



**HAL**  
open science

## Decision making tool for the choice of maintenance strategies of tunnels

Aurélie Talon, Pierre Breul, Nouredine Rhayma

► **To cite this version:**

Aurélie Talon, Pierre Breul, Nouredine Rhayma. Decision making tool for the choice of maintenance strategies of tunnels. 51st ESReDA Seminar, Oct 2016, Clermont-Ferrand, France. hal-04046891

**HAL Id: hal-04046891**

**<https://uca.hal.science/hal-04046891>**

Submitted on 27 Mar 2023

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# Decision making tool for the choice of maintenance strategies of tunnels

TALON Aurélie, BREUL Pierre, RHAYMA Nouredine  
Blaise Pascal University – Pascal Institute – UMR 6602  
2 avenue Blaise Pascal  
63100 Aubière, France

## Abstract

*The current inspection strategy applied to tunnels is mainly based on visual inspection. However, this type of inspection only detects apparent damages without linking them to their causes. A new monitoring methodology has been proposed consisting in integrating monitoring tools to better characterize the geometrical and mechanical state of different tunnel components (lining, contact interface and surrounding ground). This methodology has been developed in the context of the ANR MEDITOSS project. In this context a maintenance tool is developed. This paper is dedicated, on the one hand to the presentation of the provided tool and on the other hand to the results of ten cases study, based on three RATP stations, that can provide the influence analysis of: (1) monitoring notes according to MEDITOSS methodology, (2) performance level targeted, (3) assignment date of budgets and (4) intervention priority according to the damage character.*

*Keywords: functional and structural performance, pathologies, spatial variability, scale change, tunnels.*

## 1. Introduction

Current inspection strategy of tunnels is mainly based on visual mechanical investigations. RATP's current policy of managing tunnel and underground structures is based on the same approach. Periodic visual inspections of tunnels are carried out to make a complete assessment of their state and behaviour. The surveys are performed by inspectors with experience in the field. They visit and inspect all the elements and structures of the network after which they issue inspection reports for each tunnel.

Mechanical investigations are generally scheduled during periods of unfavourable climatic conditions (primarily very cold weather, high temperatures, etc.). The whole of the network is inspected and each apparent fault is located and mentioned.

Visits can also be performed in the framework of a scheduled detailed inspection carried out at least once every five years or in that of an exceptional detailed inspection when major disorders of the structure are detected.

During these investigations, specific inspections and additional tests can be carried out to obtain further information [13, 14, 15]. All the results of the investigation are examined and classified by tunnel. Each fault is indexed and a score is assigned

according to the type and seriousness of the fault. Scores vary from 1 to 7; a score of 1 is given to minor faults while a score of 7 to degraded structures. The score given is the result of the combination of a class (indicating the state of the structure) with an optional index (assessing the risk of the anomaly).

Once the faults are recorded, a score of the structure's general health is established. In general cases it corresponds to the most frequent fault score. The general health score is attributed to tunnels, corridors and stations. It varies from 1 to 6 (1 characterizes the state of a new structure, 6 that of a state close to ruin). According to the general health score, a decision concerning the maintenance operation to be performed can be taken. Estimation of the general state of underground facilities is important for managers in order to perform optimized maintenance. However, this system of control provides only the apparent faults and does not relate them to their causes. This aim of the MEDITOSS Project is to propose a new monitoring methodology that completes the visual mechanical investigations.

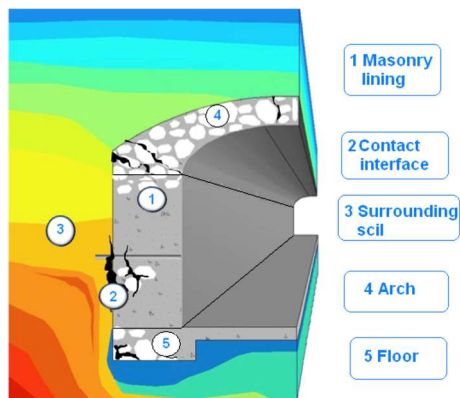
The second section is dedicated to the presentation of the main parts of this project and the diagnosis tool. The third section presents its results and the tunnel state quotation. The section four and five concern the maintenance tool and its results.

