RISK-BASED REPLACEMENT STRATEGIES FOR REDUNDANT DETERIORATING REINFORCED CONCRETE PIPE NETWORKS

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ABSTRACT

This paper gives an example of how predictive models of the deterioration of reinforced concrete pipes and the consequences of failure can be used to develop risk-based replacement strategies for redundant reinforced concrete pipe networks. It also shows how an accurate deterioration prediction can lead to a reduction of agency costs, and illustrates the limitation of the incremental intervention step algorithm. The main conclusion is that the use of predictive models, such as those developed by Oxand S.A., in the determination of replacement strategies for redundant reinforced concrete pipe networks can lead to a significant reduction in overall costs for the owner of the structure.

Keywords: Optimal management strategies, redundant pipe networks, incremental intervention step algorithm, deteriorating concrete pipes

INTRODUCTION

Reinforced concrete pipe networks used to transport water deteriorate with time due to environmental conditions, such as chloride-induced corrosion of the steel reinforcement, and if not maintained will eventually fail [1]. The risks associated with the failure of reinforced concrete pipe networks, defined herein as the probability of failure multiplied by the consequences of failure, and how they change with time, play a crucial role in determining the optimal replacement strategies for the pipes within these networks [2]. Consequences of failure include the interruption to service and the damage that results from the failure itself, such as the flooding of the buildings that house the pipes or nearby buildings or roads.

Although risks can be diminished by periodically replacing deteriorated pipes [3], there are potentially high costs associated with replacing pipes, including the cost of removing the existing pipes, the cost of the new pipes and the cost of service interruption of a temporary closure. Optimal replacement strategies for the pipes must therefore be determined by minimising both the risks and the cost of replacement for the pipes in the network, as well as how these risks and costs change with time and the effectiveness of the replacement in reducing future risks. Optimal replacement strategies are herein referred to with the abbreviation for optimal management strategy, OMS. Replacement strategies are one type of management strategy. In this paper an example of how OMS's can be determined for redundant reinforced concrete pipe networks using predictive models of deterioration and considering both the consequences of failure and the redundancy of the network is given.

RISK-BASED OBJECTIVE FUNCTION

To determine risk-based OMS's the objective function is defined to minimise cumulative overall costs (both agency costs and risks) (Eq. 1). By using Eq. 1 as the objective function both the redundancy of the network and the deterioration of the pipes, are taken into consideration in the estimation of the probability of failure of the system, P_{fsys}. The costs of failure, C_f are then multiplied by the P_{fsys} and added to the agency costs, C_a. The minimisation of these overall costs throughout the investigated time period will give the OMS.

$$Minimise \quad \lambda = \sum_{t=0}^{T} (C_a)_t + \sum_{t=0}^{T} (P_{fsys} \cdot C_f)_t \tag{1}$$

where:

$$\sum_{t=0}^{T} (C_a)_t \text{ = cumulative agency costs; and} \tag{2}$$

$$\sum_{t=0}^{T} (P_{fsys} \cdot C_f)_t \text{ = cumulative risk} \tag{3}$$

The probability of failure of a parallel system, $P_{fsys}^{parallel}$, is given by Eq. 4, and the probability of failure of the branches in a parallel system, which are in series, P_{fsys}^{series}, is given by Eq. 5.

$$P_{fsys}^{parallel} = 1 - \prod_{i=1}^{n} \left(1 - P_{fi}^{branch}\right) \tag{4}$$

where:

P_{fi}^{branch} = the probability of failure of the branches in the parallel system

$$P_{fi}^{series} = \prod_{i=1}^{n} P_{fi}^{section} \tag{5}$$

where:

$P_{fi}^{section}$ = the probability of failure of the sections in the branches

The deterioration is taken into consideration by assuming that the pipes are in a constant condition state for each time interval in the investigated time period and evaluating the probability of the pipes in each of these condition states for each successive time interval. The probability of passing between condition states from one time interval to the next is described using Markov models. In Markov models the condition ratings take the form of discrete states in order to reduce the complexity associated with continuous ranking systems [4].

PREDICTIVE MODELS OF PIPE DETERIORATION

Markov models and semi-Markov models are used to model the deterioration of the pipes. Markov models are commonly used, in management systems, to model the deterioration of infrastructure assets, such as pipes [5] and road bridges [4]. Semi-Markov models, however, have been used to incorporate changes in failure mode that may occur as a function of both time and the number of previous breaks [6]. As an unchanging failure mode is assumed in this example Markov models are considered adequate.

