

# Sydney Harbour Tunnel – Technical Aspects Of Asset Maintenance Strategies For Long Term Serviceability

M Marosszky<sup>1</sup> ZT Chang<sup>1</sup> RL Munn<sup>1</sup> I Cox<sup>2</sup> B Cherry<sup>3</sup> P Walters<sup>4</sup>  
<sup>1</sup>Australian Centre for Construction Innovation University of NSW Australia  
<sup>2</sup>Connell Wagner Pty Ltd Neutral Bay NSW Australia  
<sup>3</sup>Physics and Materials Engineering Monash University Australia  
<sup>4</sup>Sydney Harbour Tunnel Company Sydney Australia

**Summary:** This paper examines techniques used in the Sydney Harbour Tunnel Asset Protection program designed to ensure the tunnel's long-term serviceability. A comprehensive maintenance program was put into place shortly after the completion of construction. State-of-the-art techniques are being employed and developed for investigations and condition monitoring. A new analytical approach has been developed for more appropriate interpretation of half-cell potential test results instead of merely relying on the criteria contained in ASTM C876. Another technique, the injection of micro-cement grouts into concrete cracks, is currently being investigated for corrosion control. Laboratory research is also being undertaken to study the influence of cracks on the corrosion of steel reinforcement in submerged marine structures. The cooperative effort of the consulting and maintenance teams combined with the use and development of advanced techniques in an ongoing maintenance program has played an important role in the tunnel's asset maintenance strategy.

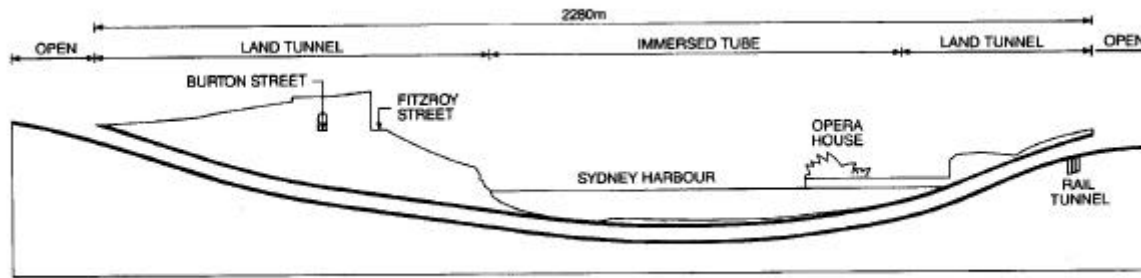
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## 1 INTRODUCTION

The Sydney Harbour Tunnel (SHT) is one of the largest privately funded infrastructure projects built in Australia. Since the tunnel's official opening in August 1992, a total of 222 million vehicles have used the tunnel. It is expected that 34 million vehicles will drive through the tunnel in 2001: about 93 thousand vehicles per day. The tunnel plays an important role in the business and the daily life of metropolitan Sydney.

The SHT comprises three main sections as well as the transition structures located between them: twin 940m land tunnels on the north shore, 960m immersed tube (IMT) section made up of eight precast units and twin 400m land tunnels on the south shore (see Fig 1). Concrete durability in the marine environment was given special attention in the design of the SHT structure. Both concretes and structures were required to meet a combination of strict performance and prescriptive properties.

Connell Wagner Pty Ltd, the designer of the tunnel structures together with their sub-consultant, the Australian Centre for Construction Innovation of the University of NSW (ACCI – formerly known as the Building Research Centre), were engaged in providing technical advise on the maintenance of this large vital asset shortly after the completion of construction. A comprehensive maintenance program – the Sydney Harbour Tunnel Asset Protection Strategy – was prepared and has been implemented on an annual basis since the tunnel's completion. The primary objective is been to ensure that a minimum of 100 years of service life can be achieved. An annual maintenance program includes clearly defined tasks such as the routine inspection of key sections, detailed investigations of selected areas or specific items, development of remedial specifications and monitoring of the execution of the remedial work, as well as review or development of new techniques for monitoring and trial remedial works.



