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Resilience and sustainability: an integrated method for quantitative assessment of a bridge – a case study

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Abstract

Sustainability and resilience are important properties of transportation infrastructure. Considering the connection and interaction between them, this paper provides an integrated method for quantitative assessment on resilience and sustainability of transportation infrastructure. In view of the complex, multi-disciplinary nature of the problem, this paper breaks the process into three logical modules that can be studied and resolved in a rigorous and consistent manner. By employing time-dependent reliability and the time-dependent probability of exceeding a damage state as parameters, a robust multi-objective maintenance decision-making method simultaneously considering effects of probable extreme events and natural deterioration is provided. By introducing the 3-D resilience model and six-parameter sinusoidal-based recovery model in resilience theory, the result of risk assessment which involves much inherent uncertainty turns to be more reasonable. Finally, advancing quantification methods of sustainability and resilience are proposed to accomplish the comprehensive assessment with a case study. The method can be used to guide informed decision making in transportation asset management, promote the construction of resilient transportation infrastructure, and accelerate the sustainable development of the city.
Keywords: resilience, sustainability, life cycle assessment.

1 Introduction

In recent years, the global climate change has triggered higher occurrence rate of natural disaster. Since a number of early constructed civil infrastructures are in poor condition, the failure of civil infrastructure function has caused enormous social and economic loss, which reminds people to recognize the importance of resilient civil infrastructure, and add it to the sustainable development strategy. Through review, we find extensive quantitative methods to assessing sustainability or resilience respectively. However, in view of the complex, multi-disciplinary nature of the problem, researchers and practitioners in these two fields often conduct the assessment separately by vaguely disposing the cross area, leading to a certain inaccuracy and incompletion.

While the concept of sustainability remains elusive, it has been recognized that sustainability model addresses simultaneously today's needs and the impacts on future generations, and is characterized by a holistic view and brings together three dimensions: ecology, economy, and society. The connotation of sustainability is very profound and human's understanding of it is gradually thorough. Dating back to 1980s, the earliest sustainability assessment of transportation infrastructure mainly adopted life-cycle cost analysis (LCCA) to estimate economic cost. As LCC has been very mature in practice, recent research on sustainability put more attention on environmental impact of the network from a system perspective. Advancing quantification methods such as economic input-output life-cycle assessment (EIO-LCA), emergy, exergy, ecological footprint, and ecological information-based approaches are then proposed.

The early definition of resilience was dated back to 1970s, even earlier than the first proposal of sustainable development in 1987 [1]. However, it didn't aroused enough attention until extreme events caused huge loss in the 21st century. The popularity of resilience leads people to think about the effect on sustainability from exceptional events. Based on the point that "Contemporary science is preoccupied with that which exists; it rarely accounts for what is missing" [2], emphasized resilience, efficiency and the return of information theory to quantify sustainability.

After that, some scholars noted the relationship between them and qualitatively provided recommendations in resilience improvement and sustainable management by dynamic modeling, like [3], some of them deal with the infrastructure system, like [4]. A more appropriate quantification method towards transportation infrastructure was given by [5], which has found out some similarities between sustainability and resilience. However, sustainability analysis and resilience analysis are still separate in the research; it just weighted the impact by the probabilities of occurrence. Most existing research assessed LCC including seismic risk, but without considering time-dependent vulnerability of the infrastructure [6]. Several recent research considered time-dependent risks of multi-hazard, like [7], whereas risk quantification is very rough for lack of application of resilience theory, and the so-called "Sustainability Assessment" does not reflect well its three dimensions. The U.S. Environmental Protection Agency has realized that understanding system resilience relative to foreseen and unforeseen stressors is one of the biggest challenges to design sustainable systems. Based on the above recognition, an integrated method for quantitative assessment on resilience and sustainability of transportation infrastructure is proposed by this paper.

