eJSE International
Special Issue: Electronic Journal of Structural Engineering 18(1) 2018

Use of Non-Destructive Methods: Case Studies of Marine Port and Bridges Structures in Surabaya

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ABSTRACT: Consideration of degradation due to harsh environments, overweight vehicles, increasing traffic and frequent earthquake events are some of the challenges to overcome when designing reinforced concrete bridges. Structural elements can be affected by a reduction in strength and stiffness due to the carbonation of the concrete cover, the corrosion of the reinforcement, excessive cracking and displacement under service load and failure. Therefore, structures need to be monitored over time to ensure that they have the sufficient capacity to resist the intended design loads. The existing condition of bridges on toll roads and in ports located in Surabaya Indonesia has been investigated using non-destructive testing (NDT) equipment. Several reinforced concrete bridges of high level of importance have been chosen as case studies considering different exposure and age of structure. Typical results from the site investigation are presented and discussed in this paper. The NDT equipment utilised in this paper includes the use of eddy current, two-chamber vacuum cell and Wenner Probe principle to assess the thickness, the air permeability and the electrical resistivity of the concrete cover, respectively. In addition, Silver Schmidt hammer was also used to measure the compressive strength of the concrete.

KEYWORDS: NDT, Structural Heath Assessment, Marine, Bridge, Indonesia

1 INTRODUCTION

Under Joko Widodo-Jusuf Kalla presidency, the Indonesian government has made a lot of efforts to bring social justice from Sabang to Merauke (PWC 2017). One of them is to open up access for every element of societies by developing new infrastructures and rehabilitating the old ones. To realise this, Indonesia has budgeted 5% of its gross domestic product (GDP) for Infrastructure (Alisjahbana 2012). In 2015, the total road network in Indonesia is 488,181 km which consists of toll road of 976 km, the national road of 47,017 km, the provincial road of 47,666 km and district road of 392,521 km (Directorate General Bina Marga 2016). By 2019, it is expected that there will be additional toll road of 1000 km, the national road of 2650 km, provincial and district road of 15,500 km. Moreover, there is a lot of governmental support for assessment of the ageing infrastructures to ensure that they can be used safely for the intended service life. As part of the repair works, 47,017 km of roads and bridge length of 446 km (in total) need to be repaired (Directorate General Bina Marga 2016). There is obvious need for fast and accurate assessment of infrastructure.

Three causes of bridges collapse are discussed in this paper. They are corrosion (due to exposure), overweight vehicle (live load) and higher earthquake magnitude (natural disaster). Corrosion has become one of the main reasons for ageing infrastructure especially in the marine environment which causes the collapse of the structure (Chalhoub 2015). Both chloride-induced corrosion and carbonation can reduce the strength and stiffness of the existing structures.

Increased weight of traffic can be another main reason why the bridges can experience a reduced service life. In Australia, the overall freight task expressed in tonne-kilometer has had an annual growth rate of over 50% in the past 35 years and the average loads carried by articulated trucks have more than doubled during this period (Mitchell 2010). In the USA, the overweight vehicle has become the third cause of bridge collapse after hydraulic events and collisions (Fiorillo and Ghosn 2017). People tend to ignore the weight limit of the bridge and assume that the bridge has the capacity to carry the imposed load. Chen (2013) stated that based on the weigh-in-motion data, there is approximately 24% of annual bridge cost in 2011 in

South Carolina allocated for maintenance and repair work due to overweight trucks.

Natural hazards can cause extensive damage to bridge structures. Indonesia, being located in the ring of fire, is prone to earthquakes. Since 1966, Indonesia has published its earthquake resistant design standard. However, from 1966 to 2002, Surabaya has the same design peak ground acceleration (PGA) of 0.15g for rock soil with 500 years return period (Dewasa 2016). Indonesian earthquake map has been updated in 2010 (SNI-1726 2012) and 2017 (Menteri PUPR 2017) and similar PGA of approximately 0.15-0.2g for rock soil with 500 years return period earthquake has been proposed. However, the last two updates have followed AASHTO (2012) that bridges should be designed for 1000 years return period (and not for 500 years return period). This corresponds to a PGA value of 0.25-0.3g according to the latest standard (Menteri PUPR 2017). While the design requirement indicates an increase in the intensity of earthquakes , the capacity of existing structures remains the same or even decreases due to deterioration. This could lead to a massive damage to the existing RC bridge structures, especially those built prior to 2012.

Both destructive testing and non-destructive testing (NDT) methods can be used to assess the current condition of the structures prior to the retrofitting processes. However, the later has gained popularity due to its ease and speed of application and cost-effectiveness (IAEA-TCS-9 1999). In the past three decades, there is a rapid development related to NDT methods. The common NDT technique used worldwide includes ultrasonic, radiographic, magnetic, electromagnetic, eddy-current, acoustic emission, half-cell potential measurement, Wenner probe principle and hardness testing (ASTM C805 / C805M 2013, ASTM C876 2015, Hellier 2013).

Related to the corrosion assessment of reinforced concrete (RC) structures, previous researchers have emphasised only one specific NDT equipment to measure the corresponding parameter affecting corrosion (AASHTO TP 95 2011, Andrade and Alonso 2004, Andrade et al. 2009, ASTM C876 2015, Gu and Beaudoin 1998, Kucharczyková et al. 2010, Nakamura et al. 2008, Paulini and Nasution 2007, Salbei et al. 2014, Song and Saraswathy 2007, Torrent 1992). Kucharczyková et al. (2010), Paulini and Nasution (2007), Torrent (1992) have used a two-chamber vacuum cell, so-called Torrent, for measuring the coefficient of air permeability (*kT*) of the concrete cover. The *kT* value can be used to measure the required time to carbonate the concrete cover, called initiation time (Kropp and Hilsdorf 1995). Other researchers used Wenner probe principle to measure the electrical resistivity of the concrete cover (AASHTO TP 95 2011, Andrade and Alonso 2004, Andrade et al. 2009, Polder 2001). The electrical resistivity is then converted to the propagation time following the recommendation from Andrade and Alonso (2004). To assess the current corrosion state of the structures, half-cell potential has been widely used (ASTM C876 2015, Gu and Beaudoin 1998, Nakamura et al. 2008, RILEM TC 154-EMC 2003). However, this requires a direct access to the reinforcement within the concrete, and hence, it is sometimes considered as a destructive test.

