BRIDGE DECK DETERIORATION ASSESSMENT BY NONDESTRUCTIVE TESTING METHODS

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โดยทั่วไปการตรวจสอบความเสียหายของพื้นสะพานคอนกรีตมักใช้วิธีการตรวจพินิจด้วยสายตาและการเจาะสำรวจ ร่วมกับการสำรวจอย่างง่าย เช่น การสำรวจโดยใช้โซ่ลากและการสำรวจเคาะฟังเสียงด้วยค้อน ซึ่งวิธีการเหล่านี้อาจไม่สามารถตรวจสอบได้อย่างถูกต้อง อย่างไรก็ตาม ในปัจจุบันได้เริ่มมีการนำเอาวิธีการสำรวจแบบไม่ทำลายหลายๆ วิธีเข้ามาใช้ในการตรวจสอบความเสียหายของพื้นสะพานคอนกรีตร่วมกับการทดสอบอย่างง่าย โดยการศึกษาในครั้งนี้ จะนำวิธีการสำรวจด้วยคลื่นเรดาร์ การสำรวจด้วยศักย์ไฟฟ้าครึ่งเซลล์ และการสำรวจด้วยคลื่นความเค้นสะท้อน เข้ามาใช้ในการตรวจสอบความเสียหายของพื้นสะพานคอนกรีต ผลที่ได้จากการสำรวจด้วยวิธีการทดสอบอย่างง่ายสามารถตรวจหาความเสียหายที่อยู่บริเวณพื้นผิวสะพานและความเสียหายที่อยู่ใกล้พื้นผิวสะพานได้ อย่างไรก็ตามการสำรวจด้วยคลื่นเรดาร์ยังสามารถหาการเสื่อมสภาพของสะพานได้โดยวัดจากการเสื่อมสภาพของเหล็กเสริมภายในเนื้อคอนกรีต ในขณะที่การสำรวจด้วยศักย์ไฟฟ้าครึ่งเซลล์จะทำให้ทราบถึงตำแหน่งที่มีความน่าจะเป็นที่จะมีการผุกร่อนของสนิมภาพในเหล็กเสริม และนอกจากนี้การสำรวจด้วยคลื่นความเค้นสะท้อน ยังสามารถตรวจหาความสมบูรณ์ภายในเนื้อคอนกรีตได้ด้วยเช่นกัน ในท้ายที่สุดผลที่ได้จากการสำรวจทั้งหมดจะถูกสุ่มเจาะสำรวจเพื่อเป็นการยืนยันผลข้อมูล

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Thanop Siriwattananuruk : BRIDGE DECK DETERIORATION ASSESSMENT BY NONDESTRUCTIVE TESTING METHODS. Advisor: Assoc. Prof. Dr. Thanop Thitimakorn, Ph.D.

In general, the inspection of the damage on concrete bridge deck is usually done by visual inspection and coring test together with simple survey such as chain drag and hammer sounding. These methods may not be able to verify damage condition correctly. However, at present, there are many nondestructive testing methods which is used to investigate the damage on concrete bridge deck together with simple testing methods. For this study, ground penetrating radar, half-cell potential and impact echo test were selected to evaluate damage condition of concrete bridge deck. The results from simple methods can be detect only damage on the concrete bridge deck or damage that located closed to concrete bridge surface. While nondestructive test i.e. ground penetrating radar can detect deterioration of bridge deck by measuring the amplitude of reinforcing steel in the concrete. Moreover, half-cell potential able to gives location where there is possibility of rust corrosion in reinforcing steel. In addition, impact echo test can evaluate integrity of concrete bridge whole concrete depth as well. In the end, all survey results will be random sampled to confirm data results.

Field of Study: Earth Sciences Student's Signature ....
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Thanop Siriwattananuruk

TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

CHAPTER 1 INTRODUCTION

Bridge is a part of the transportation network system. It is the basic structure that has been constructed throughout the country, most of which are reinforced concrete bridge. Bridge structures may be occurred defect or damage after construction and being used for a long time. Surveying and checking the condition of bridge structure is important to assessing the service life. In addition, planning the repair of the bridge structure at an appropriate time will help to save on maintenance costs.

Bridge deck is a main structure of bridge system that supports the weight directly from vehicles. It is the first part where damage is often observed. The survey and inspection of bridge deck structure is necessary to be carried out periodically to monitor and inspect physical conditions. In general, the inspection of the damage of concrete bridge structure on general survey can be done by using visual inspection method together with chain drag and hammer sounding. The above surveys are appropriate for the preliminary evaluation of bridge deck because it can be carried out easily and quickly. However, the survey data is quite limited and cannot assess the quality of the internal concrete.

Currently, nondestructive testing (NDT) has been developed to be able to use a variety method and more convenient. There are many methods that can be applied in surveying and testing on bridge deck structure in order to inspect the properties and quality of concrete floor slab for more details. These methods of testing have advantages, disadvantages and suitable for inspection in various ways. Selecting the suitable test type and test method will help reduce the cost of testing and get more information on the pinpoint. Moreover, it will help to reduce the construction repair budget.

For this study, 3 mains of the nondestructive testing methods were used to detect damage of concrete bridge deck: (1) ground penetrating radar (GPR), (2) half-cell potential and (3) impact echo (IE). Additionally, the simple tests such as visual inspection, hammer sounding and chain drag were also carried out. Finally, coring was conducted to verify the interpretation.

1.1 OBJECTIVES

To assess the capability of nondestructive testing of 3 methods: (1) ground penetrating radar, (2) half-cell potential and (3) impact echo for checking the damage of concrete bridge deck which is comparable with general test data i.e. visual inspection, chain drag and hammer sounding. Finally, coring data will be used to compare the survey results and crosschecking result together.

CHAPTER 2 LITERATURE REVIEWS

Inspecting and managing bridges in Thailand's inventory with limited resources is challenging for bridge owners. The challenge is further complicated by the fact that the average age of these bridges is more than 10 years. More specifically, bridge decks require the most frequent maintenance and preservation because, on average, they deteriorate faster than all other bridge components. This is because of the routine application of weathering process from rain fall and sustained traffic load in addition to environmental effects.

Recently, bridge owners across the country worked toward implementing asset management plans and performance-based management to maintain, preserve, and improve the highway system. An essential component of this approach is to have reliable and quantitative information regarding the physical condition of structures and a greater understanding of their deterioration processes. The use of nondestructive evaluation technologies is complementary to the current state of the practice for assessing the condition of structures, which is based on visual inspection and manual sounding techniques. Nondestructive testing methods enable periodic assessment of structures without causing damage and compromising their structural integrity and provide information about defects invisible to the naked eye.

For this chapter, the principle of testing, surveying and interpretation of 3 nondestructive testing methods were explained. All methods used in this study as follow: -

(1) Ground penetrating radar (GPR)
(2) Half-cell potential
(3) Impact echo (IE)

In additions, mechanics and damage that occur in concrete bridge deck will be described at the end of this chapter.

2.1 PRINCIPLE OF TESTING

General guidelines for the inspection of bridge deck damage are carried out by using a simple tool such as visual inspection, chain drag, hammer sounding or etc. However, at present, nondestructive testing methods have been introduced to detect damage on bridge deck. These methods are based on geophysical surveys consisting of seismic survey, electro-chemical and electromagnetic wave survey. These principles have been used to design and fabricate test equipment that is more suitable for road or pavement inspection applications. For the commonly used methods for checking the damage of current concrete bridge deck were shown in Table 1.

Table 1 Nondestructive testing methods and usefulness of inspection damage on bridge deck (Gucunski et al., 2011)

Nondestructive testing methods	Application for inspection
Ground penetrating radar (GPR)	Used in positioning the reinforcement and depth of the reinforcing steel from concrete surface and the thickness of concrete slab
Half-cell potential	Indicate the possibility of rust corrosion in the reinforcing steel
Impact echo (IE)	Used to check integrity of concrete i.e. crack, delamination or honeycomb cavities

However, each testing method is appropriate for specifically degree of damage and types of damage. Testing result based on each method will be responds to material properties of damage (Fig. 1). Examination with a half-cell potential will be suitable for checking the reinforcement steel corrosion which is the part of the structure inside the concrete. In addition, ground penetrating radar survey can detect deterioration of reinforcing steel, as well as other damage that appears inside the concrete. Last, impact echo will be suitable for checking integrity in concrete such as crack, delamination and honeycomb cavities in concrete.

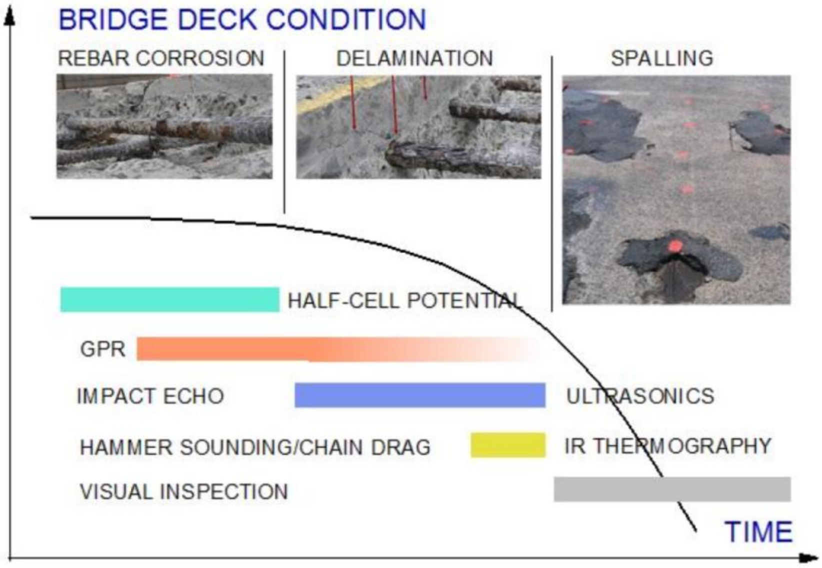


Figure 1 The type of damage and appropriate methods of examination (Gucunski et al., 2011)

For this part, it will be explained the survey and test principle of three nondestructive testing methods such as (1) ground penetrating radar, (2) half-cell potential and (3) impact echo. There are details of various methods as follows.

2.1.1 GROUND PENETRATING RADAR

Ground penetrating radar surveying or commonly known as “GPR” is a geophysical surveying methodology that uses electromagnetic waves (EM) to detect the subsurface variation or objects. The device consists of a transmitter and receiver and processing unit, which are connected by a transmission cable line. The main components of the ground penetration radar (Fig. 2) consist of a signal generator that controls the radar wave (Tx) to move out. The radar wave will move at a speed at 0.12 meters/nanosecond approximately (in the concrete material). When the waves reach the boundaries of the material layer that have different electrical properties, it will reflect to the test surface. Then, it will be measured by a receiver.

There are two radar receiver-transmitters. One system is called monostatic, and the other is bistatic. The monostatic system consists of the receiver and transmitter in the same device. The bistatic system, the transmitter and receiver are separated. The choice of any system in survey will depend on the purpose of data collection. However, bistatic system have advantages in common midpoint (CMP) data storage.

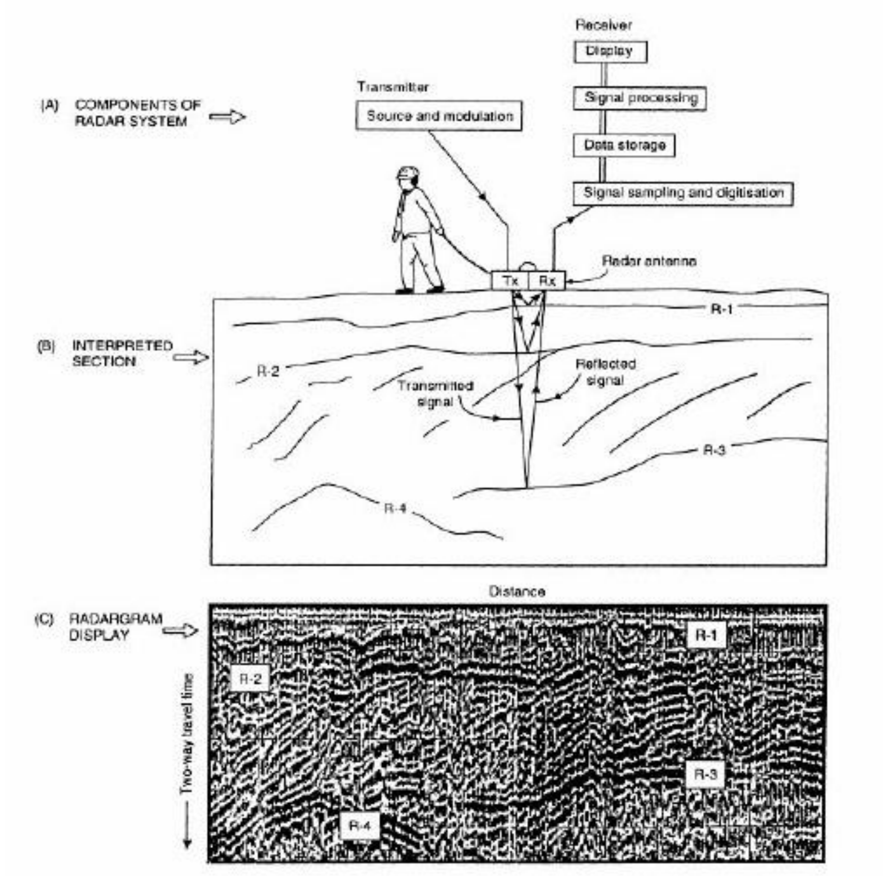


Figure 2 Subsurface survey using radar (A) Ground penetrating radar components (B) Data interpretation and (C) 2D Radar wave signal (Reynolds, 1997)

2.1.2 HALF-CELL POTENTIAL

A half-cell potential survey is a very popular survey method which is used to check the corrosion of steel within concrete by using basic knowledge of electro-chemistry investigation. The measured result will be compared with the American society for testing and materials (ASTM) standards so that indicate the probability of iron corrosion in concrete. This method can detect damage throughout the lifetime of the concrete structure (Elsener, 2003).

The survey principles of this method (Fig. 3), the operation begins with connecting the negative electrode to the reinforcing steel and connecting the positive electrode to the reference electrode which will be placed on the concrete surface. The measured electrical difference can be used to assess the degree of probability of corrosion damage in reinforcing steel as shown in Table 2.

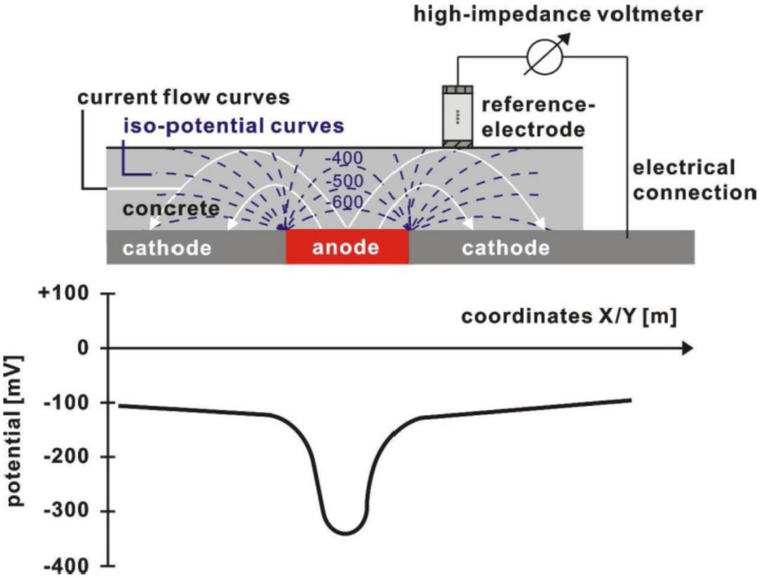


Figure 3 Principle of half-cell potential measurement (Baumann, 2008)

Table 2 The degree of probability of corrosion damage compared to the measured electrical potential (ASTM, 1999)

Measured the electrical difference	The probability of corrosion in the reinforcing steel
More than -200 mV	90% possibility that it will not corrode
Between -200 mV and -350 mV	The proportion of corrosion will increase
Less than -350 mV	90% possibility that it will corrode

2.1.3 IMPACT ECHO

Impact echo test is a method for nondestructive testing of concrete structure that is based on the use of impact generated stress wave. Transient stress pulse is introduced into a test object – such as concrete slab, concrete wall, etc. – by mechanical impact on the surface (Nowak, 2012). The stress pulse propagates into the object along spherical wave fronts as P-wave (compression waves) and S-wave (shear wave). In addition, a surface waves (Rayleigh wave or R-wave) travels along the surface away from the impact point. The P-wave and S-wave are reflected by internal interfaces or external boundaries. The arrival of these reflected waves, or echoes, at the surface – where the impact was generated – produces displacements that are measured by a receiving transducer and recorded on a digital oscilloscope. Because of the wave patterns associated with P-wave and S-wave, if the receiver is placed close (approximately 50 mm) to the impact point, the waveform is dominated by the displacement caused by the P-wave arrivals.

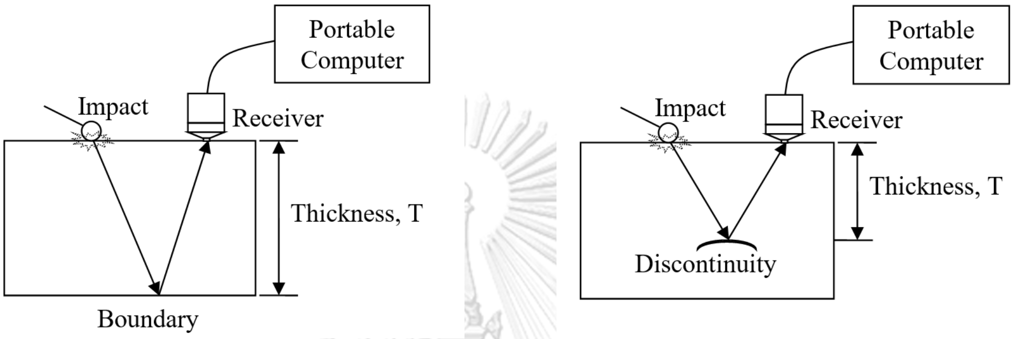
According to Figure 4, the stress pulse, which is generated by the impact, travels back and forth between the boundary and the top surface (case A) or the flaw and the top surface (case B). Each time the pulse reaches the top surface, it produces a characteristic displacement. Therefore, the waveform is periodic, and the period is equal to the travel path (2T) divided by the P-wave speed. The frequency is the inverse of the period (Equation. 1), so, the frequency (f) is:

$$f = \frac{V_p}{2T} \qquad \dots (1)$$

Where V_p is the P-wave speed which has been determined from an impact echo test performed in a known thickness area of the structure. If the frequency content of a waveform can be determined, the thickness of structure or distance to a reflecting interface can be calculated (Equation 2):

$$T = \frac{V_p}{2f} \qquad \dots (2)$$

The time domain of the displacement waveforms will be transformed to frequency domain with the aid of signal processing method. The frequency content of the digitally recorded waveforms is obtained by using the Fast Fourier Transform (FFT) techniques, which states that any waveform can be represented as a sum of sine curves, each with a particular amplitude, frequency and phase shift.



A. Thickness measurement B. Anomaly detection

Figure 4 Principle of impact echo test (Nowak, 2012)

In addition to the three main nondestructive testing methods above, this study also conducted tests on bridge deck using other methods including visual inspection, chin drag and hammer sounding. Furthermore, exploration drilling will be used as a comparison and confirm the test results.

2.2 MECHANISMS AND DAMGE CAUSED ON CONCRETE BRIDGE DECK

Reinforced concrete structure such as roads, bridge or other facilities, it tends to deteriorate overtime due to causes by using under the overload design, used for a long time or fatigue within the concrete structure or corrosion of steel reinforcement. The nature of the damage detected in the bridge structure has the mechanism on 3 processes i.e. (1) physical damage, (2) chemical deterioration damage and (3) biological deterioration damage. Deterioration damage caused by these processes can be classified each mechanism as shown in Table 3.

Table 3 Damage caused based on each mechanism in concrete bridge structure

Damaged caused by chemical processes	Damaged caused by physical processes	Damaged caused by biological processes
- corrosion - carbonation - alkali-silica reaction - crystallization - leaching - oil and fat influence - salt and acid actions	- creep - fatigue - temperature - overload - shrinkage - water penetration	- accumulation of dirt and rubbish - living organism activity

Bridge deck damage have many characteristics that occurred based on several processes. Moreover, the distinctive and common characteristics founded in Thailand or topographical terrain consist of 5 main criteria as follow:

2.2.1. CORROSION

Corrosion is an electrochemical process that have anode electrodes, cathode electrodes and electrical conductors. Moisture concrete is also considered as electrical conductor, while the steel buried in concrete acts as anode and cathode (Fig. 5). The electric current flows from the anode to the cathode. As a result of this reaction, the metal volume increases due to Fe (iron) being oxidized to $Fe(OH)_2$ and $Fe(OH)_3$ and occurred slag formation in the form of $Fe(OH)_3{\cdot}3H_2O$ (rust).

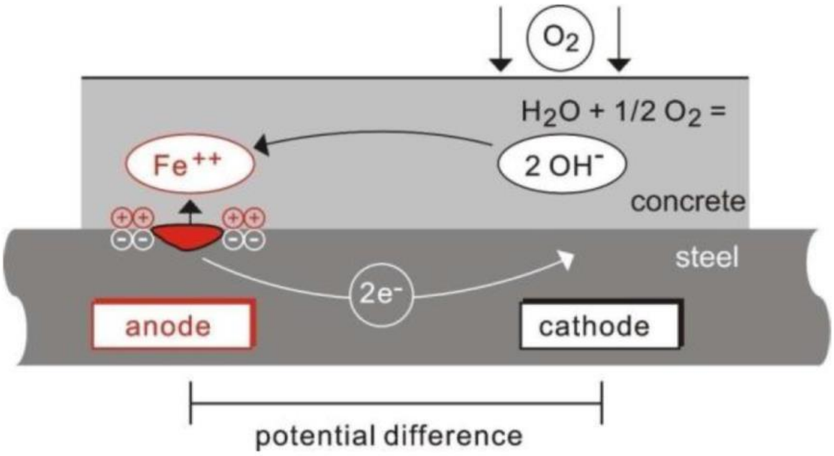


Figure 5 The corrosion process of steel in concrete (Baumann, 2008)

2.2.2 DELAMINATION

Delamination mainly occurred from the expansion of reinforcing steel due to corrosion and rust in the structure. When the steel expands, pressure is pushed, lead to concrete surface on outside to be pushed out and formed on fissure parallel to the structure surface. Anomaly investigation can be inspected by knocking with hammer and listening to the sound or using drag chains along the concrete surface. The limitation of equipment also depends on depth and size of the fissure.