A Markov model describes a stochastic process where the conditional probability of any future event, such as being in condition state j, given any past event and the present state $X_t = i$, is independent of the past event and depends only on the present state. The conditional probabilities $P\{X_{t+1} = j | X_t = i\}$ are called transition probabilities. The transition probabilities in a Markov model can be determined using Poisson and negative binomial based regression techniques [7, 8] and can be correlated to actual deterioration models [9] albeit not perfectly. The possible transition probabilities are often shown in matrix form. The form of the Markov models used in this example (Eq. 6) is based on the five-state model shown in Fig 1.

$$
\begin{array}{c} \\ X_1 \\ X_2 \\ X_3 \\ X_4 \\ X_5 \end{array}
\begin{array}{ccccc}
X_1 & X_2 & X_3 & X_4 & X_5 \\
\left\{\begin{array}{ccccc}
\mathbf{1-(p_{12}+p_{13}+p_{14}+p_{15})} & p_{12} & p_{13} & p_{14} & p_{15} \\
0 & 1-(p_{23}+p_{24}+p_{25}) & p_{23} & p_{24} & p_{25} \\
0 & 0 & 1-(p_{34}+p_{35}) & p_{34} & p_{35} \\
0 & 0 & 0 & 1-p_{45} & p_{45} \\
0 & 0 & 0 & 0 & 1
\end{array}\right\}
\end{array}
\tag{6}
$$

where p_{ij} = transition probability from condition state X_i in year t to condition state X_j in year t + 1. For example, column 1 row 1 (in bold, Eq.1) shows the probability of being in condition state X_1 at t+1 if the pipe is in condition state X_1 at time t. Note the $p_{ij} = 0$ for i > j. This imposes the constraint that pipes cannot improve in condition. Also $p_{55} = 1$ because this is the worst possible condition state and it is an absorbing state, i.e. once a pipe has entered this state it cannot leave without an intervention.

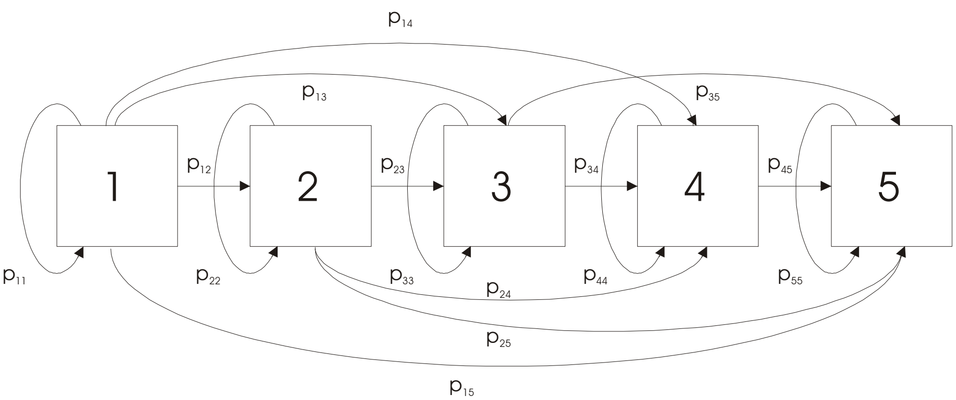


Figure 1. State transition diagram for five-state pipe example

The probability of being in condition state X_j, in year t + 1 can be determined through the application of the total probability theorem (Eq.7).

$$p_j^{t+1} = \sum_{i=1}^{j} P_{ij} \cdot p_i^t \tag{7}$$

where p_i^t = the probability of being in condition state X_i, in year t.

EXAMPLE NETWORKS

To illustrate how predictive models of the deterioration of redundant reinforced concrete pipe networks and the consequences of failure can be used to develop risk-based replacement strategies a simple parallel network is used (Fig. 1a). To illustrate the limitations of an incremental intervention step algorithm both the two-section parallel network (Fig. 1a) and the four-section parallel network (Fig. 1b) are used. The difference between the two networks is that in network 1, branch 1 and branch 2 have only one section each, whereas in network 2 branch 1 and branch 2 have two sections each. Each section in both networks consists of 1500 pipes in series. The pipes in the network are classified into 5 different condition states (CS), which are defined in Table 1 [3].

