특집

건축 토목구조물의 비파괴검사방법

The Role of Nondestructive Evaluation in Infrastructure Terotechnology

사회간접자본시설의 손상도 평가, 진단, 보수 · 보강에 있어서 비파괴검사의 역할

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It is broadly agreed that an intelligent revitalization of decaying Civil Infrastructure System (CIS) can be achieved through three technologically importat areas of study (Terotechnology): deterioration science, assessment technology, and renewal engineering. In this paper, an overview of the role of nondestructive evaluation (NDE) in CIS Terotechnology is presented. The condition-based maintenance approach requires effective NDE methods for global condition monitoring and detailed inspection of structures. Nationally and internationally acknowledged critical CIS/NDE research priority areas are surveyed and the conclusions are drawn from the current state for suggesting potential future use of NDE in CIS assessment and renewal including repair technology and emerging construction materials.

1. Introduction

Human civilization has been evolved from the Stone Age with the technological renovations and innovations of civil infrastructure systems. Truly marvelous technological advancements have been achieved from then to now for building this civilized world. The CIS in any nation is the major artery of the national transportation network and the backbone of the industrial conglomeration. It is thus obvious that a failure of proper construction and

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maintenance of the CIS will end up with tremendous deleterious impact on the society as well as damage on her industrial strength. Maintaining healthy CIS should thus be placed in the top priority of national technology agenda for survival of the nation in the highly competitive world marketeplace.

It should be realized that all man-made materials and structures are aging. In particular, structures in CIS are in potential danger of catastrophic disaster under the circumstances of neglected maintenance, resulting in loss of precious public properties and, worst of all, invaluable human lives. Such worst case scenarios can be prevented or at least minimized by means of effective maintenance through nondestructive evaluation.

Negligence of research in CIS for the last 30 years has resulted in the problems of transportation performance degradation, aging infrastructure, poor quality of life and higher risk of disastrous structural failure. As a consequence, research and development in CIS is now placed in one of the high priority technological investments among the federal agencies of the United States.

In this article, an attempt will be made to identify current needs for research and development in civil infrastructure systems. The potential role of nondestructive evaluation(NDE) in the areas of CIS condition assessment and renewal will be discussed. Current state of CIS studies in the U.S. will be briefly discusses, followed by a discussion of several important areas of research.

2. Significance and Needs of R&D in Civil Infrastructure

The CIS, by definition, includes all industrial and public mass transportation infrastructure (such as highways, railways, bridges, airport, subways and mass transit systems), buildings and structures of all kind, telecommunication facilities, chemical plants, power generation and delivery systems and so forth. It is obvious that the success of a nation's industrial growth and competitiveness in the world marketplace depends heavily on the quality and effectiveness of the CIS. Therefore, for any country in the world, either developed or developing, the CIS is the nation's major investment. For example, the CIS in the U.S. is comprising approximately of 20 percent of the nation's stock of physical capital according to Aschauer(1990). Munnell's recent estimates (1992) place the value of the nation's public works infrastructure at $2.7 trillion. Spending associated with the U.S. public capital stock is a large component of her total construction activities, estimated to be between 25 and 30 percent of the current annual expenditure of approximately $450 billion, and growing rapidly as estimated by the Civil Engineering Research Foundation(1991).

Unfortunately, many of the civil infrastructure systems are aging and exhibiting various stages of decay and sometimes, failure. For example, recent reports by the U.S. Department of Transportation (1990) and U.S. News & World Report (1995) indicate that over 25 percent of the interstate highway system is in poor shape and that approximately 42 percent of the 576,460 road bridges in the United States need repair or replacement of which 23 percent are structurally deficient and another 19 percent are functionally obsolete.