**Fig 1. Longitudinal Section of the Sydney Harbour Tunnel**

The Asset Protection Strategy program has been implemented over the past years. This paper examines some of the techniques used and developed to date in the implementation of this maintenance program.

## **2 SOME TECHNIQUES USED AND DEVELOPED IN THE MAINTENANCE PROGRAM**

To ensure the long-term serviceability of any infrastructure, it is important to use the most advanced techniques available, both in the investigation phase and in maintenance. This maximises the likelihood of early detection of defects and may even reduce the remedial work needed. Further an improved understanding of the progress of deterioration and its mechanisms allows appropriate maintenance strategies to be determined and preventive measures to be implemented. Several state-of-the-art techniques have been employed in the SHT Asset Protection Program for on-site monitoring and investigation. These include the GECOR device with a sensor-controlled guard-ring for corrosion rate evaluation, the impact-echo system for non-destructive evaluation of concrete defects and the installation of reference electrodes for monitoring potentials of reinforcing steel near the external surface of the submerged tunnel sections. New techniques and analytical tools have also been developed for more effective monitoring, analysis and remedial treatment. This paper describes some of the main techniques and their applications in the SHT Asset Protection Program.

### **2.1 Crack movement monitoring**

Although many modern concretes develop strength more quickly than those produced fifty or sixty years ago, they are more prone to cracking. (Burrows, 1997). Steel reinforcement has been used to control crack width development; but reinforcement does not prevent cracking. Cracks may adversely affect the watertightness of concrete and the need to seal active cracks is common in underground concrete structures. To achieve the effective crack sealing, understanding the nature and the causes of crack movement in a particular structure are essential. Using thin, brittle glass strips as “tell-tales” is a simple practice to detect crack movement. However, based on ACCI’s laboratory testing, a DEMEC strain gauge device was chosen for more effective monitoring of crack movement.

At selected locations, a pair of DEMEC gauge studs was epoxy cemented on either side of a crack. The movement between the gauge studs was then measured regularly with a DEMEC gauge. While theoretically and under ideal conditions the DEMEC gauge can measure a relative movement of about 0.002mm, in practice on a field structure, an accuracy of 0.01mm is more realistic due to the imperfections of the gauge studs, and the operator induced variations.

Over the years it has been observed that crack widths vary seasonally, with cracks becoming wider in winter and narrower in summer. This phenomenon is mostly due to the seasonal differences in the relative humidity and temperature. This finding has led to the recommendation that to achieve a more effective seal, active cracks should be repaired in winter (at their widest). Furthermore, this technique has also identified that seasonal crack movements in the thinner, unreinforced land tunnel sections are more significant (maximum of 0.2 mm), while the crack movements in the heavily reinforced thick tunnel wall sections are negligible (less than 0.05 mm). These differences in movement have influenced the crack sealing strategy. In the unreinforced land tunnel sections flexible polyurethane resin and foam injection have been used rather than rigid epoxy resin injection. In the thicker, reinforced concrete walls less flexible materials, such as micro-cement grout, can perform effectively. A discussion of the crack sealing materials can be found in the latter part of this paper.

### **2.2 Routine inspection of key areas**

Programmed routine inspection of key areas is essential for a facility like the Sydney Harbour Tunnel. Early detection of potential defects can avoid unanticipated risks and may also reduce the cost of remedial work. Such inspections have proven to be invaluable as part of the SHT maintenance strategy.

On the first such inspection, an area with some hollow sounding patches was identified in a cast in situ concrete section of the tunnel. Immediate action was undertaken to secure the area as a precautionary measure. These *drummy patches* were removed with pressure water jetting during the following maintenance shutdown period. A total of approximately 5 square metres was

found in this area where cement render had been applied over previous epoxy repair patches. Remedial actions had been undertaken in this area and further monitoring of this area is included in the inspection program.