## **2. MEDITOSS Project and diagnosis tool**

A new monitoring methodology has been proposed consisting in integrating monitoring tools to better characterize the geometrical and mechanical state of different tunnel components (lining, contact interface and surrounding ground). This methodology has been developed in the context of the ANR MEDITOSS project (methodology of monitoring of tunnels and underground work in service). This project integrates four items: (1) the characterization of work components from monitoring tools relevant to site constraints, (2) method development for inspection that integrates spatial variability, coupling of data and scale change (from measurement to state assessment of the station), (3) numeric modelling that allows forecasting the state development of works and (4) the development of a decision making tool for the choice of a maintenance strategy. This paper is dedicated to the fourth item.

The new monitoring strategy developed [7, 8] is based on the inspection of panels 10 meters long and 3 meters wide, by coupling four techniques: ground-penetrating radar (GPR), light dynamic penetrometry (Panda) [4] coupled with a geoendoscope [1] (figures 2) and, finally, mechanical impedance [3] (figure 3). This methodology is added to the classical visual inspection. The inspection provides a quantitative characterization at the scale of the panel of the different tunnel components (figure 1). This evaluation covers:

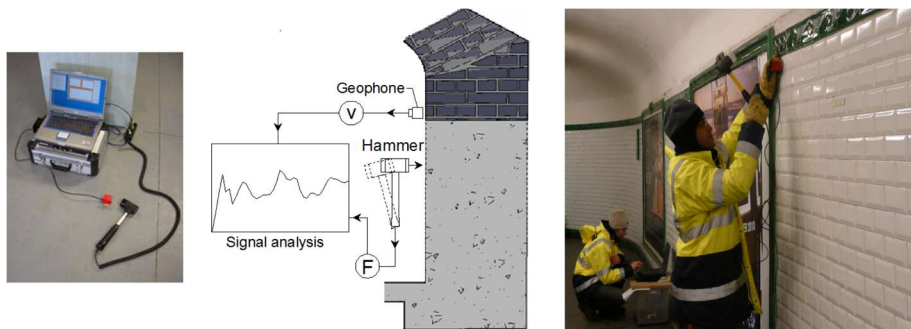
- The mechanical and geometrical assessment of the lining [2]. The thickness of the masonry that can be assessed using GPR measurements, impedance (for the healthy part) and geoendoscopic measurements;
- The mechanical quality of the masonry is assessed by geoendoscopic measurements;
- The quality of the contact between the masonry and the surrounding ground. This is assessed by penetrometric and geoendoscopic measurements;
- The quality of the surrounding ground is assessed by penetrometric and geoendoscopic measurements.



**Figure 1.** Different components of a tunnel



**Figure 2.** Principle and example of penetrometric and geodendoscopic measurements



**Figure 3.** Principle and example of mechanical impedance measurements

This monitoring strategy is applied to preselected “panels” (figure 4) and a “panel note” will thus be allotted according to the state of the masonry (thickness and mechanical characteristics), the state of the contact between the masonry and the surrounding ground and the state of the surrounding ground for each panel. This score ranges from 1 to 7.



**Figure 4.** Example of the Meditoss panel inspection

This new inspection methodology has been tested successfully under real conditions in different stations of the French RATP network. In order to improve the maintenance management of these works, it is necessary to optimize the installation and the number of panels. This optimization is also related to the financial and logistic constraints mentioned above (work in service, long lengths, etc.).

### **3. Diagnosis results and tunnel state quotation**

In order to harmonize the notation or scoring system of the underground works and minimize the subjectivity due to the RATP's visual notation, we propose the following steps to provide a general score for the structure:

- Listing all the faults in a corridor or tunnel (obtained during RATP's visual inspections or during MEDITOSS mechanical investigation);
- Assigning a score to each fault. When a MEDITOSS panel is installed at the position of the fault, the score of the latter will be that resulting from the MEDITOSS panel, if not it will be that of the RATP visual inspection. The two rating scales are voluntarily comparable;
- To combine each pair of faults, 2 by 2, according to the scoring system presented in table I. This results in a failure and a score;
- To reiterate the previous stage until a final score is obtained for a corridor or tunnel.

The main idea is to take into account all the scores obtained from the results of the mechanical investigation panels and/or the visual inspection scores, and then compare them 2 by 2 until obtaining a final score. In this comparison, as given in table I, the structural and functional aspects of the faults are taken into account.

The score resulting from the comparison of two faults can be the maximum score, the average score or the score of a fault considered more significant than the others. Certain faults, even minor from a structural point of view, are treated with greater urgency because of their impact on RATP's operations. For example, vault infiltrations can obstruct the circulation of users in access tunnels. In this case, we took into account the functional impact on the operation of the RATP in addition to the structural impact of a fault.

