How smart sensoring improve tunnel resilience: from theoretical model to future application

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ABSTRACT: Preventive maintenance has gained more and more attentions since tunnel performance would inevitably degrade against time. It is generally accepted that smart sensoring could in some way assist in the decision for preventive maintenance. However, the timing and cost-benefit when using smart sensoring is quite vague. With regard to this circumstance, applying resilience analysis for tunnels could evaluate the effectiveness of smart sensoring rigorously. The resilience is explained conceptually as the ability of a tunnel to absorb the disruption and the ability to recover to the acceptable performance level. Using the framework of resilience model proposed by the authors recently, this paper illustrates explicitly the timing and cost-benefit in using the smart sensoring to improve the tunnel resilience. It has been derived that if the response time to disruption when applying smart sensoring were n times faster than the time using the traditional monitoring technique, the loss of tunnel resilience could be n^2 times less than the loss in traditional way. The merit of using smart sensoring for tunnel resilience is thus numerically appreciated. Furtherly, preliminary study on resilience-based strategies for two types of repair works for tunnel is presented. One is the repair for disrupted tunnel subjected to unexpected extreme disruption and the other is repair for preventive maintenance under the condition of degradation of tunnel performance in long-term. The time duration and cost-benefit have been included in this design where the multi-objective optimization is applied.

1 INTRODUCTION

The numbers of the operated metro and road tunnels are increased incredibly in the world and China as well. Engineers are facing the ever growing pressures for maintenance and repair of tunnels under operation. The system resilience could reflect its ability to absorb the disruption caused by hazards and the subsequent ability to rapidly recover the performance to its normal level (Ayyub, 2014; Francis and Bekera, 2014). This resilience concept could potentially offer a possibility to assess the timing and repair strategy for preventive maintenance of structures (Wang and Ellingwood, 2015). Hence, needless to say, it is greatly welcomed if a tunnel structure could have a strong resilient ability to remain its function at a high level. But, how to make a tunnel more resilient under the current technology and facilities? It is not clear at present.

The smart sensoring technique, e.g., wireless sensoring network (WSN), nowadays is becoming an effective way to implement a real-time monitoring on the structural health state (Huang, et al., 2013). It might be generally accepted that smart sensoring could in some way assist in the decision for preventive maintenance. But quite often, in view of the additional cost during the long-term monitoring before a real disruption happens to the tunnel structures, the benefit of real-time monitoring usually is not well appreciated by the decision makers.

The authors (Huang and Zhang, 2016) have presented a resilience model for shield tunnel linings under extreme surcharge. This model has been applied to a real tunnel disruption case in Shanghai. From the case study, the effect of real-time monitoring on the tunnel resilient ability has been firstly discussed but without a rigorous derivation. Thus, this paper tries to rigorously derive the effect of real-time monitoring on resilient ability of tunnels. Based on the real-time monitoring technique, preliminary study on resilience-based design of repair strategy for two types of repair is discussed at the end. Before that, the resilience analysis model for tunnels is briefly reviewed.

2 RESILIENCE OF SHIELD TUNNEL

Before a detailed description of the tunnel resilience, the index for tunnel performance should be first specified. An index should be easily measured in site and significantly reflecting the structural response. The tunnel horizontal convergence ΔD is adopted in this paper (shown in Fig. 1), which is probably the widely used index both in practices (JTG/D70-2004, 2004) and researches (Mair, 2008).

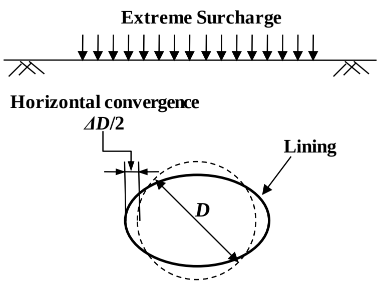

Figure 1 Performance index of lining convergence

Eq. 1 is denoted as the performance index $Q_n(t)$ by a normalization transformation form with ΔD, where ΔD_0 is the initial convergence deflection once the tunnel is built and $\Delta D(t)$ is the convergence at time t which can consider the degradation effect with time.

