CASE STUDY
Durability Investigation, Service Life Prediction and Life Cycle Cost Analysis of Rehabilitation Options for a Pier Structure

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Introduction

- Investigation of a 30 year old barge pier structure located in a tropical marine environment

- Structure comprises of a reinforced concrete deck supported by steel H-section piles driven into the seabed

- Principal defects reported:
  - spalling and cracking of concrete on under-deck
  - corrosion on steel piles

View of upper concrete deck

View of upper concrete deck

View of under deck and steel piles

View of under deck and steel piles

Scope of Investigation Work

- Determine
  - Causes (chlorides? cover? concrete quality?)
  - Extent (localized or widespread)
  - Severity (within or exceeded normally expected)

  of observed defects

- Recommend appropriate remedial works for rehabilitation of structure

- Life-cycle cost estimation was prepared to show the financial commitments over the remaining 30 year life-cycle of the structure using different options

Sequence of Investigation Work

- Desktop review of information and preliminary visual inspection

- Detailed investigation program
  - **Field testing** – dimensional survey, extraction of core samples, concrete cover measurements, half-cell potential measurements, impact echo tests
  - **Chemical analysis** – mix composition and chloride content
  - **Petrographic examination** of concrete core samples

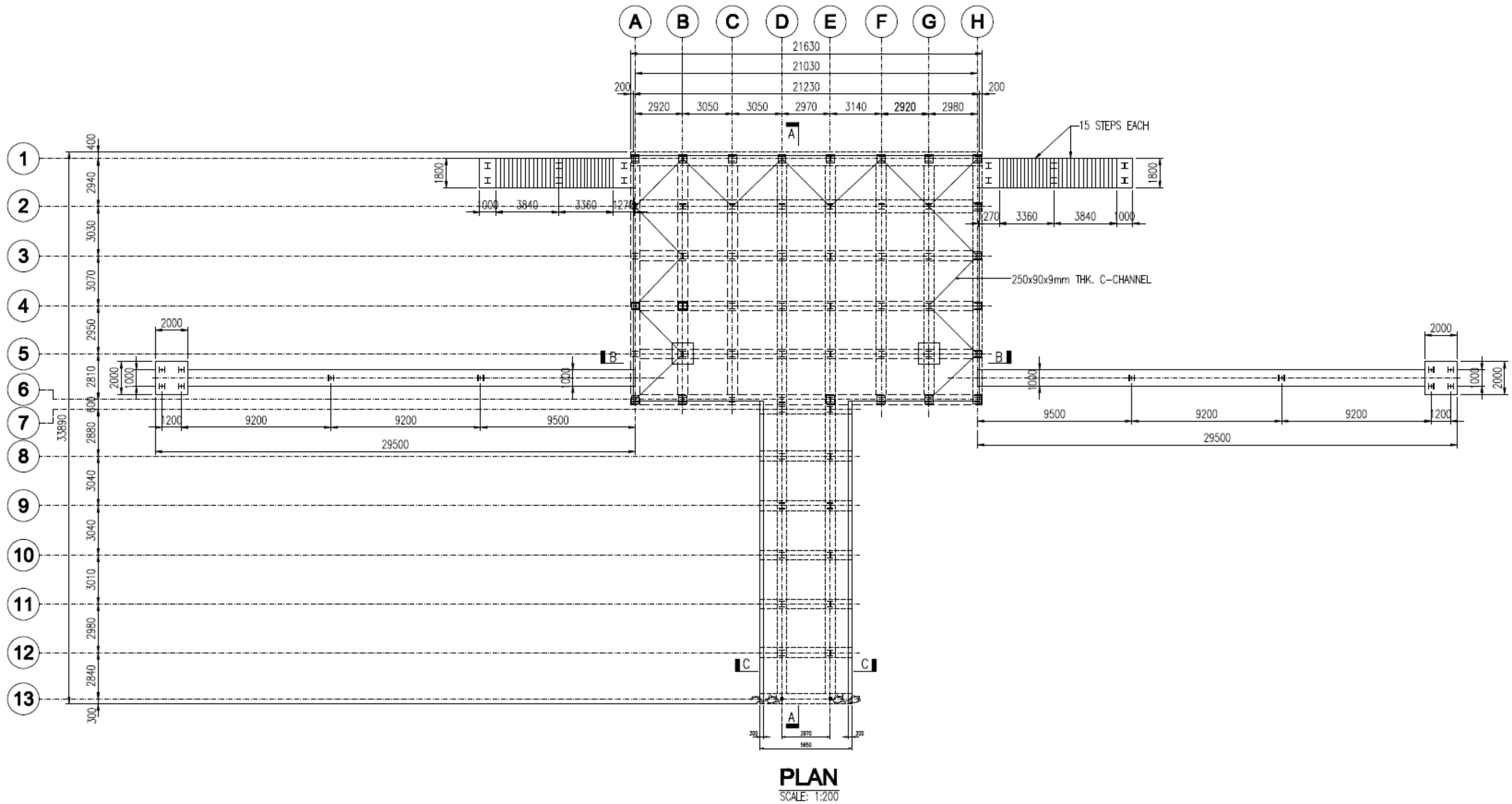
- Modeling and service life prediction of time to initiation of corrosion and cracking

