Structural Health Monitoring for Optimization of Concrete Bridge Management

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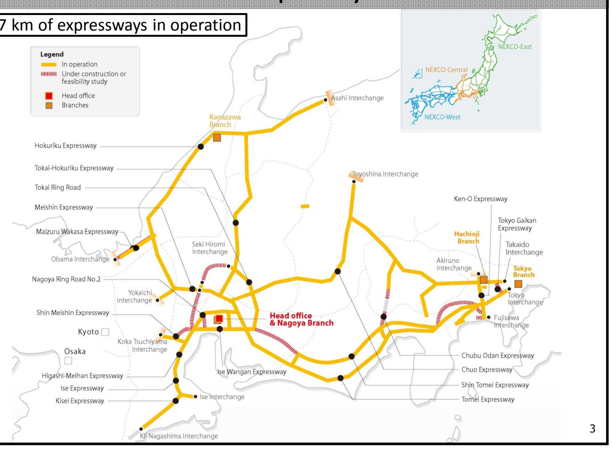
Outline

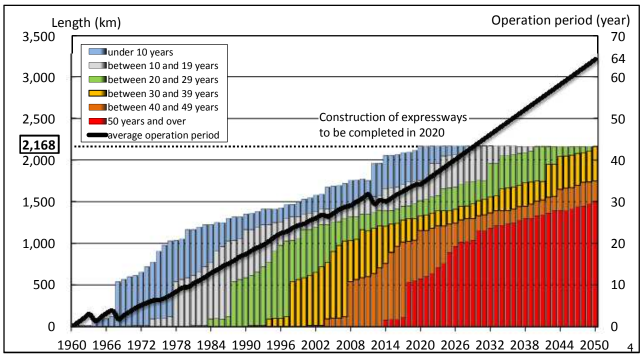
NEXCO-Central Expressway Network

2,007 km of expressways in operation



Opening year and operation period

- ✓ Average operation period : 30 years
- ✓ 40 % of the expressways operated for more than 40 years



Background and motivation

- ✓ Damaged and deteriorated bridges in increasing numbers in recent years
- ✓ Increasingly difficult to keep bridges in good condition as they age
- ✓ Limited financial and human resources available for bridge maintenance

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Need to make bridge maintenance more efficient and reliable

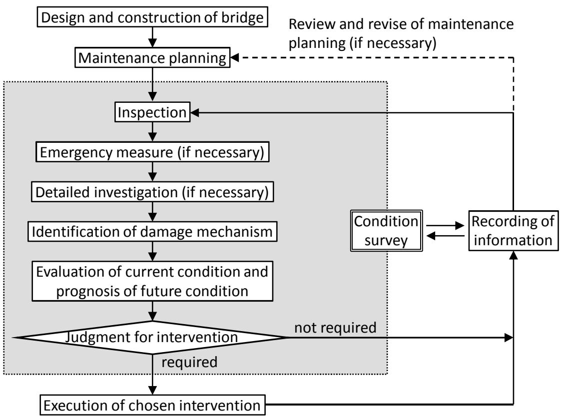
How?

Utilize Structural Health Monitoring (SHM) technology

So far, no systematic investigation into utilization of this rapidly advancing technology for NEXCO-Central's bridge maintenance

- Define the role of SHM
- Understand the limit of SHM
- Consider the strategy to utilize SHM

General Flow of Bridge Management



Expected Roles of SHM in Bridge Maintenance

For enhancement of efficiency and reliability of condition survey

Role 1 Complement hands-on visual inspection conducted every five year. Cover intervals between inspections

→ *Most in-demand, but challenging as it is unclear what, how and to what extent SHM can do*

Role 2 Provide quantitative data for screening of condition after significant events such as earthquakes and typhoons

→ *Currently covered by emergency protocols where condition screening is specified to be done by ad hoc inspections*

Role 3 Provide quantitative data for evaluation of current condition and prognosis of future condition

→ *Helpful in terms of life cycle management*

What to be monitored in Role 1 and 3?

*For the time being, Role 2 is unnecessary because emergency protocols function well.

Two Approaches to Bridge Safety

Control and measurement of loads

Mechanical loads
- ✓ Traffic loads
- ✓ Seismic force

Environmental loads
- ✓ Airborne sea salts
- ✓ Carbon dioxide

Man-made loads
- ✓ De-icing agents
- ✓ Defective workmanship

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Role 3: Monitoring of load

What load to be measured?

Monitoring of condition

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"Identification of damage"

Damages
- ✓ Buckling
- ✓ Cracking
- ✓ Corrosion
- ✓ Delamination
- ✓ Scouring
- .....