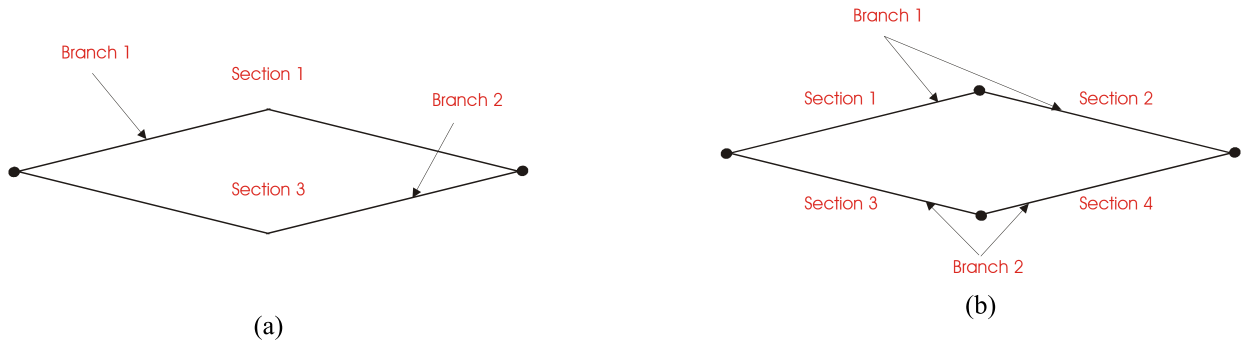


Figure 1. (a) Network 1, (b) Network 2

Table 1. Condition states for underground reinforced concrete pipes [2]

Condition state	Physical description
1	Near perfect condition
2	Some superficial deterioration
3	Serious deterioration, requiring substantial maintenance
4	Level of deterioration affects the fabric of the asset, requiring major reconstruction or refurbishment
5	Level of deterioration is such to render the asset unserviceable

It is assumed that inspection of the entire network is performed prior to the determination of the OMS, and that one quarter of the pipes (375) in each section is in each of the condition states, i.e. there are 375 pipes initially in CS1, CS2, CS3 and CS4 for each of the sections. All pipe deterioration is assumed to be the same and is described by the medium deterioration matrix shown Fig. 2.

Slow deterioration:

$$\begin{Bmatrix} 0.995 & 0.005 & 0 & 0 & 0 \\ 0 & 0.995 & 0.005 & 0 & 0 \\ 0 & 0 & 0.995 & 0.005 & 0 \\ 0 & 0 & 0 & 0.995 & 0.005 \\ 0 & 0 & 0 & 0 & 1 \end{Bmatrix}$$

(a)

Medium deterioration:

$$\begin{Bmatrix} 0.990 & 0.010 & 0 & 0 & 0 \\ 0 & 0.990 & 0.010 & 0 & 0 \\ 0 & 0 & 0.990 & 0.010 & 0 \\ 0 & 0 & 0 & 0.990 & 0.010 \\ 0 & 0 & 0 & 0 & 1 \end{Bmatrix}$$

(b)

Fast deterioration:

$$\begin{Bmatrix} 0.980 & 0.020 & 0 & 0 & 0 \\ 0 & 0.980 & 0.020 & 0 & 0 \\ 0 & 0 & 0.980 & 0.020 & 0 \\ 0 & 0 & 0 & 0.980 & 0.020 \\ 0 & 0 & 0 & 0 & 1 \end{Bmatrix}$$

(c)

Figure 2. The deterioration matrices for (a) slow deterioration, (b) medium deterioration and (c) fast deterioration

The four possible interventions on each section of each network are to replace all of the pipes that are initially in each condition state, i.e. CS4, CS3, CS2 and CS1. This means that there are 8 possible interventions on network 1 and 16 possible interventions on network 2 (Table 2). All interventions are assumed to cost 100 *mu* (mu = monetary units). It is assumed that if an intervention is not done and failure (defined as CS5) occurs, that the pipe where the leak occurs is replaced and the rest of the network is not. This has the effect of leaving the network in basically the same overall condition state, i.e. the probability of failure of this section of pipe is basically not changed, and the expected failure costs in the upcoming year therefore remain unchanged. The cost of failure is 1000 *mu*, or 10 times the intervention cost.