2.2.3 SPALL

In the most cases, the cause is similar to the occurrence of fissure. The concrete that is cracked off as a result of the force being exerted by impactor or climate change which pressure or expansion of large concrete mass is possible. However, areas where corrosion in reinforcing steel may be considered an area that is prone to concrete cracking.

2.2.4 SCALING AND DISINTEGRATION

Scaling and disintegration are caused by the peeling off of the mixture in the concrete which generally occurs around the concrete surface. Scaling and disintegration at a slight level of damage will not cause the coarse aggregate loss, while moderate to severe damage will increase the size of the large concrete mixture. Moreover, in the extreme damage level, there will be peeling off of the large concrete mixture and the concrete cement as well.

2.2.5 CRACK

Since some cracks are a possible cause of the structure damage, they have been considered to be very important and necessitated to repair. Thus, it necessary to be repaired. However, most cracks may not require repair, or some cracks cannot be repaired. The width of the cracks can be considered a very important. If the crack become wider due to the weight pressed or collapse of the structure, repairing should be carry out structural improvements as necessary. Nevertheless, the width of cracks may be changed according to the temperature.

CHAPTER 3 RESEARCH METHODOLOGY

For this study, survey and test on the concrete bridge deck were divided into 3 parts: (1) general survey, (2) nondestructive survey and (3) cross checking the test results. Details of the methods of survey and testing are as follows:

3.1 GENERAL SURVEY

The general survey is an examination of simple survey which is classified as a general method for investigate the damage on concrete bridge deck. The survey consists of visual inspection, chain drag and hammer sounding. Details survey method and equipment are summarized here in.

3.1.1 VISUAL INSPECTION

Conducted an examination with the naked eye together with basic inspection equipment without electronic devices such as a ruler or crack width gauge. The operation is performed by experienced inspectors who will help to provide information regarding to nature of damage or structure deterioration. However, inspection by the above methods can indicate the location of damage that occurs on the surface area only.

3.1.2 CHAIN DRAG

Chain drag survey is the traditional and most commonly used method. Distress on concrete bridge deck can detected by dragging chain on the concrete bridge surface in order to hear the sound that is generated. Concrete without damage will generate a clear sound, while the separated concrete will produce a buzzing sound or a hollow sound.

The dimensions of chain drag, according to ASTM D4680, require 460 mm (18 inch) long chain, 6 mm (1/4 inch) in diameter, 4-5 lines connected to copper pipe or aluminum pipe size 610 mm long. And, attach the 610-910 mm (2-3 ft) long pipe to the center of the copper or aluminum tube for handle (Fig. 6).

This method will be carried out with 0.5x0.5 meters spacing in longitudinal direction and transverse direction of bridge like a gridline pattern. Position of distress will be marked on the bridge deck plan.

Figure 6 Chain drag equipment based on ASTM D4580

3.1.3 HAMMER SOUNDING

In general, sounding by using hammer to knock is an evaluate method that is used in conjunction with visual inspection. The survey was conducted by using hammer to knock every 0.50x0.50 meters spacing in longitudinal direction and transvers direction of bridge. If the sound is a bass sound or feel the resonance from a slight knock, it refers to the concrete has slipped or appear a hollow under the concrete surface. However, evaluating concrete condition by hammer sounding cannot be used to assess the deep damage in the concrete structure.

In addition, hammer sounding can be used to assess the quality of concrete performance in term of quality as well. When knock the concrete with high strength, shape sound will be generated and feel the reflection force from the tap quietly clear. For low quality concrete and low strength concrete, a deep bass sound will be generated and slight resonance from the tap.

3.2 NONDESTRUVTIVE TEST

Damage detection of concrete bridge deck by using nondestructive testing in this study consists of 3 methods: (1) ground penetrating radar, (2) half-cell potential and (3) impact echo. Details survey equipment and testing method are summarized here in.

3.2.1 GROUND PENETRATING RADAR

Conducted a survey by using GSSI's StructureScan Pro, United State of America with a main frequency of 1,600 MH_z by dragging along the survey line that is set every 0.50 meters in longitudinal direction and transverse direction of bridge. The survey line is defined in 2 directions i.e. (1) longitudinal direction which is parallel to the bridge and (2) transvers direction which is perpendicular to the bridge. The longitudinal survey will explore the reinforcing steel or air cavities resting in the transverse direction of the bridge, while the transverse survey line will look for reinforcing steel or air cavities that lie parallel to the bridge.

The result obtained from the ground penetrating radar survey will be processed by using GSSI's Radan program. The radar signal will appear as an image of the reflected signal of the radar wave in a dark-bright band which depends on the intensity of the reflected signal (Fig. 7). The position of the reinforcing steel will appear as the conical effect of the inverted cone, while the air cavity will give an abnormal reflection signal when compared to the adjacent signal.

The survey results can be used to specify the position of steel or cavity on the image result. The horizontal axis shows the distance along the survey line and the vertical axis shows the depth from the surveyed concrete surface.

In addition, the position of the reinforcing steel can be analyzed for amplitude, which will be used to evaluate the deterioration of the reinforcing steel. For simple calculation, reading amplitude from rebar can be convert to decibel (dB) as equation 3. After that, 90^{th} percentile normalized amplitude in dB unit will be plotted as the distribution of deterioration of reinforcing steel (Barnes et al., 2008).

$$A_{dB} = 20 \times \log_{10} \frac{A}{A_0} \qquad \dots (3)$$

where: A_{dB} is Normalize amplitude [dB]

A is Reading amplitude data

A_0 is Normalize amplitude reference = 32,767

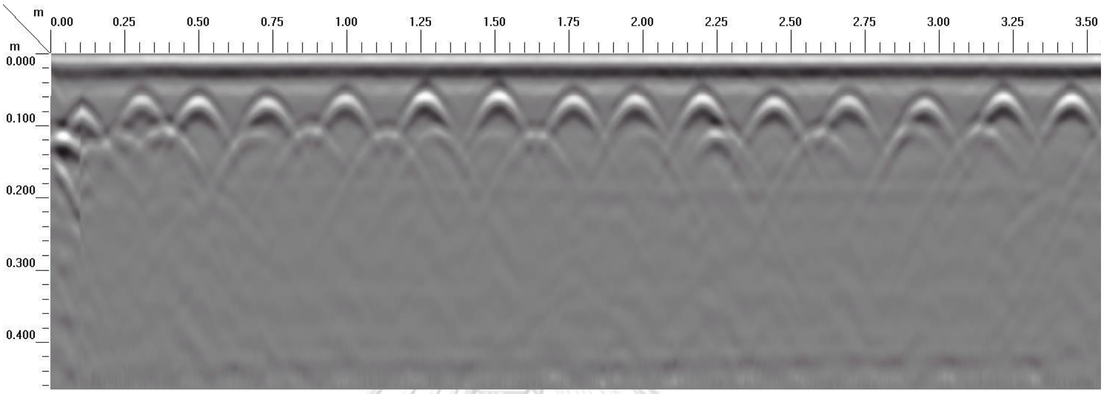


Figure 7 Example of ground penetrating radar signal image

3.2.2 HALF-CELL POTENTIAL

Conducted a survey using Proceq group’s Profometer corrosion, Switzerland. In this survey, one pole must be connected to the reference electrode and the other to be reinforced steel which embedded in concrete bridge. The survey was carried out by dragging the reference electrode along the survey line. The survey line was defined at every 0.50 meters spacing in transvers direction of bridge. While dragging the reference electrode along each survey line parallel to bridge, the system will record the average voltage difference at ever distance 0.50 meters interval. The electric potential difference data in each survey line will be created to plot a map showing the distribution of areas where the possibility of reinforcement corrosion based on the criteria consideration in Table 2.

3.2.3 IMPACT ECHO

Conducted a CTG-2 of Oslon Instrument, Inc, United State of America. The instrument consists of a stress wave generator and a receiver which placed near each other. The survey is conducted by placing the equipment at the location that needs to be investigated. Test position was defined at 1.0 meters spacing in longitudinal direction and transverse direction of bridge. Beginning test by creating a stress wave from solenoid impactor which is a signal generator. Solenoid impactor is suitable for detecting irregularities in the concrete at depth less than 0.30 merters. But, if wanting more depth, impactor may be use a round hammer to generate instead. The test will be replete produced 3 times per test position to reduce data discrepancies.

The test results will be analyzed with Oslon's WinCTG program in form of frequency domain (Fig. 8). Then, depth from the test surface will be calculated based on stress wave velocity. For normal concrete, the stress wave which encounter boundary between concrete floor and air on bottom concrete bridge deck will reflected back with highest amplitude of a particular frequency. In the case of abnormal concrete interior i.e. crack appeared, test result will have another frequency band with high amplitude occurring in the signal. As the test result in abnormal concrete, it will found a higher frequency than the frequency that reflected from the bottom of concrete bridge because the waves will reflect from the anomaly and move backward more quickly than the reflected wave which reflected from bottom concrete bridge deck.

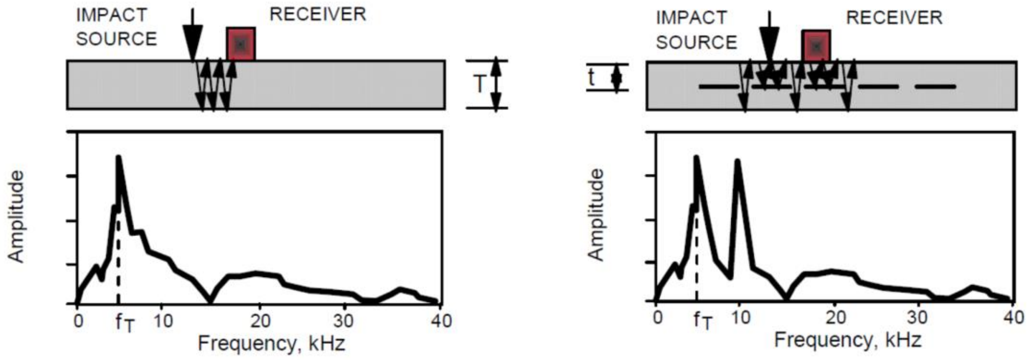


Figure 8 Characteristics of the test results by impact echo test on normal concrete condition (left) and abnormal concrete condition (right) (Gucunski et al., 2011)

3.3 CROSS CHECKING

According to the results from general survey and nondestructive test survey, both normal area and suspected anomaly area will be random cross checked with concrete drilling. For this study, concrete drilling can be drilled only in the topping layer around 0.10 meters depth from bridge deck surface. For precast concrete which located under the topping concrete was not allowed by department of highway to be drilled. The concrete random drilling was be classified into 2 characteristics: -

(1) Concrete observation, this characteristic will be drilled to observed concrete core. One position shall be drilled to measurement the thickness of topping concrete layer, and other position may be drilled to evaluated defect that located in topping layer. This drilling method can be evaluated for general survey results and nondestructive test results i.e. ground penetrating radar result and impact echo result.
(2) Rebar observation, this area will be drilled to remove concrete cover out. The rebar will be observed and evaluate degree of corrosion. This category is suitable for cross check ground penetration radar result and half-cell potential result.

For concrete drilling, it was constructed by rotary drilling with diamond coring bit, single core barrel diameter 4 inches accordance with ASTM C42.

CHAPTER 4 STUDY AREA

For this chapter, it will mention to the bridge that has been selected in accordance with various conditions and criteria so that choose one bridge to survey and test for assessing the damage of the bridge. Moreover, detailed information of the selected bridge in this study and the determination of test position also found as follows.

4.1 CONDITION AND CRITERIA FOR CONSIDERING THE BRIDGE SELECTION

For this study, reinforced concrete bridge was selected because it is a popular and widely used in the recent. The bridge surface should be portland cement concrete (PCC), which have the same material of whole bridge. The bridge surface should not be overlaid with other material, i.e. asphalt concrete, because it will not be able to observe the actual damage in the structure or only the major damage will be observed.

4.2 SELECED BRIDGE

Khong 15 bridge (Fig. 9) is a reinforced concrete bridge located on route 305 Rangsit-Nakhon Nayok (outbound side), at 37+570 km. The bridge has a width around 10 meters, a length of about 80 meters, consisting of 3 traffic lanes. In this study, only 1 left lane is selected, and 9 sub-long sections of the bridge can be divided (Fig. 10).

Figure 9 Klong 15 bridge on route 305 Rangsit-Nakhon Nayok (outbound side)

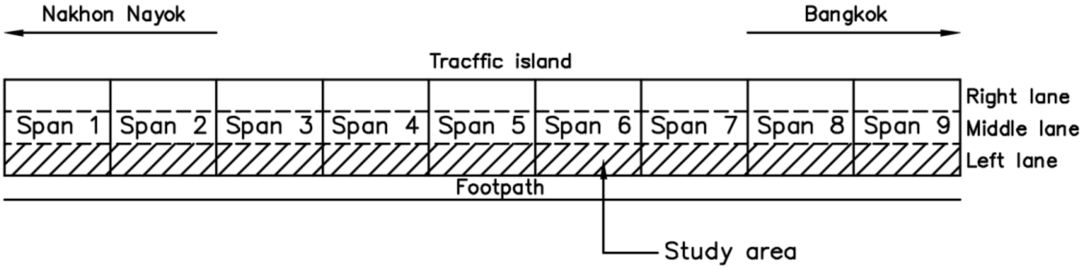


Figure 10 Bridge segmentation for surveying

4.3 DETAILS OF SELECTED BRIDGE

The Khlong 15 bridge is a plank girder structure which consisting of a precast plank girder beam with 0.25 meters thickness in span 8 meters length and 0.31 meters thickness in span 9 meters length. In addition, topping concrete is poured over 0.10 meters thickness accordance with the standard drawing of the department of highways (Fig. 11).

For the Khlong 15 bridge, it composes of 9 bridge span which can be classified into 3 sections as follows: -

(1) Section 1 consists of bridge beam in span 1-3. Each beam has 8 meters length approximately.

(2) Section 2 consists of bridge beam in span 4-6. Each beam has around 9 meters length.

(3) Section 3 composes of bridge beam in span 7-9. Each beam has 8 meters length approximately.

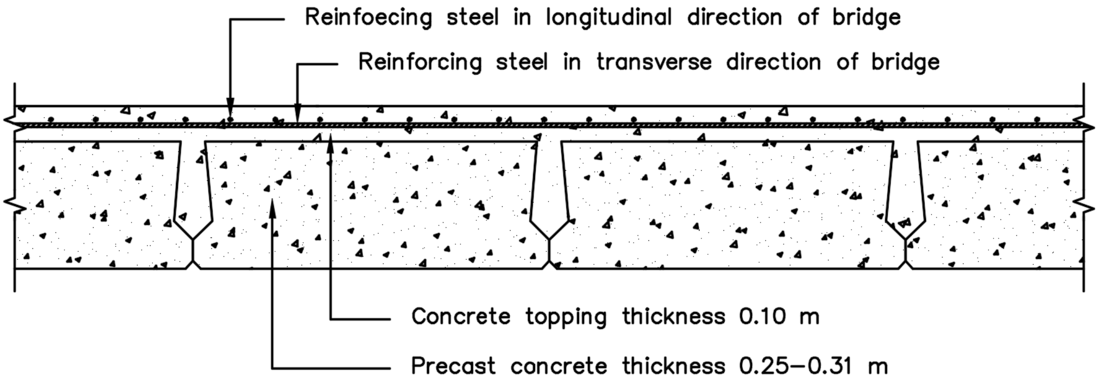


Figure 11 Typical section of Klong 15 bridge

4.4 DETERMINATION OF TEST POSITIONS

For damage inspection of concrete bridge, the investigation will be divided into 9 sections according to the bridge span. For each section, test position was defined as a gridline system (Fig. 12). The frequency of the gridline is 0.50-1.00 meters spacing, depended on data collection by each method.

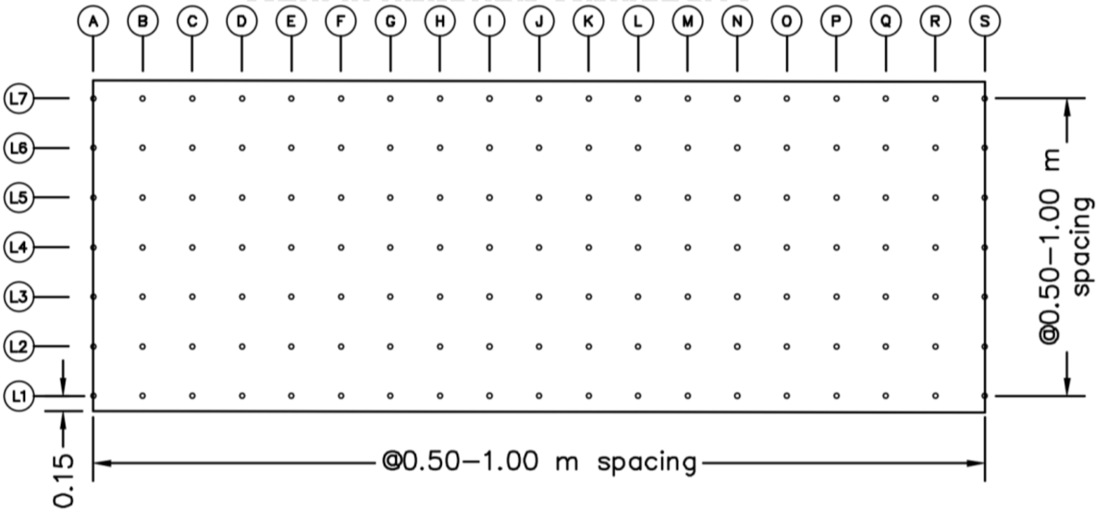


Figure 12 Testing location on bridge deck on each section

CHAPTER 5 RESULTS

Based on the results of survey and testing on concrete bridge deck by using general methods which consist of 3 methods i.e. visual inspection, chain drag and hammer sounding. In addition, 3 methods of nondestructive test including ground penetrating radar, half-cell potential and impact echo. Last but not least, the results were be cross checked with random coring test. Details of test results on each method can be summarized as follows.

5.1 VISUAL INSPECTION

Most part of the bridge deck were in fair conditions which can still be used. However, severs damage was found. For example, concrete spalling can be observed and the steel reinforcement was exposed around the middle section (Fig. 13). Most of the damage surface was shown in longitudinal cracks (Fig. 14) at the wheel path and halfway between the wheels. For transverse cracks, it can be observed together with longitudinal cracks. In addition, concrete spall also found at the middle part of bridge span in transvers direction (Fig. 15).

Moreover, other damage i.e. concrete scaling and pothole was also observed as well (Fig. 16).

Figure 13 Concrete spall until reinforcing steel level

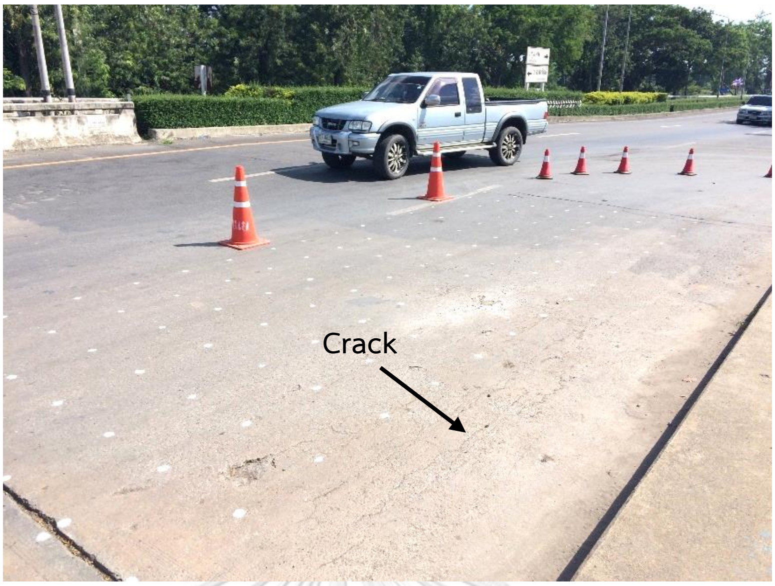


Figure 14 Longitudinal and transverse cracks on bridge deck

Figure 15 Concrete spall on the middle bridge span

Figure 16 Concrete scaling on along wheel path

The damage location based on visual inspection on each section was shown in Fig. 17-25.

