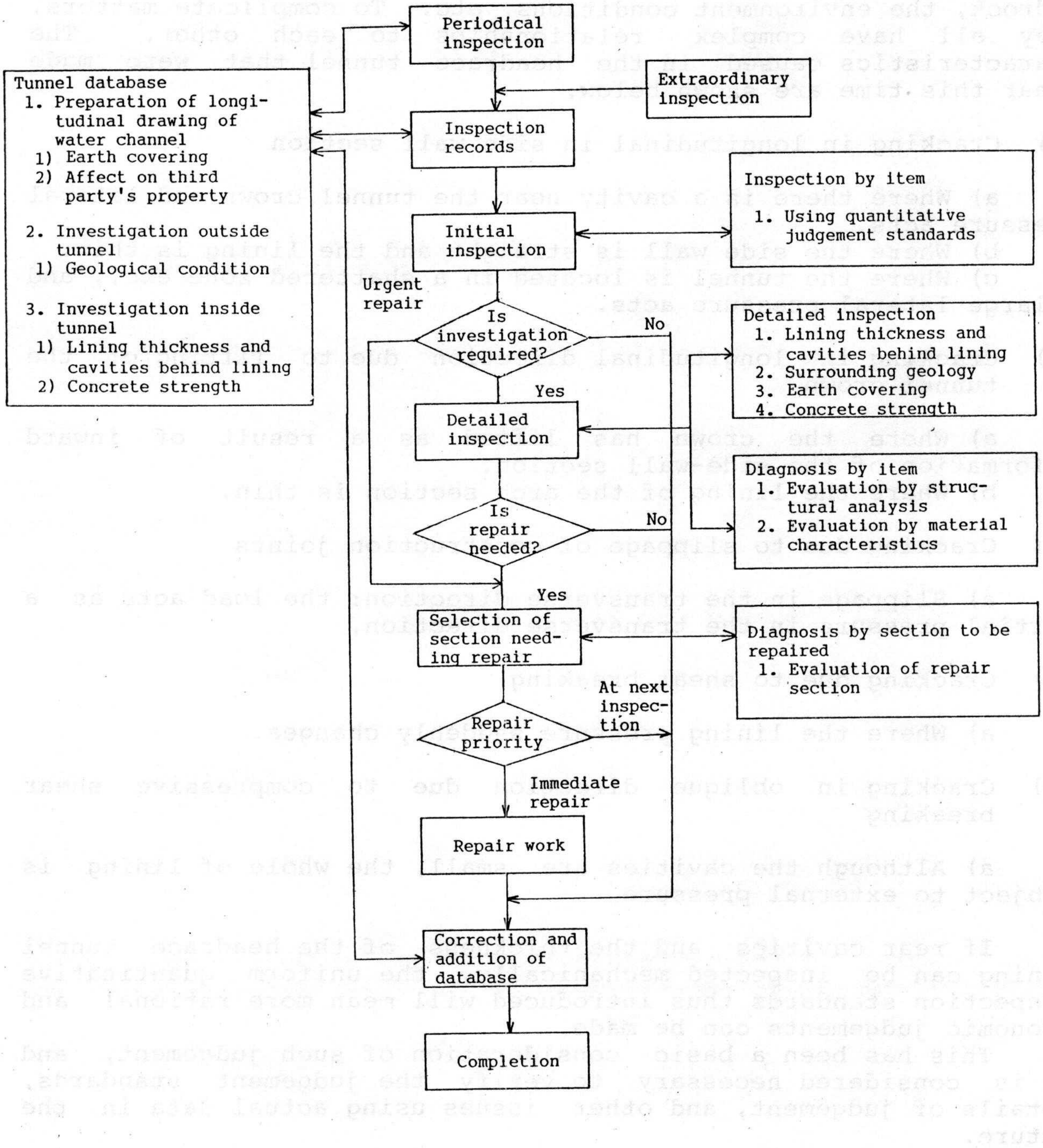

Fig. 1 Total inspection system procedure