$$Q_n(t) = \frac{\Delta D_0}{\Delta D(t)} \tag{1}$$

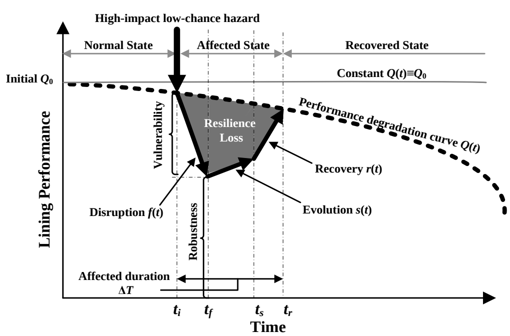

Figure 2 Definition of convergence resilience for tunnels

The resilience is explained conceptually as the ability of a system to absorb the disruption caused by hazards and the ability to recover to an acceptable performance level (Ayyub, 2014). Fig. 2 has illustrated the detailed frame of lifetime performance evolution for tunnel convergence. In general, there are three stages including before surcharge, after surcharge and after recovery. The resilience assessment locates in the second stage, i.e., after surcharge.

Once the surcharge is loaded at time t_i, the tunnel convergence will make a response to this action. The performance will then experience a decrease described by function $f(t)$. The residual performance f_d after this response (at time t_f) stands for the robustness of the tunnel lining. Due to the time cost for decision-making process, the performance will experience a relative stable evolution illustrated by function $s(t)$. Then, once the recovery measures are implemented at time t_s, the recovery will take place until the time t_r reaching to an acceptable level of performance. Hence, the resilience metric can be visually explained by the ratio of the area for the performance evolution function, i.e., $f(t)$, $s(t)$ and $r(t)$, over the area of normal performance function $Q_n(t)$. Mathematically, the resilience index is calculated by following equation:

$$\mathrm{Re} = \frac{t_f - t_i}{t_r - t_i} F + \frac{t_s - t_f}{t_r - t_i} S + \frac{t_r - t_s}{t_r - t_i} R \tag{2a}$$

$$F = \frac{\int_{t_i}^{t_f} f dt}{\int_{t_i}^{t_f} Q dt} \tag{2b}$$

$$S = \frac{\int_{t_f}^{t_s} s dt}{\int_{t_f}^{t_s} Q dt} \tag{2c}$$

$$R = \frac{\int_{t_s}^{t_r} r dt}{\int_{t_s}^{t_r} Q dt} \tag{2d}$$

Several dimensions can be covered in the above metric of the resilience, including degradation, robustness, vulnerability, rapidity and recovery. Details are summarized in Table 1.

Table 1. Resilience dimension and its property

Dimension	Symbol	Property
Degradation	f_i	Degraded performance Q_n(t) at t_i
Robustness	f_d	Residual performance at t_f
Vulnerability	f_i=f_i-f_d	Performance loss at t_f
Rapidity	ΔT=t_r-t_s	Speed of recovery
Recovery	f_r	Recovered performance

3 EFFECT OF SMART SENSORING ON TUNNEL RESILIENCE

The rapidity is a crucial dimension in assessing the tunnel resilience. The smart sensoring could increase the response time of disruption of tunnels and further increase the rapidity of recovery. If there is an ideal tunnel structure that its performance do not degrade with time t as shown in Fig. 3. In other words, the performance Q is always equal to unit. However, once the tunnel is unfortunately disrupted by extreme hazard at time t_i, the tunnel performance has been reduced to f_d (f_d<1) through a period of time ΔT_1. After implementing the repair measures on the disrupted tunnels, the performance has been recovered to normal state (i.e., Q=1) through a period time of ΔT_2. By applying the above mentioned resilience metric, the calculated resilience index Re_1 could be expressed as below:

$$\mathrm{Re}_1 = \frac{1+f_d}{2} \tag{3a}$$

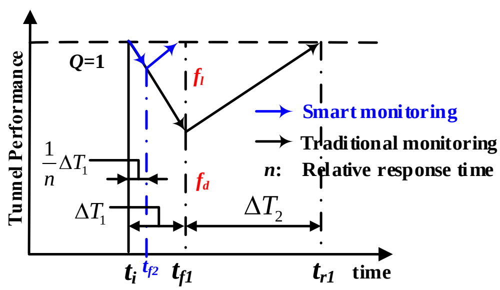

Figure 3 Difference of performance transition curves between smart sensoring and traditional monitoring