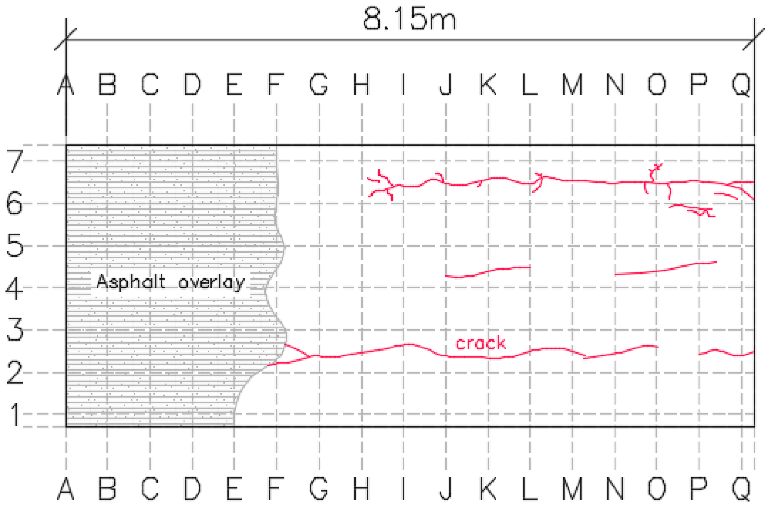


Figure 17 Damage location based on visual inspection on span no. 1

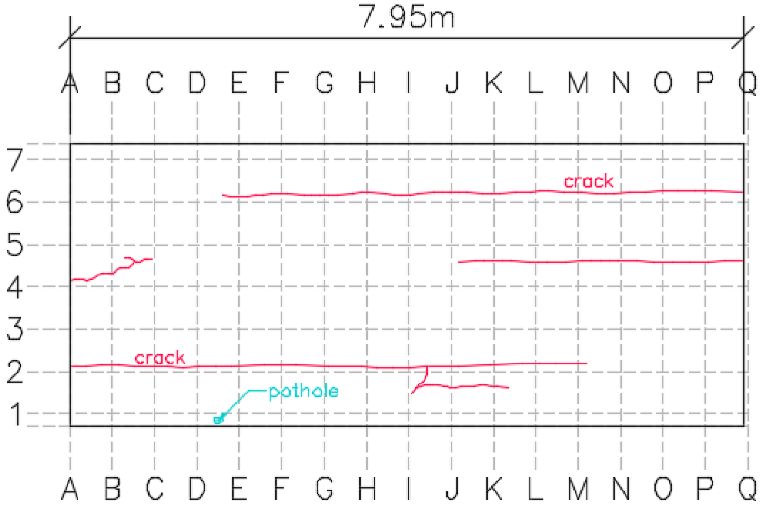


Figure 18 Damage location based on visual inspection on span no. 2

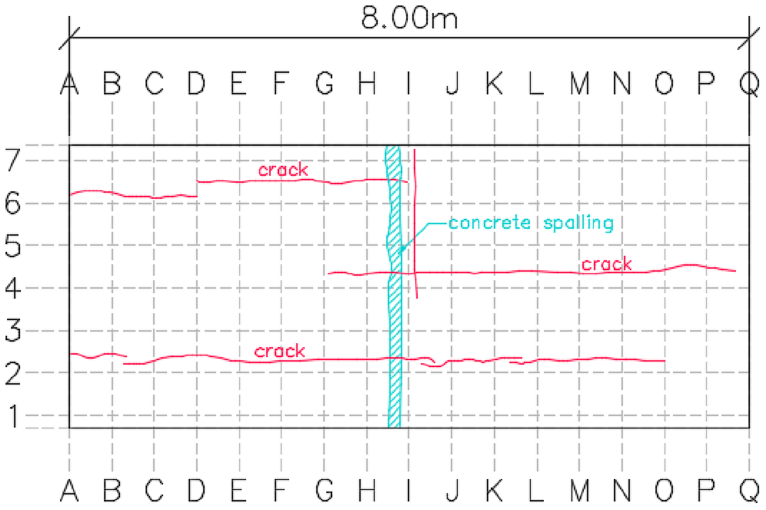


Figure 19 Damage location based on visual inspection on span no. 3

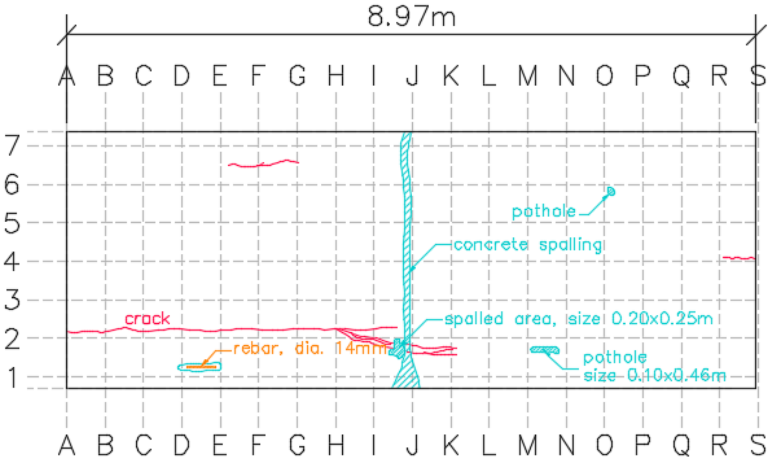


Figure 20 Damage location based on visual inspection on span no. 4

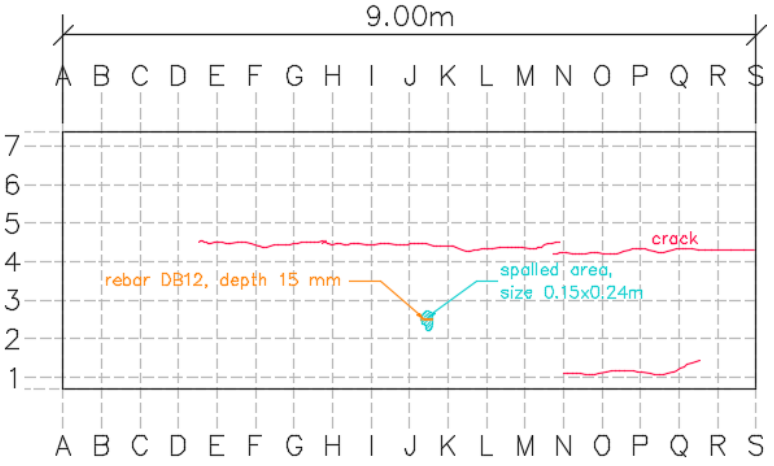


Figure 21 Damage location based on visual inspection on span no. 5

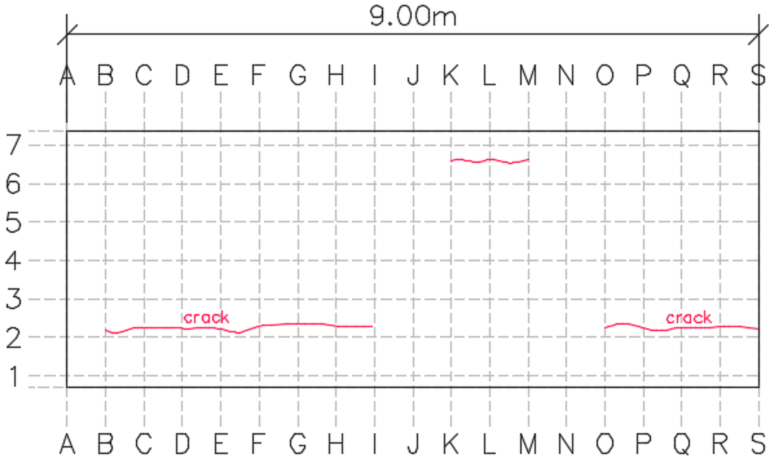


Figure 22 Damage location based on visual inspection on span no. 6

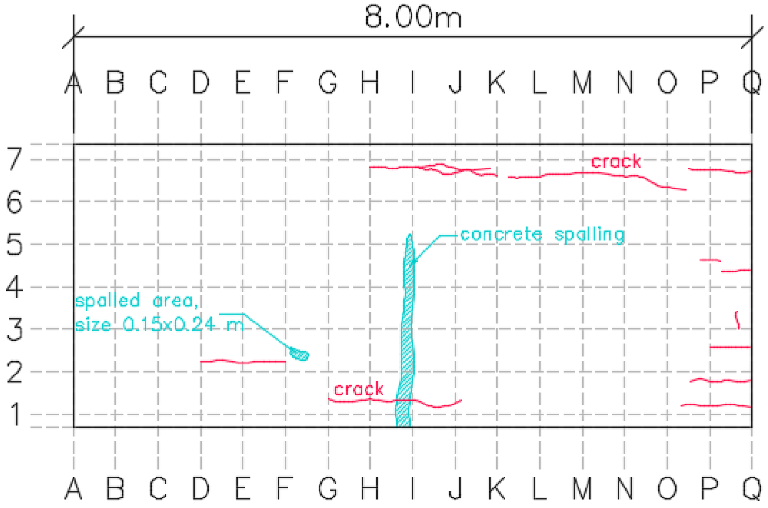


Figure 23 Damage location based on visual inspection on span no. 7

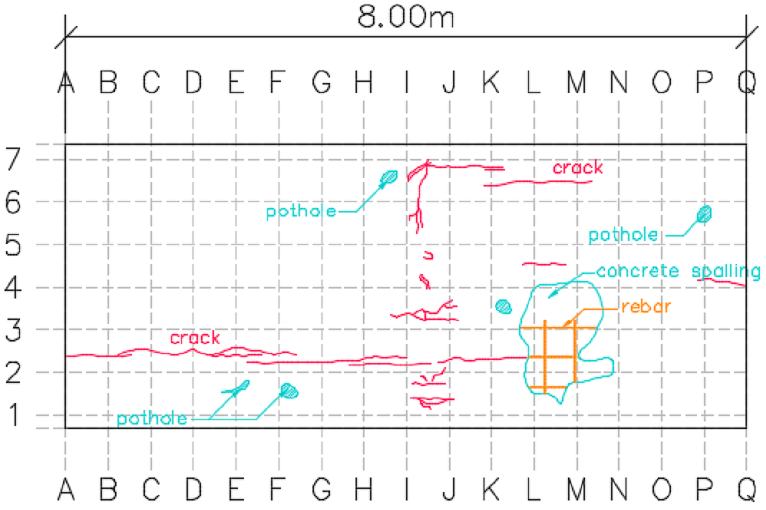


Figure 24 Damage location based on visual inspection on span no. 8

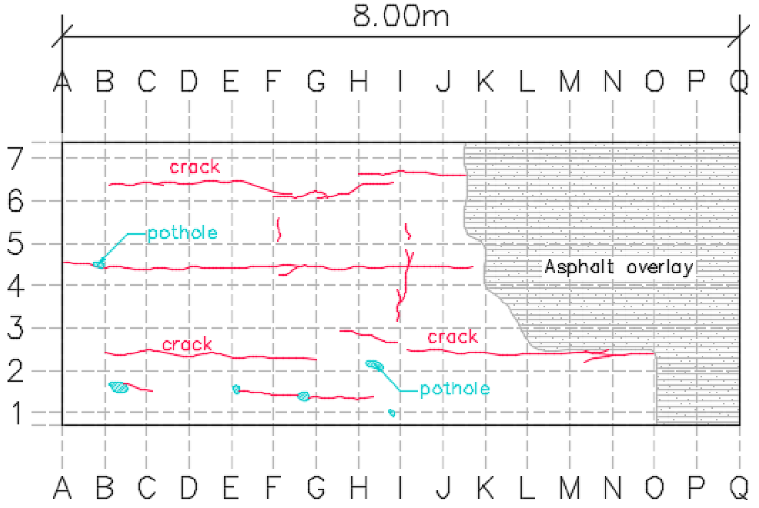


Figure 25 Damage location based on visual inspection on span no. 9

5.2 CHAIN DRAG

Chain drag (Fig. 26) was carried out with 0.50x0.50 meters spacing approximately along the specified survey line in order to specify the location of the crack underneath concrete bridge deck or cavities beneath the concrete surface.

Survey results from each area (Fig. 27-35) shown that damage in concrete bridge deck were scattered in to span no. 3, 4, 7, 8 and 9. Concrete defect covered wide area. However, mostly damage found on left wheel path of traffic lane. In addition, concrete defect also found in transvers direction, clearly visible at span no. 4, 5, 6 and 8. For concrete defect on right wheel path also found that there is little damage.