**Table I:** The various partial decisions.

		Score of visual inspection of RATP												Score of MEDITOSS panel				
		Post						Vault										
		Infiltration		Cracking		Deep sound		Infiltration		Cracking		Deep sound						
	Struc.	Func.	Struc.	Func.	Struc.	Func.	Struc.	Func.	Struc.	Func.	Struc.	Func.	Struc.	Func.				
Score of visual inspection of RATP	Infil.	Struc.	Ave.	Ave.	Max	Crack.	Max	Infil.	Infil.	Max	Crack.	Max	Infil.	Infil.	Max	Pert. Mat.	MED. Score	
		Func.	Ave.	Ave.	Crack.	Ave.	Crack.	Deep sound	Infil.	Infil.	Crack.	Crack.	Crack.	Crack.	Crack.	Deep sound	Ave.	MED. Score
	Crack.	Struc.	Max	Crack.	Ave.	Crack.	Max	Crack.	Max	Crack.	Crack.	Max	Crack.	Crack.	Crack.	Max	Max	MED. Score
		Func.	Infil.	Ave.	Crack.	Post	Ave.	Crack.	Post	Infil.	Infil.	Crack.	Crack.	Crack.	Crack.	Crack.	Deep sound	MED. Score
	Deep sound	Struc.	Max	Deep sou.	Max	Deep sou.	Ave.	Deep sound	Max	Max	Max	Deep sound	Max	Deep sound	Deep sound	Max	Max	MED. Score
		Func.	Infil.	Ave.	Crack.	Post	Ave.	Deep sound	Ave.	Infil.	Infil.	Crack.	Crack.	Crack.	Crack.	Crack.	Deep sound	Max
	Infil.	Struc.	Infil.	Infil.	Max	Infil.	Max	Max	Ave.	Max	Max	Max	Max	Infil.	Infil.	Max	Max	MED. Score
		Func.	Max	Infil.	Crack.	Infil.	Crack.	Max	Max	Max	Max	Crack.	Crack.	Crack.	Crack.	Crack.	Crack.	Infil. score if > to MED. score
	Vault	Crack.	Struc.	Max	Crack.	Max	Crack.	Max	Crack.	Crack.	Crack.	Crack.	Crack.	Crack.	Crack.	Crack.	Max	MED. Score
			Func.	Infil.	Crack.	Crack.	Crack.	Crack.	Crack.	Crack.	Crack.	Crack.	Crack.	Crack.	Crack.	Crack.	Crack.	Crack.
	Deep sound	Deep sound	Struc.	Max	Deep sou.	Max	Deep sou.	Max	Deep sou.	Max	Deep sou.	Max	Deep sou.	Max	Deep sound	Max	Deep sound	Max
			Func.	Deep sou.	Ave.	Max	Ave.	Max	Max	Ave.	Max	Max	Max	Max	Max	Max	Max	Max
Score of MEDITOSS panel		MED. Score	MED. Score	MED. Score	MED. Score	Max	Max	Max	MED. Score	MED. Score	Max	Max	MED. Score	MED. Score	Max	Max	Ave.	

Table I above provides a summary of the various partial decisions. For example, if we consider a score for infiltration in the post, which is a functional fault (detected during an RATP visual inspection) and, on the other hand, a score for cracking in the post, which is a structural fault (detected during a visual inspection of the tunnel), then the

score selected (grey box with bold edges in Table I) will be the cracking score. When the score of the MEDITOSS mechanical investigation is available as well as the score for material loss in the vault (structural disorder detected during an RATP visual inspection), the resulting score will be the maximum score.

#### 4. Maintenance tool

The aim of the maintenance tool (Figure 5) is here to determine:

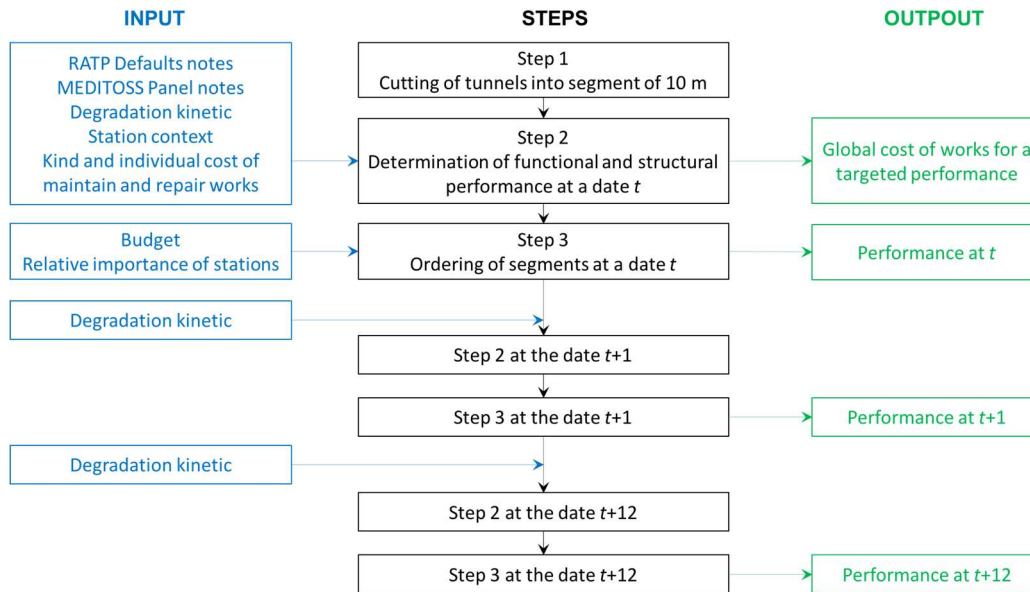
- The global cost for maintenance and repair works that have to be done at the date  $t$  for a given functional and structural performance,
- The ordering of tunnel segments to maintain and repair as regards a given budget at  $t, t+1, \dots, t+12$  years,
- The functional and structural performances of the whole tunnels of the RATP at the end of the application of the strategy of maintenance and repair determined by ordering.

The global quotation of stations that is the result of the previous section 3 allows to pre-select the station for the maintenance process. The stations with the higher note are pre-selected. The selection is extended to all the stations if the maintenance budget is enough.

The first step of the tool consists into cutting tunnels and station corridors into segment of 10 m. This size had been chosen as it corresponds to the length of a MEDITOSS auscultation panel.

During the second step we associate to each segment the worst default considering maintenance aspect. The default note can provide from a visual inspection of the RATP or a MEDITOSS auscultation panel. If the both (visual inspection and MEDITOSS panel) are available, we retain the note associated to the MEDITOSS panel. Among a set of defaults, the worst will be the one with the highest repair cost and the faster degradation kinetic.

From default notes associated to each segment, we are able to determine the functional and structural performance of each segment considering an algorithm detailed in [12]. Knowing maintain and repair cost of each kind of default and by taking levels of functional and performance performances, we are able to deduce, at a date  $t$ , the global cost for maintenance and repair works. We consider the following three main defaults: infiltration, cracking and deep sound.



**Figure 5:** Approach for optimisation of strategies for auscultation, maintenance and repair works of RATP tunnels

The third step ordering the works to led. This step is based on the knowledge of the budget allocated for the year  $t$  (on the basis of the global cost defined at step 2) and the relative importance of each station. The relative importance is characterised by the daily visit of stations (number of incomer and leaving); we based this assessment on the development of the PhD Thesis of Paterna Hidalgo [9].

At the end of this step (maintenance and repair of priority segments), we are able to provide a cartography of the structural and functional performances of the whole segments:

- Maintained and repaired segments will have the performance level given at the step 2,
- No maintained and no repaired segments will have the initial performance level (deduce from default notes).

Then, on the basis of the degradation kinetic of defaults, we deduce the default notes of each segment at the date  $t+1$ . Then, we apply the steps 2 and 3 in order to deduce the segments to maintain and repair in priority considering the budget allocated to the year  $t+1$  and the cartography of the structural and functional performances at the year  $t+1$ .

We repeat the implementation of default ageing to the segments and the steps 2 and 3 until the year  $t+12$ .

We realise assessment from  $t$  to  $t + 12$  years as the maintenance overall strategy of the RATP is of 12 years.

This approach is based on:

- methods and results from MEDITOSS project:
  - notes of MEDITOSS panel [6] and notes of station deduce of MEDITOSS panels [11];



- links between default and kind of maintenance and repair works [10];
- degradation kinetic of RATP tunnels (RATP expertise and [5]);
- default notes and the context given by the legal statements and the visual inspections of RATP;
- data provided by the RATP for the development of this approach:
  - kind and cost of maintenance and repair works associated to each kind and note of default;
  - ordering method of the stations.