An infrastructure deteriorates with time, mostly resulted from aging of the materials, excessive use, overloading, climate conditions, lack of sufficient maintenance, and difficulties encountered in proper inspection methods. All of these factors contribute to the obsolescence of the structural system as a whole. As a consequence, repair, retrofit, rehabilitation, and replacement become necessary actions to be taken to insure the safety of the public(Scalzi et al., 1990)

A significant technological advancement in the CIS is in urgent need to meet the requirements of the strong demand on the intelligent performance evaluation and renewal of the CIS. The research and development needs in infrastructure technology are justified by two relevant reports: The first report was published by the Office of Technology Assessment(OTA) of the U.S. Congress(1991). This study was undertaken at the request of the Senate Committee on Environment and Public Works and the House Committee on Public Works and Transportation. Among the important conclusions emerging from this study was OTA's assessment that changes in federal programs management, investment policies and R&D are in urgent need. More specifically, the study suggested that it was essential to collect information that will enable the government to refocus support for short-term R&D to target applied technologies that will improve the condition, extend the life, and increase the capacity of existing public infrastructure; then using the data as a base, develop and implement long-term systems R&D programs to address future needs.

The second justification is from the report by the Civil Engineering Research Foundation (1991). This report explores the research needs in the civil engineering including design and construction. Five major research thrust areas are identified, of which infrastructure revitalization was listed in the first place. These areas were further developed into priority research initiatives including developing tools to make smart management decisions, extending useful life of the infrastructure, and identifying structural problems through diagnosis.

The National Science Foundation(NSF) of the U.S. recently presented new vision and strategy in their report entitled Civil Infrastructure System Strategic Issues(1994). The new strategy emphasizes systems integration at all levels and specifically addresses the the the areas of future research. A brief description of each of the four thrust areas are the following: *Deterioration science* is concerned with the mechanisms controlling how materials and systems break down and wear out during normal use and when subjected to natural and technological hazards. *Assessment technology* addresses the need to assess the condition of CIS resources. *Renewal engineering* deals with the development of new materials and methods to extend and enhance the useful life of CIS. *Institutional effectiveness and productivity* pursues effective decision making on CIS. These four strategic areas reflect the complexity and multidisciplinary character of research needs.

Nondestructive evaluation plays a role in the aforementioned strategic plan from a variety of points of view. NDE technology has been evolved in the past decades by leaps and bounds particularly in the defense and aerospace industries. Despite such advancements, techniques associated with inspection and monitoring of large-scale structures are still in premature state so that there must be significant technological improvements in order to meet the requirements of the strong demand on the intelligent performance evaluation and renewal. Particularly, research in NDE of large-scale, fracture critical structures and concrete structures such as steel bridges, offshore structures, nuclear power plants, electric power generation and delivery systems, manufacturing systems, maritime structures, pavements, buildings, dams and tunnels, and other dispersed civil structures are in great demand.

3. Terotechnology and Condition-Based Maintenance

The role of NDE in Terotechnology is becoming more important and broadly acknowledged in the community of CIS management and technology. Terotechnology is a basic maintenance physical assets (Williams et al. 1994). The British Standards Institution (1984) defines Terotechnology as a *combination of management, financial, engineering, building and other practices applied to physical assets in pursuit of economic life cycle costs.* The definition is expanded by Hodges (1991) to note that in practice, *Terotechnology is concerned with the specification and design for reliability and maintainability of plant, machinery, equipment, buildings and structures, with their installation, commissioning, operation, maintenance, modification and replacement, and with feedback of information on design, performance and costs.*

Maintenance in general can be categorized into two basic strategies: unplanned maintenance and planned maintenance(Figure 1). Unplanned maintenance strategy is more colloquially known as "run-to-failure," essentially is the "do nothing until it fails" option. This type of maintenance carries out to no predetermined data. Under this category, two situations may be considered. Firstly, when a structure fails and halts its intended function, a maintenance may be carried out to restore the structure to the state that it can perform its required function. This kind of maintenance is so called the *corrective maintenance*. The second scenario can be considered when there is expected consequences of dangerous events due to the failure of the structure. *Emergency maintenance* is carried out for this case where it is necessary to put in hand immediately in order to avoid serious consequences. Note that, in this case, constraints are applied which limit the flexibility of maintenance actions and possible optimization of cost and technology. Unplanned maintenance is therefore suitable only under the condition when this kind of