Figure 26 Chain drag test on bridge deck

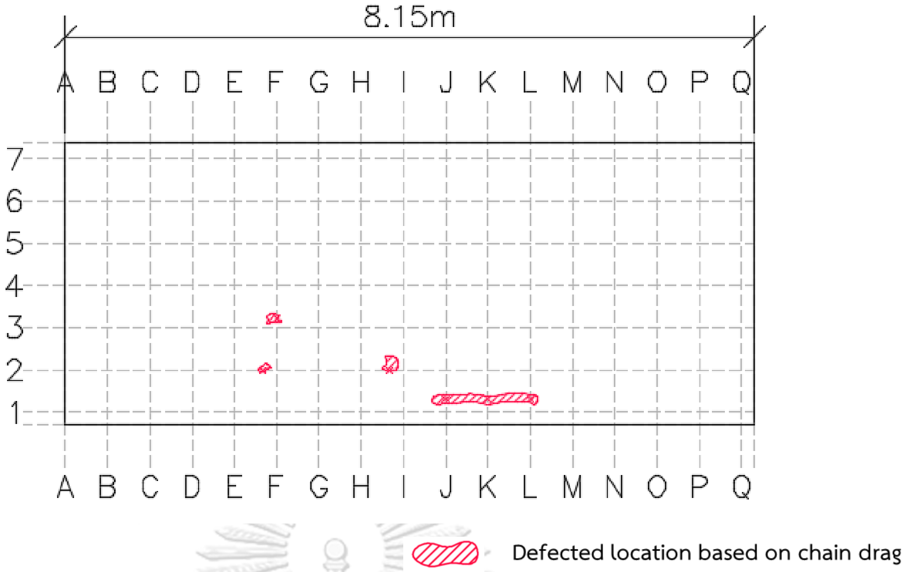


Figure 27 Defect location based on chain drag on span no. 1

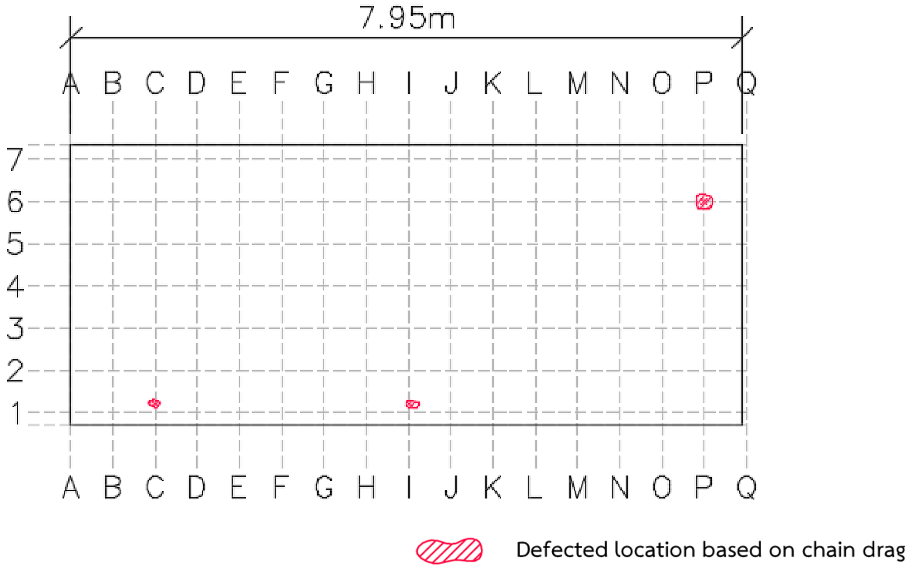


Figure 28 Defect location based on chain drag on span no. 2

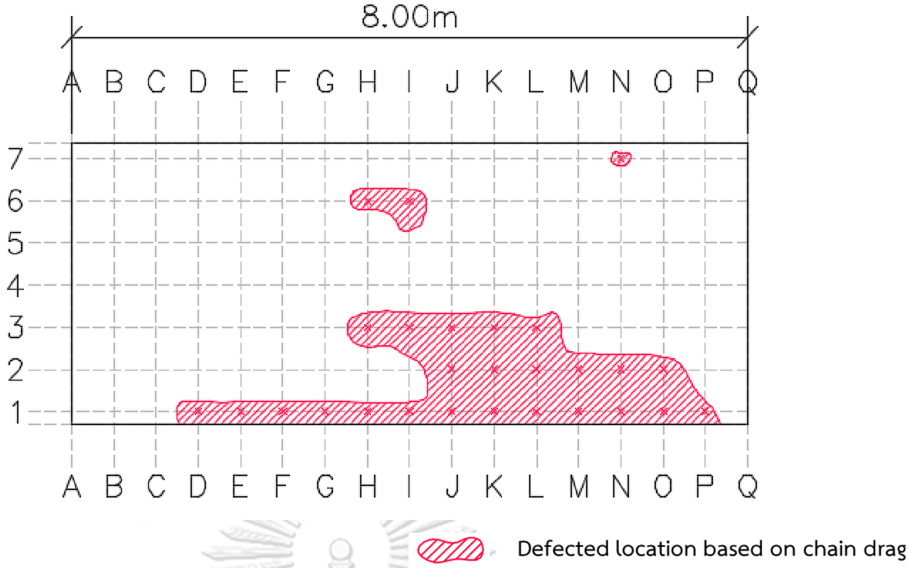


Figure 29 Defect location based on chain drag on span no. 3

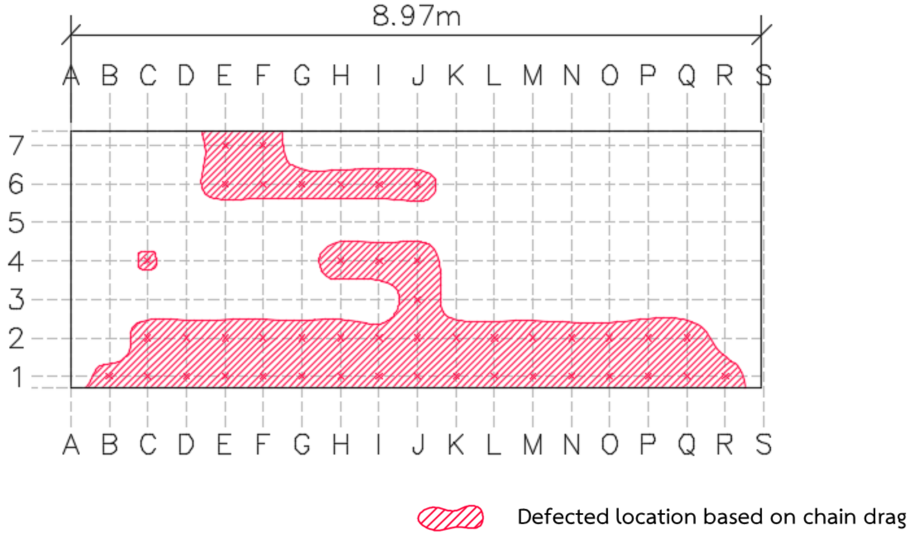


Figure 30 Defect location based on chain drag on span no. 4

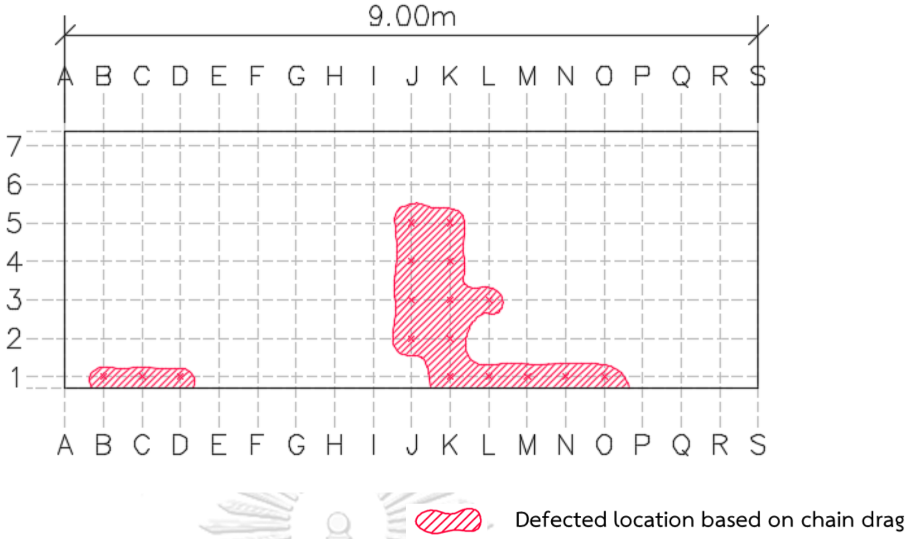


Figure 31 Defect location based on chain drag on span no. 5

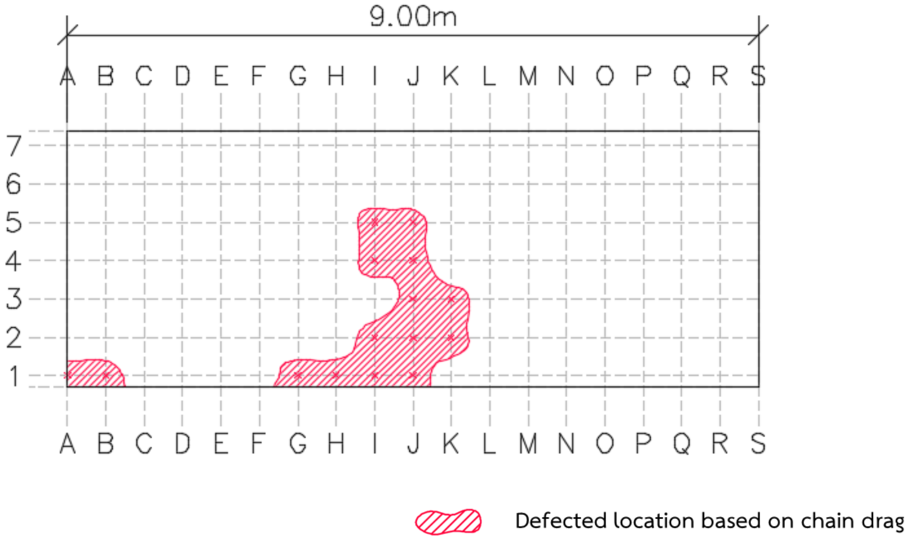


Figure 32 Defect location based on chain drag on span no. 6

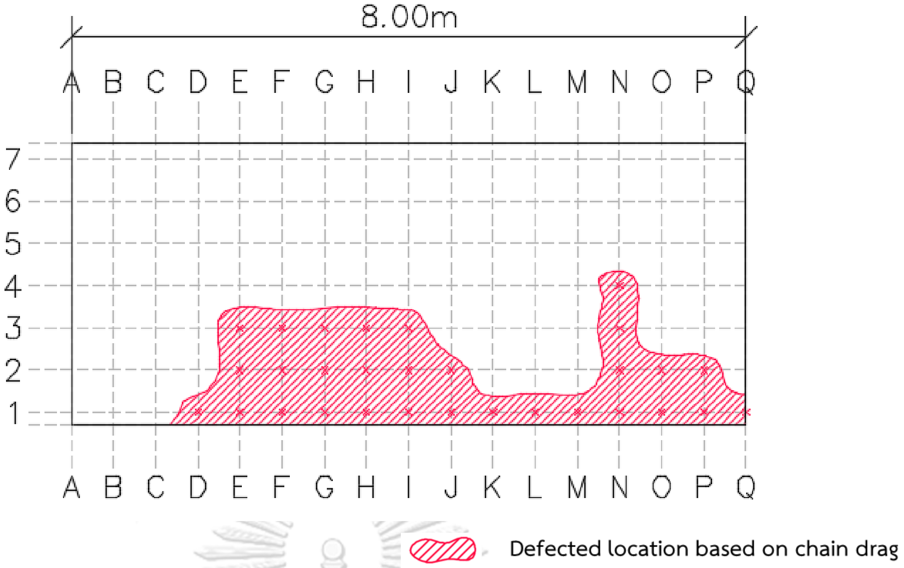


Figure 33 Defect location based on chain drag on span no. 7

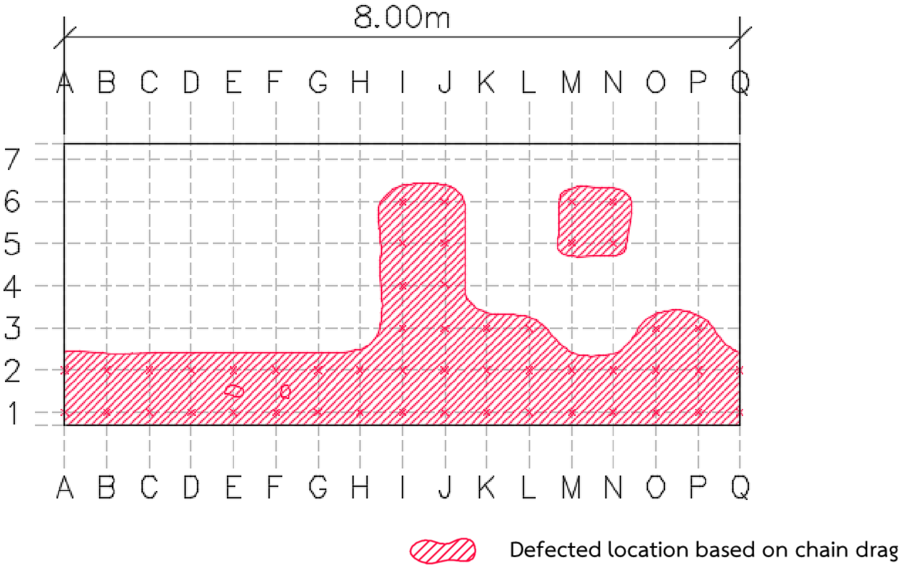


Figure 34 Defect location based on chain drag on span no. 8

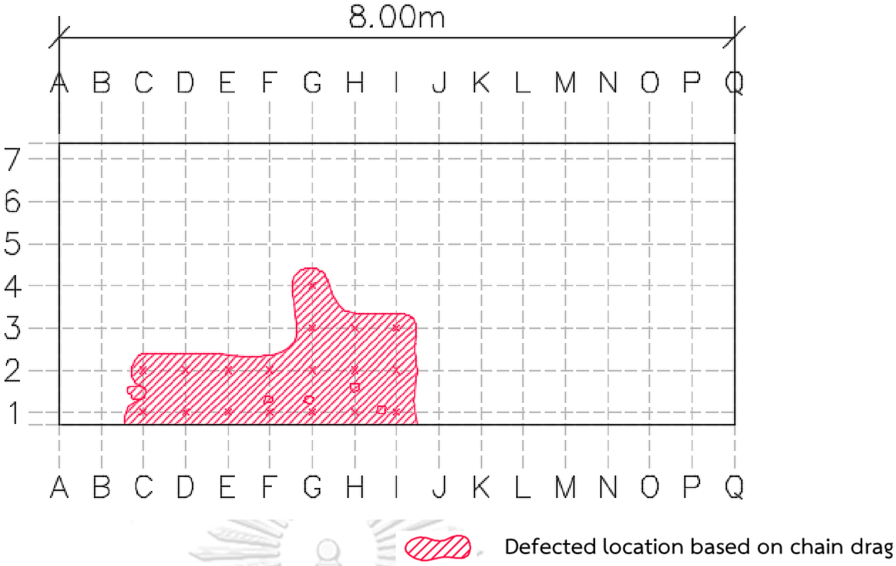


Figure 35 Defect location based on chain drag on span no. 9

5.3 HAMMER SOUNDING

Hammer sounding (Fig. 36) is conducted at the specified test position with 0.50x0.50 meters spacing to identify the location of concrete defect underneath concrete surface. Concrete deflect may be concrete spall, concrete slips off or crack.

The results of hammer sounding (Fig. 37-45) found that the damage usually found in bridge span no. 3, 4, 7, 8 and 9 or about 20-30% area of bridge surface. In addition, defect in bridge deck also found in 0.50-1.00 meters size.

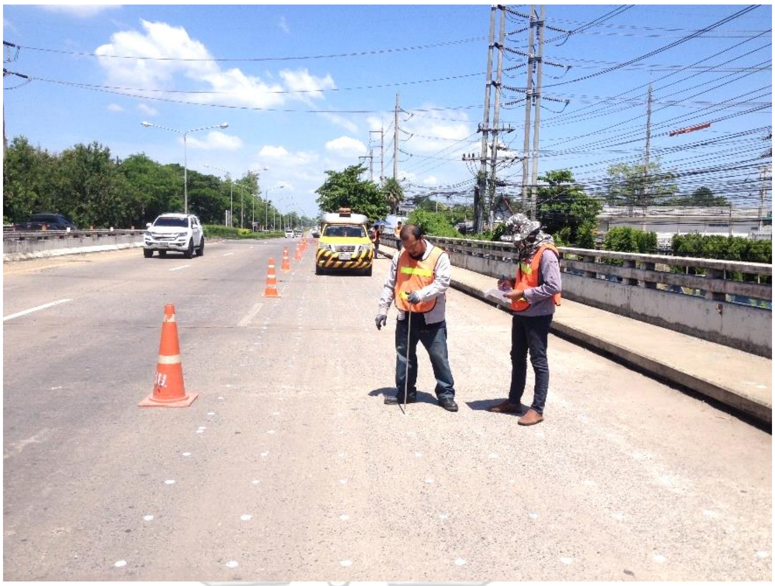


Figure 36 Sounding test on bridge deck

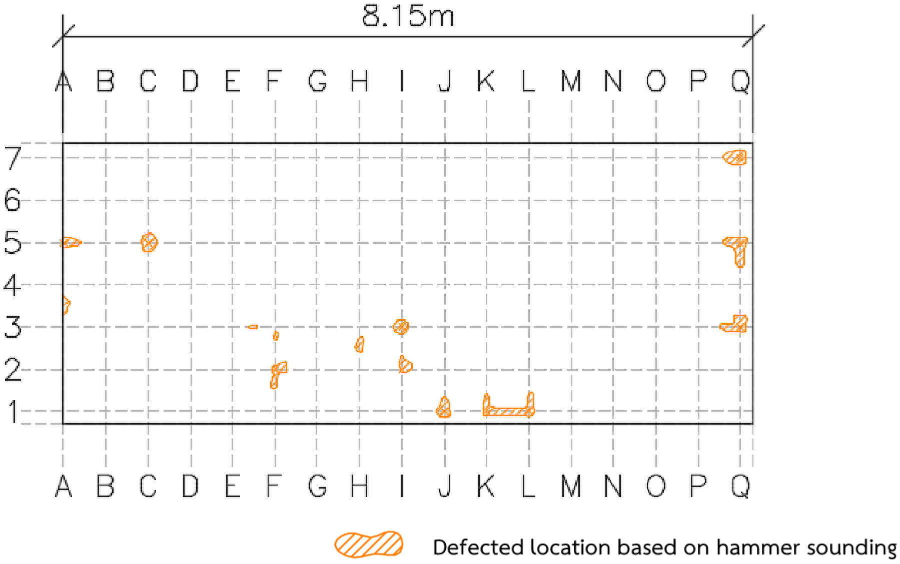


Figure 37 Defect location based on hammer sounding on span no. 1

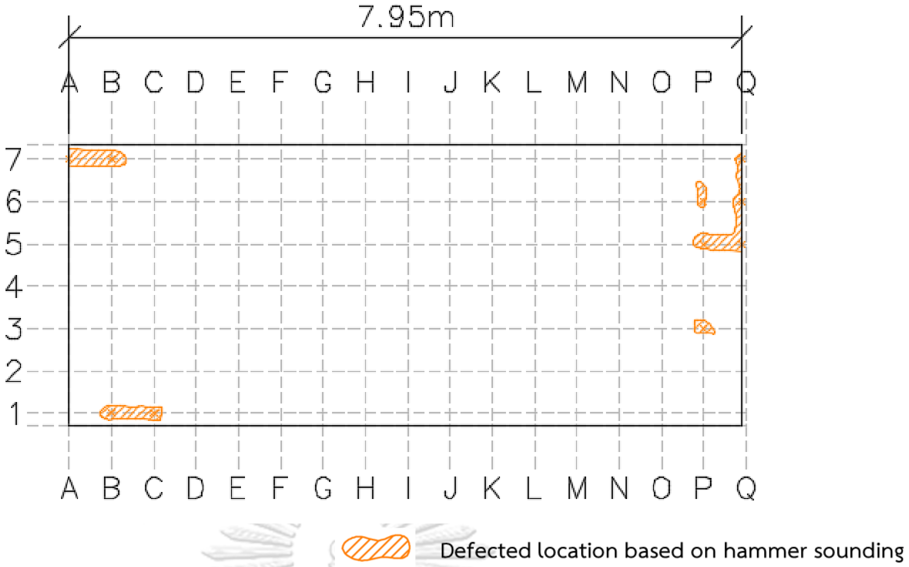


Figure 38 Defect location based on hammer sounding on span no. 2

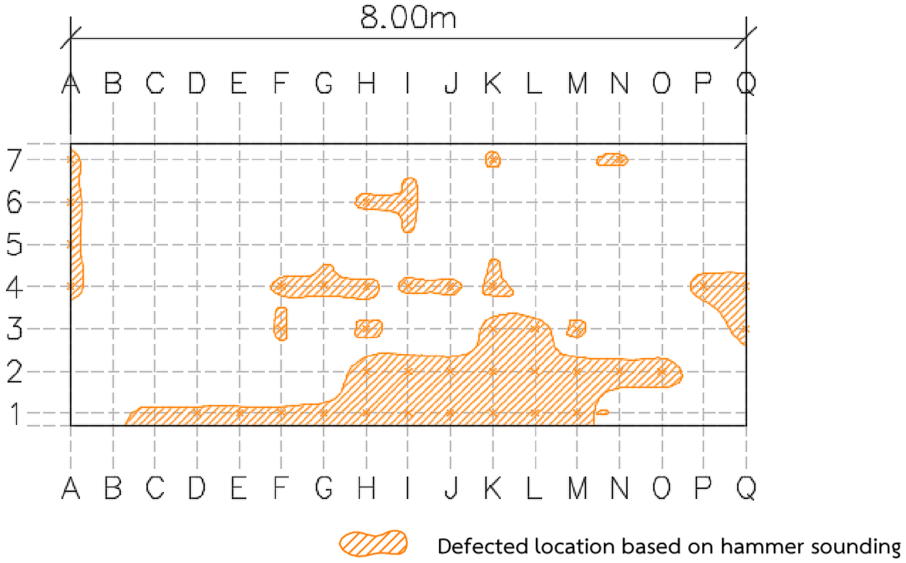


Figure 39 Defect location based on hammer sounding on span no. 3

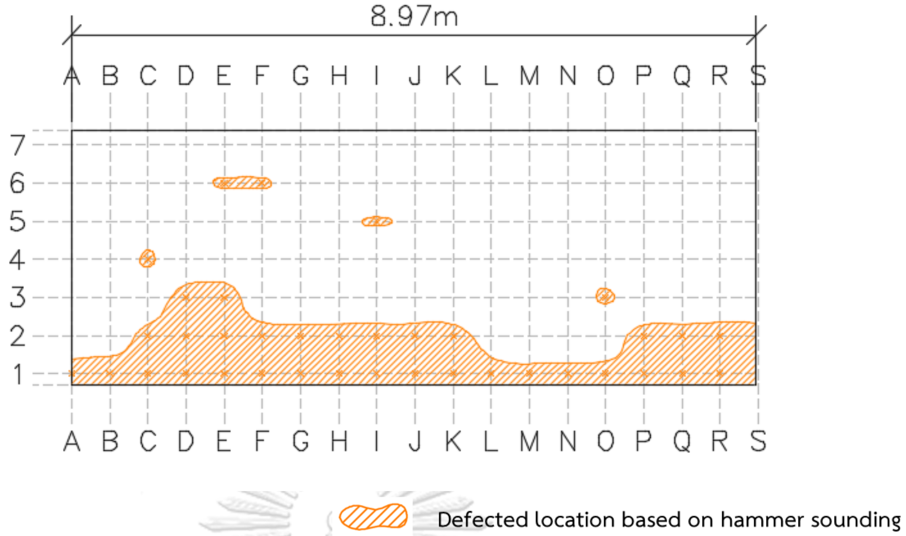


Figure 40 Defect location based on hammer sounding on span no. 4

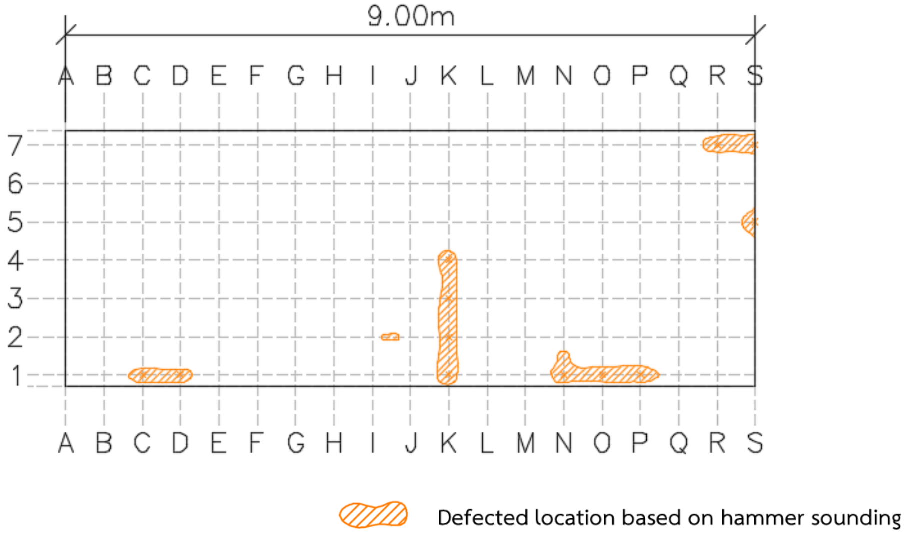


Figure 41 Defect location based on hammer sounding on span no. 5

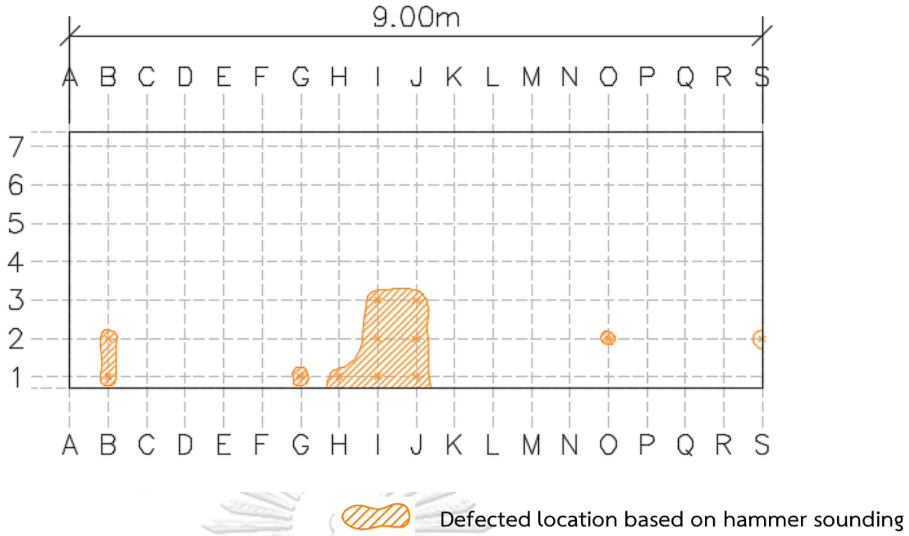


Figure 42 Defect location based on hammer sounding on span no. 6

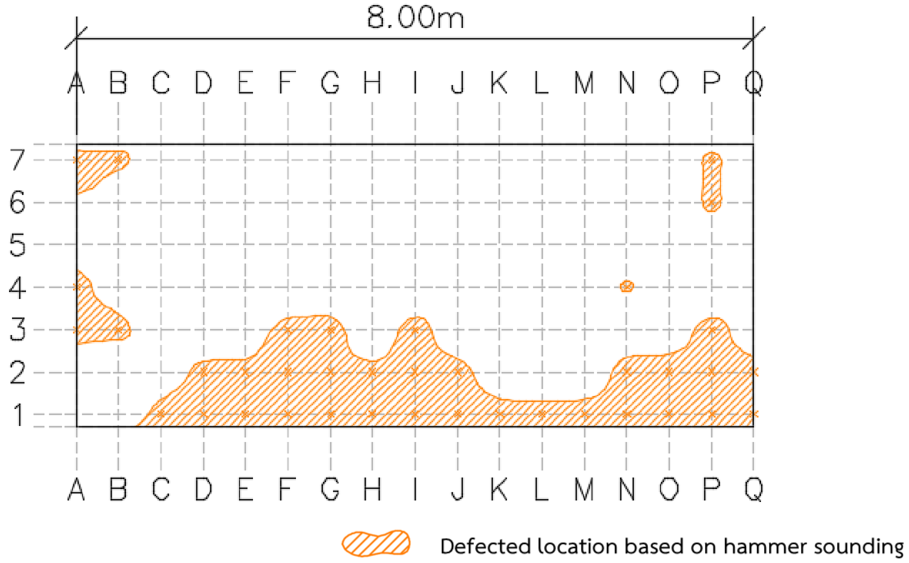


Figure 43 Defect location based on hammer sounding on span no. 7

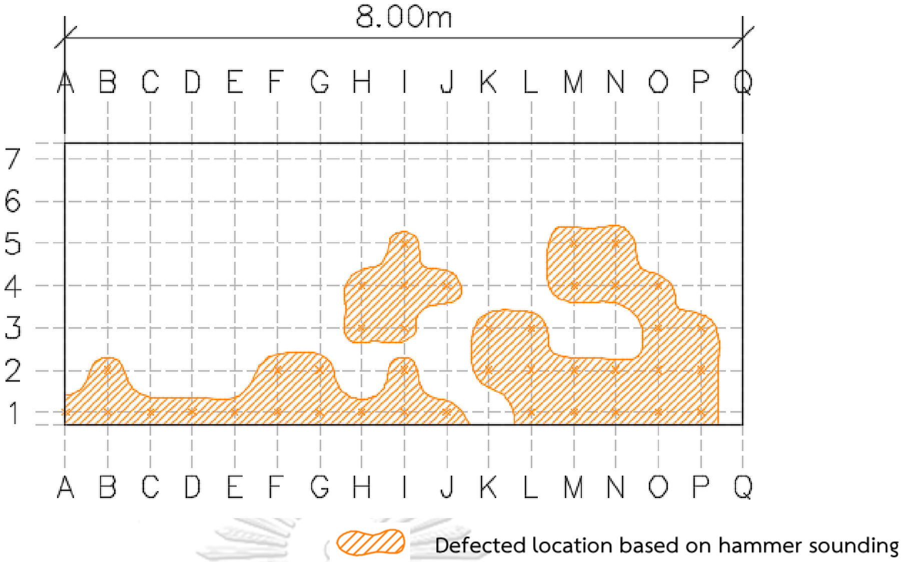


Figure 44 Defect location based on hammer sounding on span no. 8

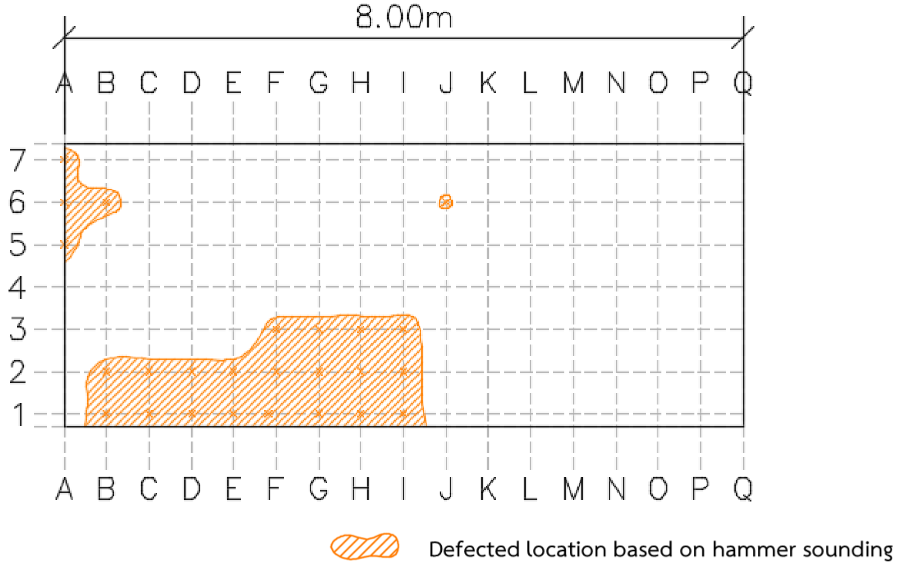


Figure 45 Defect location based on hammer sounding on span no. 9

5.4 GROUND PENETRATING RADAR

Ground penetrating radar results are displayed as a reflection of the radar wave. Position of reinforcing steel will have dielectric value different from concrete. So, radar pathways will be deviate look like a conical invert cone shape (Fig. 46).