During another inspection, a small area with a particular crack pattern was found in the roof of a precast section. Further investigation using X-ray Fluorescence Spectrometry and chemical analyses identified that the sample comprised a thin layer of cement slurry. Presumably, this was the excess slurry used to coat the pump line before concrete was pumped into this section and the fine cracks with the particular pattern were probably due to the shrinkage of the cement slurry under the restraint of the surrounding concrete. Remedial measures involved the removal of the drummy surface layer and the repair with an appropriate repair system.

### 2.3 Half-cell potential testing and interpretation

The half-cell potential technique has been used to monitor corrosion in selected areas of this structure from the outset. Half-cell potential testing is a widely used technique for on-site evaluation of the corrosion risk of concrete structures. ASTM C876-91 provides the following guidelines for the interpretation of the half-cell potentials measured with the copper and copper sulfate electrode (CSE) on concrete structures:

- those more negative than -350mV > 90% probability of active corrosion
- those between -200 mV and -350 mV 0% probability of active corrosion
- those more positive than -200mV < 10% probability of active corrosion

However, these guidelines were empirically developed in the United States based primarily on potentials measured in highway bridge decks affected by de-icing salts (Stratfull, 1973, and Van Daveer, 1975). It has since been observed that the characteristic potential ranges can shift significantly for concrete structures under different environmental conditions — such as marine environments or where carbonation of concrete is significant. While Borgard et al. (1991) reported no corrosion for steel at potentials more negative than -350 mV (CSE), Elsener et al. (1990) found severe corrosion at much less negative potentials.

Because the relationship between potential values and corrosion risks differ significantly in different environments, the analysis of risk on the basis of local potential gradients rather than the potential values is recognised to be a better way of identifying active corrosion sites (Elsener and Bohni, 1990). Broomfield (1997) also proposed that active locations in carbonated concrete might be indicated by potential differences greater than 150 mV over a space of one metre.

Based on experience in corrosion investigation in the field, one of the authors, Z. T. Chang has developed a new approach for the analysis of half-cell potential results. Chang firstly noted that locations with a higher potential gradient include not only more negative sites but also more positive ones. However, those locations associated with more negative conditions are characterised by both a higher potential gradient and a more negative potential value. He then developed the *Potential Curvature Method* on the theoretical basis that higher positive curvature values pick up more anodic locations with a higher potential gradient as well as a more negative potential value. A numeric method has been developed to analyse and identify more anodic locations with higher positive potential curvatures.

While further work is still needed to develop the performance criteria linking potential curvature values and the probability of active corrosion, at this stage a characteristic potential curvature value is proposed based on the potential gradient of 200 mV/m. The locations with potential curvatures greater than this characteristic value are considered to have moderate to high corrosion risks of active corrosion. The *Potential Curvature Method* has now been successfully used in many ACCI site investigations of different concrete structures. The method has been shown to be an effective tool for corrosion evaluation in concrete structures, regardless of whether they are in a marine environment or primarily affected by carbonation. Details of the *Potential Curvature Method* are presented in another paper (Chang et al., 2002) in this proceeding.