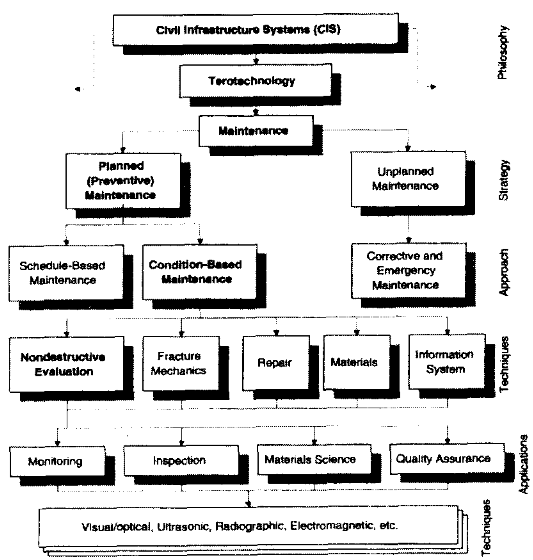

Fig. 1 Role of NDE in CIS Maintenance.

operation is a low cost option and when there is no danger of human lives involved. Some cosmetic structures such as antenna covers and street lighting posts may be maintained by this strategy.

In contrast to unplanned maintenance, planned maintenance is an option organized and carried out with forethought, control and the use of records to a predetermined plan. This strategy is in the domain of preventive maintenance that includes schedule-based maintenance (SBM) and condition-based maintenance (CBM). The schedule-based maintenances are carried out at predetermined intervals or corresponding to a criteria to reduce the probability of failure. These approaches are more cost-effective than the unplanned maintenance option. However, they have some inherent difficulties mainly concerning the establishment of reliable criteria whereby the predetermined interval is set up. Statistical approaches of structural failure may not be ideally suited for establishing such criteria. Maintenance of CIS is particularly difficult by these criteria mainly because there is no 'standard' design philosophy. As an example, it may be possible, but not necessarily optimal, to establish a maintenance interval with relatively high probability of failure prevention for aircraft maintenance interval with relatively high probability of failure prevention for aircraft maintenance plans since all DC-10's are created equal and they experience similar deterioration patterns. Similar criteria may be applied for other passenger airplanes such as Boeing models. By contrast, constructed facilities are designed and built differently. For instance, San Francisco's Golden Gate Bridge constructed in 1937 is quite different in all aspects of design and construction methods from the modern bridges. Probability of failure prevention in this case is by no means reliable at all.

Due to the huge spendings associated with CIS renewal, maintenance actions should be performed intelligently through a cost-effective strategy, particularly for maintaining large structural systems. Probably the most efficent, appropriate and preferable option for CIS maintenance is the condition-based maintenance approach because these preventive maintenance actions are carried out depending on the predetermined knowledge of the actual structural condition. The condition of the structure is assessed to identify the degradation rates by means of either routine inspection or continuous monitoring of the system and components through nondestructive evaluation. There are some perceived advantages of this strategy over other approaches(Davies, 1990). First and formost, an early knowledge of impending failure may reduce failure rate and increase the structural reliability. Secondly, actual condition knowledge and accurate failure prediction allows sufficient flexibility for the maintenance plans. Diagnostic potential is present in this approach and can pinpoint impending component failure together with the cause of the failure. The use of NDE routines also permits system modification, to remove identified cause of failure modes and thereby improve inherent design reliability and minimize the renewal cost. Another advantage is its increased flexibility if used in conjunction with an adaptive control system that improves system reliability.

It is clear that NDE plays a forefront role in CBM. Inappropriate NDE techniques may jeopardize the whole maintenance system due to the increased number of false signals, which will induce undesirable safety(false accept) or undesirable economy(false reject). Thus, it is very important to improve the reliability of NDE techniques employed for CIS diagnostics. The optimal NDE methods should be used for different materials and structural systems.