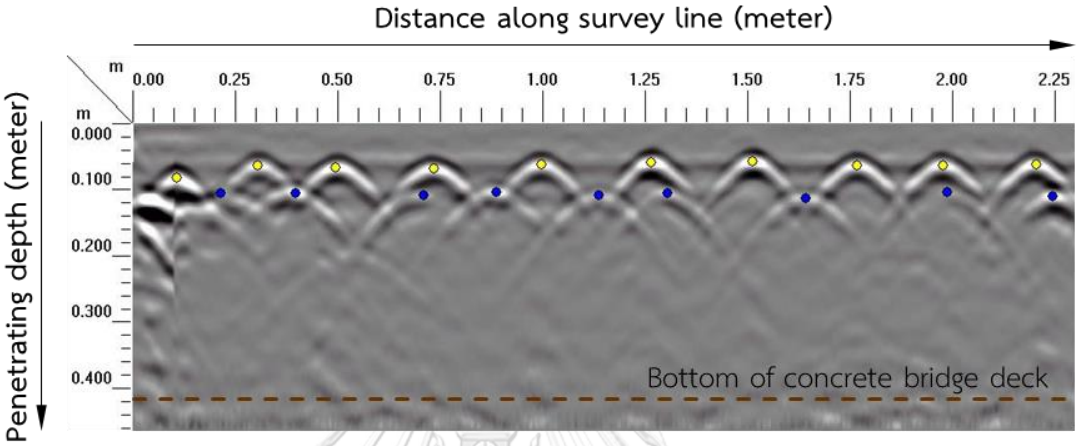


Figure 46 Example of ground penetrating radar results

From the signal example in Fig. 46, it obtained from ground penetrating radar survey. It can be found significant signal characteristic as follow: -

(1) Reflected signal from 1st layer of reinforcing steel (yellow point) which is located in topping concrete layer (0.10 meters thick). The reinforcing steel was found every 0.25 meters spacing approximately with 0.06 meters depth from test surface

(2) Reflected signal from 2nd layer of reinforcing steel (blue point) which is located inside of precast concrete. The reinforcing steel was found every 0.30 meters spacing approximately at 0.11 meters depth from test surface.

(3) Reflected signal from concrete bridge bottom (brown dashed line) which is an interface layer between concrete material and air. This interface was appeared as dark-bright strip at 0.41 meters depth from test surface.

Furthermore, crack in concrete can be detected by ground penetrating radar. The result will be displayed as a black-white band (Fig. 47), which caused by radar wave transmitted through two difference mediums between concrete material and air inside concrete crack.

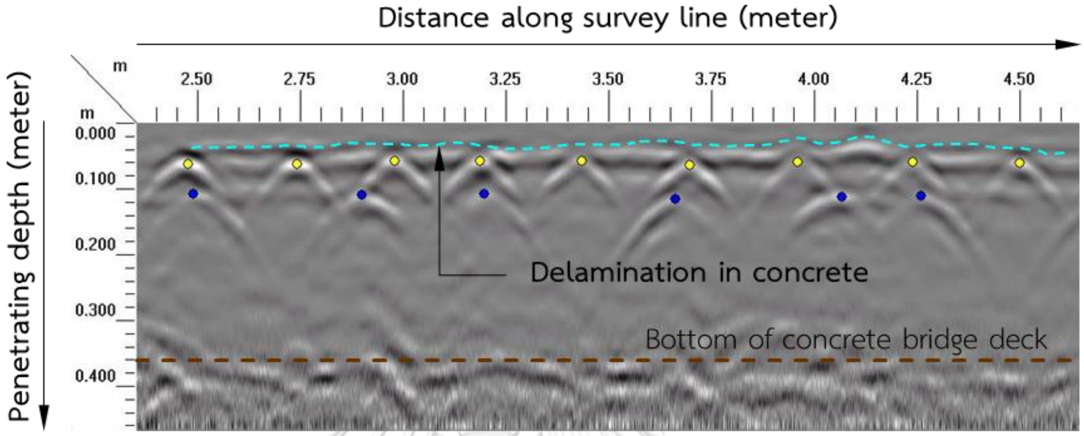


Figure 47 Delamination reflection in concrete

From the position of reinforcing steel, the amplitude of the iron head can be used to analyze the deterioration in concrete based on corrosion of rust inside the steel. Corrosive steel will reflect a radar wave as shown in low amplitude, while the steel with little corrosion will make a greater amplitude.

The result of amplitude analysis through the GSSI Radan's bridge deterioration module on each section was shown as in Fig. 48-56. Normalized amplitude range between 15 dB and 45 dB. From this amplitude range can be specify relative degree of deterioration into 3 levels; -

(1) Deterioration amplitude more than 35 dB. This group was classified as a good condition, streel may be have a little corrosion or does not have corrosion.

(2) Deterioration amplitude range 20 dB to 35 dB. This group was specified as a fair condition, reinforcing steel may be have partial corrosion. Most corrosion may be occurred only on surface steel.

(3) Deterioration amplitude less than 20 dB. This area with low amplitude may be have more corrosion in reinforcing steel as classified as poor condition for concrete bridge deck. Steel surface may be found corrosion.

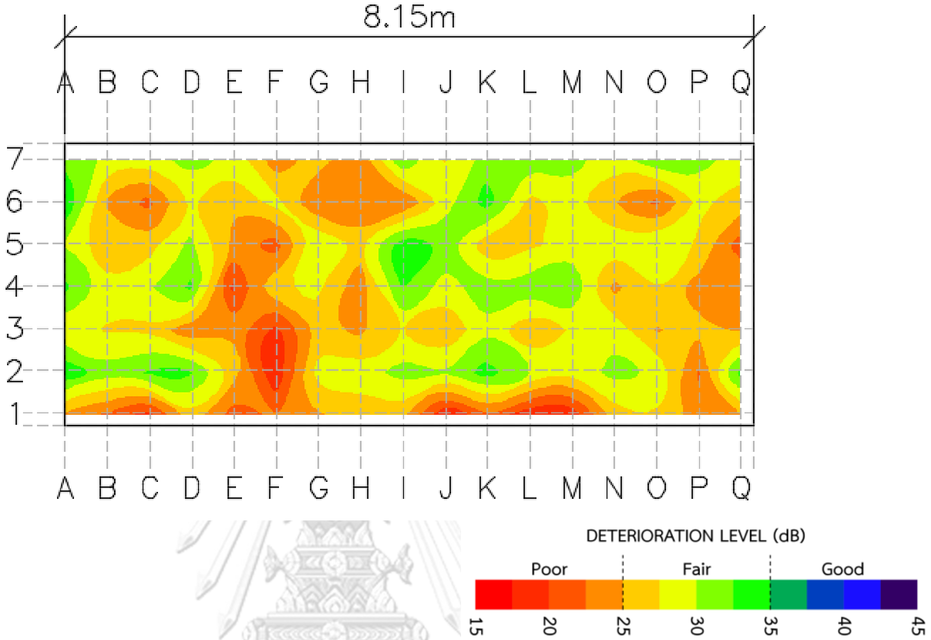


Figure 48 Deterioration map based on ground penetrating radar on span no. 1

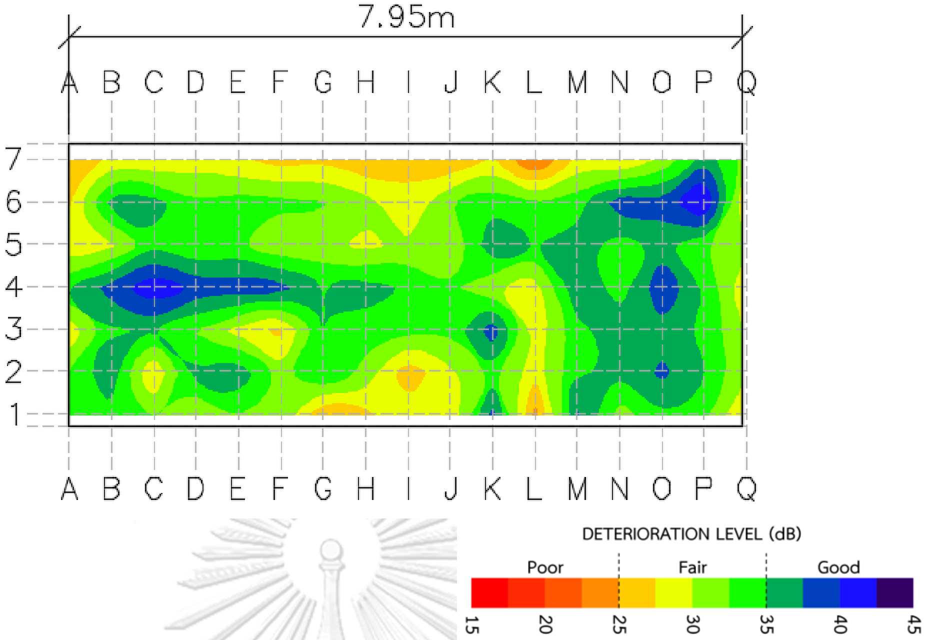


Figure 49 Deterioration map based on ground penetrating radar on span no. 2

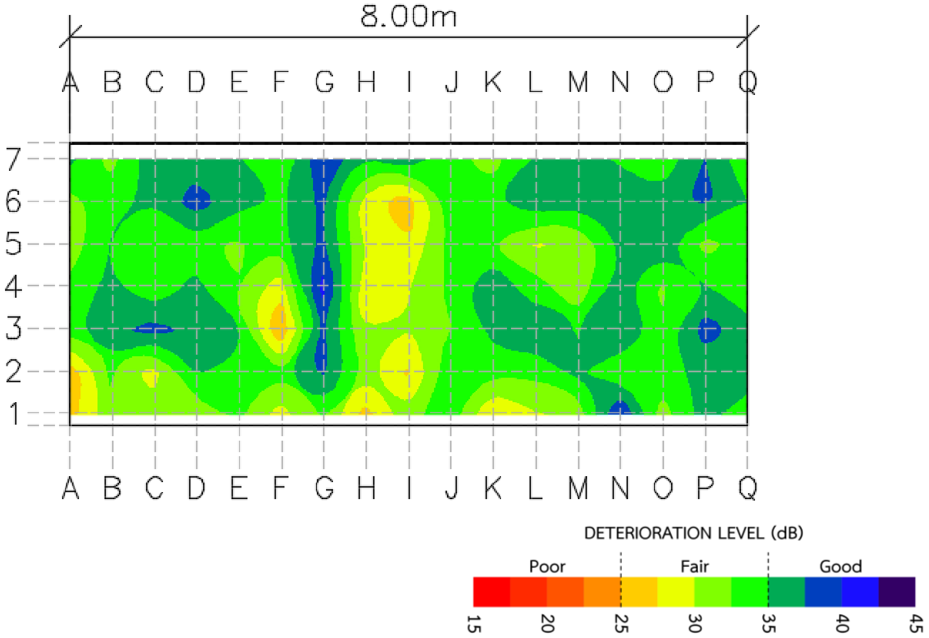


Figure 50 Deterioration map based on ground penetrating radar on span no. 3

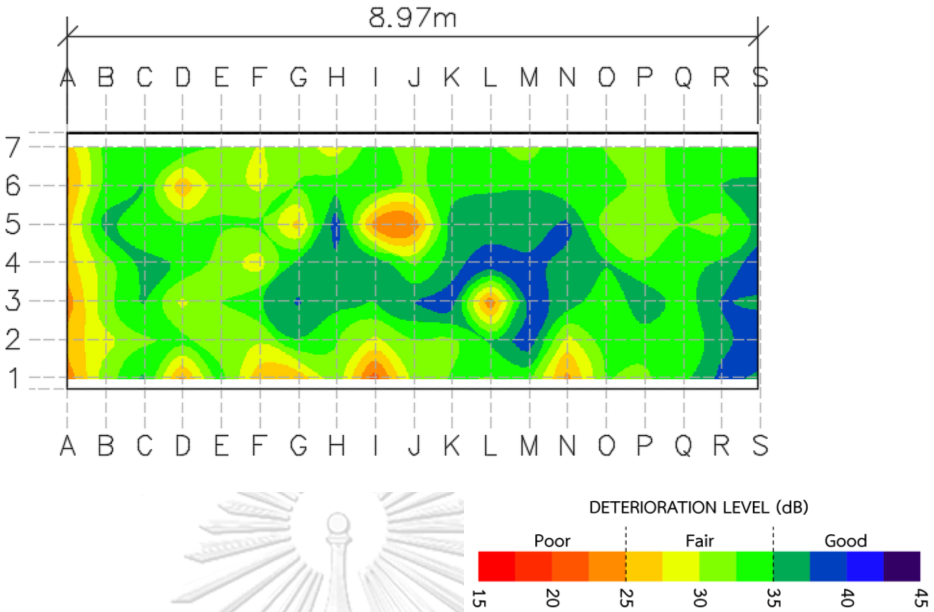


Figure 51 Deterioration map based on ground penetrating radar on span no. 4

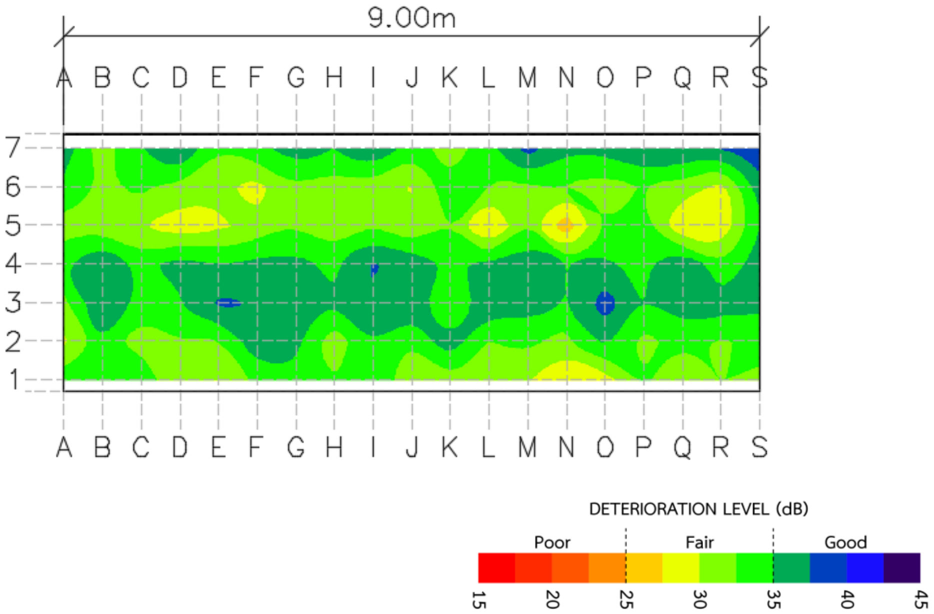


Figure 52 Deterioration map based on ground penetrating radar on span no. 5

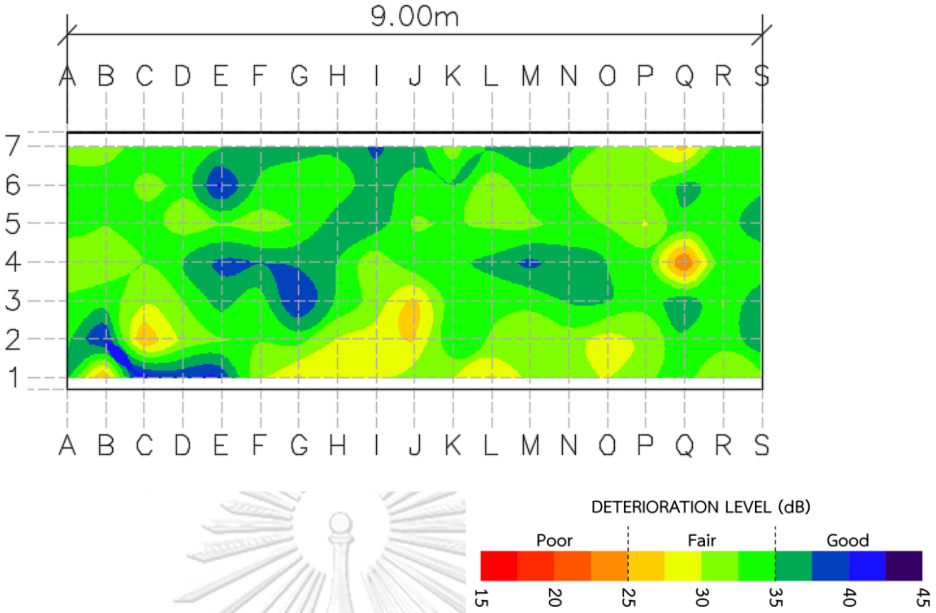


Figure 53 Deterioration map based on ground penetrating radar on span no. 6

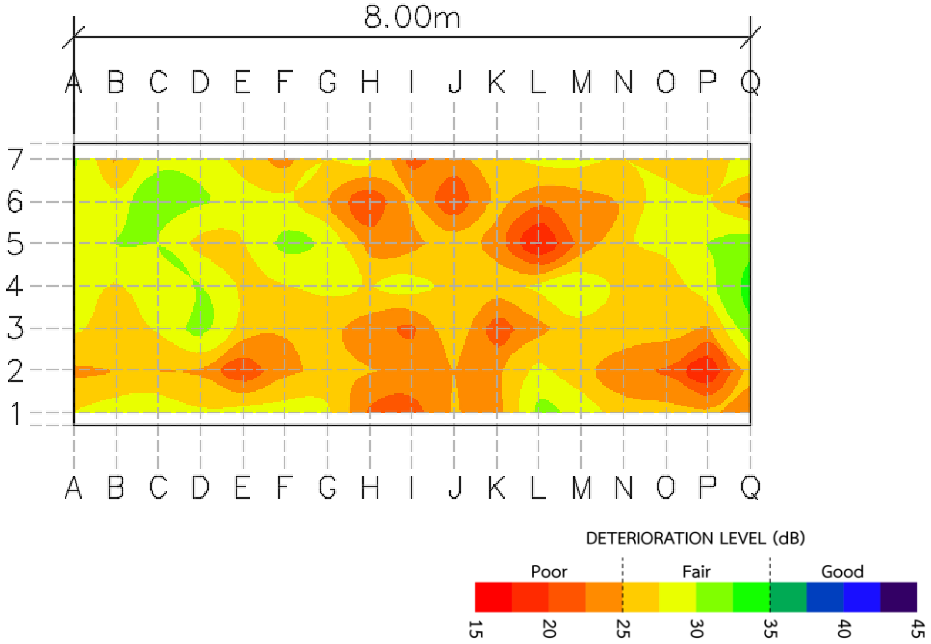


Figure 54 Deterioration map based on ground penetrating radar on span no. 7

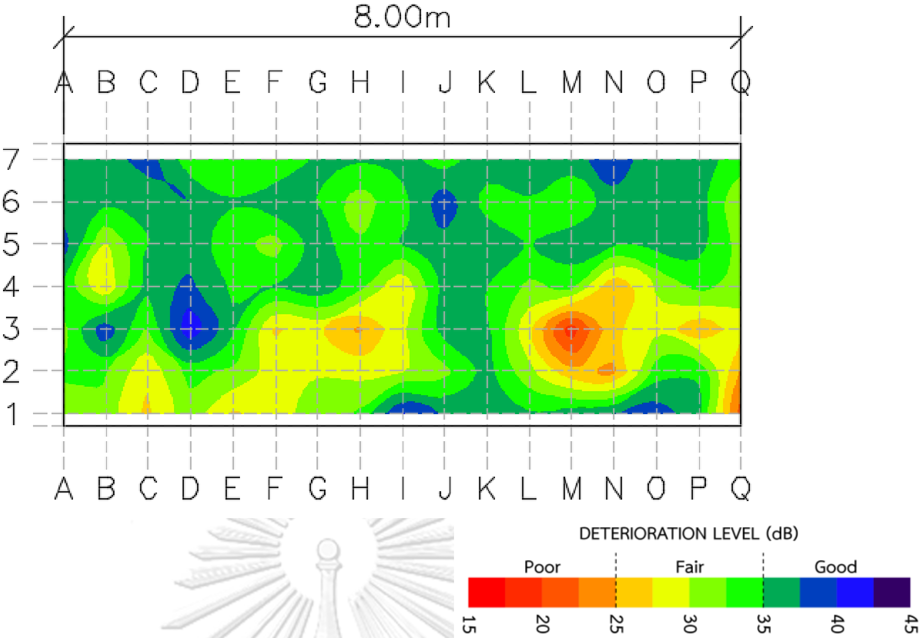


Figure 55 Deterioration map based on ground penetrating radar on span no. 8

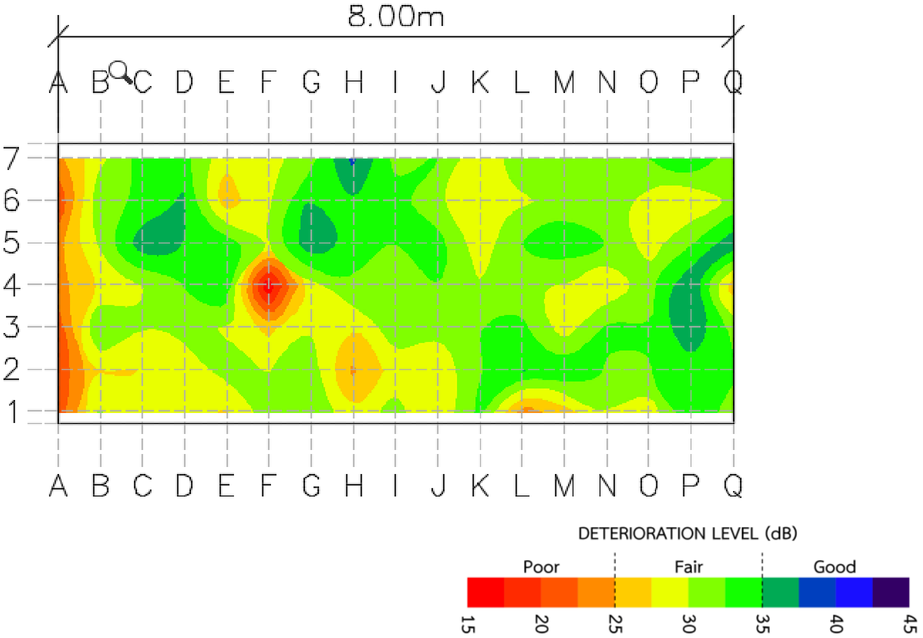
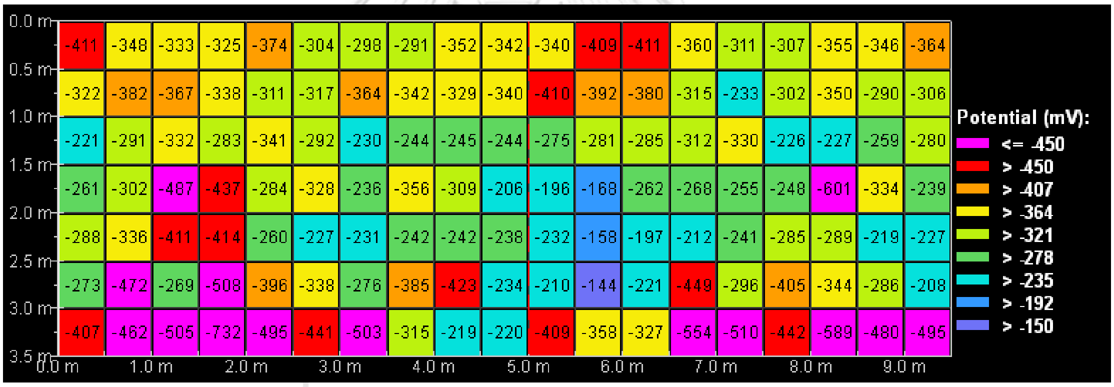


Figure 56 Deterioration map based on ground penetrating radar on span no. 9

5.5 HALF-CELL POTENTIAL

Half-cell potential result along the survey line at 0.50 meters spacing are displayed electrical potential average value every 0.50 meters (Fig. 57). The horizon axis shows distance along the survey line (in meter), while the vertical axis shows the survey line spacing (in meter). The values obtained from sech survey line will be drawn into a map showing the deterioration of the reinforcing steel (Fig. 58-66) based on the ASTM C876.