Related to the strength assessment, hardness testing using Silver Schmidt hammer is the most common NDT method used to measure the concrete compressive strength of the existing concrete element. The existing structural conditions of structures should be used to determine the structural capacity in resisting the increased demand (from vehicles or extreme events such as earthquakes).

A framework has been proposed in this paper to assess the condition of existing critical infrastructure considering various cases using several types of NDT methods. This framework should provide information related to available equipment and procedures to assess existing infrastructures. It should be useful for the stakeholders and asset owners in prioritising inspection and future structural work including repairing, retrofitting or replacing the structural elements entirely.

Four RC bridges have been chosen as case studies considering different exposure and age of the structure. Two of those are the trestle RC bridges at Terminal Peti Kemas and Terminal Teluk Lamong at Port of Tanjung Perak Surabaya and the other two are RC bridges at Toll Waru and Toll Sumo in Surabaya. The NDT equipment utilised in this paper includes Profometer (Proceq SA 2014) which uses eddy current, Torrent (Proceq SA 1995) which uses two-chamber vacuum cell and Resipod which uses Wenner probe principle (Proceq SA 2016) to assess the thickness, coefficient of the air permeability and the electrical resistivity of the concrete cover, respectively. In addition to that, Silver Schmidt hammer was also used to measure the compressive strength of the concrete. The results of the NDT measurement including a brief discussion of the results are presented in this paper.

2 CASE STUDY

The location of two RC bridges at Port of Tanjung Perak and two RC bridges at Tollway in Surabaya which has been chosen as the case study is shown in Figure 1. The first and second RC bridge at the seaport of Tanjung Perak is shown as “TL” for Teluk Lamong and “TPS” for Terminal Peti Kemas. The first and second RC bridge at the tollway is shown as Toll Sumo and Toll Waru. These bridges are identified as typical critical infrastructures around the port environment. The trestle bridges connect the land and the berth and the toll road bridges provide a transportation link between local areas to wider Java area. The trestle bridges are heavily used by trucks transporting goods to and from the port. Failure of these bridges can cause a significant economic loss to the country because Port of Tanjung Perak is one of the busiest ports in Indonesia.

A major difference between the bridges located at the port and those at tollway is the environment. The marine environment at the seaport can increase the chloride-induced corrosion rate whereas the traffic environment at tollway can increase the carbonation rate. A brief overview of each bridge is described in the following subsection.

Figure 1. Google earth of the location of four RC bridges considered in this research

2.1 *Longitudinal RC beams at the bridge in the seaport of Tanjung Perak*

The TPS bridge was built in 1984 and has 102 spans with a length of 15 meters for each span (TPS 2013) as shown in Figure 2. Each span is simply supported on top of the cross beam through rubber bearing. The cross beam is then supported by a group of steel piles covered by anti-corrosion coating. The bridge deck has an expansion joint every 20 spans to allow the longitudinal movement of the bridge. The cross-section of the bridge obtained from BGA (2010) is shown in Figure 3.

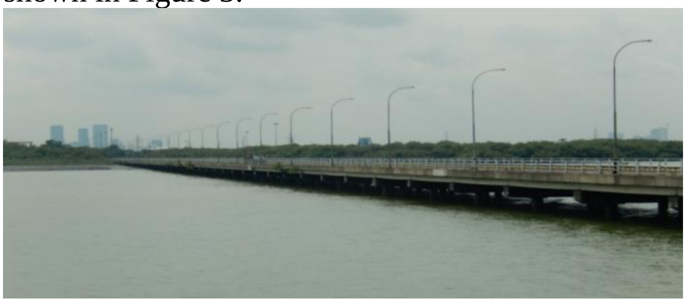


Figure 2. View of the TPS bridge from the domestic berth

The design compressive strength of the concrete and the yield strength of the rebar is 40 MPa and 400 MPa, respectively. In 2010, the longitudinal T beam has been repaired by grouting the cracks and adding two concrete fibre reinforced polymer (CFRP) Sika CarboDur type S10-12 along the bottom of the beam (BGA 2010). The width and the thickness of the CFRP are 100 and 1.2 mm, respectively. The tensile strength and Young's modulus of the CFRP is 2800 and 165,000 MPa, respectively.

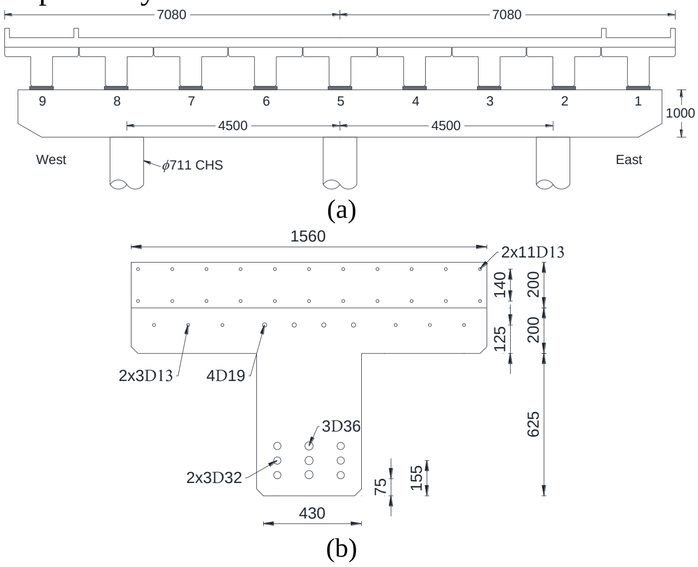


Figure 3. TPS bridge: (a) Cross-section of the bridge looking north; (b) The details for one longitudinal beam

The TL bridge has post-tensioned RC beams and was built in 2010 as shown in Figure 4. The bridge considered in this research has 20 spans with a length of 40 meters for each span and it connects the office of the Port of Teluk Lamong and the land in Java Island Each. Each span consists of 5 precast segments and is also simply supported on top of the cross beam through rubber bearing. The cross beam is then supported by a group of the spun pile with a diameter of 800 mm and concrete grade of 58 MPa. The cross-section of the I girder of the bridge at the end and at the midspan is shown in Figure 5.

