Special feature article

"Visible" Maintenance

Professor, Department of Civil Engineering, School of Engineering, the University of Tokyo
Yozo Fujino

1. The Power of Images

Many readers are probably familiar with the famous accident in the field of bridges, namely, the Tacoma Narrows Bridge in 1940. It had large wind-induced vibration and brought down just under half a year after completion. The late emeritus professor Atsushi Hirai, my mentor professor of our faculty two generations ago, started the study of wind-resistant long-span bridges using the wind tunnel of Department of Aeronautics and Astronautics of our university just after the World War II. In the early 1960s, he built a large-sized wind tunnel that he financed himself, and produced numerous pioneering results. Those results have benefited construction of long-span bridges in Japan and abroad, including the Honshu-Shikoku Bridges. I heard from Prof. Hirai that he had a chance to watch the film of the Tacoma Narrows Bridge collapsing in a movie theater during the war, and this made him start the wind-related bridge study. If the film had not existed, and if Prof. Hirai had not seen it, he may never have set out the study of wind-resistant long-span bridges. Actually, there were many other collapses of suspension bridges by wind before the accident of the Tacoma Bridge, but those did not lead to academic study. After the Tacoma Bridge accident, wind resistance was actively studied, and construction of long-span bridges was at its peak. I suppose that was because the impressive image of the film drove much young talent to this field. The last scene of the film where the bridge falls is truly dramatic and memorable no matter how many times I watch it.

Just over a year ago, a large truss bridge in Minnesota, USA, suddenly collapsed. That was reported on TV and in newspapers even here in Japan, and it triggered society to question if Japanese bridges are safe. Surprisingly, a monitor camera caught the very moment of the collapse, and we can see the scene on the Internet (URL: http://en.wikipedia.org/wiki/Image:35wBridgecollapse.gif).

That bridge, which we would now regard as frail, was constructed in the late 1960s as a product of a time when people thought lighter was better. There was concern over fatigue for many years, and rust was severe. Investigation of the bridge had thus been commissioned to the University of Minnesota and consulting companies since 2001. They conducted a broad-ranging investigation mainly on the fatigue of the materials, and had increased the frequency of inspections. The final investigation report of National Transportation Safety Board (NTSB) will be reportedly made public in autumn 2008, but has not yet been released as of the writing of this article. We now know that there were design errors in some panel points where truss components were connected to each other. The prevailing view is that heavy material of repair slabs happened to be placed right on the panel points with the design error, and that caused the collapse. We could learn a lot from the fact that the primary cause was simply a design error of the panel points, which were unexpected points that experts did not take into account at all. Of the many pictures taken at inspections and checks, some taken in 2003 show out-of-place deformation of the plates in question. How could such an accident occur in a country that is universally recognized as advanced in the area of bridge management including inspection? There is no end to the questions this incident provoked.

Unfortunately, the images did not catch the panel points that we consider as the cause of the collapse. On the other side of the bridge, however, we can see how truss girders bent and broke at the gusset plates that had only half the specified thickness because of a similar design error. The video clip that demonstrates how

Profile

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1949	Born in Tokyo
1972	Bachelor of Engineering, the University of Tokyo
1976	Ph.D. (Civil Engineering), University of Waterloo
1977	Research Assoc., Earthquake Research Institute of the University of Tokyo
1979	Assistant Professor, Institute of Structural Engineering, University of Tsukuba
1982	Associate Professor, Department of Civil Engineering, the University of Tokyo
1990	Professor, Department of Civil Engineering, the University of Tokyo
1997	Melchor Chair Visiting Professor, the University of Notre Dame, Indiana, USA
2002	Concurrently served as Science Advisor of the Ministry of Education, Culture, Sports, Science and Technology through 2004
2008	Director of Global Center of Excellence for Sustainable Urban Regeneration, the University of Tokyo

Currently Professor, Department of Civil Engineering, School of Engineering, the University of Tokyo

Other main posts:
Vice President of the International Association for Bridge and Structural Engineering
President of the International Association on Structural Control and Monitoring
President of the Japan Association for Wind Engineering
Others

easily and fragilely a bridge can collapse gives an intense impression. That will symbolize the difficulty and importance of maintenance long into the future.

2. Does Maintenance Have What it Takes to be in the Lead Role?

In Japan, it is said that the era of continuous construction of infrastructure is over and lead role will now go to maintenance.

The shift from new construction to preventive maintenance is just now starting in the area of roads. I think that the lead role for railways has essentially gone to maintenance even longer.

Since the late 19th century, Japan has made enormous investment in social infrastructure, which has brought about huge stock of infrastructure. Railways have been built much earlier than roads; and some tracks and facilities that are constructed before the World War II, or even before that, are still used. While construction of the Shinkansen network is still proceeding and we are facing a new railway era, I do not think that new construction will show a sharp increase in future because of various domestic situations. Thus, it is no wonder that maintenance is said to have taken the lead role. I wonder if people in other fields see so too.