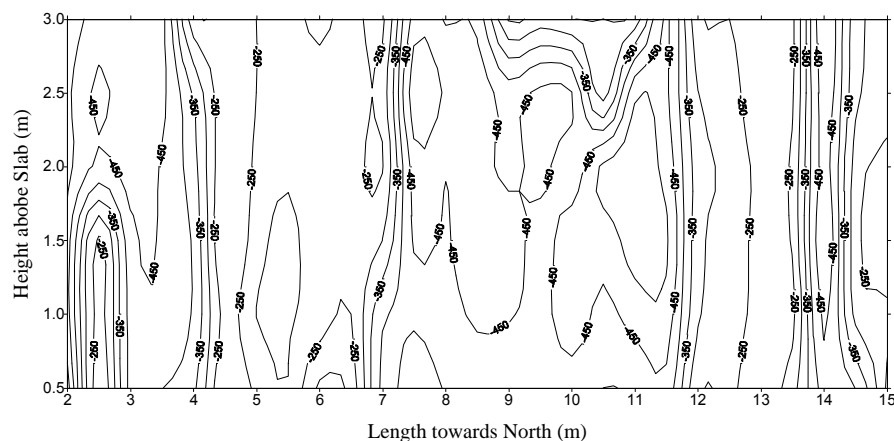
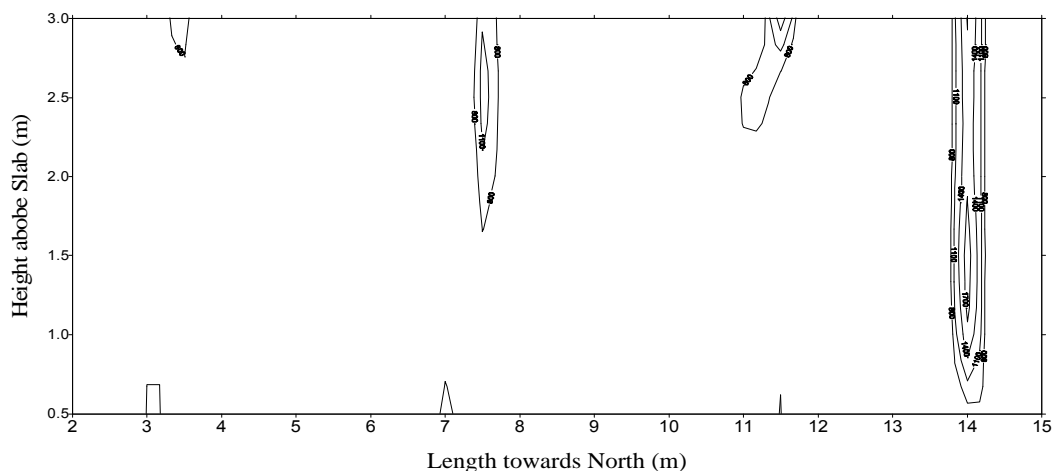


Fig 2. Half-Cell Potential Contour Map in an Inspected Area

In one area of the land tunnel sections, half-cell potentials more negative than  $-350$  mV (CSE) had been measured over most of this area. Figure 2 shows the contour map of the half-cell potentials in this area. In spite of these high negative potentials, at two high negative potential locations (one on a crack and the other on uncracked concrete) the steel reinforcement was exposed and found to be free of corrosion.

While a great portion of this area has high negative potentials, the denser potential isolines indicate the locations of higher potential gradients. It is noteworthy however that the denser potential isolines at the x-coordinate of 2.5 m indicate a more cathodic location with less negative potentials. Care must be taken when making assessments based on potential contour maps to differentiate between anodic and cathodic locations.



**Fig 3. Potential Curvature Map Highlighting Locations of Higher Corrosion Risks**

Figure 3 shows the potential curvature map of the same area based on the ACCI's *Potential Curvature Method*. Figure 3 shows that despite the high negative potential values measured over this area, the potential curvatures are not significantly high except for the location at the x-coordinate of 14 metres, where there is a crack on a construction joint. A steel bar intersecting with this crack was exposed and exhibited general corrosion over a length of 20mm.

#### 2.4 On-site corrosion rate investigation

Half-cell potential measurement and the ACCI's *Potential Curvature Methods* have been successfully used to provide a clear identification of locations with moderate to high corrosion risks. However, the rate of corrosion cannot be determined from these results. For the assessment of service life of existing structures, the rate of reinforcement corrosion at critical sections also needs to be evaluated. Corrosion rate measurements combined with half-cell potentials are also very useful in the evaluating the effectiveness of remediation measures, such as crack sealing methods and the use of corrosion inhibitors to control the corrosion of steel reinforcement.