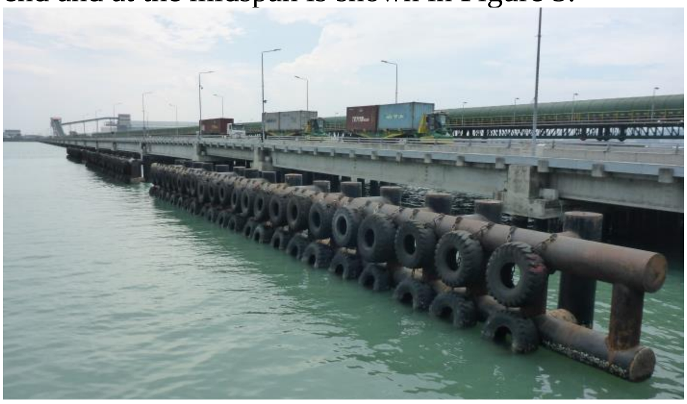
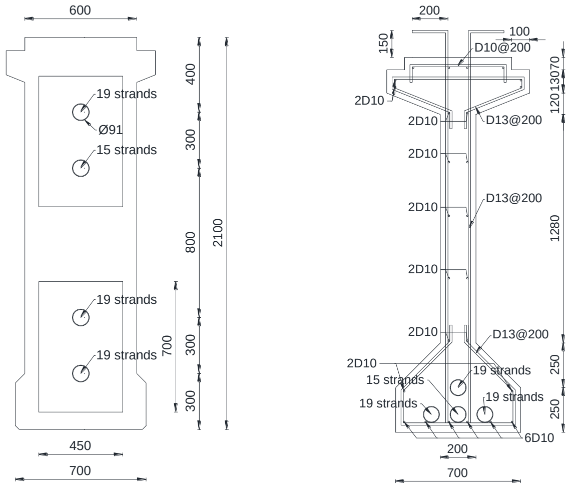


Figure 4. View of the TL bridge from the berth

The design compressive strength of the concrete at jacking and at service is 46 MPa and 58 MPa, respectively. The yield strength of the rebar is 390 MPa when the diameter is larger than 10 mm and

240 MPa when the diameter is smaller or equal to 10 mm. The thickness of the concrete cover is 40 mm at top and bottom and 30 mm at the sides. There is no repair or assessment that has been done since the bridge is relatively new.



(a) (b)

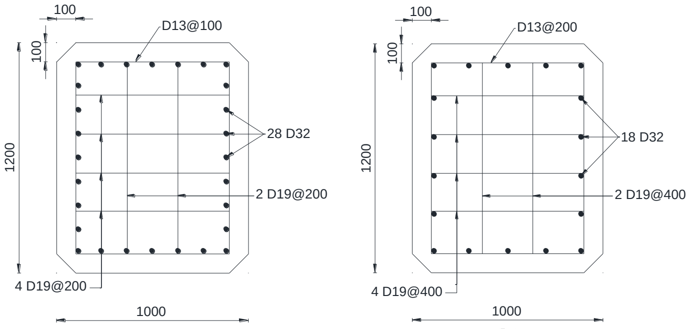
Figure 5. Cross-section of the I girder: (a) at both ends; (b) at the midspan

2.2 *RC columns at the bridge in Tollway*

RC columns have been used as the case study instead of the beam in the case of tollway due to the difficulty in accessing the beam. There RC columns in Pier-1 have been chosen at Toll Waru as shown in Figure 6. The column has a height of 5.46, 5.68, and 5.9 metres from left to right, respectively. The three columns are supporting 10 RC beams with a length of 30 and 16 metres spanning from each side of the column to the adjacent column. The cross-section of the column is shown in Figure 7. The concrete compressive strength of 29 MPa and steel yield strength of 400 MPa was used in the design. The thickness of the concrete cover is 70 mm.

Figure 6. RC bridge in Toll Waru with Pier-1 at the left side of the picture

In toll Sumo, an exterior RC column from the three columns in one pier has been chosen since there was no access to the remaining columns as shown in Figure 8. The column has a height of 4.31 metres. One pier (with three columns) supports 10 girders with a length of 30 metres which are simply supported by the piers.

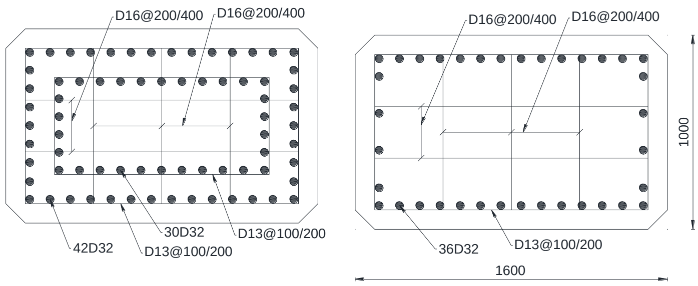


(a) (b)

Figure 7. Cross-section of the RC column in Toll Waru: (a) All columns half bottom; (b) All columns half top

Figure 8. RC bridge in Toll Sumo with the exterior column at the right side of the picture

The concrete compressive strength of 29 MPa and steel yield strength of 400 MPa was used in the design. The thickness of the concrete cover is 100 mm. The column consists of two precast sections, i.e. half bottom and half top as shown in Figure 9. Each of the half sections has two different spacings of the stirrups. The smaller spacing is used for the quarter bottom of the column (Figure 9(a)) and quarter top of the column (Figure 9(b)).