Table 2. Interventions

Network 1			**Network 2**					
Inter-vention	**Pipe section**	**Pipe groups**	**Inter-vention**	**Pipe section**	**Pipe groups**	**Inter-vention**	**Pipe section**	**Pipe groups**
1	1	Pipes initially in CS4	1	1	Pipes initially in CS4	9	3	Pipes initially in CS4
2	1	Pipes initially in CS3	2	1	Pipes initially in CS3	10	3	Pipes initially in CS3
3	1	Pipes initially in CS2	3	1	Pipes initially in CS2	11	3	Pipes initially in CS2
4	1	Pipes initially in CS1	4	1	Pipes initially in CS1	12	3	Pipes initially in CS1
5	3	Pipes initially in CS4	5	2	Pipes initially in CS4	13	4	Pipes initially in CS4
6	3	Pipes initially in CS3	6	2	Pipes initially in CS3	14	4	Pipes initially in CS3
7	3	Pipes initially in CS2	7	2	Pipes initially in CS2	15	4	Pipes initially in CS2
8	3	Pipes initially in CS1	8	2	Pipes initially in CS1	16	4	Pipes initially in CS1

OPTIMAL REPLACEMENT STRATEGIES

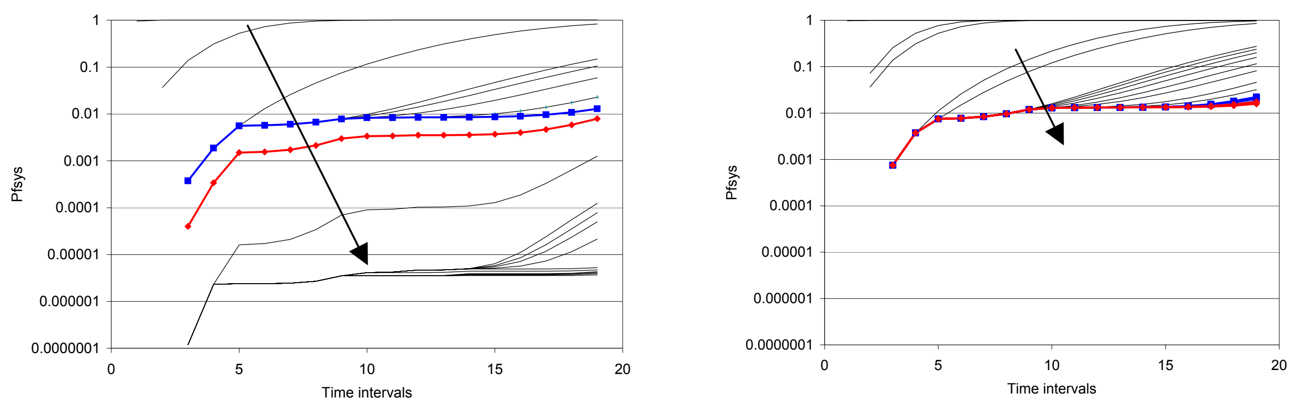
The OMS's were determined for a 100-year period with no restriction on the number of interventions per time interval (each time interval consists of 5 years) using an incremental intervention step algorithm. An incremental intervention step algorithm means that the optimal intervention and time of the optimal intervention were determined one intervention at a time. For example, to determine the optimal interventions for a two-intervention management strategy, intervention 1 is first determined and then it is assumed that this intervention (both the pipes to replace and the time to replace them) would not be affected by performing intervention 2. Intervention 2 is then determined. This type of algorithm is not always valid as can be seen when comparing the OMS's for the two networks (Table 3). Complete enumeration and dynamic programming were used to find for each successive intervention.