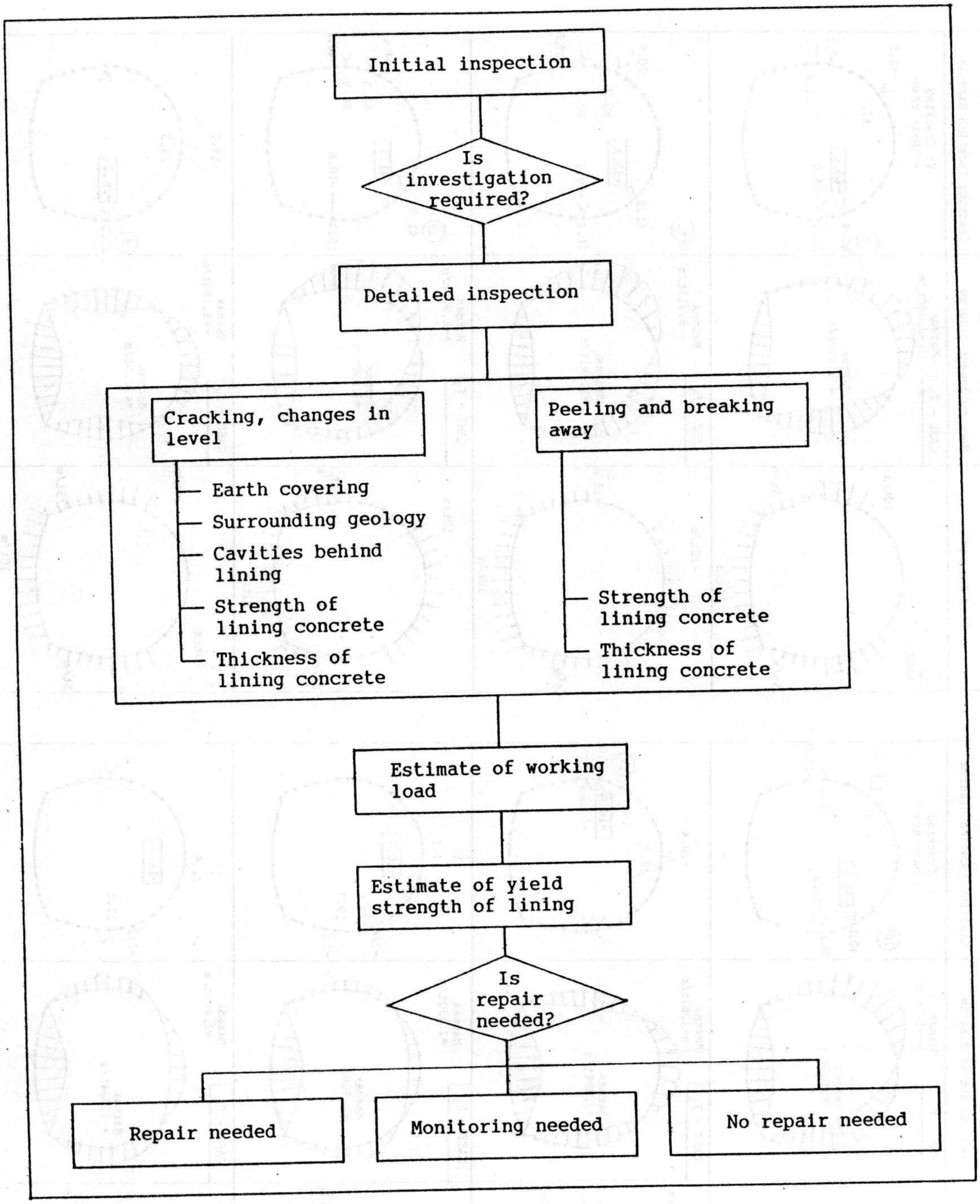

Fig. 2 Judgement process for scouring

Fig. 3 Situation of occurrence of cracking