(a) (b)

Figure 9. Cross-section of the exterior RC column in Toll Sumo: (a) All columns half bottom; (b) All columns half top

3 PROPOSED FRAMEWORK

Figure 10 shows the flowchart for the proposed framework to assess the condition of the existing RC structures. The steps are explained as follows:

i. The as-built drawing should be obtained prior to assessing the structure.

ii. Confirming specification using non-destructive testing (NDT) equipment.

Profometer (Proceq SA 2014), which is based on Eddy current, is used in this study to check the thickness of the concrete cover and the arrangement of the rebar. Moreover, concrete compressive strength has been measured by using Silver Schmidt hammer (Proceq SA 2017) which convert hardness to compressive strength of concrete. The result is then compared with the design values. Having the comparison between the as-built drawing and the results obtained from the NDT, a conservative value may be used for further steps.

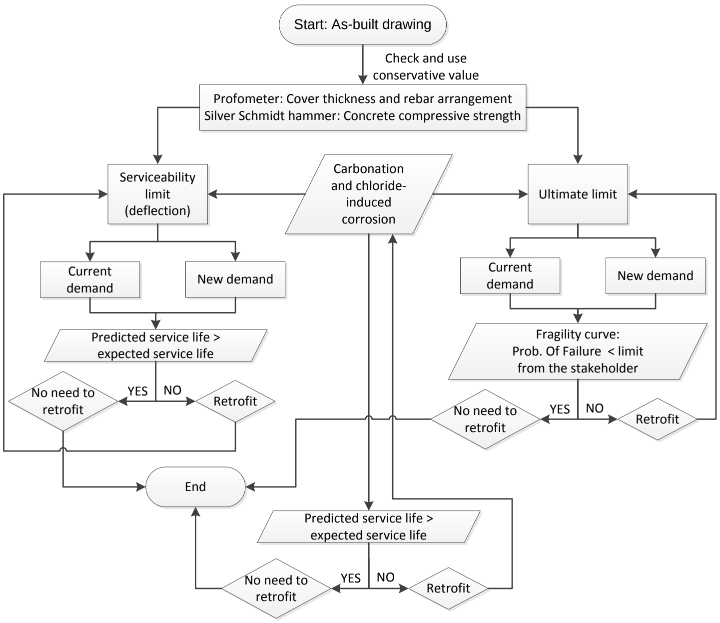


Figure 10. The proposed framework to assess the condition of the existing RC structures

iii. Measuring the carbonation and the corrosion rate and predict the service-life due to the corrosion.

The service life of the structure due to the corrosion is defined by summing up the initiation time and propagation time (Andrade et al. 2009). This service life is calculated based on an assumption that there is neither excessive crack nor concrete spalling during the life of the structure.

The initiation time is related to the carbonation rate which can be obtained based on the coefficient of the air permeability of the concrete cover (Kropp and Hilsdorf 1995). Torrent (Proceq SA 1995) is used in this research to measure the coefficient of air permeability of the concrete cover. Moreover, the propagation time is related to the corrosion rate which can be calculated from the electrical resistivity of the concrete cover (Andrade and Alonso 2004). Resipod (Proceq SA 2016) which is based on Wenner probe principle is used in this study to measure the electrical resistivity of the concrete cover. It should be noted that Torrent should be used on a dry surface, whereas, Resipod should be used on a wet surface.

Corrosion can be deemed to have occurred if the initiation time measured by using Torrent is less than the age of the corresponding structure, causing reduction in the bar diameter. The reduced rebar diameter can reduce the capacity of the structure and the structure may no longer satisfy the serviceability and the ultimate limit state. Moreover, if the predicted service life is smaller than the expected, the structure may need to be retrofitted.

iv. Measuring the current deflection and predict the service-life based on the deflection over time.

Interferometric radar can be used to measure the deflection as well as the natural frequency of the structure at its current state (IDS 2012). Comparing the current frequency with the one obtained when the structure was newly constructed, the deterioration rate of the structure can be measured. Moreover, considering the data obtained in the previous steps, the deflection of the structure also can be determined by analytical method. If the predicted service life obtained based on the deterioration rate is smaller than the expected one, the structure needs to be retrofitted.

v. Quantifying the capacity of the existing structure subjected to the current and future demand (from vehicles or extreme events such as earthquakes) in terms of probability.

The capacity of the existing structure is analysed based on the previously obtained data, i.e. the reduced rebar diameter due to corrosion, the actual measured concrete cover and the actual measured concrete compressive strength. This capacity is then compared to the current and future demand. As stated previously that the earthquake demand becomes higher in the recent code, the capability of the structures in resisting needs to be re-assessed. Moreover, the new increased demand from overweight vehicles should be also taken into account. The uncertainties associated with the material properties and the demand can be considered in developing fragility curves. When the probability of the failure for a certain demand is higher than the limit set either by the standard or by the stakeholders, the structure needs to be strengthened.

4 RESULTS AND DISCUSSION

Due to the length limitation of the paper, this paper only shows the results obtained from several types of NDT equipment, i.e. Profometer, Silver Schmidt hammer, Torrent and Resipod.

4.1 *Longitudinal RC beam at TPS bridge*

Since the TPS bridge is recently retrofitted (in 2010), it is expected that the thickness of the concrete cover remains the same. Therefore, profometer was not used during the inspection. A concrete cover of 75 mm to the main rebar was reported during the retrofitting process (BGA 2010).

Table 1 shows the results obtained from hammer test. The result obtained from each test is the average from 10 readings. The results are conservative since it represents the 10^{th} percentile value based on the recommendation from ASTM C805 / C805M (2013). The RC beams in span 90 were chosen as the sample. Several locations have been selected, such as the web and the flange of beam 1 and 2 and web of beam 4, 7 and 8 (refer to Figure 3(a) for the location of the beam). The average and the standard deviation for all the results is 51.7 and 9.6 MPa, respectively. Based on these two results, the mean value of 64 MPa was derived. However, both the 10^{th} percentile and the mean value are higher than the design compressive strength of 40 MPa.