Table 3. Ranking of interventions

	Example network 1				Example network 2			
Number of inter-ventions	Pipe section	Pipe group	Intervention time	Incremental reduction in overall costs (*mu*)	Pipe section	Pipe group	Intervention time	Incremental reduction in overall costs (*mu*)
1	**1**	**4**	**t_1**	**6420**	**1**	**4**	**t_1**	**-77**
2	**1**	**3**	**t_2**	**10719**	**2**	**4**	**t_1**	**4526**
3	**1**	**2**	**t_6**	**1354**	**1**	**3**	**t_2**	**1743**
4	1	1	t_{10}	-51	**2**	**3**	**t_2**	**9486**
5	1	4	t_{10}	-51	**1**	**2**	**t_5**	**1081**
6	1	3	t_{11}	-62	**2**	**2**	**t_6**	**1324**
7	1	2	t_{13}	-90	1	1	t_{10}	-52
8	3	4	t_3	-95	2	1	t_{10}	-52
9	3	3	t_3	-93	2	4	t_{10}	-51
10	3	2	t_5	-99	1	4	t_{10}	-51
11	3	1	t_{15}	-100	1	3	t_{11}	-63
12	3	3	t_{15}	-100	2	3	t_{11}	-62
13	3	4	t_{14}	-100	1	2	t_{12}	-86
14	3	2	t_{15}	-100	2	2	t_{13}	-90
15	1	2	t_{11}	-100	2	1	t_{15}	-98
16	1	3	t_{10}	-100	1	1	t_{15}	-98
17	1	1	t_{11}	-100	1	4	t_{15}	-98
18	1	3	t_{13}	-100	2	4	t_{15}	-98
19	1	4	t_{12}	-100	1	3	t_{15}	-100

The OMS's, which can be read from Table 3 once the number of interventions desired are known, are determined for the both networks assuming discount rates of 0 %. For example, if it is desired to have only 4 interventions in the investigated 100-year period the OMS is to replace the pipe groups 4, 3, 2 and 1 at t_1, t_2, t_6 and t_{10} respectively for network 1. The negative values in Table 3 indicate where it is no longer beneficial to perform an intervention, i.e. the agency costs are higher than the possible reduction in expected failure costs. All values are rounded to the nearest monetary unit. In Tabéle 3, this means that it is only beneficial, given the C_f, C_a and deterioration matrices used, to replace pipe groups 4, 3 and 2 in branch 1 for both networks (section 1 for network 1 and sections 1 and 2 for network 2). These interventions are shown in bold in Table 3.

On network 1 the seven most beneficial interventions are to replace the pipes on branch 1 from best to worst (pipe groups 4, 3, 2, and 1, and then 4, 3, 2 again) at time intervals t_1, t_2, t_6, t_{10}, t_{10}, t_{11}, and t_{13}, respectively. It is not until the probability of system failure is sufficiently small throughout the entire investigated time period (Fig. 3a) that replacing pipes in the second branch of the parallel network becomes the most beneficial. This occurs at the 8th intervention, shown in bold with squares in Fig. 3a. Fig. 3a shows the cumulative probability of system failure of network 1 and network 2. The decreasing probability of failure of the networks (in the direction of the arrow) occurs because each successive curve is generated using a management strategy with an additional intervention. For example, in Fig. 3a., the bold line with squares is the cumulative probability of failure of network 1 when an OMS consisting of 8 interventions is used. The bold line with diamonds in Fig. 3a is the cumulative probability of failure of network 1 when an OMS consisting of 9 interventions is used.



(a) (b)

Figure 3. The cumulative probability of system failure for all of the OMS's shown in Table 3 (a) network 1 (b) network 2

On network 2 all interventions are found to be on branch 1. This is an error due to the use of the incremental intervention step algorithm, which only looks at one intervention at a time. It should suggest repairing network 2 in the same order that it suggests repairing network 1. The interventions that should be the same, i.e. the pipes and the location of the pipes that should be replaced, but are not, are shown as shaded cells in Table 3. Instead of suggesting that the pipes on branch 2 (sections 3 and 4) in network 2 are the most beneficial to replace, as they are on network 1 (section 3 – interventions 8 and 9), the incremental intervention step algorithm suggests, that the optimal interventions are on branch 1 (sections 1 and 2 - interventions 15, 16, 17, and 18). By not changing branches on network 2 the cumulative probability of system failure throughout the 100-year (20 time interval) period remains much higher than for network 1. The cumulative probability of system failure after the intervention 8, and after intervention 8 and 9, on branch 2, on network 1, are in bold in Figure 3a. It can be seen that there are order of magnitude drops in the probability of system failure with successive interventions. The cumulative probability of system failure after each of the four successive interventions that should be the equivalent of the interventions 8 and 9 on network 1, on network 2, are in bold in Figure 3b. It can be seen that there is very little further reduction in the cumulative probability of system failure.

This inability to switch branches occurs because, by only looking at one intervention at a time the incremental intervention step algorithm never "sees" the future benefit of doing an intervention on the more deteriorated branch in the parallel network, i.e. if only the benefits of performing one intervention at a time are compared the largest benefit will always come from performing the intervention on the branch that has already had one intervention if the probability of failure of the other branch is high (which in this example it is). The incremental intervention step algorithm should therefore only be used in situations where it is not required to "see" the benefit of future interventions.