2 Background information of the bridge in Gansu, China

Because bridges are considered to be relatively vulnerable to extreme events in a transportation network, a built crossing bridge is selected as the assessment object. The bridge shown in FIGURE 1 (a) is part of the Wuguan expressway in Gansu province, China, where belongs to earthquake-prone areas. The designed basic acceleration of ground motion (with 10% probability of exceedance within 50 years) is 0.4g. The engineering foundation of the bridge is class II (According to design standard of China). The natural period of the intact bridge is 0.45s. The heights of piers are 10.0m and 7.0m separately. The designed service life is 100 years.

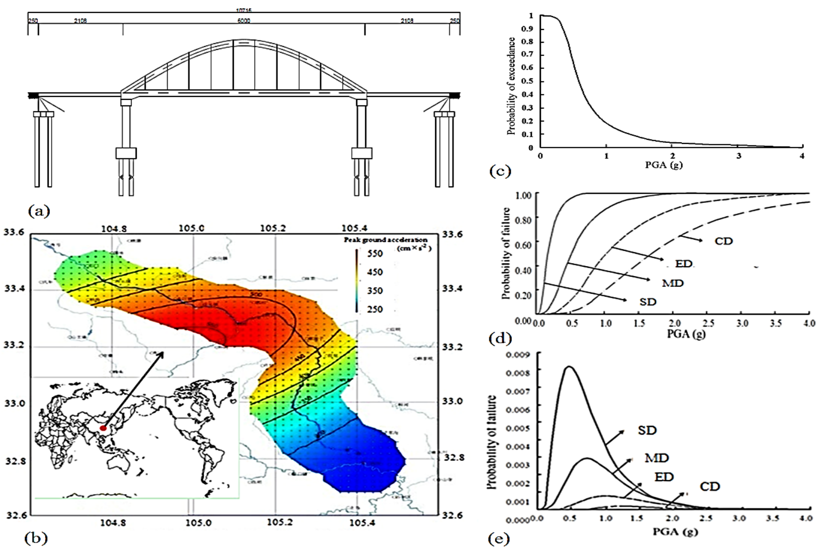

Figure 1: (a) Front layout of bridge structure (unit: cm), (b) earthquake hazard map in peak ground acceleration with the 10% probability of exceedance within 50 years, (c) seismic hazard curves for 50 years at the site of the bridge, (d) fragility curves in intact condition and (e) PD in intact condition.

3 Time-dependent probability of exceeding a certain damage state

For ease of demonstration of analytical procedure, only the seismic hazard is expressed. The software HAZUS-MH MR4 distributed by the US FEMA can be used to provide necessary data for American bridges. Here we explain the procedure with the Chinese case.

Figure 1(e) shows the process to acquire time-dependent probability of exceeding a certain damage state (hereinafter expressed as PD) in intact condition within the PEER framework. According to [8] the seismic hazard curve can be generated for the specific bridge location with data provided by [9] (Figure 1(b) and (c)). Next, 46 earthquake ground motions are selected, which includes records from historic earthquakes as well as artificially generated consistent with the site conditions. An attenuation function is used to calculate the curvature ductility values of the bridge with an obtained strength reduction factor. Comparing the curvature ductility value with that of damage limit states, we can get the fragility curves (as shown in Figure 1(c)). The damage state is divided into five categories (from HAZUS 99) (as shown in Table 2). Fragility curves provide the conditional probability statements of bridge vulnerability of a certain damage state as the functions of the ground motion intensity measure (i.e. PGA).

Given the seismic hazard curve and the fragility curves in intact condition, the original probability of exceeding damage state j is calculated from Eq. (1):

$$P_j(t_0) = \int_0^\infty p_j(x) \left|\frac{dH(x)}{dx}\right| dx \quad (1)$$

where $p_j(x)$ is probability of suffering the damage state j under the PGA of x; $H(x)$ is the annual probability of exceeding the PGA of x.

Due to the time-dependent reliability, the fragility curves should be updated through the lifetime of the infrastructure. According to [10], probability of exceeding the damage state j at year t is calculated from Eq. (2):

$$p_j(t) = P_j(t_0) + A_j.t - N_t.P_M(t) \quad (2)$$

where A_j is the slope of the line that shows the rate of change in PD over time. $P_M(t)$ is the effect of a single maintenance activity, N_t is the maintenance times in t years.