The on-site testing of the corrosion rate of reinforcement in concrete is a recent technique. The GECOR device with a "sensor controlled guard ring" is one of the standard pieces of equipment designed for use in the field. Over recent years it has been used in on-site investigations and the following interpretation criteria have been proposed (Broomfield et al, 1994):

$I_{\text{corr}} < 0.1 \mu\text{A}/\text{cm}^2$	Passive condition
$I_{\text{corr}} = 0.1 \text{ to } 0.5 \mu\text{A}/\text{cm}^2$	Low to moderate corrosion rate
$I_{\text{corr}} = 0.5 \text{ to } 1.0 \mu\text{A}/\text{cm}^2$	Moderate to high corrosion rate
$I_{\text{corr}} > 1.0 \mu\text{A}/\text{cm}^2$	High corrosion rate

The corrosion current density of  $1 \mu\text{A}/\text{cm}^2$  is equivalent to an average corrosion penetration depth of 0.012 mm/year. The corrosion rate measured with the GECOR device is an average value for the rebar surface under the sensor area. However, if corrosion occurs only at a few pits within the area, the average corrosion rate will underestimate the maximum corrosion penetration depth in the pits. Some research has suggested that the maximum penetration of localized pitting could be between 4 to 10 times the general corrosion depth over the steel surface (Gonzalez et al, 1995).

A GECOR device was used to investigate selected areas of the tunnel structure, one of which was the area discussed in the preceding section as having high negative half-cell potentials. The test results showed that the reinforcement at four uncracked locations was all in a "passive" (Broomfield et al, 1994) condition, despite high negative potentials of about  $-500$  mV being recorded at two of the four locations. At another two locations intersecting the cracks, the direct GECOR test results indicated one location had a "low to moderate" corrosion rate and the other was indicated as being "passive". However, since the crack zone localises corrosion the direct GECOR test results underestimate the local corrosion rate. A multiplier of 7 was used to estimate the local current densities at locations intersected by cracks. This modification brought the estimated corrosion rate to

the category of “low to moderate” at one location and of “moderate to high” at the other. The location with “moderate to high” corrosion rate is on the crack at the x-coordinate of 14 metres where the highest potential curvatures were found with the ACCI potential curvature analysis (see Fig 3).

Generally, the initial results obtained with the GECOR device had fairly good correlations with the locations identified with the potential curvature method and the observation of corrosion conditions of the exposed reinforcement. However, some variables need further investigation. These include the use of an approximate corrosion constant, the assumption that there is a uniform corrosion condition and that the measured steel area is confined under the sensor. These factors need to be studied further both in laboratory investigations and in real structures before the service life of an asset can be predicted based on corrosion rate evaluation.

## **2.5 Development of crack injection technique with micro-cement grouts**

Cracks in this structure mostly occurred in the sections that were cast in situ. Most cracks have been repaired using a cementitious material with crack sealing properties derived through crystallisation reactions. Moisture penetration at the repaired locations has been substantially stopped. However, the potential curvature analysis indicates that there is still a relatively higher corrosion risk at some cracks, despite the fact that they have been fully sealed. In order to suppress the corrosion of the reinforcement in crack zones a trial injection of super-fine cement grout was undertaken.

Theoretically, cement grouts are ideal for sealing cracks in concrete. They should suppress corrosion activity by reinstating a high pH environment and by chemical binding free chloride ions. In practice the coarse grain size (up to 100µm) of normal portland cement limits its application for crack grouting. However, the development of micro-cement (MC) products with a maximum grain size smaller than 12µm or even 6µm has created new possibilities.

The first on-site trial was undertaken on two open cracks with a surface crack width of 0.5 mm. The penetration of the MC grout was assessed by taking 90mm long cores on the cracks. Grout was found to penetrate up to 90mm down to a crack width of 0.1 to 0.2mm. One of the two cracks treated is in a reinforced section and the half-cell potentials along the crack were found to shift towards more positive by an average of 77mV twelve months after the injection.