In this benchmark problem, if the smart sensoring technique could be used before the disruption happens, the reduction of performance could be captured once it is being reduced. Thus, suppose the time period for tunnel response time in this case of applying smart sensoring equal to $1/n$ times ΔT_1, as shown in blue arrow line in Fig. 3. By applying the same repair measures, the recovery duration could also be $1/n$ times ΔT_2 on the basis of geometric laws. In other words, by applying the same repair measures, the rapidity of recovery by using smart sensoring could be n times faster than the traditional monitoring system. It could be derived further that the area of performance loss in Fig. 3 for the smart sensoring case could be n^2 times smaller than that for the traditional sensoring case. The resilience index Re_2 for the smart sensoring case could be generally n^2 times larger than the Re_1 for traditional sensoring case and is represented as below:

$$\mathrm{Re}_2 = 1 - \frac{1}{2n^2}(1-f_d) \tag{3b}$$

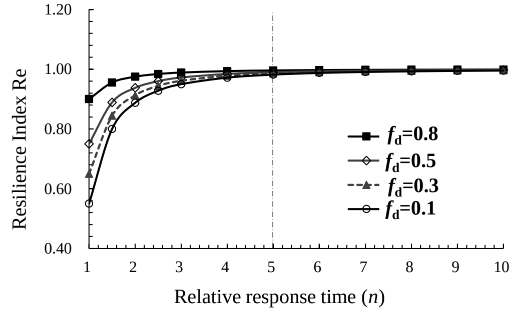

Figure 4 Effect of rapidity of response time by using smart sensoring on the tunnel resilience

Given the robustness performance f_d after the disruption at the level of 0.8, 0.5, 0.3 and 0.1, by applying Eq. 3b, the calculated index Re_2 for smart sensoring case could be plotted against the relative response time coefficient n. It is clear that the coefficient n could greatly affect the results of Re_2. If n is larger than 5, the resilience could be incredibly high and almost equal to unit. That is to say, the tunnel performance could be strongly resilient, regardless of the vulnerability under disruption. This is the reason that the smart sensoring could improve the tunnel resilience even with the same repair or rehabilitation techniques.

Table 2 Comparison of resilience dimension between smart sensoring and traditional sensoring in this benchmark problem

Dimension	Effect of smart sensoring
Response duration	$1/n$
Vulnerability	$1/n$
Robustness	$A - B/n$
Rapidity	$1/n$
Resilience	$C - D/n^2$
Resilience loss	$1/n^2$

Note: Parameter A, B, C, and D is constants when the case is specific and could be calculated by Eq. 2.

Table 2 has summarized the overall effects of smart sensoring on tunnel resilience expressed by using relative response time coefficient n. Since the loss of resilience is related to second order of n, i.e., $\Omega(n^2)$, it thus could clearly indicate the great effect of smart sensoring on the tunnel resilience.

4 RESILIENCE-BASED REPAIR STRATEGY

It is generally realized that resilience analysis should be helpful in assessing the repair strategy in terms of timing and measure for infrastructures. Usually, there are two types of repair works. One is the repair for disrupted tunnel subjected to extreme hazards. The other is the repair for deteriorated tunnel due to material degradation effect in long-term. For the first type of repair, the recovery duration is always the most critical requirement because the social impact due to the stop of tunnel operation is quite significant and usually unacceptable. Hence, by applying the resilience-based repair strategy, the optimal repair parameters could be found to minimize the recovery duration. For the second type of repair, the cost might be the most critical issue compared to the time duration in long-term. By applying the resilience-based repair strategy, the optimal timing to do the recovery could be found to minimize the recovery cost. Hence, the objectives of the resilience-based repair strategy for these two types of repair is different, which is discussed in detail as below:

4.1 Scenario 1: Hazard-caused disruption case

For the first scenario, the disruption due to hazard occurs before any notification or preparation. Hence, after discovering the disruption, the response time in decision making and recovery usually is limited. The stop of operation could trigger the community instability and social risk. Hence, there should be a clear deadline of the recovery, saying $\boldsymbol{T}_{\mathbf{max}}$. Apart from the duration, the disrupted performance f_s after the decision making and the recovered performance f_r after the recovery should be larger than a minimum requirement, saying $\boldsymbol{F_d}$ and $\boldsymbol{F_r}$, respectively. As for the overall performance evaluation, the resilience of disrupted tunnel under such a type of hazard should be larger than a minimum resilience index $\mathbf{Re_{min}}$. Subjected to all these conditions, by varying the duration time $\boldsymbol{t_s}$ and $\boldsymbol{t_r}$ and the recovery parameter vector $\boldsymbol{A_r}$, the objectives of the resilience-based repair strategy for scenario 1 is essentially an optimization that maximizes the index Re and f_r, while minimizes the cost C and total time duration ΔT. The optimization algorithm is described in Fig. 5.