The input parameters of this approach are:

- the given performance for the RATP tunnels,
- the global and annual budget for the auscultation, the maintenance and the repair works.

## 5. Results

We applied this tool to three RATP stations, that represents 164 segments of 10 m. In the context of this applications, we test and compare:

- influence of monitoring notes according to MEDITOSS methodology (cases 1 and 2);
- influence of the performance level targeted (cases 1, 3, 4 and 5),
- influence of assignment date of budgets (cases 1, 6 and 7),
- influence of the intervention priority according to the damage character (cases 1, 8, 9 and 10).

The case 1 consists into taking into account the MEDITOSS auscultation panels and divide fairly, on the 12 years of management, the budgets of maintenance and repair works.

The case 2 does not take into account the MEDITOSS auscultation panels and divide fairly the budgets on the 12 years of management.

The cases 3 to 10 take into account the MEDITOSS auscultation panels.

The cases 3, 4 and 5 consist into respectively repair 75%, 50% and 25% of the segments.

The case 6 consists into divide fairly the global budget of maintenance and repair works on the first 4 years of management.

The case 7 consists into allocated 50% of the global budget of maintenance and repair works at the first year and the other 50% at the year 7.

The case 8 firstly focus on the repair of all the defaults of cracking and then on the other defaults according to the proposed approach of ordering.

The case 9 firstly focus on the repair of all the defaults of infiltration and then on the other defaults according to the proposed approach of ordering.

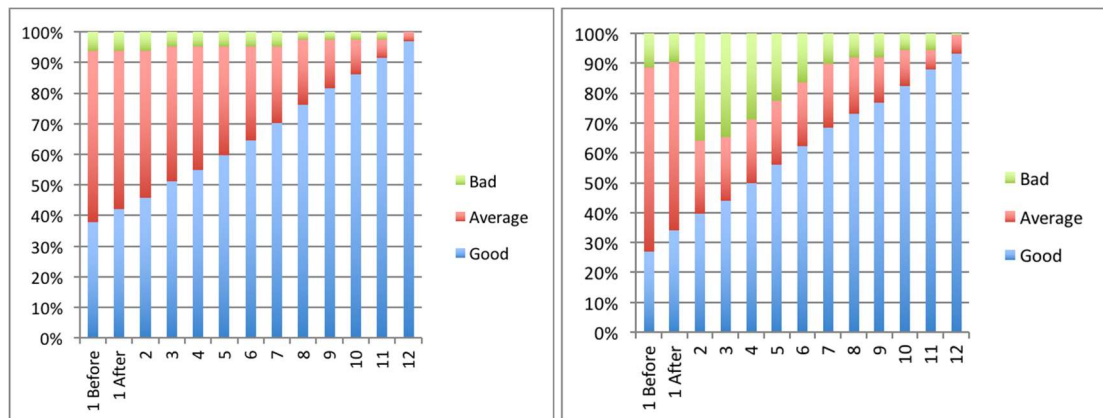
The case 10 firstly focus on the repair of all the defaults of deep sound and then on the other defaults according to the proposed approach of ordering.

At the end of the management period (12 year) the whole works are not necessarily done. The Table II regroupes for the ten case studied: the global cost at  $t$ , the expenses done during the 12 years of management, the necessarily budget to repair 100% of the segment at the end of the management period.

**Table II:** Synthesis of costs at  $t$  and at the end of the management period.

Cases	Case detail	Global cost at $t$	Expenses on the 12 years of management	Needed budget to repair 100% of segments after 12 years
1	With MEDITOSS	3 951	3 796	155
2	Without MEDITOSS	3 290	3 070	220
3	75% of segments	2 963	2 886	1 065 (77 for 75%)
4	50 % of segments	1 976	1 846	2 105 (130 for 50%)
5	25 % of segments	988	781	3 170 (207 for 25 %)
6	100% of the budget on the first years	3 951	3 916	35
7	50% of the budget on year 1 + 50% of the budget on year 7	3 951	3 951	0
8	Cracking first	3 951	3 856	95
9	Infiltration first	3 951	3 811	140
10	Deep sound first	3 951	3 846	105

Owing to the individual cost of work, the Table II points out that one should better done the work on the same time (cases 6 and 7) rather that divide fairly the repair on the 12 years of management.