$P_j(t_0)$ has been calculated, 1.66E-03, 7.22E-04, 2.22E-04, 5.01E-05 for SD, MD, ED and CD respectively, with the calculate process is shown in Figure 1(e). Other parameters are related to the optimal maintenance plan.

4 Restoration process under certain damage states

Because the objective of which is to find the best restoration strategy state within minimum loss under a certain damage caused by natural deterioration or extreme events, this paper introduces the resilience concept system of Bruneau and Reinhorn [11] for acute care facilities [11] and the six-parameter sinusoidal-based recovery expectation curve of Bocchini and Frangopol [12] in resilience theory, and develop them to be applicable to normal maintenance strategies as well as restoration (repair/replacement) strategies for comprehensive assessment. Different strategies can be adopted toward the same damage state. Target of the optimal restoration strategy is minimizing the total cost C.

$$C_{total} = C_{dir} + \int \big(1 - Q(t)\big).C_{ind} dt \quad (3)$$

Because the social loss induced by the disruption of the traffic can cause direct and indirect costs that overwhelm the monetary loss owing to the structural damage (the following calculation results can prove), and the Cind of same damage state is the same, the target translates to minimizing $\int(1-Q(t))dt$, which is resilience proposed by Bruneau and Reinhorn [11]. The quantitative value of resilience can be obtained from the six-parameter sinusoidal-based recovery expectation curve defined by Bocchini *et al.* [13] which reflects the gradual change process along with time of the performance. The six parameters are residual function Qr, the idle time interval δi, the recovery duration δr, the target functionality Qt, and two more parameters called s and A, which control the position of the inflection point and the amplitude of the sinusoidal curve, respectively (as shown in Figure 2(a)). In principle, all these parameters can be modeled as independent random variables.

Each strategy corresponds to a recovery curve with the target of minimizing Resilience. The optimal recovery expectation curve of every damage state is shown in Figure 2(b), using solid lines of different colours. It also shows the recovery curve of preventive maintenance strategy (chemical grouting method) and essential maintenance strategy (replacing the components method) in Figure 2(c).

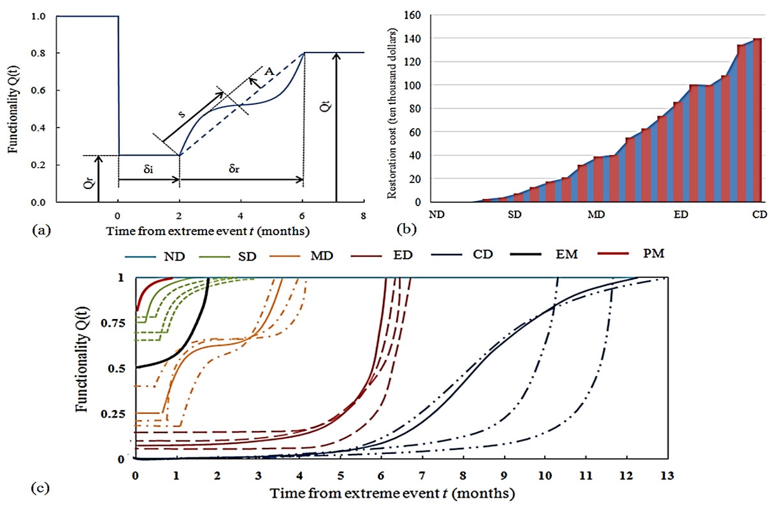

Figure 2: Process to determine restoration strategy. (a) six-parameter bridge recovery function (b) relationship between rehabilitation expense and damage state (c) the recovery pattern associated with different types of damage and maintenance.

4.1 Construction cost

According to 25 samples of engineering practice, we get the relationship between rehabilitation expense and damage state of bridge as Figure 2(b).