Table 1. Readings obtained from Silver Schmidt hammer for TPS bridge

Location	Concrete compressive strength (MPa)		
	Result 1	Result 2	Result 3
Beam 1 web	51	50	42.5
Beam 1 flange	56	38.5	-
Beam 2 web	55.5	59	50
Beam 2 flange	48.5	52	-
Beam 4 web	57.5	63	-
Beam 7 web	56	-	-
Beam 8 web	58.5	-	-

Figure 11 shows the coefficient of the air permeability (*kT*) obtained by using Torrent. The values on the right vertical axis represent the quality of the concrete cover on the air permeability. Very good concrete cover is denoted as “1”. It is followed by good (2), normal (3), bad (4) and very bad (5). Two measurement locations have been chosen, i.e. at the unpainted flange and at the painted web. Three readings have been done for each location. The average *kT* value for the unpainted flange and the painted web is 12.3×10^{-6} m^2 (very bad) and 0.624×10^{-6} m^2 (normal), respectively. It means that the painted surface has better concrete cover quality than the unpainted one.

Figure 12 shows the electrical resistivity of the concrete cover obtained by using Resipod. The higher the resistivity, the lower the corrosion rate as shown in Table 2. From Figure 12, it is shown that the measurement which was taken on the painted web has higher resistivity value compared to that taken on the unpainted flange. Again, the painted surface provides a good advantage, i.e. increases the electrical resistivity of the concrete cover. The average resistivity value for the web and flange is 374.3 and 220.3 kΩcm, respectively. Moreover, the standard deviation of 41.6 and 37.8 kΩcm is obtained for the web and the flange, respectively. If a conservative result is required, the value at 5% probability of exceedance needs to be calculated. It corresponds to 305.9 and 158.2 kΩcm for the web and flange, respectively. Both the mean value and the value at 5% of probability exceedance are much higher than the limit for low corrosion rate. This means that the quality of the concrete cover to prevent the ingestion of the chloride to the reinforcement is very good.

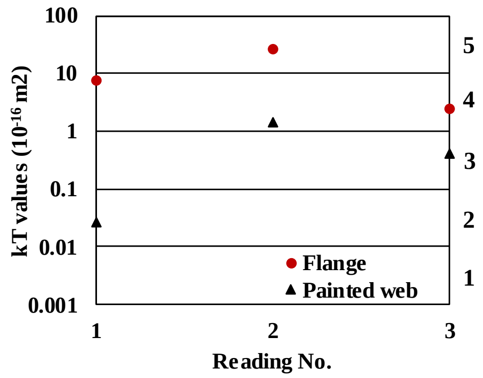


Figure 11. The coefficient of the air permeability for TPS bridge

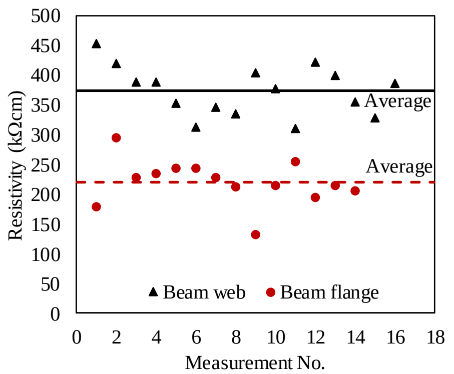


Figure 12. The electrical resistivity of the concrete cover for TPS bridge

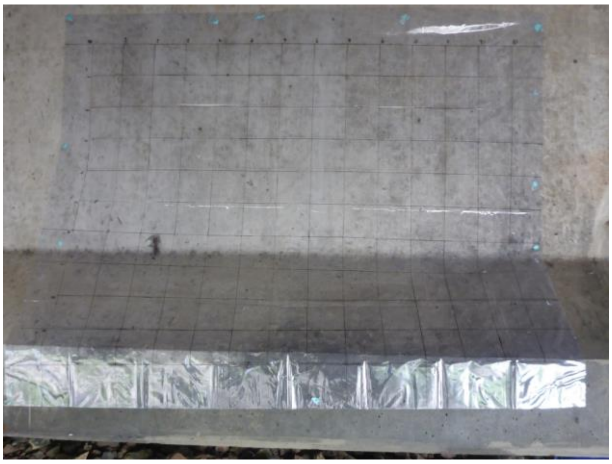
Table 2. Interpretation of the resistivity value.

Risk of corrosion	Resistivity (ρ) in kΩcm	Corrosion rate	Resistivity (ρ) in kΩcm
Negligible	≥ 100	Low	≥ 20
Low	50 to 100	Low to moderate	10 to 20
Moderate	10 to 50	High	5 to 10
High	≤ 10	Very high	≤ 5

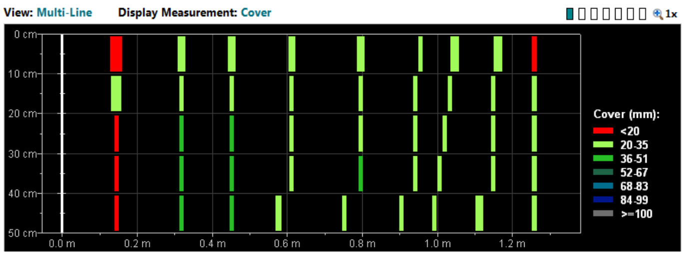
4.2 *Longitudinal RC beam at TL bridge*

As mentioned previously, TL bridge is quite new (built in 2010) compared to the TPS bridge. This means that the quality of the structure should be similar to the as-built drawing. However, since there is a good access to the I-girder, profometer is used to confirm the location of the rebar and the thickness of the concrete cover. The web of girder 2 span 3 (G2S3) was chosen as shown in Figure 13(a). The result obtained from profometer by scanning the web horizontally to observe the concrete cover and the location of the stirrups is shown in Figure 13(b).

The average thickness of the concrete cover obtained from Profometer is equal to 28.9 mm which is very close to the value stated in the as-built drawing which is 30 mm. Moreover, the spacing of the stirrups closer to the end of the beam segment is equal to 105 mm which is also very similar to that in as-built drawing which is 100 mm. However, the spacing of the stirrups away from the segment end is equal to 160 mm which is smaller than that in as-built drawing which is 200 mm. The actual beam has been built as specified on the as-built drawing with a conservative value in the stirrups spacing in the middle of the beam segment.