**Figure 6:** Evolution of the distribution of structural (on the left) and functional (on the right) performance for the case 1 during the 12 years of management

As an example, Figure 6 indicates the evolution of the distribution of structural and functional performances of the segments of the case 1, at date  $t$  before and after the works and during the 12 years of management. For these figures, we consider three groups of states: good (notes of 1 and 2), average (notes of 3 and 4) and bad (5, 6 and 7).

The Table III synthetizes the segments that have to be repaired at the beginning of the management period, the ones repaired at the end of the 12 years of management and the ones still to be repaired at the end of this period.

**Table III:** Synthesis of segments to repair, repaired and still to repair.

		Number of segments to repair	Number of segments repaired	Number of segments still to repair
Case 1	With MEDITOSS	121 / 164 (74%)	116 / 121 (96%)	5 / 121 (4%)
Case 2	Without MEDITOSS	106 / 164 (65%)	98 / 106 (92%)	8 / 106 (8%)
Case 3	75% of segments	121 / 164 (74%)	90 / 121 (74%)	31 / 121 (26%)
Case 4	50 % of segments	121 / 164 (74%)	56 / 121 (46%)	65 / 121 (54%)
Case 5	25 % of segments	121 / 164 (74%)	22 / 121 (18%)	99 / 121 (82%)
Case 6	100% of the budget on the 4 first years	121 / 164 (74%)	120 / 121 (99%)	1 / 121 (1%)
Case 7	50% of the budget on year 1 + 50% of the budget on year 7	121 / 164 (74%)	121 / 121 (100%)	0 / 121 (0%)
Case 8	Cracking first	121 / 164 (74%)	118 / 121 (98%)	3 / 121 (2%)
Case 9	Infiltration first	121 / 164 (74%)	117 / 121 (97%)	4 / 121 (3%)
Case 10	Deep sound first	121 / 164 (74%)	118 / 121 (98%)	3 / 121 (2%)

For the ten cases tested, the number sum of repaired segment and still to repair segment is equal to the number of segment to repair. This fact means that have no occurrence of new defaults that have to be repaired during the management period. This noticing is due to the default kinetic that it is slow as regards the considered management period.

### 5.1 Influence of monitoring notes according to MEDITOSS methodology

The number of segments in “average” state at the date  $t$  is more important when considering the MEDITOSS approach (case 1). But gradually of the repair years, the structural performances for the both cases extend to the same distribution. We observe the same tendency for the functional performances.

### 5.2 Influence of performance level targeted

We study the evolution of structural performances of segment versus the time when we reduce the percentage of repaired segments: 100% for the case 1, 75% for the case 3, 50% for the case 4 and 25% for the case 5. As logically, we observe that the percentage of segments in “average” state rise with time and inversely proportionally to the percentage of repaired segments.

### 5.3 Influence assignment date of budgets

We analyse the evolution of structural performance of segments versus modifications of allocated date of budgets: equal distribution on the 12 years for the case 1, 25% during the first 4 years for the case 6 and 50% at the year 1 and 50% at the year 7 for the case 7.

The proportion of segments in “god” state since the first year is really higher for the case 7 than the proportion of the case 6, which is higher than the proportion of case 1. The proportion is equal for the cases 6 and 7 at the end of the year 2; that is to say when the allocated budgets are equal. Then, the proportion of segments in “god” state is higher for the case 6 ate the end of years 3 and 4 to be extended to 100%. The proportion of segments in “god” state is also extended to 100% at the end of year 7 for the case 7

when 100% of budget is allocated. The case 1 is extended more slowly to the same proportion at the end of the management period.

#### **5.4 Influence of intervention priority according to the damage character**

We compare the evolution of structural and functional performances of segment according to the intervention priority to the damage character: ordering approach proposed for the case 1, firstly 100% of cracking for the case 8, firstly 100% of infiltrations for the case 9 and firstly 100% of deep sound for the case 10.

The evolution of structural performance of segment is overall equal for these different cases.

As regards the functional performance is concerned, the proportion of segments that have a “bad” performance is weakest for the case 9, since the year 2 in comparison of the other cases. Indeed, there are the infiltrations that generate as soon as the year 2, segments in state 7. Consequently, the strategy 9, by favouring the repair of infiltrations, quickly repair segments in “bad” state in comparison of the other cases.