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4.2 Social cost

Social cost under every damage state need to discuss two conditions.
(i) Under condition that the increase of functionality is less than 20%, like PM, few vehicles choose to detour, most social cost is from traffic jam on the repaired bridge. The social cost of PM is

$$C_{social}^{PM} = \int_0^{t_r} L_{ef}.\sum_{k=1}^{K}(C_{tj,k}.ADT_k)/(speed_k^{pre} - speed_k^{post}(t))dT \quad (4)$$

$$speed_k^{post}(t) = \frac{speed_k^{pre}.(1+0.15(\frac{ADT}{capacity})^4)}{1+0.15(\frac{ADT}{Q_{PM}(T).capacity})^4} \quad (5)$$

where k indicates the type of vehicles; ADT_k is the numbers of vehicles of type k per day on the bridge; L_{ef} is the length of the expressway that may affected by traffic jam due to EM; $C_{tj,k}$ is the running cost of vehicles of type k due to the traffic jam; $speed_k^{pre}$ is normal speed of vehicles of type k; $speed_k^{post}$ is average speed of vehicles of type k on repaired bridge; $Q_{PM}(T)$ is functionality recovery path of PM.
(ii) Under condition that the increase of functionality is less than 20%, like EM, SD, MD, ED and CD, we assume that the traffic is redistributed to a new balance state in which the speed in the repaired bridge keeps the same and the social cost is totally from detour. Social cost include operation cost, time cost and the cost of traffic accident, the social cost of damage state j is

$$C_{social}(j) = C_{distance}^{s}(j) + C_{time}^{s}(j) + C_{ta}^{s}(j) \quad (6)$$

$$C_{time}^{s}(j) = \int_0^{t_r}[1 - Q_j(T)].C_{time}.dT \quad (7)$$

$$C_{time} = \sum_{k=1}^{K}\sum_{n=1}^{m} ADT_k.s_{kn}.l_n\frac{t_k^{value}}{v_n} \quad (8)$$

$$C_{distance}^{s}(j) = \int_0^{t_r}[1 - Q_j(T)].C_{distance}.dT \quad (9)$$

$$C_{distance} = \sum_{k=1}^{K}\sum_{n=1}^{m} ADT_k.s_{kn}.l_n.c_k^{distance} \quad (10)$$

$$C^{S}{}_{ta} = C_{ta}.t_r \quad (11)$$

$$C_{ta} = \sum_{k=1}^{K}(TC_k^{post} - TC_k^{pre}).W_k.t_r \quad (12)$$

where $C_{time}, C_{distance}, C_{ta}$ is the daily time cost, daily vehicle running cost and daily accident cost due to the lost functionality respectively; ; n indicates the detour path; m is the total number of detour; s_{kn} is the ratio of vehicles of type k on detour n; l_n is additional travel distance of detour n. v_n is average speed of vehicles on detour n. t_k^{value} is VOT for vehicles of type k; $c_k^{distance}$ is the cost per mile covered by vehicles of type k. $Q_j(T)$ is functionality recovery path of damage state j; t_r is the recovery time; TC_k^{post} is the daily traffic accident rate during the recovery time; TC_k^{post} is normal daily traffic accident rate; W_k is the loss when traffic accident happen to vehicles of type k. The values of main parameters are listed in Table 1.

Table 1: Characteristics of the maintenance and seismic restoration strategies.

Damage state	Maintenance strategy		Seismic restoration strategy				Data sources
	Preventive Maintenance (PM)	Essential Maintenance (EM)	Slight Damage (SD)	Moderate Damage (MD)	Extensive Damage (ED)	Complete Damage (CD)	
Best estimate damage ratio	/	/	3%	8%	25%	100%	ATC-13
Residual functionality	80%	50%	75%	25%	10%	100%	HAZUS-MH MR4
Idle time interval (weeks)	0	0	1	2	2	4	Engineering experience
Recovery duration (months)	0.75	1.5	1.5	3	5	12	Engineering experience
Construction cost （$）	22500	54000	87587.5	350350	788287.5	1401400	Engineering experience
Environmental cost（$）	5320.2	60830.1	6956.1	81153.3	238822.6	435668.4	Calculated
Social cost($)	148200	23487938	3746939	35065638	1.04E+08	1.88E+08	Calculated

4.3 Environmental cost

The restoration costs of the optimal normal maintenance strategies and seismic restoration strategies under different damage states are shown in Table 2.