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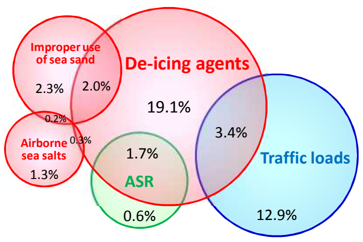
Role 1: Damage detection

What damage to be detected?

Loads on Bridges to be Measured

Main factors leading to damages on NEXCO expressways (three companies)



Other factors
- Defective grouting
- Insufficient covercrete thickness
- Honeycomb in concrete

Unmeasurable
- ✓ Alkali Silica Reaction (ASR)
- ✓ Improper use of sea sand

Unsuitable for monitoring
- ✓ De-icing agents

Measurable, but unnecessary to monitor. Influence of de-icing agents on bridges varies depending on various conditions.

Role 3 of SHM

Traffic loads

Bridge weigh-in-motion system

Airborne sea salts

Atmospheric corrosion monitoring [steel bridges]

Damage on Concrete Bridges to be Detected by SHM

Damages observed in the components of concrete bridges

Components	Concrete	Steel (rebar, prestressing tendon)
Damage mechanism	carbonation, freeze-thaw cycle, alkali silica reaction, fatigue, wearing, shrinkage	chloride attack, fatigue
Damage	cracking, delamination, spalling, scaling	corrosion, cracking, fracture
Damage characteristics	# Slowly progress # Damage states understood by hands-on visual inspection	# Slowly progress # Damage states not understood by visual inspection # Damages to prestressing tendons significantly influence structural integrity

Role 3 of SHM

Fracture of prestressing tendons

By what methods can it be detected accurately and reliably?

Experimental Studies

- ✓ Investigation into SHM techniques for detection of fracture of prestressing tendons in prestressed concrete (PC) members
- ✓ Conducted by NEXCO Research Institute

	Objectives	Experimental tests
1	Evaluate the validity of modal analysis methods in detecting prestressing tendon fracture	● Forced vibration test of a removed PC girder ● Cut four of the five strands one after another ● Examine vibration-damping properties
2	〃	● Forced vibration test of a PC beam with a single rod ● Gradually decrease prestressing force in the rod ● Examine the natural frequency
3	Evaluate the validity of acoustic emission (AE) techniques in locating prestressing tendon fracture	● Fifteen AE sensors on a 9 m long PC beam ● Corrode and fracture three of the five strands ● Analyze elastic wave propagation
4	Evaluate the influence of cement grout on elastic wave propagation in AE techniques	● PC beams with a grouted or ungrouted single strand ● Corrode and fracture the strand ● Compare AE peak amplitude

Summary of Experimental Results

- ✓ Vibration-damping properties of the prestressed concrete girder specimen didn't change until 60% of the prestressing steel strands were fractured
- ✓ As the prestressing force in the the steel rod decreased, the natural frequency of the prestressed concrete beam specimen also gradually decreased; however, it was 1.3 % reduction at the most
- ✓ Fracture of prestressing steel strands in the prestressed concrete beam specimen was located by installing several AE sensors
- ✓ AE peak amplitude obtained from fracture of a grouted strand was smaller than that obtained from fracture of an ungrouted strand
- ✓ With increasing distance from the location of strand fracture, obtained AE peak amplitude became larger in the case of an ungrouted strand, while it became smaller in the case of a grouted strand

Discussion

Modal analysis methods not suitable for detection of prestressing tendon fracture

→ Structural behavior : The dynamic response of prestressed concrete members insensitive to change in prestressing force

→ Sensor performance : Existing accelerometers incapable of detecting slight difference in the dynamic behavior

AE sensor networks probably utilized for detection of prestressing tendon fracture

Some challenges to be addressed in the implementation

- ✓ Background noise from many other sources (cars, rain, etc.) disturbing AE measurement → Reliable data filtering method
- ✓ Durability of monitoring equipment, in particular sensors. No maintenance between periodic detailed inspections [five years]
- ✓ Selection criteria for bridges on which SHM is implemented. Impractical to instrument all prestressed concrete bridges in the expressway network in terms of costs [more than 1,500 prestressed concrete bridges]

Conclusion

- ✓ Three roles of SHM in bridge maintenance are proposed. Among them, the most needed but challenging is complement to hands-on visual inspection where SHM is expected to detect damage between inspections
- ✓ Fracture of prestressing tendons is chosen as damage to be detected by SHM for prestressed concrete bridges considering its large influence on the bridge structural integrity
- ✓ Modal analysis methods are not appropriate for detecting fracture of prestressing tendons despite being popular SHM techniques
- ✓ Although there are some demanding issues to be addressed, the AE technique is a promising method for detecting fracture of prestressing tendons
- ✓ SHM should be implemented in a limited number of carefully-selected bridges by considering its cost-effectiveness