According the survey results, it was found that bridge with high deterioration of steel are found in bridge span no. 4, 6 and 8, or exceeding 80% of the bridge deck. In addition, the bridge span no. 3, 5 and 7 also have possibility of corrosion in reinforcing steel as well. For another bridge span, possibility of corrosion in steel can be only found in small area.



-411	-348	-333	-325	-374	-304	-298	-291	-352	-342	-340	-409	-411	-360	-311	-307	-355	-346	-364
-322	-382	-367	-338	-311	-317	-364	-342	-329	-340	-410	-392	-380	-315	-233	-302	-350	-290	-306
-221	-291	-332	-283	-341	-292	-230	-244	-245	-244	-275	-281	-285	-312	-330	-226	-227	-259	-280
-261	-302	-487	-437	-284	-328	-236	-356	-309	-206	-196	-168	-262	-268	-255	-248	-601	-334	-239
-288	-336	-411	-414	-260	-227	-231	-242	-242	-238	-232	-158	-197	-212	-241	-285	-289	-219	-227
-273	-472	-269	-508	-396	-338	-276	-385	-423	-234	-210	-144	-221	-449	-296	-405	-344	-286	-208
-407	-462	-505	-732	-495	-441	-503	-315	-219	-220	-409	-358	-327	-554	-510	-442	-589	-480	-495

Figure 57 Example of half-cell potential result

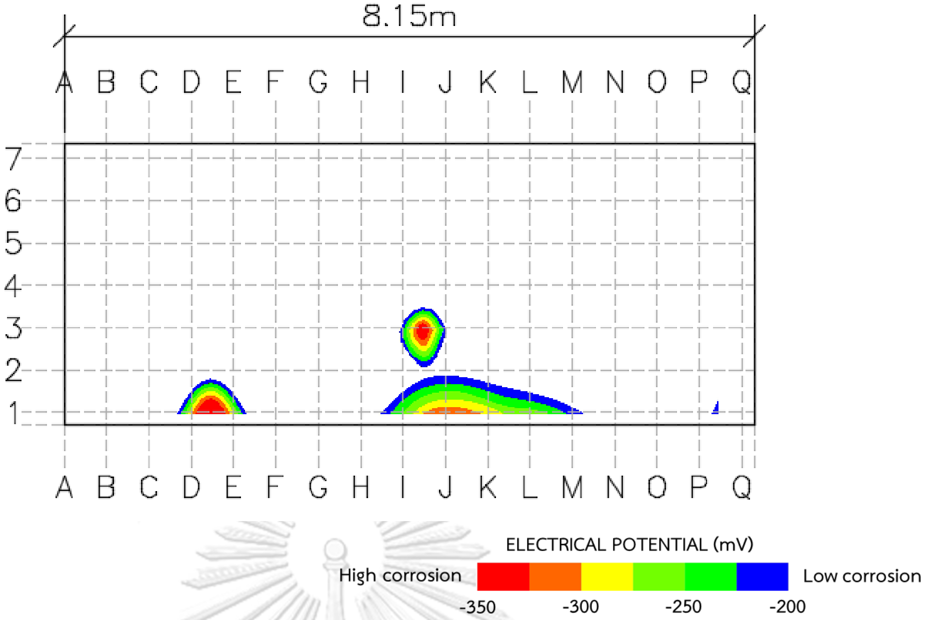


Figure 58 Possibility location of corrosion based on half-cell potential on span no. 1

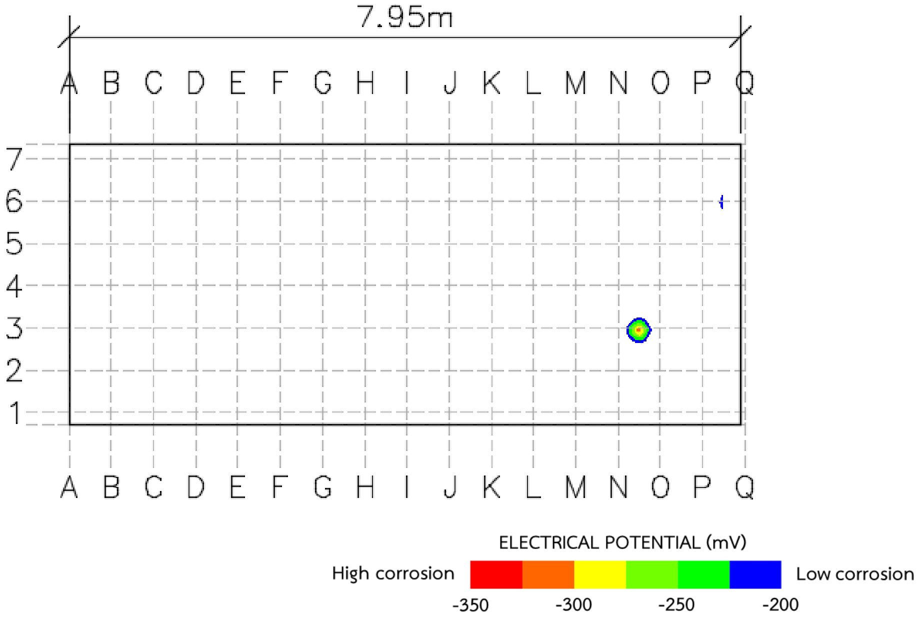


Figure 59 Possibility location of corrosion based on half-cell potential on span no. 2

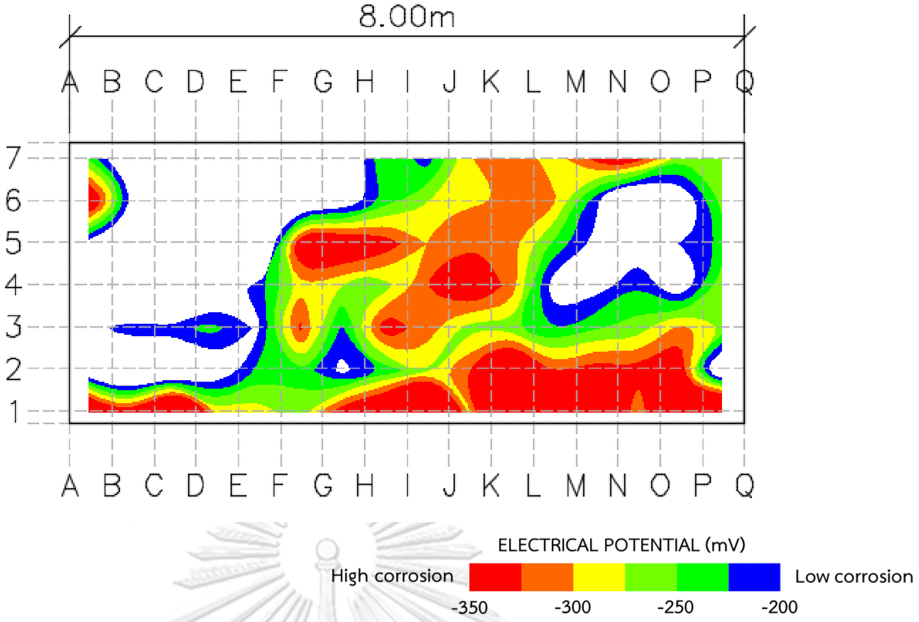


Figure 60 Possibility location of corrosion based on half-cell potential on span no. 3

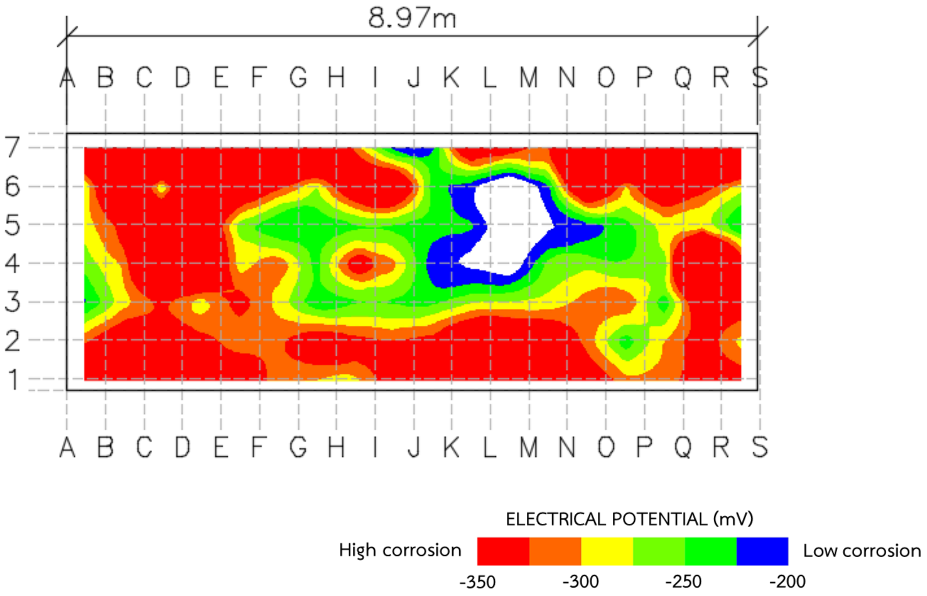


Figure 61 Possibility location of corrosion based on half-cell potential on span no. 4

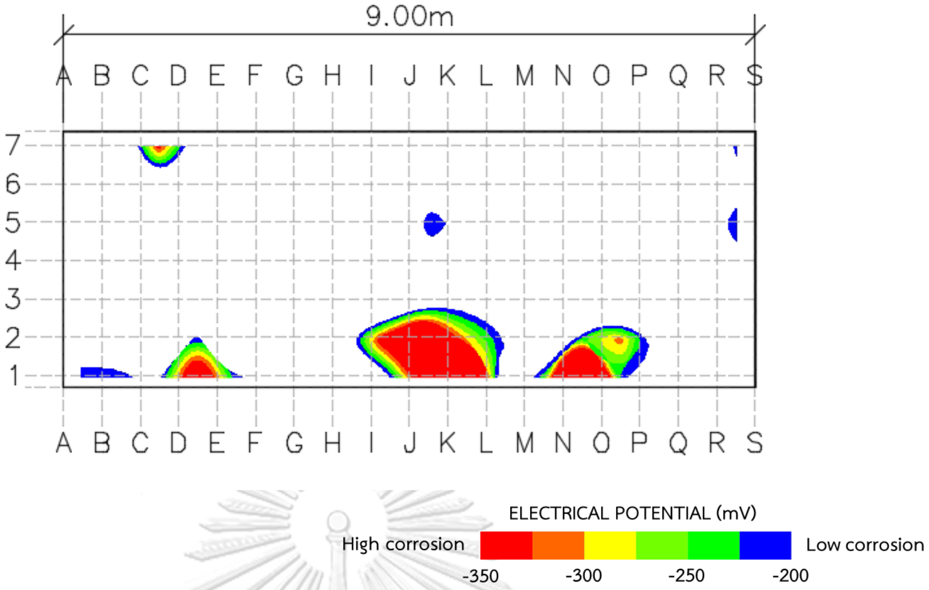


Figure 62 Possibility location of corrosion based on half-cell potential on span no. 5

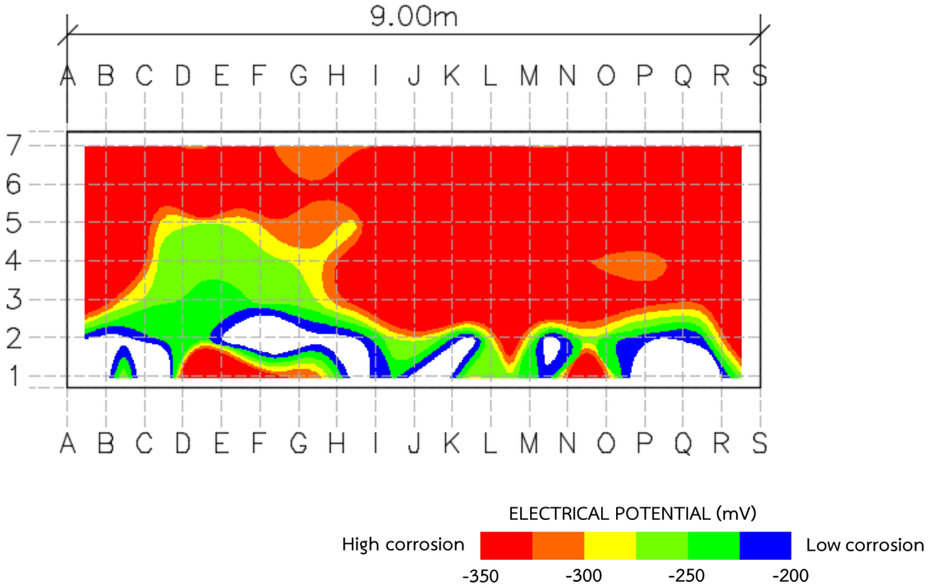


Figure 63 Possibility location of corrosion based on half-cell potential on span no. 6

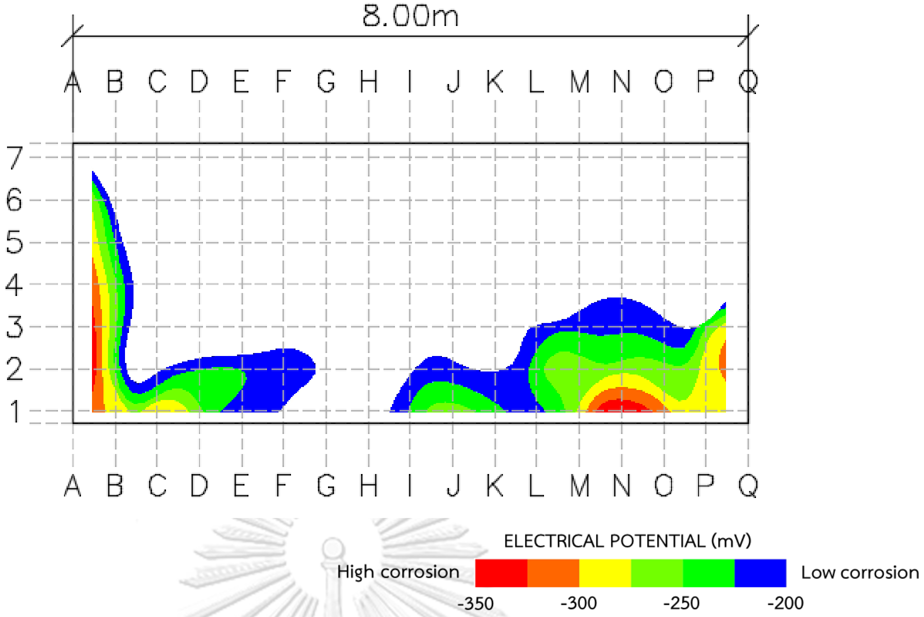


Figure 64 Possibility location of corrosion based on half-cell potential on span no. 7

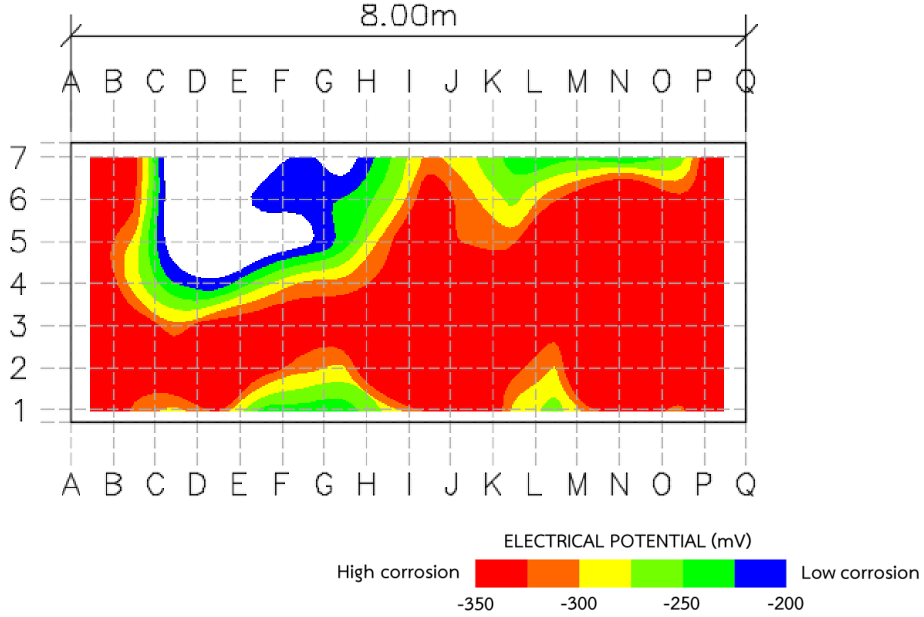


Figure 65 Possibility location of corrosion based on half-cell potential on span no. 8

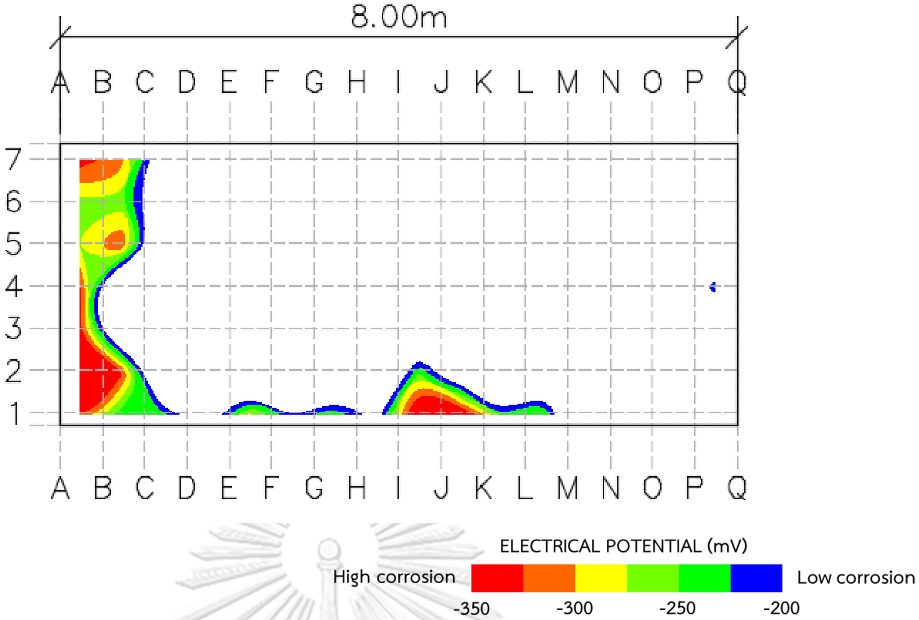


Figure 66 Possibility location of corrosion based on half-cell potential on span no. 9

5.6 IMPACT ECHO TEST

The result of impact echo test by using hammer to generate stress wave (Fig. 67) compose of 2 graphs: (1) time domain result and (2) frequency spectrum result. Depth of anomaly can be found by convert from frequency value by specific stress wave velocity in concrete around 3,800 meters/seconds (calibrated velocity at know thickness portion). Details of significant reflection signal as follows: -

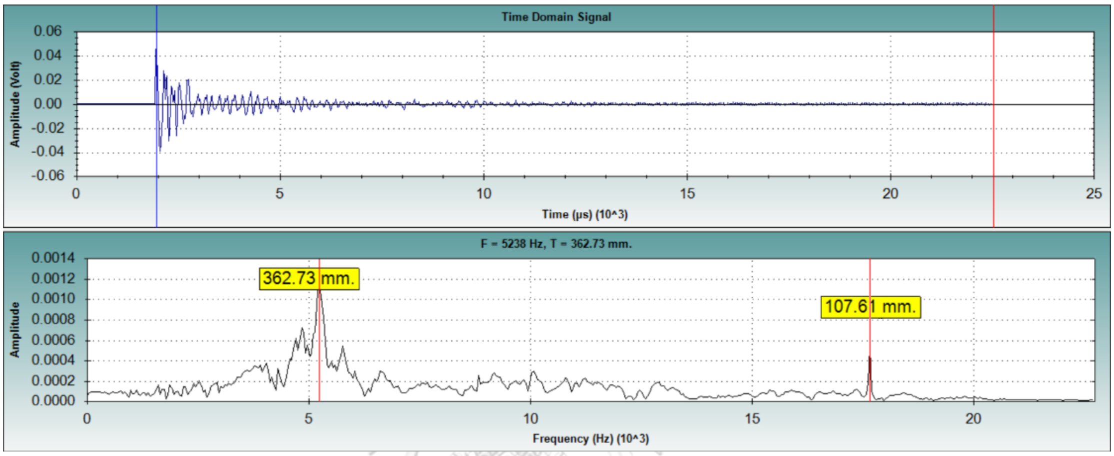


Figure 67 Example of impact echo test on bridge deck

From the signal as shown in Fig. 67, it was found that the significant anomaly characteristics are as follow: -

(1) Reflected signal from interface layer between concrete topping layer and precast concrete at 0.11 meters depth from test surface.