Table 2: Statistical descriptors and deterministic parameters used for the social cost analysis.

Deterministic parameter	Value			Reference
ADT Cars	67500			Highway Administration
ADT Trucks	8750			Highway Administration
Normal speed of cars（km/h）	80			Highway Administration
Normal speed of Trucks（km/h）	60			Highway Administration
Average detour additional travel distance of cars（km）	18.5			Assumed
Average detour additional travel distance of Trucks（km）	24.5			Assumed
The average length of crowded road due to EM(km)	2			Highway Administration
Average rate of accidents	0.348			Literature (*30*)
Average rate of accidents during erection	0.588			
Average cost of every accident（US$）	1930			
Number line of the bridge	4			Highway Administration
Traffic flow capacity of bridge(pcu/h/lane)	1600			Assumed
Random variable	Mean	COV	Distribution type	
Time cost of cars（$/h）	13	0.21	LN	Assumed
Time cost of trucks（$/h）	15	0.23	LN	Assumed
Operation cost for cars($/km)	0.12	0.19	LN	Literature (*14*)
Operation cost for trucks($/km)	0.56	0.19	LN	
Operation cost for cars due to traffic jam($/h)	1.1	0.2	LN	
Operation cost for trucks due to traffic jam($/h)	6.2	0.26	LN	

5 The optimal maintenance schedule

Figure 3(a) shows the performance of the bridge in its service life. Hatami and Morcous [14] presented the method to establish deterioration model. For

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simplicity two stage function is employed, natural deterioration curve without any maintenance is obtained.

Knowing that the initial value for reliability is $\beta_0 = 7.0$, deterioration start at 15a, average deterioration rate is 0.10/a, the limitation value can be accepted is 4.2; the initial value for state of bridge is $V_0 = 88$, deterioration start at 10a, average deterioration rate is 1.8/a, the mini-mum value can be accepted is 39. The original PD with no deterioration and the function of time-dependent PD has been discussed in section 4.1. Operation and maintenance strategies of bridge include periodic detection, annual maintenance, preventive maintenance (PE), essential maintenance (E). Chemical grouting method is adopted as preventive maintenance strategy to delay the deterioration proceeding of the bridge, while component replacement method is adopted as essential maintenance strategy to improve the performance of the bridge. Taking time-dependent PD, time-dependent reliability and the condition state as constrains, taking the minimization of the probabilistic maintenance cost (sum of normal maintenance cost and seismic cost) as objective, using genetic algorithm to obtain the optimal maintenance schedule and the minimum probabilistic maintenance cost. Synchronously the time-depend PD is updated over the service life (Figure 3(b)). With single cost in Table 2, yearly maintenance expenses and seismic risk are then totaled and discounted back to the base year to achieve the net present value (NPV) of the construction, social, and environmental costs (as shown in Table 3).

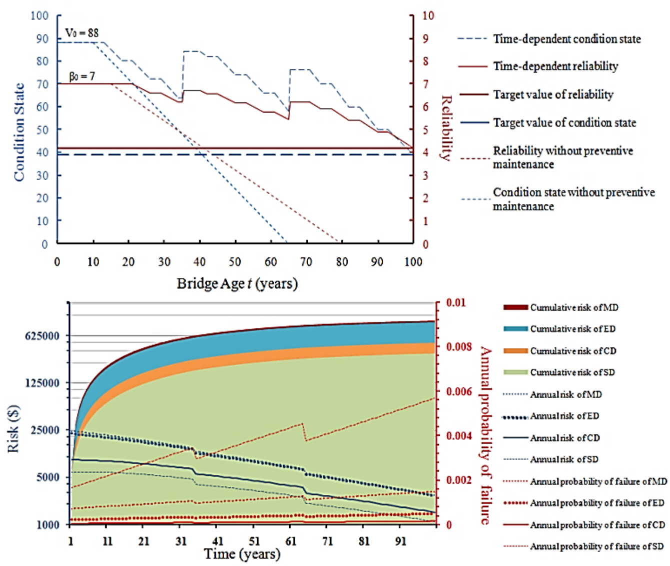


Figure 3: (a) Time-dependent reliability and state of bridge and (b) time-dependent seismic risk cost.