Find:	$(\boldsymbol{t_s}, \boldsymbol{t_r}, \boldsymbol{A_r})$
Subject to:	$\boldsymbol{t_i} \leqslant t_r \leqslant \boldsymbol{T}_{\mathbf{max}}$, $f_s \geq \boldsymbol{F_d}$, $f_r \geq \boldsymbol{F_r}$, $\mathrm{Re} \geq \mathbf{Re_{min}}$
Objectives:	Maximizing resilience index Re; Maximizing recovered performance f_r Minimizing cost C Minimizing time duration ΔT

Figure 5 Optimization algorithm of repair strategy for scenario 1.

The recovery parameter vector includes two sets of parameters. One is the parameters for repair measures $a_{r,1}$, including the type of measure, the intensity of measure, etc,. The other is the parameters for smart sensoring frequency $a_{r,2}$. Because different frequency could result in different cost and the final recovered performance.

$$A_r = \left[a_{r,1}, a_{r,2} \right] \tag{4}$$

The cost during the decision making and recovery stage include the time cost due to the breakdown of tunnels, the cost for repair measures and the cost for smart sensoring implementations, as shown in Eq. 5.

$$C_{\mathrm{tol}} = C\left(\Delta T\right) + C\left(\mathrm{repair}\right) + C(\mathrm{WSN}) \tag{5}$$

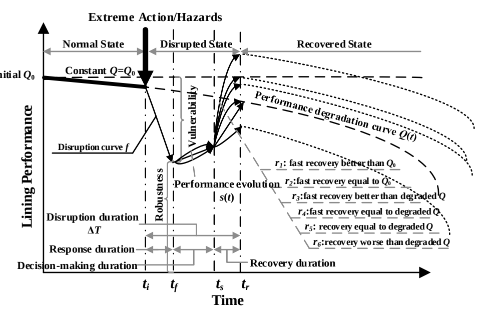

Figure 6 Transition curves with different recovery measures for a disrupted tunnel.

A graphical explanation of the above optimization algorithm is shown in Fig. 6. The performance disruption curve f is determined in the case of scenario 1. The varied parameter is the time t_s and t_r in the horizontal axis and the performance f_s and f_r. However, the performance f_s and f_r is determined by many of factors, including the structural properties of tunnel lining, the repair measures and the smart sensoring strategy in terms of devices and frequency. The effect of smart sensoring on the transition curves has been mentioned in previous session. From the graphical point of view, the less the performance area loss has, the higher the resilience index could obtain. But, the overall optimization results from the above algorithm might not be the one with fast recovery better than initial performance Q_0 since the time duration and cost effect have been included.

4.2 Scenario 2: Degradation-caused case

For the second type of repair, apart from the tunnel operational performance, the overall cost during the long-term operation management is prior to the time duration in the recovery stage since engineers could well prepare to do the rehabilitation works. Figure 7 shows an example of this type of repair. In this case, it differs from the previous discussed performance transition curves. The natural degradation curve is just the disruption curve as shown in Fig. 2. It is widely accepted that the tunnel performance could be deteriorated due to time-dependent factors on material in long-term. Hence, engineers have to do the preventive maintenance for degraded tunnels. However, the question of the preventive maintenance is to find a best timing for conducting the rehabilitation or repair works. As shown in Fig. 7, it needs to be decided for engineers whether we should repair the degraded tunnel at the 1st year of operation, 5th year or something later than that. It matters with the robust tunnel performance, sensoring frequency, maintenance cost and maintenance time duration.

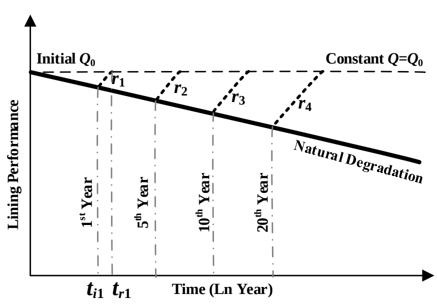

Figure 7 Transition curves with different repair measures for a naturally degraded tunnel

The question of repair timing could be partially answered by doing the following optimization analysis. By varying the time t_i that starts to do the repair work, time t_r that the repair work is finished and varying the repair parameter vector A_r (mentioned previously), the objectives of this optimization is to maximize the resilience index Re and recovered performance f_r and minimize the overall cost C and time duration in recovery ΔT. The condition is that 1) the degraded performance f_i and recovered performance f_r should be larger than the required minimum $\boldsymbol{F_i}$ and $\boldsymbol{F_r}$; 2) the cost should be limited within the maximum acceptable level of $\boldsymbol{C_{max}}$; and 3) the overall resilience index should be larger than the minimum requirement $\mathbf{Re_{min}}$.