ACCURATE DETERIORATION PREDICTION

To investigate the importance of accurate determination of deterioration speeds on redundant reinforced concrete pipe networks, the OMS's consisting of up to 19 interventions are determined for network 1 using three different deterioration speeds; slow, medium and fast (Table 4). Slow, medium and fast deterioration speeds are defined in this example by the deterioration matrices shown on Fig. 2. Slow deterioration is defined as having a 0.5 % chance that a pipe will pass out of its condition state in one time interval. Medium deterioration is defined as having a 1 % chance that a pipe will pass out of its condition state in one time interval. Fast deterioration is defined as having a 2 % chance that a pipe will pass out of its condition state in one time interval. A discount rate of 0 % is used. For the slow deterioration speed it can be seen that no interventions were selected after the 13th intervention. This is because the improvement in the probability of system failure is small enough to be negligible. Any additional expenditure after 12 interventions is simply a waste of agency money.

Table 4. OMS for example network 1

	Deterioration speed											
	Fast				Medium				Slow			
Number of interventions in OMS	Section	Group	Intervention time	Cumulative overall costs (*mu*)	Section	Group	Intervention time	Cumulative overall costs (*mu*)	Section	Group	Intervention time	Cumulative overall costs (*mu*)
0	-	-	-	18993	-	-	-	18953	-	-	-	18664
1	1	4	0	14700	1	4	0	12533	1	4	0	6918
2	1	3	1	4520	1	3	1	1813	1	3	1	422
3	1	2	5	1026	1	2	5	459	1	2	4	310
4	1	1	9	908	1	1	9	510	3	4	2	407
5	1	4	9	781	1	4	9	560	3	3	2	500
6	1	3	10	704	1	3	10	623	3	2	7	600
7	1	2	12	755	1	2	12	712	3	1	12	700
8	3	4	2	844	3	4	2	807	3	3	11	800
9	3	3	2	915	3	3	2	901	3	4	12	900
10	3	2	4	1002	3	2	4	1000	3	2	15	1000
11	3	1	13	1101	3	1	14	1100	1	1	1	1100
12	3	3	14	1201	3	3	14	1200	1	4	4	1200
13	3	4	14	1300	3	4	13	1300	1	1	1	1300
14	3	2	14	1400	3	2	14	1400	-	-	-	1400
15	1	2	10	1500	1	2	10	1500	-	-	-	1500
16	1	3	9	1600	1	3	9	1600	-	-	-	1600
17	1	1	12	1700	1	1	10	1700	-	-	-	1700
18	1	3	12	1800	1	3	12	1800	-	-	-	1800
19	1	4	12	1900	1	4	11	1900	-	-	-	1900

The cumulative overall costs for the OMS's for the three deterioration speeds for network 1 are shown in Figure 4. The number of interventions in the OMS that will maximize cumulative overall savings is indicated with a large circle. It can be seen that for slow deterioration a replacement strategy with 1, 2 and 3 interventions will result in savings of 11745, 18241 and 18353 *mu*, respectively (Fig. 4a). If a fourth intervention is done there will actually be a decrease in overall savings to 18257 *mu*. This is because the agency costs for the intervention are higher than the possible reduction in expected failure costs. For medium deterioration a replacement strategy with 1, 2 or 3 interventions will result in 6420, 17139 and 18494 *mu*, respectively (Fig. 4b). A replacement strategy with 4 interventions will also decrease overall savings (18443 *mu*). If the deterioration speed is fast, the 6 intervention OMS will result in the largest overall savings, 18288 *mu*, and performing the seventh intervention will result in a decrease in overall savings (Fig. 4c).

The importance of accurate estimation of deterioration speed lies in the ability to determine the appropriate number of interventions to have in the OMS. For example, in network 1, if there is medium deterioration and it is wrongly estimated to be fast, the agency costs will be 100 % higher than necessary. The cumulative agency costs for the OMSs for the slow, medium and fast deterioration speeds are shown in Fig. 4d. Of course this depends on the C_f, C_a and the exact deterioration matrices used to describe the deterioration. If there is slow deterioration speed and it is estimated to be a medium deterioration speed the same interventions will be recommended and the agency costs (and overall costs) will be no different.