- Life cycle cost analysis to determine cost effective rehabilitation option

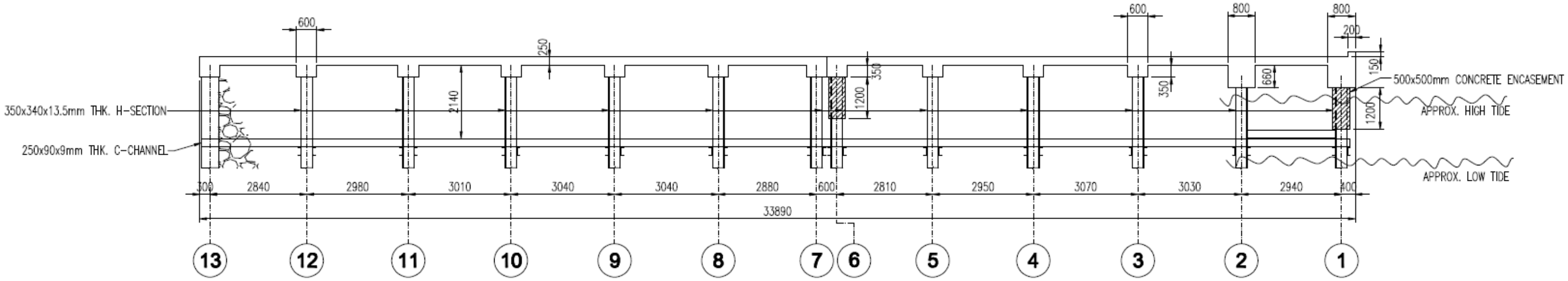
Desktop Review

- No drawings for the 30-year barge structure
  - Dimensional survey to reproduce the drawings of the structure.
- No reinforcement details for the concrete upper deck
  - Breakouts needed to measure the size and number of main reinforcement
  - Concrete cover measured using electronic cover-meter
- No information on the concrete used
  - Concrete cores needed to collect samples
  - Samples tested for chlorides and quality
- No information on repairs carried out earlier
  - Cracks and spalling recurring on previously repaired areas