(2) Reflected signal from bottom concrete of the bridge at 0.36 meters depth from test surface.

According to impact echo results, the integrity of concrete bridge was in fair condition, sever damages were found in some section based on considering the frequency group. If the frequency was higher than half of the reflected signal from bottom bridge, it may be considered to be a slightly damage. And, if found a frequency that was higher than the reflected signal from the bottom bridge, it may be considered as severe damage criteria.

Impact echo result of each bridge deck section was shown in Fig. 68-76. The color shade was proposed integrity condition criteria and description on concrete member as shown in Table 4.

Table 4 Integrity condition and description on concrete bridge deck (Gucunski et al., 2011)

Integrity condition	Description	Impact on structure
Good condition (green)	No anomaly was found	No effect
Fair condition (yellow)	Minor anomaly matters – such as small void or honeycomb in small areas – were found inside the test specimen	These anomalies usually not significantly affect to the structure integrity and stability
Poor condition (red)	Major anomaly matter – large internal crack/flaw, large void or honeycomb in large area, etc. – were probably found inside the test specimen	These anomalies maybe affect to the structure integrity and stability. Additional testing should be carried out to confirm the size and position of anomaly matters such as core drilling

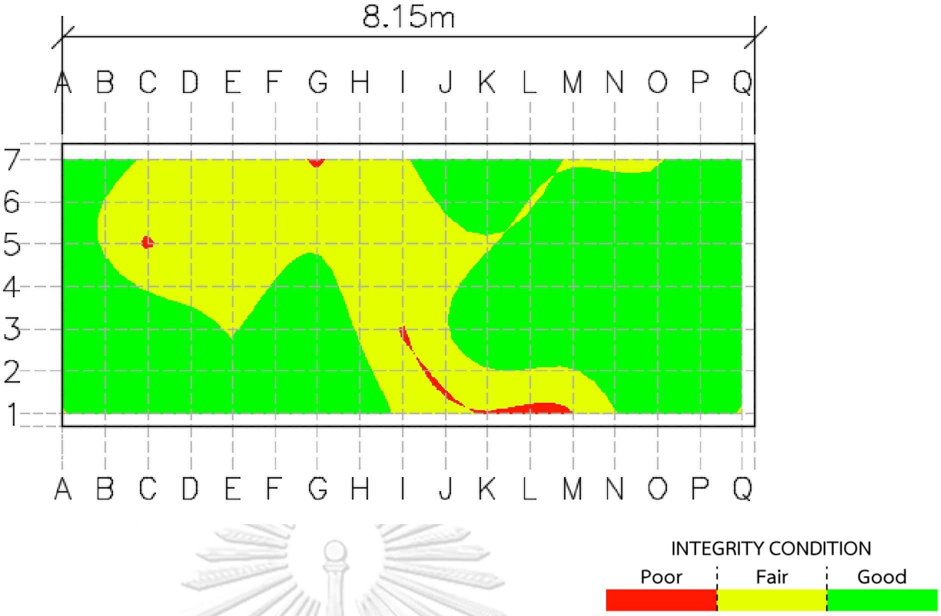


Figure 68 Integrity of concrete based on impact echo test on span no. 1

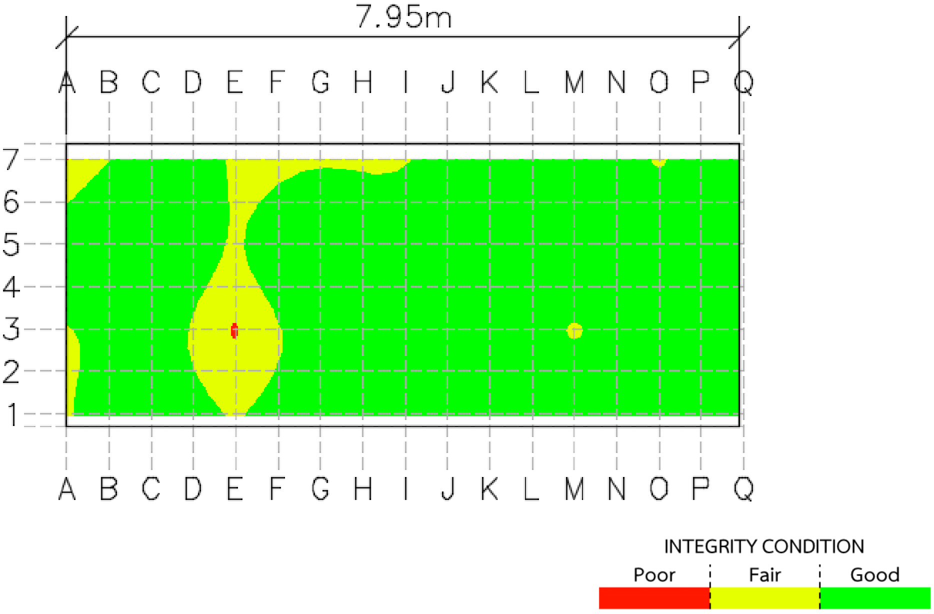


Figure 69 Integrity of concrete based on impact echo test on span no. 2

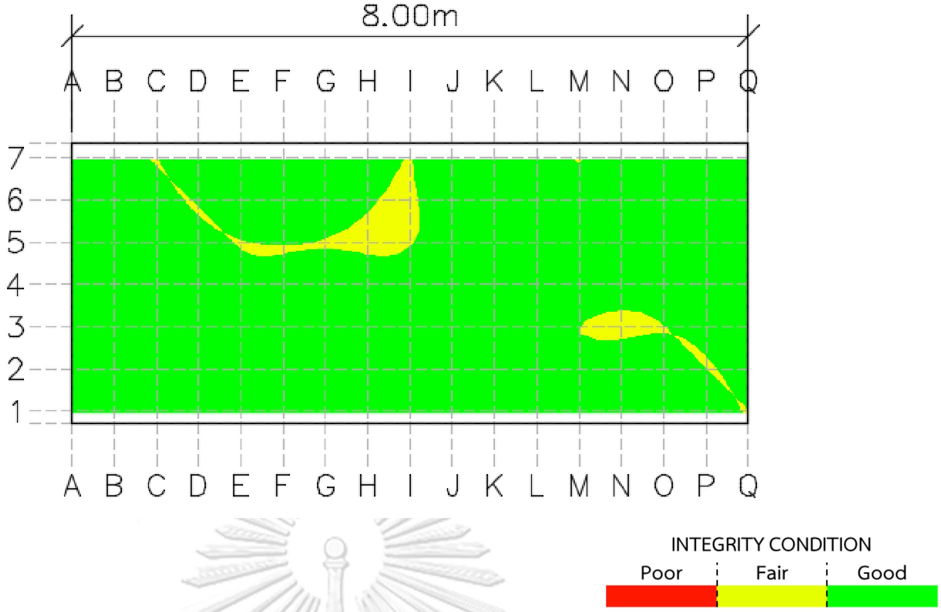


Figure 70 Integrity of concrete based on impact echo test on span no. 3

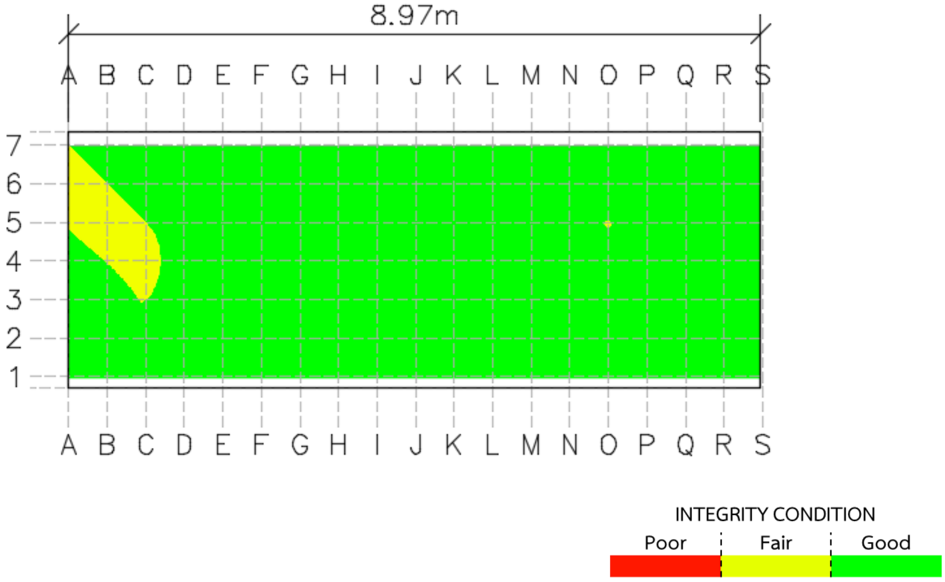


Figure 71 Integrity of concrete based on impact echo test on span no. 4

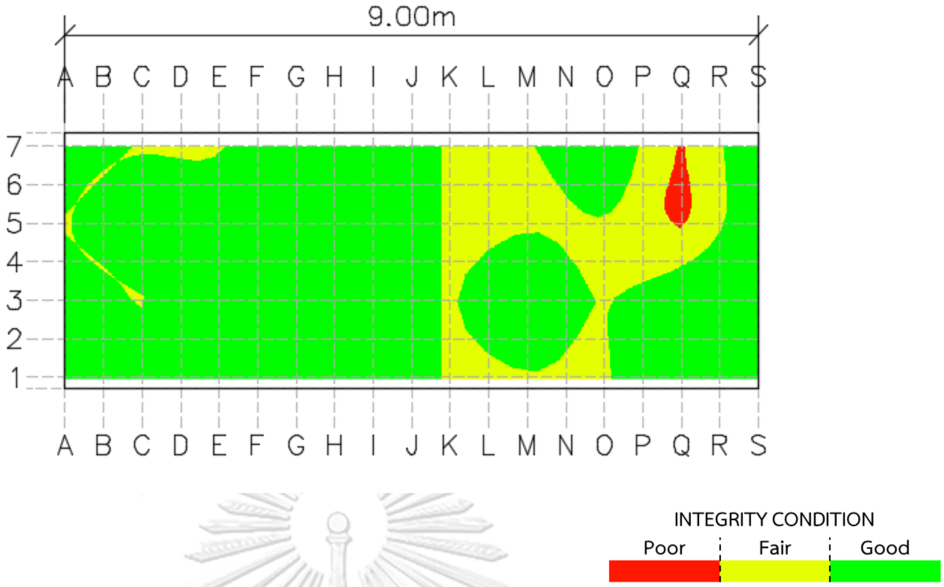


Figure 72 Integrity of concrete based on impact echo test on span no. 5

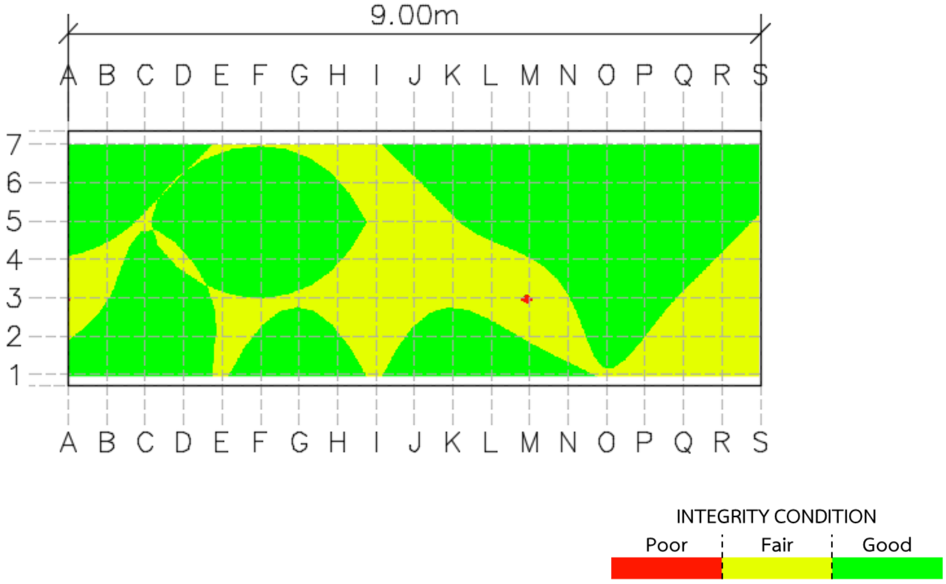


Figure 73 Integrity of concrete based on impact echo test on span no. 6

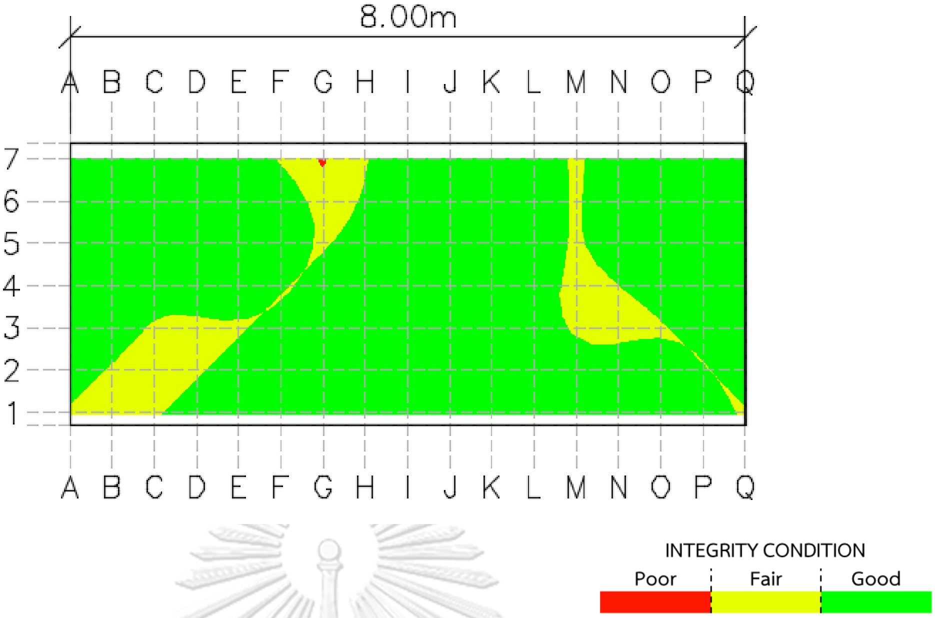


Figure 74 Integrity of concrete based on impact echo test on span no. 7

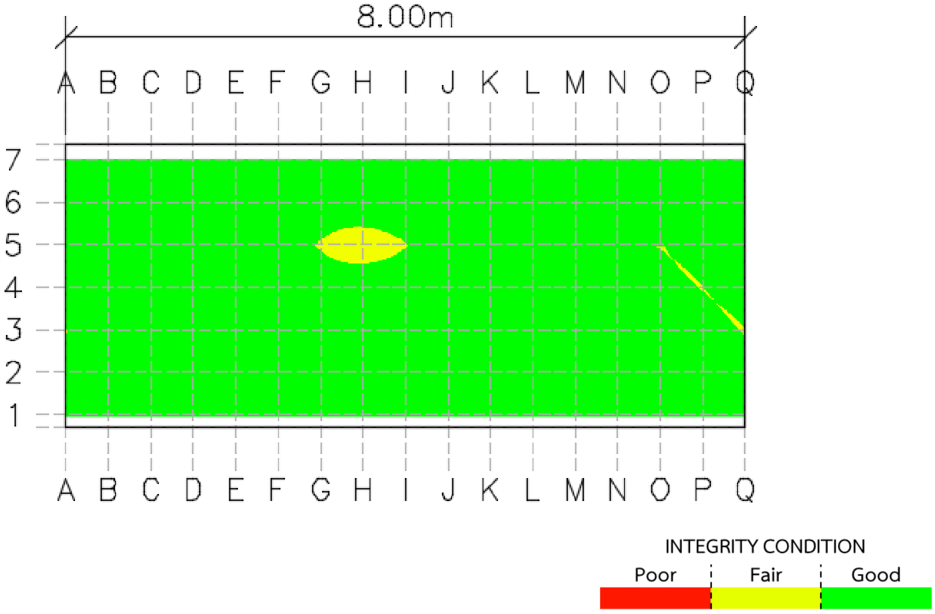


Figure 75 Integrity of concrete based on impact echo test on span no. 8

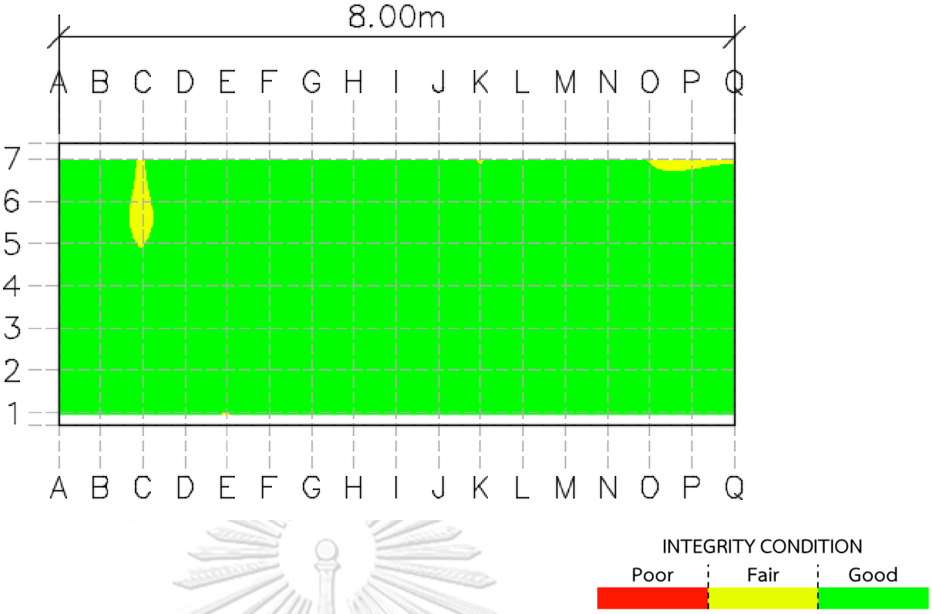


Figure 76 Integrity of concrete based on impact echo test on span no. 9

5.7 CORE SAMPLING TEST

Based on results from each test method (Fig. 77), it presents a defect location along the bridge deck. For ground penetrating radar, high deterioration was shown as red area with 15 dB amplitude, while low deterioration was shown as blue area with 45 dB amplitude. Deterioration value based on ground penetrating radar was on only classified in relative to adjacent area. For half-cell potential, high probability of corrosion (90% of corrosion) occurred was shown as red area, while low probability of corrosion (10% of corrosion) was shown as white area. Finally, poor damage condition in concrete based on impact echo test was shown as red area, in the other side, green area refers to on anomaly was found in concrete bridge.

In order to illustrate anomaly that evaluate from each test method. Concrete core sampling was required to be cross check the test result. First, typical concrete bridge structure should be confirmed. Easily and safety, concrete topping was be drilled. One concrete drill hole was done on bridge span no. 2 at gridling C/4. Core sampling result showed 0.11 meters thickness of concrete layer (Fig. 78) and found another layer of concrete which located under this layer.

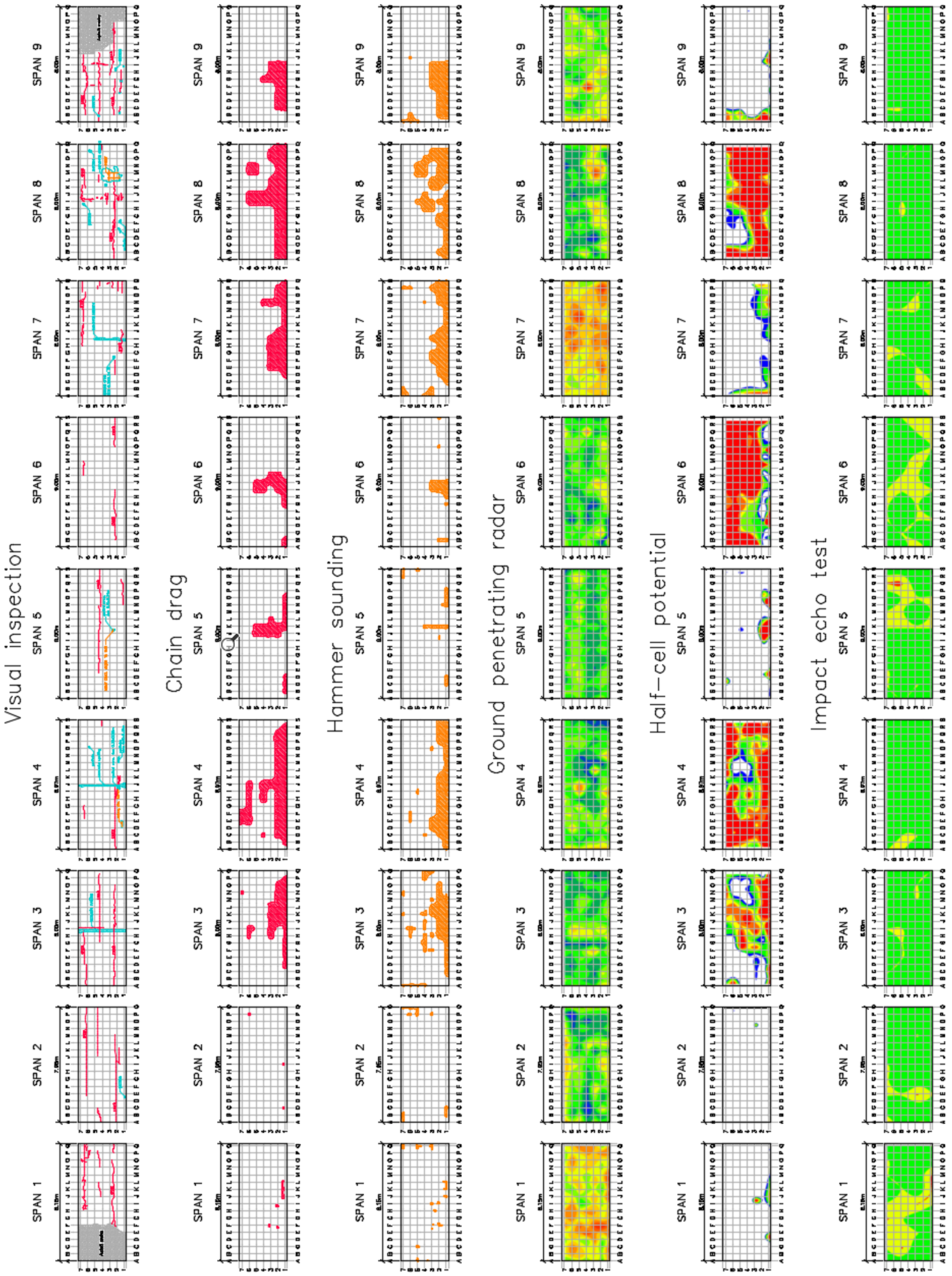


Figure 77 Summarized survey results from each test method

Figure 78 Concrete sample located on bridge span no.2 at gridline C/4

The results of drilling in the area where the crack was detected under the concrete surface at bridge span no. 4 gridline E/2 and bridge span no. 7 gridline E/2 by chain drag, hammer sounding and ground penetrating radar methods showed that the crack was found under concrete surface at 0.01-0.03 and 0.03-0.04 meters depth from bridge deck surface respectively as shown in Fig. 79-80.