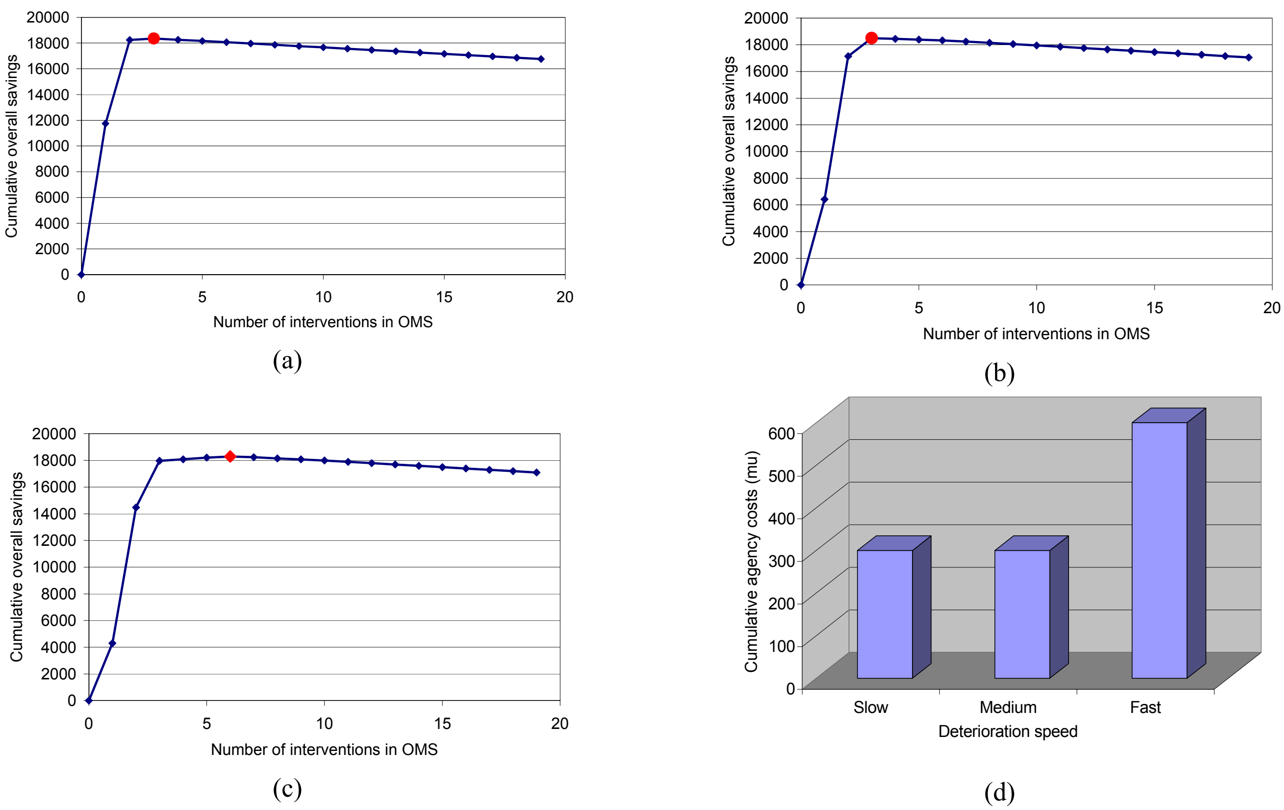


Figure 4. Cumulative overall costs vs. number of interventions performed from optimal sequences for network 1 (a) slow deterioration, (b) medium deterioration, (c) fast deterioration, and (d) Cumulative agency costs for each intervention

CONCLUSIONS

This example shows that:

1) Risk-based optimal management strategies can be determined for redundant reinforced concrete pipe networks using predictive models of the deterioration and considering both the consequences of failure and the redundancy of the network
2) The incremental intervention step algorithm can only be used on networks where it is not required to “see” the benefit of future interventions.
3) Predictive deterioration models can be used to determine risk-based replacement strategies for redundant reinforced concrete pipe networks taking into consideration the functioning of the network as a whole.
4) The use of risk-based replacement strategies can determine when additional agency spending is unnecessary.
5) Accurate deterioration prediction can result in substantial savings in agency costs.

Future work needs to concentrate on the accuracy of the deterioration models used in predicting future deteriorating of underground reinforced concrete pipes.

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