Find:	$(\boldsymbol{t_i}, \boldsymbol{t_r}, \boldsymbol{A_r})$
Subject to:	$f_i \geq \boldsymbol{F_i}$, $f_r \geq \boldsymbol{F_r}$, C $\leqslant$ $\mathbf{C_{max}}$, Re $\geq$ $\mathbf{Re_{min}}$
Objectives:	Maximizing resilience index Re; Maximizing recovered performance f_r Minimizing cost C Minimizing time duration ΔT

Figure 8 Optimization algorithm of repair strategy for scenario 2.

These two types of optimization inevitably involve the multi-objective optimization method. The Pareto front is formed due to the multi-objectives since all the objectives hardly could be optimized simultaneously (Juang, et al., 2013; Gong, et al., 2014).

5 CONCLUSION

As the mileage of operated tunnels in cities has been boost up these days, the preventive maintenance and emergency response to the tunnel disruption due to hazards is becoming more and more important. The presented resilience analysis coupled with the implementation of smart sensoring technique could in some way assist the decision maker in a scientific manner to propose a repair strategy for "unhealthy" tunnels. Some of the conclusion could be drawn from this paper as below:

1. By applying the smart sensoring technique in the structural health monitoring system, if the response time could be n times faster than that using traditional technique, the tunnel resilience loss is n^2 times less than the loss for traditional monitoring. This is how the smart sensoring technique to improve the structural resilience.

2. Coupling with the smart sensoring technique, the resilience model could be applied into the design of two types of repair works. The first is the repair for unexpected disruption of tunnel caused by hazard. The resilience-based design could obtain an optimal repair parameters in terms of specific measure, vol-

ume. The second is the repair for preventive maintenance for naturally degraded tunnel due to material time effect in long-term. The resilience-based design could obtain an optimal timing to start the repair.

It should be noted that this is the preliminary study on the resilience-based repair strategies in preventive maintenance. The performance degradation curve in these two types of repair works plays an important role, but at present it has not been well understood by tunnel engineers. Hence, the performance degradation curve should be first cleared up before a concrete resilience-based design of repair strategies.

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REFERENCES

Ayyub, B. M. (2014). "Systems resilience for multihazard environments: definition, metrics, and valuation for decision making." *Risk Analysis*, 34(2), 340-355.

Francis, R., and Bekera, B. (2014). "A metric and frameworks for resilience analysis of engineered and infrastructure systems." *Reliab. Eng. Syst. Saf.*, 121, 90-103.

Gong, W., Wang, L., Juang, C. H., Zhang, J., and Huang, H. (2014). "Robust geotechnical design of shield-driven tunnels." *Computers and Geotechnics*, 56, 191-201.

Huang, H.-w., and Zhang, D.-m. (2016). "Resilience analysis of shield tunnel lining under extreme surcharge: Characterization and field application." *Tunnelling and Underground Space Technology*, 51, 301-312.

Huang, H. W., Xu, R., and Zhang, W. (2013). "Comparative Performance Test of an Inclinometer Wireless Smart Sensor Prototype for Subway Tunnel." International Journal of Architecture, Engineering and Construction, 2(1), 25-34.

JTG/D70-2004 (2004). "Code for design of road tunnel." Ministry of Transportation of the People's Republic of China, Beijing.

Juang, C. H., Wang, L., Liu, Z. F., Ravichandran, N., Huang, H. W., and Zhang, J. (2013). "Robust Geotechnical Design of Drilled Shafts in Sand: New Design Perspective." *Journal of Geotechnical and Geoenvironmental Engineering*, 139(12), 2007-2019.

Mair, R. J. (2008). "Tunnelling and geotechnics: new horizons." *Geotechnique*, 58(9), 695-736.

Wang, N. Y., and Ellingwood, B. R. "Disaggregating Community Resilience Objectives to Achieve Building Performance Goals." Proc., 12th International Conference on Applications of Statistics and Probability in Civil Engineering (ICASP12).