4. Role of NDE in Infrastructure Life Cycle

Figure 2 illustrates an ideal life cycle of a structure and the role of NDE in the cycle. When a need for a new structure is justified and financed, the project is initiated by establishing the planning and design philosophy. In this stage, structural designers should consider not only the serviceability but also the safety. Proper design of major structural components and correct detailing are as important as maintaining the structure's longevity. The member selections should meet the standards of design specifications (AISC, 1994, for example) and every design detail should be fully considered and fully accomplished to ensure the safety and serviceability of the structure.

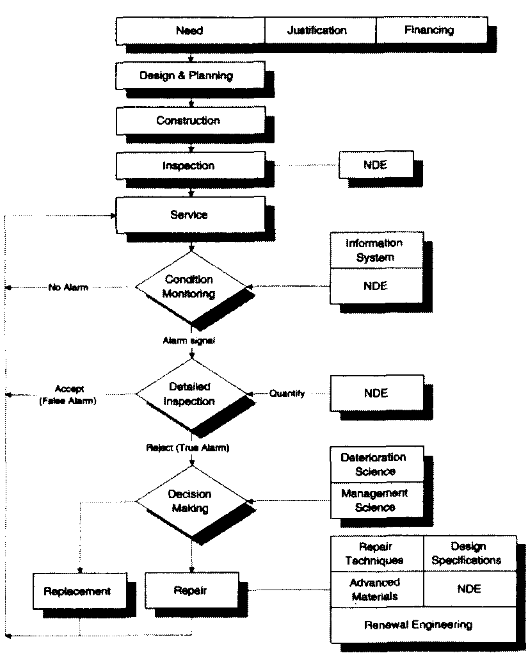

Fig. 2 Life cycle of CIS and the role of NDE.

During and after the construction, the structure should be inspected to check if all the design requirements are satisfied. Equally importantly, the structural safety is also checked by detecting and eliminating possible fabrication defects such as porosity and initial thermal cracking introduced in welded joints, or other inherent defects. NDE obviously plays an important role in this inspection step. After the structure passes the proof test, it goes under service for its full function and the lifetime maintenance cycle begins.

It ought to be mentioned at this point that NDE is divided into two categories of methods that involve "inspection" and the methods that involve "monitoring." Inspection techniques concern cracks or other defect characterization while monitoring techinques look at changes in the behavior of the structure or components under loading. One of the emerging research demands for civil infrastructure is the development and application of long-term continuous monitoring which can be helpful for evaluating structures, making decisions of preventive maintenance, and further examining new design approaches. An effective continuous monitoring or surveillance system is required to identify damage and deterioration state of the structure and then issue early warning signals when the extent of damage exceeds certain threshold, to eliminate or minimize the possibilities of sudden collapse of the structure.

Unfortunately, however, there exist numerous old structures that are not equipped with such monitoring devices. There are alternative options to deal with existing structures: The first option is to instrument them using new technology while the second option is to inspect them in a regular basis. The continuous monitoring is a better long term investment over the periodic inspection option despite its high initial costs, only when the remaining useful life of the structure is long enough to justify the cost of upgrade. Each case should be carefully evaluated by comparing the replacement and the upgrade costs. It may by concluded from this fact that the development of economic monitoring system for existing structures is highly desired. The conglomeration of individual structures in a region or a nation should be considered as a global infrastructure system so that they should be monitored in system-wide scale. A variety of information technologies such as geographic information system (GIS) may be used for this case.