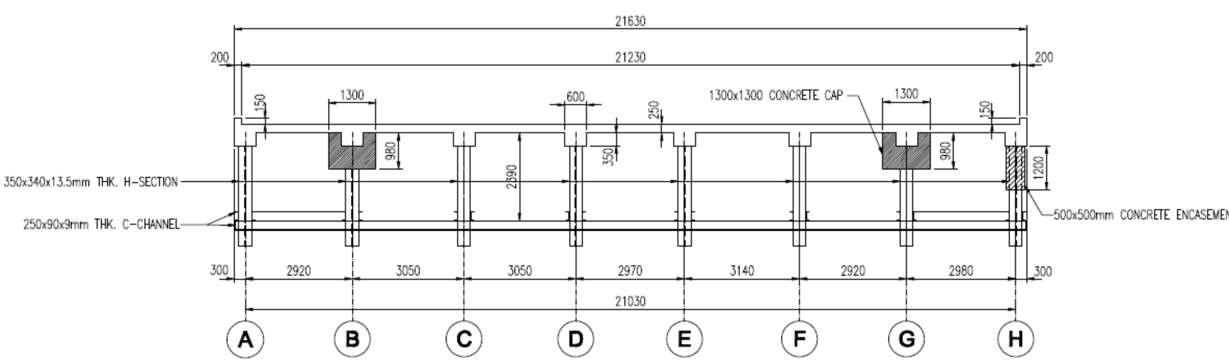
Dimensional Survey



Dimensional Survey



SECTION A-A
SCALE: 1:100



SECTION B-B
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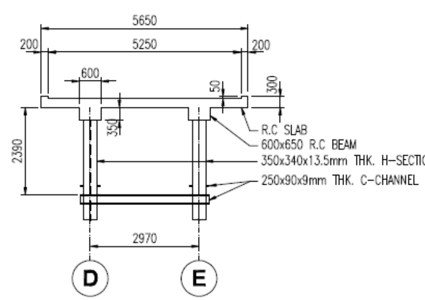

SECTION C-C
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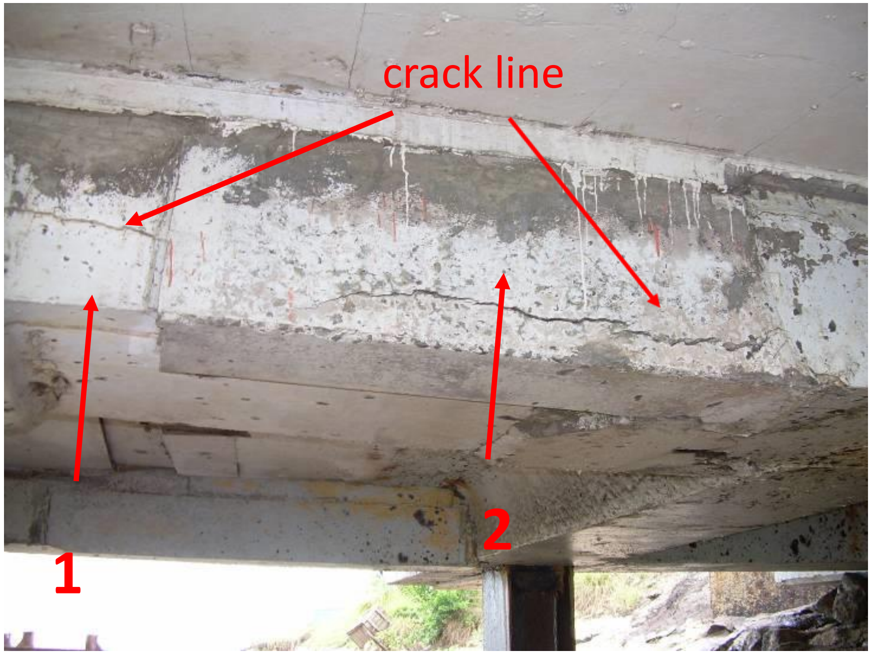
Visual Inspection - Defects observed

Cracking and spalling of soffit concrete

Visual Inspection - Defects observed



Cracking of concrete on beams (repaired & un-repaired areas)

Visual Inspection - Defects observed

Corroded flanges on steel piles

Field and Laboratory Testing

- Chloride concentration levels on extracted core samples:
  - Concrete cover ranged from 50~70mm
  - Chloride content measured at 25mm depth increments
  - 3 depth increments from the surface
  - Chloride content measured:
    - 0 – 25mm = 1.5 %
    - 25 – 50mm = 0.9 %
    - 50 – 75mm = 0.5 %
  - All exceeded the 0.4 % threshold(1) for initiation of corrosion stage causing reinforcement corrosion