### **6. Conclusion**

This paper is structured around the presentation of the MEDITOSS project, of the developed diagnosis method, the result of this diagnosis that led to the quotation of the global state of RATP tunnels. This quotation allows the pre-selection of tunnels for the step of implementation of the maintenance tool. We then present the ordering tool of inspection, maintenance and repair works. We apply this tool to three tunnels of the that represent 164 segments. After, we have compared ten different management strategies in order to study four aspects: the influence of monitoring notes according to MEDITOSS methodology, the influence of performance level targeted, the influence of assignment date of budgets and the influence of intervention priority according to the damage character.

The perspectives of the proposed approach and models concern the strong hypothesis considered: the kind and cost of works, the allocation and the ordering of works and the degradation kinetics. Indeed, in order to simplify the approach and the models, we do not detail the kind of works to done and we consider the main pathologies that affect tunnels and stations. It will be useful to define more precisely the kind of works in order to better correspond to the present approach led by the RATP. Currently, we assign a kind of work to each segment while the current use considers the opportunity of works. That is to say that juxtaposed segments may be repair in the same time. The model should be refined in that way. The proposed degradation kinetics are linear. In order to refine these results, it should be interesting to analyse more precisely the feedback of RATP for each kind of pathology and to numerically model the evolution of structural state of stations and tunnels of the RATP.

### **Acknowledgements**

This work was carried out in the framework of the MEDITOSS ANR project. The authors thank RATP for making it possible to use the results of the measurements performed on its network.

## References

- [1] Breul, P., Gourves, R. and Boissier, D. (1999) In situ granular materials characterization using endoscopy. In: Proceedings of the international symposium on imaging applications in geology - geovision 99, Liege, Belgium.
- [2] Chiessi, V., D'Orefice, M., Scarascia Mugnozza, G., Vitale, V. and Cannese, C. (2010) Geological, geomechanical and geostatistical assessment of rockfall hazard in San Quirico Village (Abruzzo, Italy). *Geomorphology*. 119.
- [3] Davis, A., Lim, M. and Germann, C. (2004) Rapid and economical evaluation of concrete tunnel linings with impulse response and impulse radar non-destructive methods. *NDT&E International*. 38.
- [4] Gourves, R. and Barjot, R. (1995) The Panda ultralight dynamic penetrometer. In: Proceedings of the XIth ECSMFE, Copenhagen, Denmark.
- [5] Kamel, T. (2013) Investigation numérique des différentes phases d'un creusement souterrain par éléments finis et une technique de couplage d'éléments finis et infinis. Thèse de doctorat de l'INSA de Lyon.
- [6] Llanca, D. (2013) Méthodologie de Diagnostic des Tunnels et Ouvrages Souterrains en Service. Thèse de doctorat de l'Université Blaise Pascal.
- [7] Llanca, D., Breul, P., Bacconnet, C. and Sahli, M. (2013) Characterization of the masonry lining of an underground structure by geoendoscopy. *Tunnelling and Underground Space Technology*. 38.
- [8] Llanca, D., Breul, P., Haddani, Y. and Goirand, P. (2013) Methodology of Diagnosis of Urban Tunnels in Service. *World Tunnel Congress*.
- [9] Paterna Hidalgo, A. (2015) Gestion patrimoniale des infrastructures de la RATP: développement d'un processus d'aide à la décision pour optimiser la stratégie de maintenance. Thèse de doctorat de l'Université Paris Est.
- [10] Rhayma, N. Talon, A. and Breul P. (2014) Méthodologie qualitative d'analyse des risques des tunnels RATP. Livrable 4.1 du projet ANR MEDITOSS.
- [11] Rhayma, N. Talon, A. and Breul P. (2014) Méthodologie quantitative d'analyse des risques des tunnels RATP. Livrable 4.2 du projet ANR MEDITOSS.
- [12] Rhayma, N. Talon, A. and Breul P. (2014) Définition d'indicateurs pertinents pour l'aide à la décision. Livrable 4.3 du projet ANR MEDITOSS.
- [13] Sandrone, F. and Labiouse, V. (2010) Analysis of the evolution of road tunnels equilibrium conditions with a convergence - confinement approach. *Rock Mech. Rock Eng.* 43.
- [14] Sandrone, F. and Labiouse, V. (2011) Identification and analysis of Swiss National Road tunnels pathologies. *Tunnelling and Underground Space Technology*. 26.
- [15] Sandrone, F. (2008) Analysis of Pathologies and Long Term Behaviour of the Swiss National Road Tunnels. Ph. D. thesis of the EPFL.