(a)



(b)

Figure 13. Profometer for longitudinal RC beam at TL bridge: (a) Measured location and (b) Thickness of the concrete cover

Table 3 shows the results obtained from Silver Schmidt hammer for TL bridge. As mentioned in Section 4.1, the results obtained from the hammer test represent the 10th percentile value. Having the standard deviation of 7.1 MPa and average of the 10th percentile value of 51.3 MPa for all the results, the mean value of 60.3 MPa has been derived. The mean value is slightly higher than the design concrete compressive strength of 58 MPa as stated in the as-built drawing.

Figure 15 shows the electrical resistivity for girder G2S3 in TL bridge. The average value at the web and at the flange is 80.2 and 42.4 kΩcm, respectively. Moreover, the standard deviation of 20.4 and 5.6 kΩcm is obtained for the web and the flange, respectively. The value at 5% probability of exceedance corresponds to 46.8 and 33.1 kΩcm for the web and flange, respectively.

Table 3. Test results obtained from Silver Schmidt hammer for TL bridge

Test No.*	Concrete compressive strength (MPa)					
	G2S3		G3S3		G4S3	
	Web	Flange	Web	Flange	Web	Flange
1	56.5	67.5	38	56	48	59
2	55.5	57.5	42	49	46	52.5
3	-	60.5	38.5	51.5	42.5	-
Average	56	61.8	45.5	55.8	39.5	58.1

* Each test represents the average value of 10 readings

Figure 14 shows the coefficient of the air permeability (*kT*) for the concrete cover of G2S3 obtained by using Torrent. The average *kT* value for the web is equal to 3.3×10^{-6} m^2 (bad) and this is higher than that for the flange which is equal to 0.68×10^{-6} m^2 (normal). This may be due to the higher compactness of the concrete mix at the bottom of the girder than that at the web.

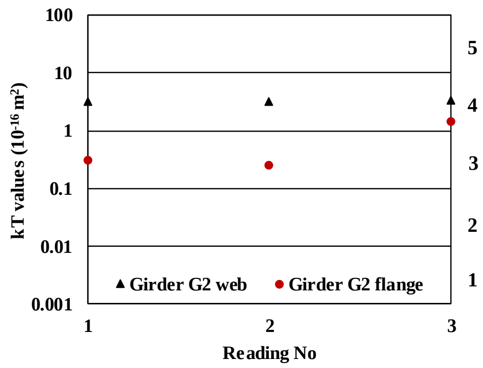


Figure 14. The coefficient of the air permeability for TL bridge

Both the mean value and the value at 5% of probability exceedance are much higher than the limit for low corrosion rate stated in Table 2. This means that the quality of the concrete cover to prevent the ingestion of the chloride to the reinforcement is quite good. However, the electrical resistivity at the bottom flange is smaller than that of the web even the thickness of the concrete cover at the bottom flange is larger than that at the web. This is may be due to the higher moisture content at the bottom flange of the beam due to closer distance to the water surface.

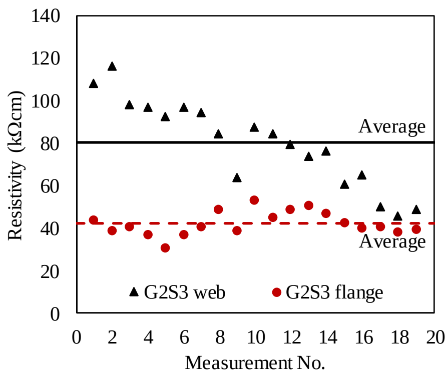
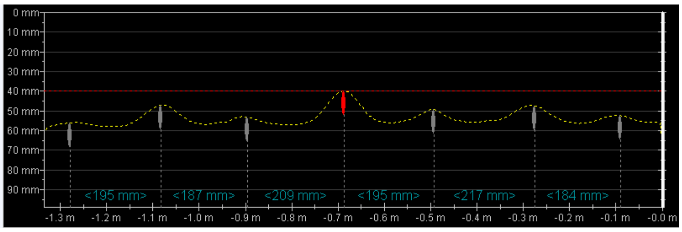


Figure 15. The electrical resistivity of G2S3 in TL bridge

4.3 *RC columns at the bridge in Tollway*

In this section, both the results obtained from Toll Waru (TW) and Toll Sumo (TS) are discussed. Figure 16(a) shows the vertical scan obtained by using profometer for an exterior column in TW. The thickness of the concrete cover is equal to 48.8 mm in average. This is smaller than the design value of 70 mm. Moreover, the average spacing of the stirrups is equal to 198 mm which is very similar to the value stated in the as-built drawing which is 200 mm.

Figure 16(b) shows the vertical scan obtained by using profometer for an exterior column in TS. The thickness of the concrete cover is equal to 63.8 mm in average. This is much smaller than the design value of 100 mm. Moreover, the average spacing of the stirrups is equal to 73 mm which is also much smaller than the value stated in the as-built drawing which is 200 mm at the measured location.



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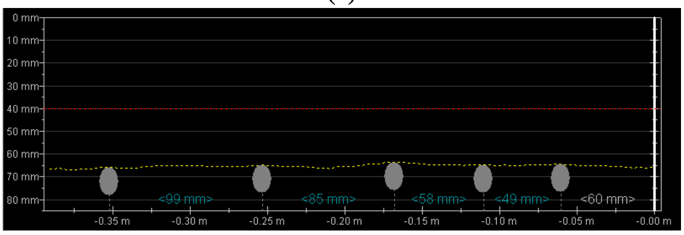

(b)

Figure 16. The concrete cover and rebar location measurement using Profometer: (a) Vertical scan for exterior column in TW; (b) Vertical scan for exterior column in TS

Table 4 shows the hammer test results for the RC columns in both bridges. The design compressive strength of the concrete for both locations is equal to 28.5 MPa. The average of 10^{th} percentile value is 54.6 and 22.5 MPa for TW and TS, respectively. The average standard deviation is 8 and 6.5 MPa for TW and TS, respectively. Moreover, the mean value is 64.9 and 30.8 MPa for TW and TS, respectively. It means that all the mean compressive strength of the RC column in both locations is higher than the design strength. However, the mean compressive strength of the RC column in TS has only a small margin with the design value.