Field and Laboratory Testing

- Half cell potential measurements in the range of -355 mV to -599 mV – **90%** probability of corrosion[2] occurring

- Criteria for determining the likelihood of corrosion occurring:

Potential Measurement (mV) ASTM C876-91:1999)	Statistical Risk of Corrosion Occurring (Suryavanshi and Nayak, 1990)
>-200	10% probability that reinforcing steel corrosion is occurring
-200 to -350	50% chance that reinforcing steel corrosion is occurring
<-350	90% probability that reinforcing steel corrosion is occurring

Prediction of service life

Initiation of corrosion

- Modeled as diffusion process using Fick's second law of diffusion[3]

- Using measured values of parameters, **time to initiation** of corrosion obtained as **8.3 to 11.5 years (T1)**

Prediction of service life

Cracking of Concrete Cover

- Semi-empirical model from literature(4) was used, based on critical amount of corrosion products needed to
  - fill void spaces around reinforcing steel and
  - generate sufficient tensile stresses to crack concrete

- Using measured values of parameters**, time to cracking** of concrete obtained as **7.5 to 12.6 years (T2)**

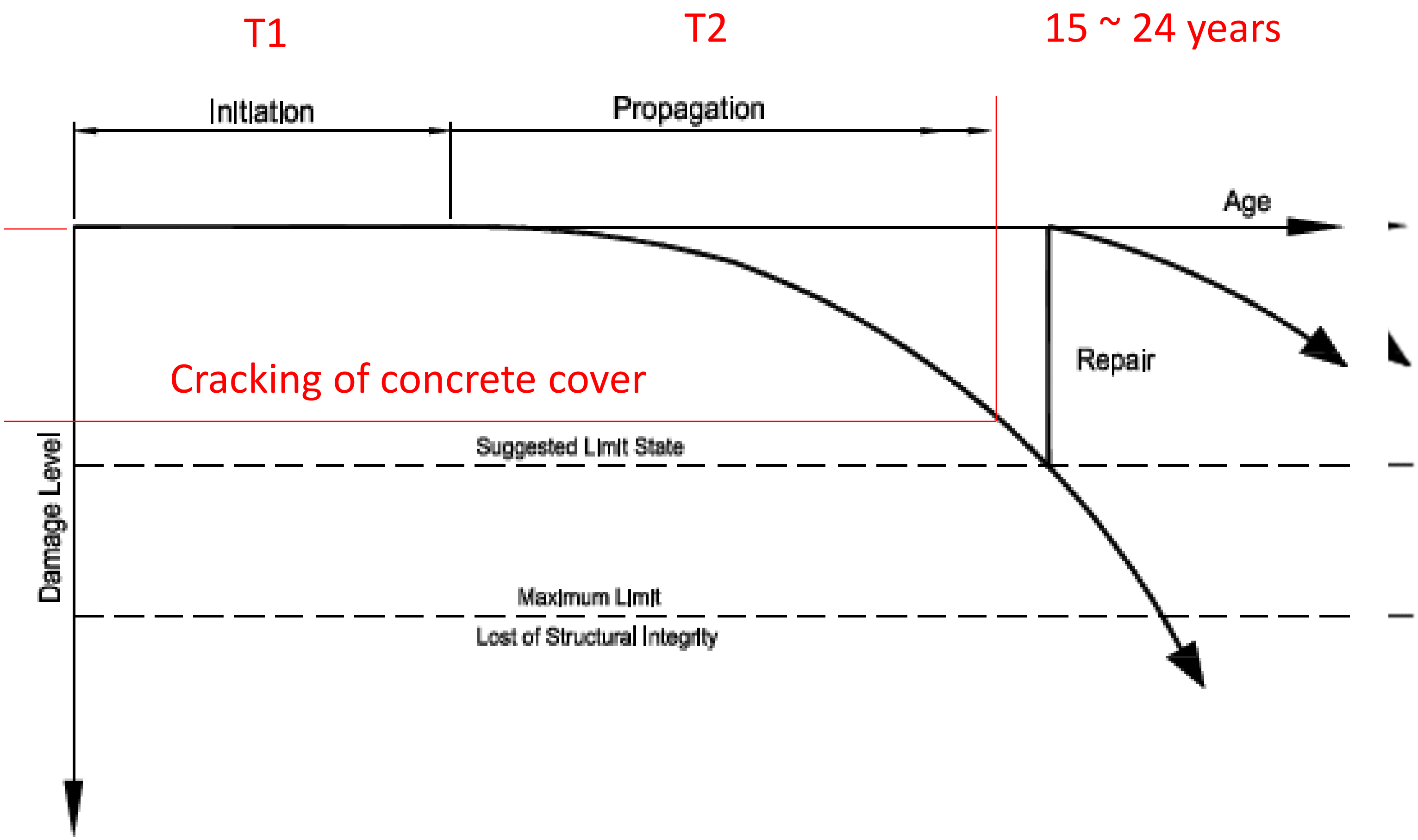
Prediction of service life

- Service life of concrete for limit state of initiation of corrosion and cracking of cover concrete was obtained as **15.8 to 24.1 years (T1 + T2)**

- With age of the structure being **30 years**, the structure found to be in **active corrosion** or **propagation** stage

- Service life prediction provided a reasonable predictive basis for:
  - determining stage of deterioration of concrete
  - planning of rehabilitation works

Prediction of service life



Remedial Recommendations

- Rehabilitation works was selected to suitably address defects observed during the investigation

- Necessary to repair defects such as spalling concrete

- Two long term rehabilitation options proposed:
  - Recurring repairs over 30 years remaining life
  - use of cathodic protection (CP) system on concrete deck and reactive repairs on steel piles

Remedial Recommendations

Necessary repairs

❖Treating/augmenting corroded reinforcement

❖Recurring delaminated/spalled concrete repairs using patch repair method

❖Repairs of steel piles by welding additional plates

❖Application of protective coating on steel piles using a high build epoxy resin

Remedial Recommendations

Cathodic Protection (CP) system

Installation of sacrificial anodes on concrete deck at:

- boundary of patch repairs to protect against macro cell corrosion, thereby mitigating corrosion of steel around patch repairs and
- non-repaired areas having highly negative potentials to slow down further corrosion of reinforcement.
- Installation every 10 years