6 Life-cycle assessment

The EIO-LCA and LCC methodology is adopted here. Economic cost including construction cost C_c and social cost C_s are quantified by LCC. Yearly probabilistic expenses are then totaled and discounted back to 2013 to achieve the net present value (NPV). Non-economic impact, defined as C_e environmental cost is quantified by LCA.

Table 3: NPV of the maintenance cost and seismic risk under the optimal maintenance plan.

Maintenance	Periodic detection	Annual maintenance	PM	EM
Maintenance effect per time	/	/	Delay the deterioration proceeding of the bridge about 3 years	State of bridge improve about 20， reliability improve about 0.8
Cost per time (thousand US$)	16	0.9	22.5	54
Starting year	5	1	10	35
Number of times	20	100	11	2
Interval (a)	5	1	8	30
NPV of maintenance cost in service life (thousand US$)	95.2	167.5	575.8	6603.7
Damage state	SD	MD	ED	CD
PD of the initial year	1.66E-03	7.22E-04	2.22E-04	5.01E-05
RISK of the initial year (US$)	6047.508	24577.28	22329.42	9125.722
Annual slope of PD[A(j)]	5.44E-05	1.05E-05	3.74E-06	1.43E-06
NPV of the seismic risk in service life (million US$)	3447.692	10671.44	10082.81	4919.125
Total RISK of all damage states (million US$)	/	/	/	29121.07

They are weighed by willingness to pay of native citizens. The total cost is denominated in U.S. dollar, expressed as:

$$C_{total} = C_c + C_s + C_e \tag{13}$$

(1) The formulation to calculate total construction cost is:

$$C_c = C_I + C_{QA} + C_{DE} - C_{RE}$$
$$+\sum_{t=1}^{T_{life}}\left[C_{an}(t) + C_{IN}(t) + \left(1-\sum_j p_j(t)\right).C_M(t) + \sum_j p_j(t).C_j\right]/(1+r)^t \tag{14}$$

where C_I is the cost of design and construction; C_{QA} is the cost of quality assurance and safety controlling; C_{DE} is decommissioning cost of the bridge; C_{RE} is the value of recycling of the bridge; C_{an} is annual maintenance costs; $C_{IN}(t)$ is the cost of periodic detection in the year t; $C_M(t)$ is the cost of EM or

PM in the year t; j indicates the damage state of the bridge; $p_j(t)$ is the probability of bridge damage state j in the year t due to the earthquake; C_j is the direct cost of damage state j; r is discount rate. T_{life} is the service life of the bridge. Substitute the data (in Table 1) into this equation, the NPV of life-cycle construction cost is 1.92 million dollars.

(2) Because the bridge in this case is across a river, we don't consider the traffic impact during construction and disposal phase. Base on the optimal maintenance plan and the corresponding seismic risk, we can calculate the total social cost:

$$C_{social} = \sum_{t=1}^{T_{life}} [\gamma_t . C_{social}^{EM} + \delta_t . C_{social}^{PM} + \sum_j p_j(t) . C_{social}(j)] / (1+r)^t \quad (15)$$

If EM is done in the year t, $\gamma_t = 1$, if not, $\gamma_t = 0$; if PM is done in the year t, $\delta_t = 1$, if not, $\delta_t = 0$. The rest is as same as above.

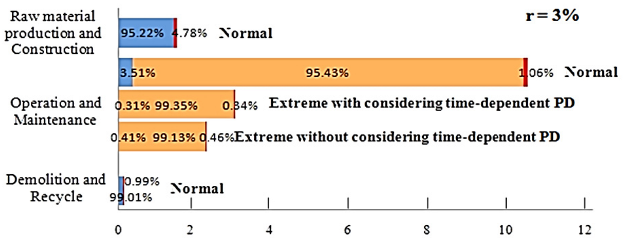
(3) For briefly, the life-cycle inventory, the main calculate process and the final results are all provided in Table 4.

Table 4: Results of environmental LCA assessment.