Figure 17 shows the coefficient of the air permeability (*kT*) obtained by using Torrent for RC columns at both locations. The average *kT* value for TW (exterior), TW (interior), and TS (exterior) is 8.8×10^{-6} m^2 (bad), 9.1×10^{-6} m^2 (bad), and 34.5×10^{-6} m^2 (very bad), respectively. It can be seen that the lower the concrete compressive strength, the higher the *kT* value. The higher *kT* value indicates that there is more water content in the concrete mix which leads to more porosity when the concrete is set.

Table 4. Test results obtained from Silver Schmidt hammer for RC column in Tollway

Test No.*	Concrete compressive strength (MPa)			
	TW_Ext	TW_Int	TS_Ext_bot	TS_Ext_top
1	60	50	16	30.5
2	60	48.5	16.5	22
3	-	-	-	29
4	-	-	-	21
Average	60	49.3	16.3	25.6

* Each test represents the average value of 10 readings

Figure 18 shows the electrical resistivity for the RC columns in both locations. The average resistivity for TW (exterior), TW (interior), and TS (exterior) is 136.2, 100.2, and 46.76 kΩcm, respectively. The corresponding standard deviation is 20.5, 15, and 4.8 kΩcm. The value at 5% probability of exceedance corresponds to 102.5, 75.7, and 38.8 kΩcm for TW (exterior), TW (interior), and TS (exterior), respectively.

A similar conclusion can be made for this specimen that since both the mean value and the value at 5% of probability exceedance are much higher than the limit for low corrosion rate stated in Table 2, the concrete cover has a good resistivity to prevent the ingestion of the chloride to the reinforcement. The electrical resistivity of the specimen in TS is smaller than that in TW. This is because of much smaller concrete compressive strength of the specimen. If the thickness of the concrete cover in TS is the same as in TW, it is expected that the resistivity for RC column in TS will be even smaller.

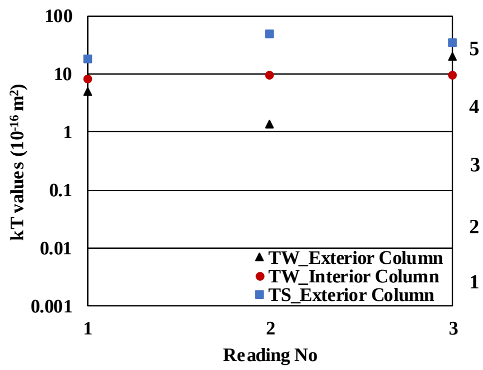

Figure 17. The coefficient of the air permeability for the bridge in Tollway

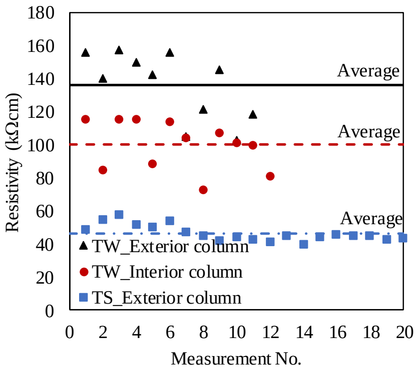

Figure 18. The electrical resistivity for the bridge in Tollway

4.4 *Further discussion*

The data obtained from the as-built drawing and obtained during the investigation is very useful for further assessment of the bridge. The structure can be modelled based on the precise information taking into account the probability of the material properties obtained from the NDT observation. The corrosion should be checked prior to the analysis of the structure to enhance the accuracy of the size of the reinforcement, in case if corrosion is present. At last, retrofit should be recommended if the structure does not satisfy the expected/required limit.

5 CONCLUSIONS

This paper has proposed a framework on how to assess the condition of existing reinforced concrete (RC) structures. The proposed framework involves the use of multiple types of NDT equipment to enhance the accuracy of the structure including the standard deviation of the material properties. Corrosion, deflection, and strength of the existing structures should be checked thoroughly.

Two RC bridges in Port of Tanjung Perak and Two RC bridges in Tollway in Surabaya has been chosen as the case study. Moreover, different exposure and age of the structure have also been considered. Due to the length limitation of the paper, this research focused only on the results of the NDT observation which are very useful for the analysis steps.

From the NDT observation, several key conclusions have been made as follows:

1. The data obtained from the as-built drawing needs to be checked using NDT equipment to confirm the accuracy of the drawing (especially the thickness of the concrete cover, bar arrangement, and the concrete compressive strength). It has been found that some of the reading is different to the information provided in the as-built drawing. This update is crucial for the analysis steps to assess the actual capacity of the structure.
2. The coefficient of the air permeability of the painted surface is smaller than that of the unpainted one. It means that the initiation time of the corrosion is longer for the painted surface than for the unpainted one.
3. In general, there is a low corrosion rate for all the structural elements investigated in this paper since the electrical resistivity is higher than 20 kΩcm. This is due to the high importance and the exposure of the structure which made the concrete cover to be quite thick.

ACKNOWLEDGEMENT

The authors would like to thank Australia Indonesia Centre (AIC) for funding Strategic Research Project 2. The contribution from the Australian Research Council's Discovery Early Career Researcher Grant (DE170100165, DE 2017 R1) is acknowledged. The equipment was purchased through an ARC LIEF Grant (LE140100053).

6 REFERENCES

AASHTO (2012) *AASHTO LRFD Bridge Design Specifications.* American Association of State Highway and Transportation Officials, Washington DC.

AASHTO TP 95 (2011) *Standard method of test for surface resistivity indication of concrete's ability to resist chloride ion penetration.* American Association of State Highway and Transportation Officials (AASHTO), USA.