The word "construction" has a brighter image in contrast to "maintenance", and that naturally interests young people. Maintenance, on the other hand, presents an image for many people of breakdowns and repairs or inspection and mending. The image the word presents is still not very positive. But is the role of maintenance really just keeping the current situation by simply fixing things that have gone bad?

3. Factors That Define Maintenance

Many structures that were made long ago were carefully built; but they were built in poorer times for the most part and the techniques used were of course not-yet perfected. Vibration of earthquakes such as the Great Hanshin-Awaji Earthquake in 1995, for example, was naturally not taken into consideration. The Japanese landscape becomes steep just a short distance from the sea, and railway tracks curve among mountains; so increasing speeds is difficult. The ground along the coast is generally not very firm; so, while replacement of trains and signal equipment is relatively easy, building structural facilities is not. Furthermore, there is strong recognition that some of the large amount of infrastructure built in Japan's period of high economic growth was designed and constructed with more emphasis on speed than quality.

There was an accident in Quebec, Canada in 2006 that received little reporting in Japan. A beam of a viaduct built in the 1970s suddenly fell of and killed five persons. The viaduct was of a cantilever structure that was highly acclaimed as a novel design at that time. The investigation committee's report stated that while there were problems with maintenance, the original design and construction work were poor. Although not an example of railways or bridges, statistics of the amount of damage from accidents of power generation facilities shows that the top cause is poor maintenance; but a close second is construction and production faults.

As they are designed and manufactured by humans, there are many cases where the product is imperfect or not produced as expected, as the accidents of the bridges in Minnesota and Quebec indicate. And furthermore, we should realize while they met the standards of that time are not up to present requirements.

There were two peaks in bridge construction in Tokyo, the first being reconstruction of bridges after the Great Kanto Earthquake in 1923, and the second new construction in the period of high economic growth before and after the 1964 Tokyo Olympic games. The number of the latter was overwhelmingly larger. Bridges of the former including the Kiyosu Bridge and the Eidai Bridge are obviously robust and massive. On the other hand, bridges of the latter were rationally designed with less steel weight. Comparing the cumulative maintenance costs of an 80-year-old bridge and a 40-year-old bridge, we find that costs for the former—older—bridge are less, which is surprising.

This fact explains how much design and construction of high quality and high durability can reduce the burden of maintenance for things such as infrastructure that should be valued for a long span of time. Construction and maintenance hence have a very close relationship to each other; so, we should consider those integrated. Current expectations are for establishing a technical system to integrate those and to create a word to describe that system.

4. Maintenance Requires Scale

Japan is often struck by earthquakes, heavy rainfall, strong winds, and other natural disasters. And the monetary amount of losses in Japan ranks second only to the USA. Japan is thus one of the major sites of natural disasters, accounting for 15% of total world losses (Fig. 1). Japan faces such severe circumstances; and furthermore, it owns enormous amounts of infrastructure, including some that are poor, that slowly but steadily deteriorate. Still, further improvement of safety and services is required while having them meet demands and needs that change over time. We need much wider and deeper technologies and work that can never be represented using the simple word "maintenance". But I am afraid most people take little note of that compared to showy new construction.

From the perspective of sustainability, global warming is a big and hot topic now. Anyone can imagine that the increase of world energy consumption at this pace is not environmentally friendly, and that it will result in depletion of resources for an increasing population. It is almost self-evident too that leaving infrastructure untouched will lead to big troubles. But is maintenance of infrastructure gaining the acceptance by society that it needs? I think that the reason of the success of the global warming prevention campaign is that rather than employing abstract slogans like "take care of the global environment", it introduces targets of reduction in CO_2 emissions, a quite clear numerical target. Setting quantitative targets also sets the direction for technical development. The environment is obviously linked to business now. Technologies to reduce CO_2 emissions attract attention, so, human and financial resources are flowing into them.

I once studied the relationship between the number of disasters and the amount of the investment in disaster prevention in the Japan National Railways era. There is no doubt of a negative correlation where investment reduces accidents. The investment effect does not appear at once, but influences situations long into the future (Fig. 2). For facilities such as plants, I found a similar negative correlation between disaster and investment; but I also found that effects of such investment appear immediately and disappear in a few years. Disaster prevention investment in infrastructure is thus not like an antibiotic, but rather like herbal medicine; one has to keep taking it for long time as its effects become apparent gradually over time. It is vital to

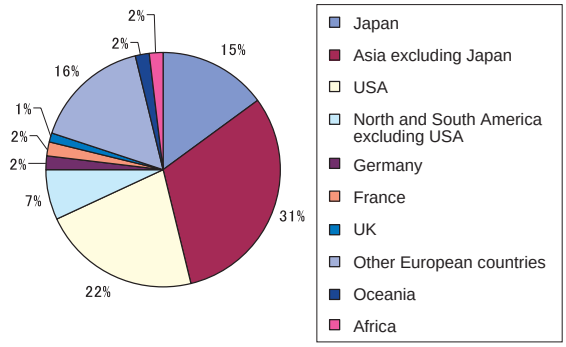

Fig. 1 Monetary Amount of Damage by Natural Disasters per Region (1970 – 2004 Total: Approx. US $1.1 trillion) (Compared to the 22% for the USA, Japan accounts for 15% of damage costs even with its greatly smaller land area, outstripping that of other countries. From the viewpoint of the density of natural disasters, Japan is by far No. 1 in the world.)