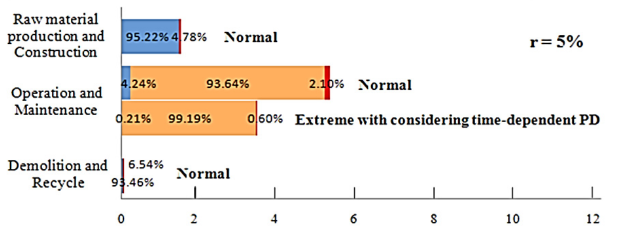
Type of items	Manufacturing and construction	Preventive maintenance	Essential maintenance	Backout
HPB235 steel/kg	75637.1	—	—	—
HRB335 steel/kg	411823.2	2809.5	4096.7	—
Steel strand/kg	44298.6	—	10241.9	—
Steel plate/kg	4916.5	—	16387.0	—
C25 concrete/m3	1261.3	29.6	99.7	—
C30 concrete/m3	1372.0	—	4.3	—
C40 concrete/m3	1298.2	88.9	421.1	—
Corrosion inhibitor/kg	—	41283.9	—	—
Structural adhesiv/kg	—	11544.7	—	—
Epoxy resin/kg	—	1233.7	—	—
Cement/t	4.4	31.2	79.4	—
PVC pipe/kg	299.7	—	123.3	—
Water/m3	8222.1	4887.7	1949.3	746.4
Gasoline/L	160.9	2428.5	831.1	13.5
Diesel/L	34157.9	10066.8	4511.2	2876.3
Electricity/(kw.h)	212181.1	7132.2	32749.2	17681.8
Type of environmental influence	Potential impact /kg	Social willingness-to-pay/$	Value of environmental influence/$	
Global warming potential	4025096.0	0.03537	142366.7	
Acidification potential	1810.3	0.10129	183.4	
Eutrophication potential	116001.4	0.14469	16784.8	
Solid waste	1120882.8	0.00402	4505.2	
Photochemical smog potential	1219.9	1.60772	1961.2	
Water resource consumption	23311689.2	0.00009	2098.8	
Standard coal	1211539.4	0.00016	190.9	
Diesel	24648.6	0.00135	33.3	
Mineral resources consumption	14830913.4	0.00032	4768.8	
Summation	—	—	172893.0	

7 Results

The results of whole life-cycle cost are shown in Figure 4. It shows that when discount rate is 3%, the total cost of life-cycle is $11,750,000, of which sustainability part is $9,055,100 and resilience part is $2,932,400. Social cost accounts for the largest proportion of the total cost, which is $9,883,700, in which social risk of extreme events is $2,913,200, accounts for 29.5%. Social risk of extreme events is $2,020,500 without considering time-dependent PD, which is reduced by 30.64% compared with that considering time-dependent PD at $2,913,200. When discount rate is 5%, the total cost of life-cycle is $6,830,600 and the social cost is $4,869,700. The proportion of environmental cost is very small because the residents' willingness to pay for environmental impact is still very low in that area in China.



	Raw material production and Construction	Operation and Maintenance			Demolition and Recycle
		Normal	Extreme with time-dependent PD	Extreme without time-dependent PD	
Construction cost	1.42	0.36	0.00	0.00	0.14
Social cost	—	9.88	2.91	2.20	—
Environmental cost	0.07	0.11	0.01	0.01	0.00



	Raw material production and Construction	Operation and Maintenance		Demolition and Recycle
		Normal	Extreme with time-dependent PD	
Construction cost	1.42	0.22	0.00	0.02
Social cost	—	4.87	1.68	—
Environmental cost	0.07	0.11	0.01	0.00

Figure 4: Composition of the cost when discount rate is 3% and 5%.