Alisjahbana A (2012) Effective public spending: The case of infrastructure. In *2012 OECD Global Forum on Development*, Paris.

Andrade C and Alonso C (2004) Test methods for on-site corrosion rate measurement of steel reinforcement in concrete by means of the polarization resistance method. *Materials and Structures* **37**(**9**): 623-643.

Andrade C, D'Andréa R, Castillo A, et al. (2009) The use of electrical resistivity as NDT method for the specification of durability of the reinforced concrete. In *Non-Destructive Testing in Civil Engineering NDTCE'09*, Nantes, France.

ASTM C805 / C805M (2013) *Standard Test Method for Rebound Number of Hardened Concrete.* ASTM International, West Conshohocken, PA.

ASTM C876 (2015) *Standard Test Method for Corrosion Potentials of Uncoated Reinforcing Steel in Concrete.* ASTM International, West Conshohocken, PA.

BGA (2010) *Strengthening calculation for the beam of the trestle in Terminal Peti Kemas Surabaya (In Indonesian).* Benjamin, Gideon & Associates Surabaya, Indonesia.

Chalhoub MS (2015) 'Effect of Reinforced Concrete Deterioration and Damage on the Seismic Performance of Structures' in Belhaq, M., ed. *Structural Nonlinear Dynamics and Diagnosis: Selected papers from CSNDD 2012 and CSNDD 2014*, Cham: Springer International Publishing, 77-95.

Chen L (2013) *Quantifying annual bridge cost by overweight trucks in South Carolina*, Master of Science thesis Clemson University, Clemson, USA.

Dewasa B (2016) 'Earthquake Regulations in Indonesia from 1966 to 2002 (In Indonesia)', [online], available: http://sipil.unnes.ac.id/index.php/tag/peraturan-gempa-indonesia/ [accessed 2018].

Directorate General Bina Marga (2016) *Strategical Plan of Ministry of General Work and Public Housing in Developing and Improving the Road (In Indonesian)*. Directorate General Bina Marga, Ministry of General Work and Public Housing, Jakarta.

Fiorillo G and Ghosn M (2017) Fragility analysis of bridges due to overweight traffic load. *Structure and Infrastructure Engineering*: 1-15.

Gu P and Beaudoin JJ (1998) *Obtaining effective half-cell potential measurements in reinforced concrete structures*. National Research Council of Canada, Ottawa, Construction Technology Update No. 18.

Hellier CJ (2013) *Handbook of Nondestructive Evaluation, Second Edition.* McGraw-Hill Education, New York.

IAEA-TCS-9 (1999) *Non-destructive testing: A guidebook for industrial management and quality control personnel*. International Atomic Energy Agency, Vienna, Austria.

IDS (2012) *IBIS-FS v. 1.0 - User manual.* IDS Ingegneria Dei Sistemi S.p.A., Pisa, Italy.

Kropp J and Hilsdorf HK (1995) *Performance Criteria for concrete Durability - RILEM Report 12.*

Kucharczyková B, Misák P and Vymazal T (2010) *The air permeability measurement by Torrent Permeability Tester* Vilnius, Lithuania: Vilnius Gediminas Technical University.

Menteri PUPR (2017) *Indonesian earthquake map 2017 (in Indonesian).* Minister of Public Work and Public Housing (PUPR), Jakarta.

Mitchell D (2010) *Heavy vehicle productivity trends and road freight regulation in Australia,* Canberra, Australia.

Nakamura E, Watanabe H, Koga H, et al. (2008) Half-cell potential measurements to assess corrosion risk of reinforcement steels in a PC bridge. In Binda, L., Prisco, M. d. and Felicetti, R., eds., *RILEM Symposium on On Site Assessment of Concrete, Masonry and Timber Structures - SACoMaTiS 2008*, RILEM Publications SARL, 109-117.

Paulini P and Nasution F (2007) Air permeability of near-surface concrete. In *CONSEC'07 Tours*, France.

Polder RB (2001) Test methods for on site measurement of resistivity of concrete — a RILEM TC-154 technical recommendation. *Construction and Building Materials* **15**(**2**): 125-131.

Proceq SA (1995) *Permeability tester TORRENT: Operating instructions*. Proceq SA, Schwerzenbach, Switzerland.

Proceq SA (2014) *Profometer PM-6 operating instructions.* Proceq SA, Schwerzenbach, Switzerland.

Proceq SA (2016) *Resipod operating instructions.* Proceq SA, Schwerzenbach, Switzerland.

Proceq SA (2017) *Silver Schmidt & Hammerlink operating instructions.* Proceq SA, Schwerzenbach, Switzerland.

PWC (2017) 'Directorate General Bina Marga focuses on development and maintenance in 2018', [online], available: https://www.pwc.com/id/en/media-centre/infrastructure-news/october-2017/directorate-general-bina-marga-focuses-on-development-and-mainte.html [accessed 06/02/2018 2018].

RILEM TC 154-EMC (2003) Recommendations of RILEM TC 154-EMC: Electrochemical techniques for measuring metallic corrosion Half-cell potential measurements - Potential mapping on reinforced concrete structures. *Materials and Structures* **36**(**261**): 461-471.

Salbei VJ, Sitters CMW and Vantomme J (2014) Non-Destructive Testing Techniques for Corrosion Assessment in Reinforced Concrete Structures in Kenya. *Civil and Environmental Research* **6**(**7**): 60-75.

SNI-1726 (2012) *Seismic resistance design standard for buildings in Indonesia (in Indonesian).* National Standardiztion Agency of Indonesia, Indonesia.

Song H-W and Saraswathy V (2007) Corrosion Monitoring of Reinforced Concrete Structures - A Review. *International Journal of Electrochemical Science* **2**: 1-28.

Torrent RJ (1992) A two-chamber vacuum cell for measuring the coefficient of permeability to air of the concrete cover on site. *Materials and Structures* **25**(**6**): 358-365.

TPS (2013) *Research on the repair work of the trestle in Terminal Peti Kemas Surabaya (Indonesian version)*. PT. TPS, Surabaya.