Figure 79 Concrete sample located on bridge span no.4 gridline E/2

Figure 80 Concrete sample located on bridge span no.7 gridline E/2

For high deterioration area based on ground penetrating radar without detected damage from other method located on bridge span no. 6 gridline N-O/5, concrete core showed as a normal concrete without cracking (Fig. 81). Nevertheless, high deterioration may be evaluation from reinforcing steel, but deterioration dose not effect to concrete properties.

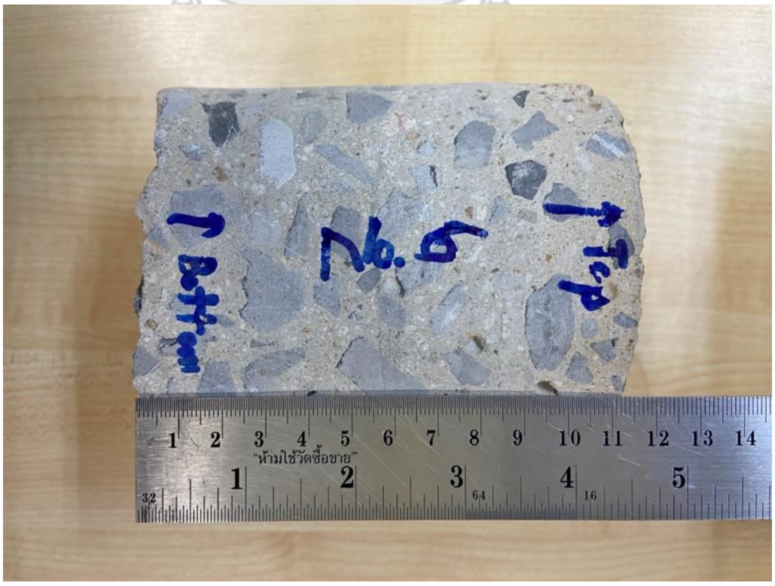


Figure 81 Concrete sample located on bridge span no.6 gridline N-O/5

For half-cell potential survey, drill sampling was be done on vary criteria belong to electrical potential as follow:

(1) According to electrical potential less than -350 mV, as shown in red area, steel sampling was be done on bridge span no. 1, 3 and 8 and gridline I-J/3, K-L/1 and H/3 respectively. Characteristic of steel was found a rust on most part of steel surface as shown in Fig. 82-84.

(2) For electrical potential more than -200 mV, as shown in white area, steel sampling was excavated on bridge no. 5, 7 and 9 at gridline N-O/5, L/5 and E/4 respectively. Steel corrosion was observed on small area as shown in Fig. 85-87.

Figure 82 Steel surface on bridge span no. 1 at gridline I-J/3

Figure 83 Steel surface on bridge span no. 3 at gridline K-L/1

Figure 84 Steel surface on bridge span no. 8 at gridline H/3

Figure 85 Steel surface on bridge span no. 5 at gridline N-O/5

Figure 86 Steel surface on bridge span no. 7 at gridline L/5

Figure 87 Steel surface on bridge span no. 9 at gridline E/4

CHAPTER 6 DISCUSSION

For this chapter, there are many topics will be explained i.e. all results discussion, differentiated results comparing each method, ability of each testing methods and suggestion testing methods for bridge owner. All interesting points will be explained follow as: -

6.1 ALL RESULTS

Bridge deck deterioration investigation on general survey and nondestructive test mostly can be evaluate in concrete topping layer (approximately 0.10 meters from bridge deck surface). For concrete evaluation in precast concrete which located under topping layer, it can be only evaluated by impact echo test.

From all testing results, it was found defect separated on every part of bridge deck. Mostly, defect was found along the vehicles track way that related to present using. Based on illustrating by general methods i.e. chain drag and hammer sounding, defect was shown mostly on the left side of vehicle track. Based on load distribution on hollow slab that similar to precast slab, if load from vehicle compressed on precast section which located on edge of bridge, it will receive highest force on bridge structure (Fig.88). Therefore, bridge portion on the left-right side of whole bridge structure should be have more damage than other part of bridge deck. However, load factor on left side part way of bridge that related to weight of vehicle such as truck have higher than right side of whole bridge that related to small vehicle. So, left side of bridge will have more damage than other part of whole bridge.

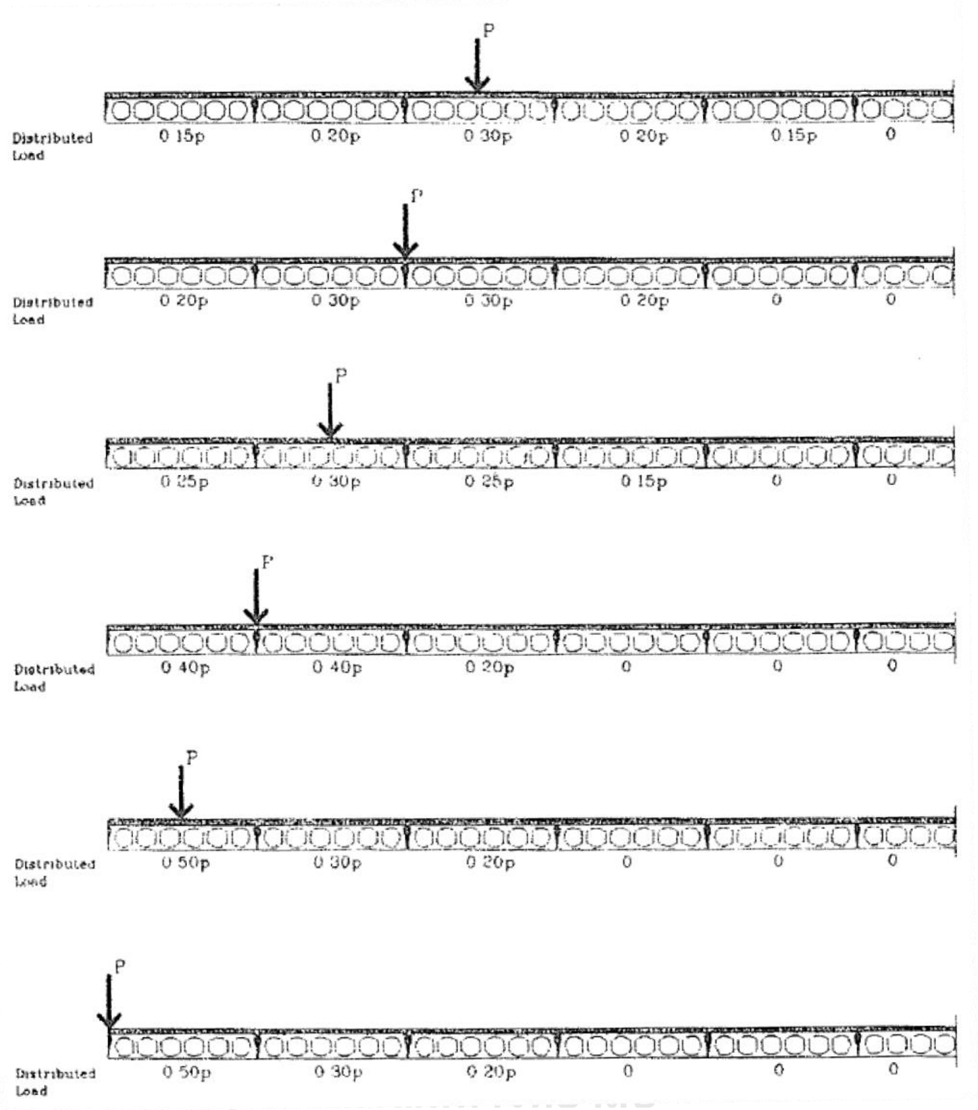


Figure 88 Load distribution on hollow core slab (GEL, 2006)

6.2 COMPARING DIFFERENTIATED RESULTS BASED ON EACH METHOD

According to all results from each method, it was found some area on bridge deck which have not defect on the same area. For this point, it may be occurred from ability of equipment or method test that responding to difference properties of defect that located in concrete bridge deck. Details of mechanism property responding and detected located from each method were summarized in Table 5.

Table 5 Details of property responding and detected located from each method

Testing method	**Mechanism property responding**	**Location of detecting**
Visual inspection	Eye contact	Surface
Chain drag	Elastic modulus	Near surface
Hammer sounding	Elastic modulus	Near surface
Ground penetrating radar	Electromagnetic	Concrete material and reinforcing steel
Half-cell potential	Electrochemistry	Reinforcing steel only
Impact echo	Elastic modulus	Concrete material

Moreover, each testing method can investigate defect position and evaluate deterioration on difference location in concrete. If there is concrete thick 1.0 meter and have steel bar in concrete (Fig.89). General survey methods can only detect defect which located only on the surface or nearby surface, while ground penetrating radar can investigate the defect that located deeper than general survey. In addition, half-cell potential can evaluate corrosion in steel bar, but it can not investigate defect in concrete. Therefore, the results that received each testing methods will be support investigation program on bridge deck deterioration investigation.

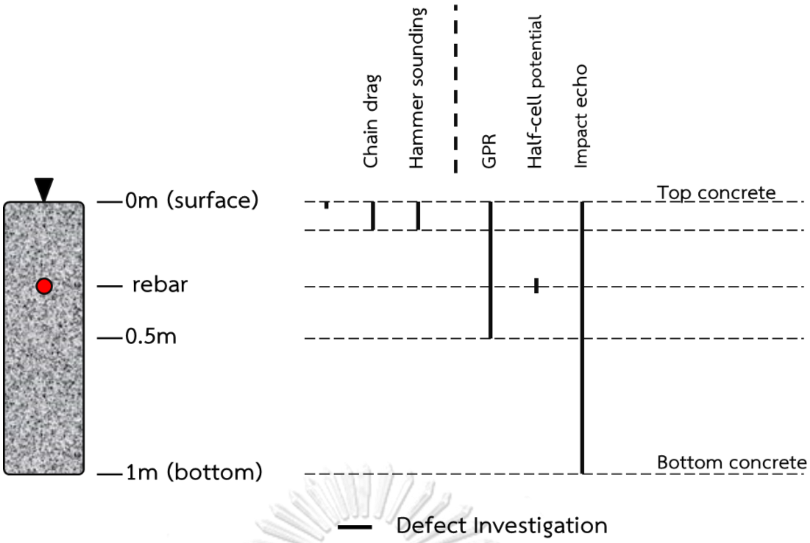


Figure 89 Ability of testing methods for defect investigation based on depth and properties of defect

6.3 ABILITY OF EACH TESTING METHOD

For ability of each testing method will be illustrated results comparing between testing methods in this study and other research. Details of each testing methods will be explained into 2 main methods follow as: -

6.3.1 GENERAL SURVEY

For this survey results which composed of visual inspection, chain drag and hammer sounding, it can survey only the damage on the bridge deck or the damage that located closed to surface concrete. Based on visual inspection, the results are clearly visible because the damage was appeared on the surface. In addition, chain drag and hammer sounding results were observed from the concrete core sampling test on span no. 4 and 7 on gridline E/2. Defects which is a horizontal crack were represented by chain drag and hammer sounding.

These methods were classified as the basic methods of bridge deck survey and maintenance because the results are not complicated. The measurements are quite realistic. Therefore, surveying by these methods was indicated in mostly manual of bridge maintenance i.e. bridge maintenance and management system book by department of highways or the standard by department of public works and town & country planning, Thailand.

6.3.2 NONDESTRUCTIVE TEST

For these surveys, it composed of 3 methods i.e. ground penetrating radar, half-cell potential and impact echo. Based on the results from above methods, it can be explained each method into 3 topics as follow: -

(1) GROUND PENETRATING RADAR

Ground penetrating radar results can be illustrated into 2 patterns: (1.1) the reflected of radar image result and (1.2) deterioration map result. These results can be discussed as follow; -

(1.1) The reflected of radar image result

For this result, it was shown a physical condition of bridge deck which evaluated from radar wave image signal. Radar wave that received the reflected wave from material will be provided an initial information i.e. position of steel, void, structure member or etc. This characteristic was cross checked with chain drag, hammer sounding and concrete core sampling. The anomaly that found on the reflected wave image results was found on other methods such as chain drag and hammer sounding as well, except streel position cannot be detected by these methods. However, steel position and defect position based on ground penetrating radar result can be evaluated by core sampling test. This function is a general concept for evaluated concrete condition (Dinh et al., 2018; Liu et al., 2020; Ma et al., 2018).

(1.2) Deterioration of bridge deck result

For deterioration of bridge deck based on amplitude analysis, amplitude of reinforcing steel in bridge structure was shown in range 15-45 dB that classified as relative data into 3 conditions i.e. good condition, fair condition and poor condition (Gucunski et al., 2011). The poor condition results usually found in wheel paths that similar to the damage observed on the surface by visual inspection.

Comparing to rebar observation on span no. 7 gridline L/5 which high deterioration based on ground penetrating radar, but low corrosion probability based on half-cell potential result, this area was found some area of corrosion on the reinforcing steel. In the other hand, rebar observation on span no. 8 gridline H/3, which moderate deterioration based on ground penetrating radar, but high corrosion based on half-cell potential, was found the corrosion occurred on the surface of steel.

By contrast, bridge deck deterioration map by Iowa department of transport and Maine department of transport, USA was found the amplitude of deterioration with -36 to -6 dB and -38 to -14 dB respectively (Gucunski et al., 2011; Parrillo & Roberts, 2006). Both results were slightly lower than this study.

(2) HALF-CELL POTENTIAL

According to half-cell potential results, most anomaly areas was located around edge of span section. The trend of anomaly was located in longitudinal direction which related to bridge using. Load from vehicles will be action along the wheel path, so, wheel paths may be found the defect first. Degree of corrosion was interpreted based on ASTM Standard C876. The results were cross checked with core sampling. For high probability area (90% of corrosion), drill hole on span no. 1, 3 and 8 gridline I-J/3, K-L/1 and H/3 respectively was found corrosion on the surface of steel, while low probability area (10% of corrosion), drill hole on span no. 5, 7 and 9 gridline N-O/5, L/5 and E/4 respectively was found some corrosion on the surface steel.

(3) IMPACT ECHO

Based on impact echo results, most of all conditions were classified as the defection in second layer concrete slab (in precast concrete layer). The defect near the surface cannot be evaluated. The impactor, hammer is used to generate stress wave may be created a long wavelength, so, the defection nearby surface may be ignore. However, boundary between topping concrete layer and precast concrete layer also was found in results. Therefore, if defect which found in topping layer, it may be a discontinuity similar to concrete contraction between topping concrete and precast concrete layer.

6.4 SUGGESTION TESTING METHODS FOR BRIDGE OWNER

If bridge owner would like to investigate bridge deterioration, this study can suggest testing method in many options follow as: -

(1) Option A

This option suitable for preliminary investigated with fastest investigation (1-2 days speeding time on bridge one traffic lane with 80 m length) consist of visual inspection, chain drag and hammer sounding. This option is a general testing method that specific in gridline bridge investigation by Department of Highway, Thailand. The advantages of this option, defect on bridge deck can be observed on the surface and underneath nearby the bridge surface. However, this option will have some missing data that defect located in deeper concrete will not be investigated.

(2) Option B

This option suitable for topping concrete investigation which may be speeding 1-2 days on site and 2-3 weeks on office working. This option composes of general survey together with ground penetrating radar and half-cell potential. All methods in this option can be investigated the damage in whole topping concrete and reinforcing steel in concrete such as horizontal delamination, horizontal crack and corrosion. This method option should be investigated annual maintenance. Disadvantages of this option is used more time to process data and need specialist to interpretation data.

(3) Option C

This option suitable for whole bridge investigation that compose of 3 (three) testing methods in general survey and 3 (three) testing methods in nondestructive tests. This option can investigate both concrete toping and precast concrete with 1-2 days on site that the same method same as the option B and 5-7 days on site testing by impact echo. Totally of this option may be using 3-4 weeks working. Disadvantage of this option is using a long time to process and need specialist to interpretation data.

CHAPTER 7 CONCLUSION AND SUGGESTION

As these results from each method, it can be concluded into 2 patterns: (1) general survey and (2) general survey together with nondestructive test.

7.1 GENERAL SURVEY RESULTS

From the results of surveying damage on concrete bridge deck by using general survey methods which consist of visual inspection, chain drag and hammer sounding. This results show that most of the damage on bridge deck is located on bridge span no. 3, 4, 5, 6, 7, 8, and 9. For bridge span no. 3, 4, 7 and 8, concrete bridge deck was found a wide damage cover more than 25% area. Defect on these methods such as concrete crack, concrete spall and delamination inside concrete.

For initial repairs, if surveyed with the above methods, it may just use overlay method with asphalt concrete to extend the lifetime of concrete pavement.

7.2 GENERAL SURVEY TOGETHER WITH NONDESTRUCTIVE TEST

For survey results based on nondestructive testing methods, it found that deterioration of bridge occurred on the area of wheel path based on ground penetrating radar analysis on each bridge section. Moreover, the results were found the highest damage in bridge span no. 1 and 7 related to other bridge span. For detection of rust in bridge system with half-cell potential, it found that 80% of bridge surface corrosion located on bridge span no. 3, 4, 6 and 8. While the bridge span no. 5 and 7 found corrosion area in some part of bridge. And the last one, impact echo test can detect damage in precast concrete layer which found in bridge span no. 1, 2, 5, 6 and 7.

To assesses damage in deep structure of bridge by impact echo test, nearly surface damage will be neglect due to characteristic of stress wave generated by hammer will be pass through delamination near surface concrete.

According to the survey results even through general survey and nondestructive test, bridge deterioration investigation should be carried both methods (general survey and nondestructive test) in order to receive defect data on concrete bridge deck and underneath concrete surface. Because defect on the surface in some characteristic may be a result of process and mechanism which occurred inside the concrete.

Although, nondestructive test may have some limitation. It should be considered before bringing it to test as follows; -

(1) **Ground penetrating radar**, this method is easy to use for distress investigation. It can be provided both physical conditions i.e. delamination or crack under concrete surface and mechanical conditions i.e. steel deterioration. However, data processing may take long times to process and results may not clear. Degree of deterioration from steel amplitude also should be study in the future. In other hand, bride deterioration based on ground penetrating radar can be used as an indirect method for investigate bridge damage condition.

(2) **Half-cell potential**, this method is quite clear for corrosion of steel investigated in concrete. However, based on cross checking by drilling found that to corrosion of steel occurred on the steel surface only, although probability of corrosion will be found to 90%.

(3) **Impact echo**, this method is a good one for concrete integrity investigate for deep structure which other method cannot evaluate. If this method was required to investigate on concrete topping, source impactor should be used solenoid impactor instead of using hammer because defect that located near top of surface can be found with high frequency wave. But, if integrity of deep structure was required, hammer is a one choice to be selected.

REFERENCES

ASTM. (1999). Standard Test Method for Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete. In *Designation: C 876 – 91*.

Barnes, C., Trottier, J., & Forgeron, D. (2008). Improved concrete bridge deck evaluation using GPR by accounting for signal depth – amplitude effects. *NDT&E International, 41*, 427-433.

Baumann, K. (2008, 10-12 June 2008). *Practical example of interpretation of half-cell measurments on reinforced concrete structure.* Paper presented at the the 12th International conference on structure faults and repair, Edinburgh, UK.

Dinh, K., Gucunski, N., & Duong, T. (2018). Migration-based automated rebar picking for condition assessment of concrete bridge decks with ground penetrating radar. *NDT and E International, 98*, 45-54.

Elsener, B. (2003). Half-cell potential measurements – Potential mapping on reinforced concrete structures. *Materials and Structures, 36*, 461-471.

GEL. (2006). คู่มือวิศวกรโยธา.

Gucunski, N., Romero, F., Kruschwitz, S., Feldmann, R., & Parvardeh, H. (2011). *Comprehensive Bridge Deck Deterioration Mapping of Nine Bridges by Nondestructive Evaluation Technologies*. Retrieved from

Liu, H., Lin, C., Cui, J., Fan, L., Xie, X., & Spencer, B. (2020). Detection and localization of rebar in concrete by deep learning using ground penetrating radar. *Automation in Construction, 118*.

Ma, X., Liu, H., Wang, M., & Birken, R. (2018). Automatic detection of steel rebar in bridge decks from ground penetrating radar data. *Applied Geophysics, 158*.

Nowak, A. (2012). *Bridge Evaluation, Repair and Rehabilitation* (Vol. 187).

Parrillo, R., & Roberts, R. (2006). Bridge deck condition assesnssment using ground penetratin radar. *ECNDT*.

Reynolds, J. (1997). *An introduction to appiled and environmental geophysics*: Wiley-Blackwell.

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