Depending on the predetermined monitoring criterion, the surveillance system should generate a warning signal in the existence of suspicious condition of excessive deterioration. If the system gives such a warning, a detailed nondestructive inspect-ion technology should be readily available in order to check the validity of the alarm signal. The inspection systems should be provided with high resolution and reliability so that it should be capable of precisedly determining the type, location, size, and orientation of the damage and flaws. If the system issued a "false" signal, the structure is back to service without any modification. On the other hand, if it was a true signal of critical deterioration, decisions should be made to deal with the issues of repair or replacement. In this regards, deterioration science such as fracture mechanics and management science, while closely linked with NDE technology, makes contributions to evaluating the remaining useful life and the cost effiectiveness of repair and renewal actions. The condition assessment and inspection schemes are to request for necessary actions such as repair, rehabilitation, and/or operation control to be taken until the structure's condition is improved and satisfies the required standards for operation.

It was shown that the infrastructure revitalization can be achieved intelligently through effective nondestructive evaluation. As the NDE identifies the problems of the aging facilities, the renewal or rehabilitation procedure is completed by means of advanced repair and patching technology as well as innovative reconstruction engineering and design philosophy. Structurally deficient or deteriorated components of a structure can be either repaired, replaced or rehabilitated by using high performance materials such as fiber reinforced concrete, metal, alloys, or advanced composite materials. In this connection, NDE plays a role in both manufacturing process monitoring and quality control/quality assurance aspects. Defects and flaws introduced to the materials during manufacturing, fabrication and repair processes ofter act as nuclei of further damage growth which is a potential cause of structural deficiencies and a structural failure. The quality of the repaired parts and new components of the structure should be thus assessed by NDE before service. Furthermore, emerging materials such as composites should be characterized and their mechanical behavior must be thoroughly understood by identifying the deterioration mechanisms. They are achieved by quantitative measurements of material properties and efficient flaw detection through nondestructive methods.

5. Renewal Engineering

The NDE technology has been advanced by leaps and bounds mainly in the areas of defense and aerospace industries for the past decades. After the termination of cold war era, however, this technology is being converted and emerging into civilian applications. There are a variety of state-of the-art NDE methods available for condition assessment, including visual methods, acoustic emission, dye penetrant, leak testion, infrared thermography, eddy current, ultrasonics, laser-based ultrasonic methods, acousto-ultrasonics, EMAT, acoustic microscope, radiography, computed tomography, NMR, SQUID, speckle interferometry, shearography, shadow moire, interferometry, and numerous other methods (ASM handbook, 1989; Krautkramer, 1990; Review of Progress in QNDE). These methods, however, are limited in capability for CIS inspection tasks because they were historically developed for inspection smaller scale mechanical and aerospace structures with high accuracy and sensitivity. As a consequence, these methods may not be best suited for monitoring and inspecting large scale structures.

There exist several other methods optimally developed and used for CIS such as impact-echo, magnetic particle, magnetic induction, fiber optic sensors, thermography, vibration monitoring and modal analysis techniques, and ground penetrating radar(GPR) methods(SPIE-1777, 1992; SPIE-2454, 1995; SPIE-2456, 1995; SPIE-2457, 1995; SPIE-2458, 1995). Some of these methods are ever finding applications because of their capabilities of continuous monitoring and inspection of broad target area in a relatively short period of time. However, they sometimes lack sensitivity of detection and often result in issuing false alarm signals. Current methods are relatively primitive and unreliable, prompting conservative, often costly decisions. Most of the inspection techniques currently employed require highly-skilled inspectors who are capable of understanding the principles they employ and analyzing data they obtain. As a result, these classical methods are very much subjective and rely on the operator's level of experience and skill. Worst of all, the inspection procedure is tedious and time consuming particularly for inspecting large structures. A challenging problem of CIS inspection is the need for detection of relatively small flaws hidden in a large structure.

This situation can be reversed with a modest research investment. Existing NDE methods should be improved for wider apeture or broader inspection area without sacrificing the sensitivity and resolution for inspecting large scale structures in short period of time and effort. First and foremost, the development of smart sensors and sensor systems suitably designed for CIS should be in the top research priority. Such sensors should be capable of detecting micro-flaws in large structures with high sensitivity and resolution manufacturable by the least expensive ways. It is desirable to develop automated inspection system preferably using a robotic system that does not require heavy involvement of human inspectors.