take a long-range view of such low-profile investment; and therefore, a long-term strategy is indispensable. I hope top management and other decision makers have a sound policy of maintenance including disaster prevention, and further hope users and society understand why such a policy is necessary. For that purpose, I suggest the need to develop an index to make the effects of maintenance visible in a broad perspective.

5. Aiming for "Visible" Maintenance

Creating an index based on traditional visual inspection might be an idea. But, can the effect of aseismic reinforcement be evaluated visually? Once train operation is suspended at large seismic vibration, operation recovery requires labor and time because facilities along the tracks have to be checked one by one. Will we continue to rely on manpower that? Traditional visual inspection has its advantages on one hand, but accidents in recent years have demonstrated the limits of such visual inspection.

What has remarkably advanced in the past decade and will doubtlessly continue advancing is technologies for measurement and information. The ability to view performance of infrastructure has significantly advanced with that. For example, large-scale calculation that has become possible now has considerably contributed to advances in prediction of deterioration of concrete for example 10 or 30 years in the future and simulation of minute and ultimate behavior in an earthquake. What is required for verification and improvement of a model is measurement values; specifically, initial conditions, boundary conditions, and internal conditions are needed. Each and every piece of infrastructure that we handle is different in design, construction, ground and use conditions. That is so to say, they are on a meso scale between macro scale and micro scale. Since the behavior of such meso-scale infrastructure is extremely complex, there are many factors that can only be understood after measurement. We even face the fundamental question what to measure. But prediction technology cannot advance without measurement. While prediction of rocks falling on railway tracks from slopes is an issue that will have to wait for future advances, we should note that there is another way of measuring where we give an

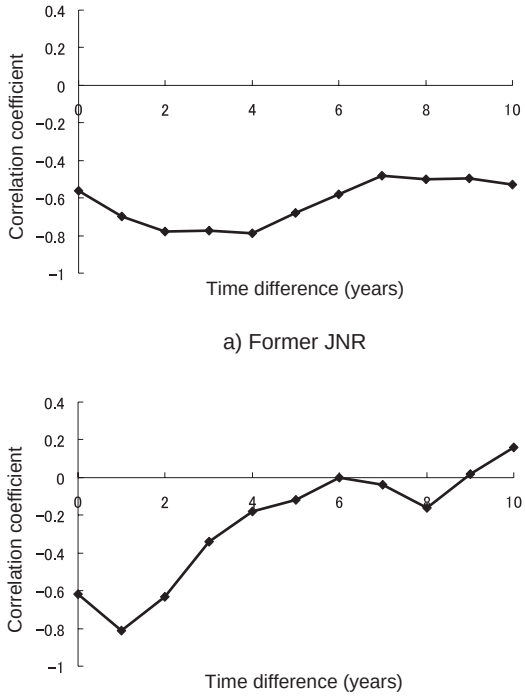

Fig. 2 Correlation Coefficient Between Number of Disasters and Disaster Prevention Investment (Those both show negative correlation, but the correlation for plants (high pressure gas) in Diagram b becomes almost zero in a couple of years (investment effect disappears) in contrast to the long-lasting negative correlation for JNR (Diagram a). Using the analogy of medicine, the former is a kind of antibiotic and the latter is kind of herbal medicine.)

alert as soon as rocks fall onto the tracks.

Roughly speaking, the risk to infrastructure depends on hazards such as seismic vibration that causes the risk of vulnerabilities of the infrastructure itself. The ability to more precisely measure hazards has been gained in this decade as demonstrated by K-net (Kyoshin-network), a public database of large earthquakes in Japan. The result of that is Now Cast and other systems that warn of seismic vibration several seconds before it arrives. But, what is not achieved yet is measurement of the infrastructure's own vulnerabilities and measurement of the risk itself. Although everyone knows that measurement of meso-scale infrastructure is difficult, I believe that performance of infrastructure cannot be made visual unless we pursue that measurement.

A railway is a complex and enormous system that includes more than just tracks and facilities. It also includes elements with different characteristics such as trains and their operation as well as station spaces. Trouble in any element can threaten safety of users. It is the railway companies that own, apply new technologies to and improve the sites for that system. Railway companies that have long histories and traditions of maintenance taking leadership in achievement of visual maintenance, and producing many maintenance engineers, should mean that maintenance is taking the lead role. I have great expectations for railway companies. And I also have confidence that such maintenance will secure safety of users and lead to the ultimate service.