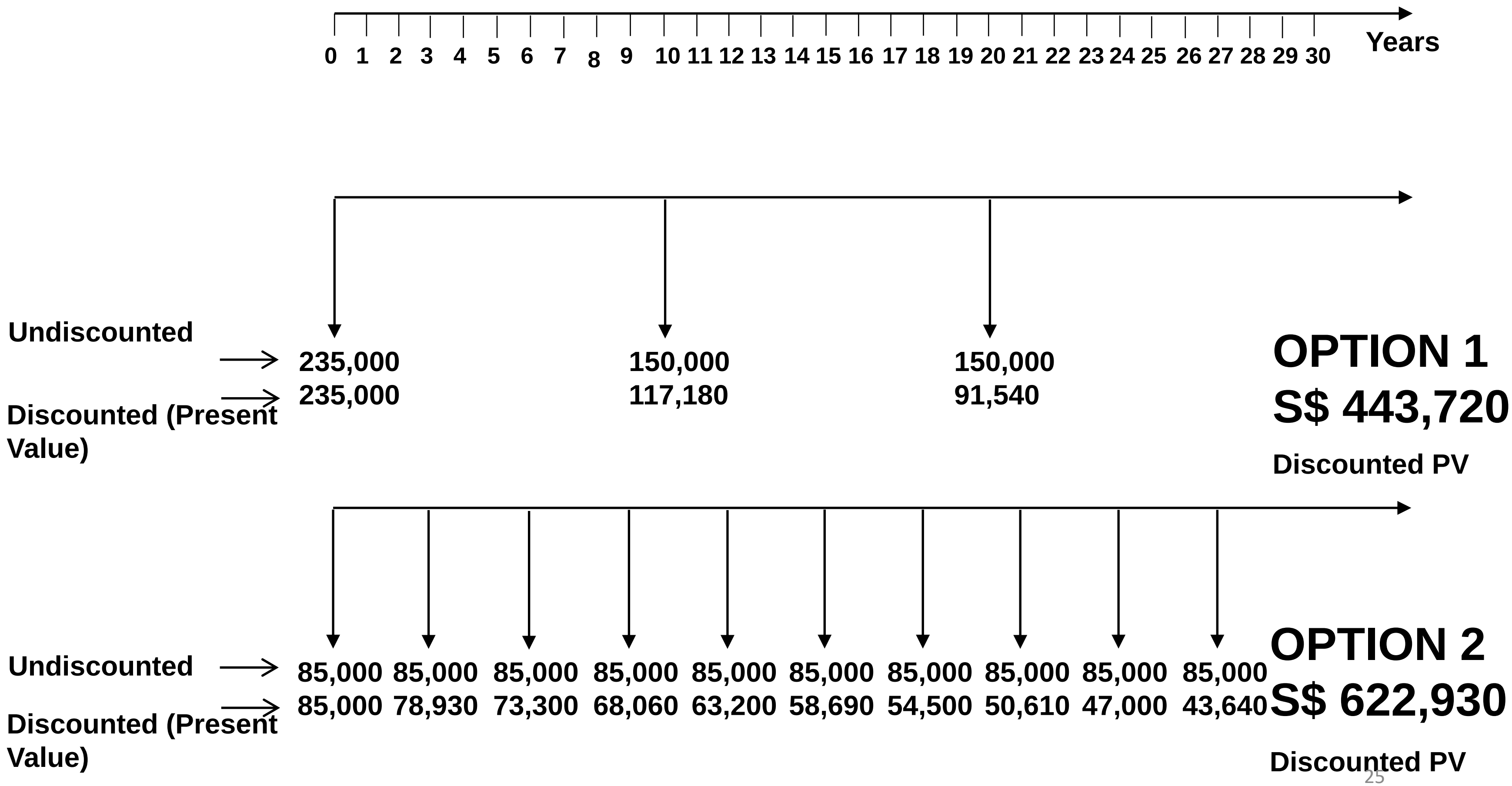
Life Cycle Cost Analysis (30 years)

Options for analysis

1. Necessary repairs + cathodic protection (CP) system (Option 1)

2. Necessary repairs + future recurring repairs (Option 2)

Life Cycle Cost Analysis (30 years)



Conclusion

- ❖ Results of durability investigation for a barge structure located in a tropical marine environment presented

- ❖ Corrosion of reinforcement and spalling of concrete found to be the most significant defects

- ❖ Service life prediction of the time to initiation of corrosion and cracking of concrete carried out

Conclusion

- Remedial recommendations proposed to address:
  - defects requiring immediate attention and
  - protection of structure from a long term perspective

- A life cycle cost analysis carried out to determine most cost effective long term option

- The use of a **cathodic protection system** (compared to recurring repairs) seen to be the most **economical** alternative from a **life cycle perspective**.

References

- (1) Chloride-induced corrosion of steel in concrete (GK Glass, NR Buenfeld, 2001)
- (2) Comparison of surface potentials of RC structures using reference electrodes (AK Suryavanshi, BU Nayak, 1991)
- (3) Initiation of corrosion modelled as diffusion process using Fick's second law of diffusion
- (4) Cracking of concrete cover. Semi-empirical model from literature (Liu, Weyers, 1996)