Identified national research focus areas in condition assessment include the development of novel smart sensors and inspection methods, evaluation and characterization of defect and damage, material characterization(e.g., elastic properties), nondestructive flaw imaging methods, automated inspection system, advanced instrumentation, evaluation of residual service life and long-term continuous monitoring. These areas are further developed into other priority initiatives: for example, probability of detection and statistical approaches, smart structures and materials, remote sensing, inspection robotice, artificial intelligence and inspection expert systems. Duke(1994) compiled the conclusions of the workshop supported by NSF and other federal agencies. The needs of research, in priority order, were presented in three principal civil engineering application areas: steel structural components, concrete structural components, and pavements. Critical structural systems that require urgent development of NDE includes the components such as pins, haagers, bolted connections, eye-bars, cable stayed anchorage, and railways. Sub-critical or medium priority components are girder webs(out-of-plane bending) and other critical components with redundancy. Auxiliary or cosmetic structural components, such as high mast lighting fixtures, signs, breakaway supports, guard rails and culverts, are put in low priority. Meanwhile, nondestructive evaluation of concrete cure quality ranks the top priority in the area of concrete structural components requiring NDE. Other high priority applications for concrete structures include bridge decks and members, tunnel walls, joints, piers, abutments, pile foundations, columns, drilled shafts, dams and pre-and post-tensionde members. Applications of road pavements that require NDE technology include virtually all kinds: plain joined, jointed concrete, continuous reinforced, flexible, and composite pavements. Components of these pavements that require inspection includs structural support, air void, moisture, thickness degradation, cracking, material properties and characteristics, delaminations, and freeze-thaw damage. In addition to these transportation infrastructure, there are numerous structures awaiting for the evolution of NDE, including buildings, utilities, and maritime structures.

As the condition is assessed, the next step is to understand why the structure decayed. A fundamental issue in understanding why the constructed facilities decay is to understand better by the science of deterioration. Major components of these studies are built around materials science and engineering mechanics. These are long established topics matured to level so that these topics may not be critical in to context of research priority. However, some further studies are necessary as a prerequisite to develop repair or patching techniques. They may be achieved through the areas of studies in, for example, strength of materials(durability and stability), fracture mechanics, damage mechanics, long-term behavior(fatigue, creep, and environmental degradation such as corrosion), structural dynamics, and risk and reliability studies.

The next step of renewal is the smart decision making. Based on the condition of deterioration, decisions should be made whether they are to be repaired, replaced, or reconstructed. Management science plays an important role in this connection, again stroongly tied with NDE. Data collected frin nondestructive inspections of individual structure should be managed by treating the CIS as a syste. In this way, globla condition of the CIS may be monitored in a systematic way. Following topics are potentially applicalble to this step: smart decision-making theory, condition-based and risk-based maintenance systems, and condition survey data inventory systems using, for instance, geographic information system (GIS) and automated mapping/facility management (AM/FM). Decision making should be closely connected to deterioration mechanisms, NDE and information technology.

Depending on the decisions made, advanced renewal technology should be readily available. Renewal, modification, and upgrading techniques are the foremost key issuse on innovative design and construction methods. They include new or modified construction materials, simulation, innovative repair and modification, and modified construction suited to robotics applications. The other relevant technolgies include performance criteria and repair strategies, demolition, disposal and recycling, preservation of national resourcesm information technology, and finally the integration of structural design, processing, fabrication and assessment procedures.

6. Conclusions

It has been shown from the previous discussion that NDE plays a very important core role in intelligent civil infrastructure reviatalization. Infrastructure should be managed by the condition-based maintenance strategy where NDE is the foremost key issue.

An integrity assessment evaluates the need for repair and provides useful information on the remaining life of a structure. Integrity is assessed by measuring the extent of flaws and damage by means of NDE methods.

Global condition monitoring and detailed inspection systems are two basic philosophies of NDE which are complementing each other.

The role of NDE in CIS becomes more important and ever increasing.

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