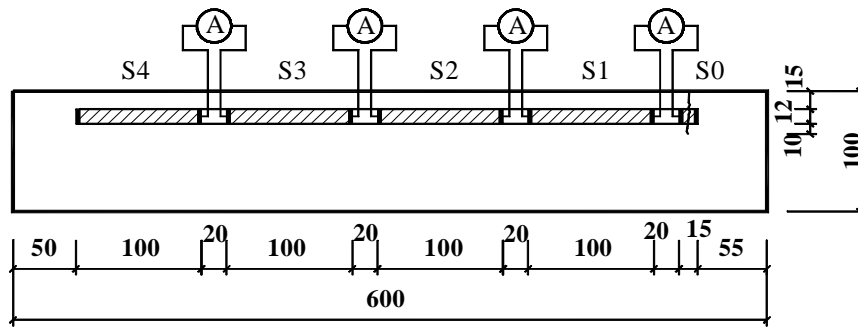
A second recent trial was carried out to inject MC grouts into previously sealed cracks. It was found that the MC grouts could be injected behind surface repaired cracks to 120mm or deeper under a high injection pressure. The half-cell potentials along these cracks are currently being monitored over time to evaluate the effectiveness of MC grout injection on corrosion reduction in the crack zone.

## **2.6 Research on influences of crack width in submerged structures**

The influences of cracking and crack width on corrosion of steel reinforcement over the long term are still a topic for debate and further research. Schiessl (1976) investigated the effects of crack width on reinforcement corrosion under marine exposure over a period of 10 years. His test results showed that the effect of crack width (less than 0.5mm) on the steel corrosion rate in the crack zones was insignificant over the long term. Schiessl (1988) explained this to be “Because the cathodic process is the dominating rate determining process, an influence of crack widths on corrosion rate nearly doesn’t exist”. Very few investigations have been conducted on the influences of cracking and crack width on corrosion of steel reinforcement in concrete submerged in seawater. In the UK “Concrete in the Ocean” research program, Wilkins and Lawrence (1983) suggested that transverse cracks up to 0.6mm wide might be tolerable in practice. However, they also warned that, because of the high conductivity of seawater, a galvanic couple might occur with a large cathode (the steel in uncracked concrete) and a small anode (the steel in a crack zone). This could result in significant macrocell corrosion in the crack zone.

The ACCI is currently undertaking research sponsored by the SHT Company into the influences of cracks on corrosion rates of steel reinforcement in concrete submerged in seawater. The details of the test procedures are described in Chang *et al* (2000) and initial test results (Chang *et al*, 2001) have shown that a significant difference was found between the rest potentials of the steel bar in sound concrete and that intersecting a crack when the concrete specimen was immersed in a 3% NaCl solution. A macrocell was formed when the two rebars were electrically connected and, as expected, the rebar intersecting the crack formed the anode.

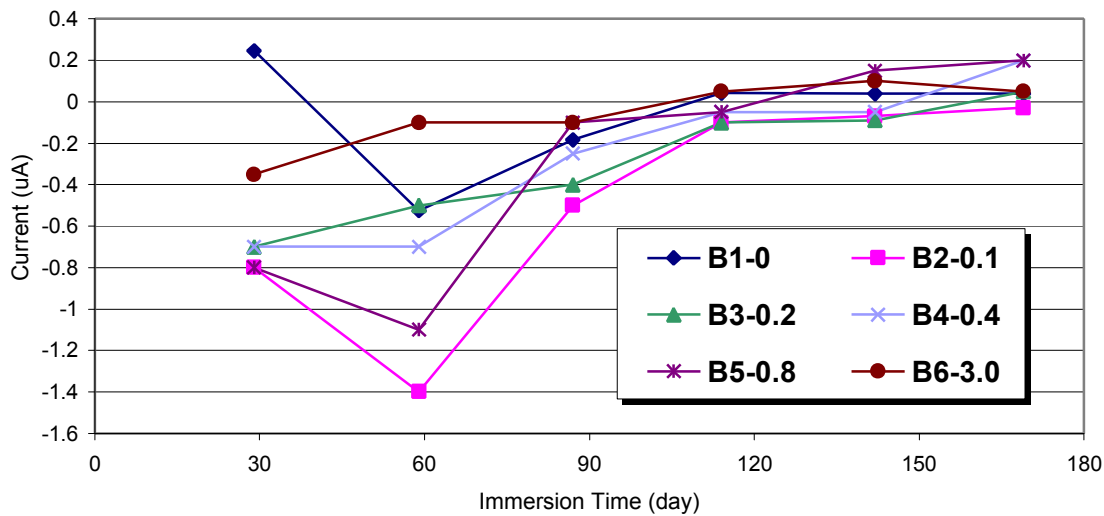
Further investigations of macrocell current flow between steel sections in uncracked concrete and intersecting a crack have been carried out with the beam specimens as shown in Figure 4. Each beam specimen contains four separate 100mm long rebar sections (S1 to S4 in Fig 4) in uncracked concrete and these rebars are in line with another short rebar (S0 in Fig 4) which intersects a concrete crack. The crack widths in a group of six beams are 0, 0.1, 0.2, 0.4, 0.8 and 3mm. The beams are immersed in a seawater tank and the macro current flow between the rebar sections in each beam is monitored with a Zero-Resistance-Ammeter.