8 Conclusions and future directions

(1) Based on deep consideration of connection and interaction between sustainability and resilience, a robust multi-objective maintenance decision-making method simultaneously considering effects of probable extreme events and natural deterioration is provided. Superior to the existing research results, it

not only considers time-dependent reliability and time-dependent PD, but also highlights the resilience theory, thereby the result of risk assessment which involves much inherent uncertainty turns to be more reasonable.
(2) According to the results in the case study, when discount rate is 3%, seismic risk accounts for 24.96% of the total cost, so importance should be attached to the comprehensive assessment. In addition, if without considering time-dependent PD, the social risk of extreme events will reduce 30.64%, which confirms the necessity of the integrated method.
(3) Based on the framework of this method, developed areas with perfect statistical system and data sharing mechanism can establish life-cycle inventory database and adopt emergy, exergy, and ecological information-based approaches to quantify sustainability of the infrastructure, then the assessment results in areas with different economic levels and different probability of extreme events can be compared.
(4) The connotation of sustainability is very profound and human's understanding of it is gradually thorough, we still cannot say we have understood all the meaning of sustainability, there is more profound connotation awaiting discovery especially in dimension of ecology.

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References

[1] Gordon, J.E. Structures. Penguin Books, Harmondsworth, UK, 1978.
[2] Michel Bruneau, Stephanie E. Chang, Ronald T. Eguchi, George C. Lee *et al*. A framework to quantitatively assess and enhance the seismic resilience of communities. Earthq. Spectra. Vol. 19, Issue. 4, 2003, pp. 733–752.
[3] Joseph Fiksel. Sustainability and Resilience: Toward a Systems Approach. IEEE Engineering Management Review, Vol. 35, No. 3, 2007.
[4] Villarreal-Marimon, Yang Gu, Yanyi He, Zhaoyang Duan, and Lizhi Wang. Sustainability and Resiliency Measures for Long-Term Investment Planning in Integrated Energy and Transportation Infrastructures. Journal of Energy Engineering, Vol. 138, 2012, pp. 87–94.
[5] Paolo Bocchini, Dan M. Frangopol, Thomas Ummenhofer, and Tim Zinke. Resilience and Sustainability of Civil Infrastructure: Toward a Unified Approach. Journal of Infrastructure Systems, Vol. 20, No. 2, 2013.
[6] Mohammed Safi, Håkan Sundquist, Raid Karoumi, and George Racutanu. Integration of Life-Cycle Cost Analysis with Bridge Management Systems. In Transportation Research Record: Journal of the Transportation Research Board, No. 2292, Transportation Research Board of the National Academies, Washington, D.C., 2012, pp. 125–133.
[7] Benjin Zhu, and Dan M. Frangopol, Dist. Risk-Based Approach for Optimum Maintenance. Journal of Structural Engineering, Vol. 139, 2013, pp. 422–434.

[8] Zhang Kai, Zhu Xi, Ni Yongjun, and Jiang Hui. Performance-Based Seismic Financial Risk Assessment for Bridge Structure. China Railway Science, Vol. 32, 2011, pp. 68–74.

[9] Zexian Zhao. Probability Prediction of Seismic Geological Hazards Along the Wu-guan Freeway. Lanzhou Earthquake Research Institute of China Earthquake Administration, 2012.

[10] Azadeh Alipour, Behrouz Shafei, and Masanobu Shinozuka. Performance Evaluation of Deteriorating Highway Bridges Located in High Seismic Areas. Journal of Bridge Engineering, Vol. 16, No. 5, 2011, pp. 597–611.

[11] Michel Bruneau, and Andrei Reinhorn. Exploring the Concept of Seismic Resilience for Acute Care Facilities. Earthquake Spectra., Vol. 23, No. 1, 2007, pp. 41–62.

[12] Bocchini, Paolo, and Frangopol, Dan M. A probabilistic computational framework for bridge network optimal maintenance scheduling. Reliability Engineering and System Safety, Vol. 96, No. 2, 2011, pp. 332–349.

[13] Alberto Decò, Paolo Bocchini and Dan M. Frangopol. A probabilistic approach for the prediction of seismic resilience of bridges. Earthquake Engng Struct., Vol. 42, 2013, pp. 1469–1487.

[14] Afshin Hatami and George Morcous. Deterioration Models for Life-Cycle Cost Analysis of Bridge Decks in Nebraska. In Transportation Research Record: Journal of the Transportation Research Board, No. 2313, Transportation Research Board of the National Academies, Washington, D.C., 2012, pp. 3–11.