**Fig 4. Concrete Beam Specimens for Macrocell Current Monitoring**

The macrocell current flowing into the rebar section exposed at the crack zone in the cracked beams was initially as high as about  $60\mu\text{A}$  after 7 days immersion, but declined rapidly to less than  $5\mu\text{A}$  after 4 weeks immersion. The macrocell current dropped further to less than  $1\mu\text{A}$  after 24 weeks immersion. This accounted for a low corrosion rate of less than  $0.01\text{mm/year}$  for the rebar surface in the crack zone.

A further important finding of this work (Chang et al, 2001) is the electrochemical evidence of the development of a more anodic state in the rebar S1 (see Fig 4) in uncracked concrete next to the rebar S0 intersecting the crack. This was indicated by a shift of the net electric current flow through S1 from the negative to the positive values as shown in Figure 5. The results in Figure 5 were measured from six beams (B1 to B6) with the crack width of 0.1 mm to 3mm. The important implication of this finding is that the corrosion penetration rate of a rebar in the local crack zone could reduce significantly with time due to spreading of the anodic surface and reduction of the macrocell effect.



**Fig 5. Net Current Flow through Rebar S1 in Beams B1 to B6 from 4 to 24 Weeks with varying crack widths**

The findings of this investigation also shed light on previous research observations of an insignificant correlation between crack width in concrete and the corrosion rate of steel in the crack zone. This could then be significantly influenced by not only the cathodic process away from the crack zone but also the development of an anodic steel surface adjacent to the crack zone and the subsequent reduction of macrocell effect.

The initial findings of this research work have added to the understanding of the mechanisms of corrosion and corrosion rate of steel reinforcement in submerged marine structures. Such theories are not yet well established. Since on-site investigations of the corrosion condition of reinforcement near the external surface of submerged structures are extremely difficult, laboratory research is needed to investigate the corrosion mechanisms under such special environments. While the current research work is continuing, some on-site investigations are also in progress within the Asset Protection Program. These include monitoring the reference electrodes installed close to the external reinforcing steel and the development of a local cathodic protection system particularly for hot-spot remediation of corrosion activity in the concrete crack zones.

### 3 SUMMARY

A comprehensive asset protection program has been undertaken for the maintenance of the Sydney Harbour Tunnel since its opening in 1992. Such a program is essential for the primary objective to ensure that a minimum of 100 years of effective service life can be achieved. State-of-the-art techniques are used in implementing this program. New investigative methods and innovative techniques have also been developed during the course of implementing the asset maintenance. Laboratory research has been undertaken to assist the determination of appropriate maintenance strategies where direct site investigation is restricted. The cooperative work of the consulting and maintenance teams together with the use and development of advanced techniques in an ongoing program has played a vital role in the development of the maintenance strategy of this major asset.

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