Pipe Condition Survey and Design for Territory-wide Replacement and Rehabilitation of Large Diameter Water Mains in Hong Kong

C K FUNG[1], LEUNG Ming-yuen[2], and ZHAI Guo-ning[3]

Abstract: The Replacement and Rehabilitation (R&R) Programme of Water Mains implemented by the Water Supplies Department (WSD) of the Government of the Hong Kong Special Administrative Region (HKSAR) involves replacing and rehabilitating of about 3000 km of aged water pipes throughout the territory. The R&R programme with works carried out in four stages is targeted for completion by 2015. Of the 3000 km aged water mains, about 320 km are large diameter water mains. Because of the high capital and social costs, it is essential to conduct a systematic pipe condition survey to develop a comprehensive and cost-effective R&R design for the large diameter water mains.

The construction programme has now entered its third stage. The special feature of this stage includes the pipe condition survey on about 135 km of large diameter water mains. About 78 km of the large diameter mains were surveyed in Kowloon areas in 2007 and 2008 and over 90% of them were installed in 1950's and 1960's. All of water mains are live mains and located in densely populated and traffic congested areas across Kowloon. A combination of techniques are utilized to assess the pipe conditions, including coating defect survey, soil corrosivity testing, pipe wall thickness measurement, visual inspection to non-buried mains, stray current measurement, etc. The survey results provide important data of the condition of the existing water mains including their likely remaining life expectancy. The data will enable an informed decision to be made on replacement or rehabilitation of the large diameter water mains and provide useful information for the design of the R&R works in the most cost-effective manner.

This paper gives an account on the different applications of the pipe condition survey adopted in Kowloon areas to arrive at a comprehensive and cost-effective replacement or rehabilitation design while minimizing water suspensions and disturbance to the customers as well as the general public. It was indicated in the survey results that the conditions of the existing water mains were found satisfactory in general and about 40% require substantial replacement or rehabilitation works. As only problematic sections of water mains identified will require costly replacement or rehabilitation works, the condition survey brings about significant saving in construction cost as compared with a full-scale replacement of the water mains which might otherwise be required.

Keywords: Pipe Condition Survey, Replacement and Rehabilitation, Large Diameter Water Mains

1. INTRODUCTION

WSD has started the Replacement and Rehabilitation (R&R) Programme of Water Mains since the year 2000. The programme requires systematic replacement and rehabilitation about 3000 km aged water mains within 15 years in four stages. The construction programme has now entered its third stage. The special feature of this stage includes the pipe condition survey on about 135 km of large diameter water mains.[1] About 78 km of the large diameter mains were surveyed in Kowloon areas in 2007 and 2008 and over 90% of the surveyed mains were installed in 1950's and 1960's. All water mains are live mains and located in densely populated and traffic congested areas across Kowloon. The large diameter water mains are the major and strategical components of the water supply network providing essential water supply to the metropolitan areas. In view of the high capital and social costs

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for the extensive works on the replacement and rehabilitation of the large diameter water mains, it is essential to launch a systematic pipe condition survey to develop a comprehensive and cost-effective design to optimize the life cycle cost as well as to minimise disruption and inconvenience to the public during construction.

2. PIPE CONDITION SURVEY METHODOLOGY

The pipe condition survey was conducted based on the framework shown in Figure 1. Desktop study was conducted at the initial stage to review the pipe information. The next stage was to take comprehensive field measurements. As one of the prime concerns for the survey works was to avoid disruption against the normal water supply, non-destructive survey techniques were employed. The field measurement results were then input into the proprietary models ***EnviroStat*** and ***PipeFail*** for analysis. The existing conditions of water mains were categorized into five grades, namely "Very Good", "Good", "Fair", "Poor" and "Very Poor" in accordance with the estimated probability of failure. The survey results were used to identify and prioritize the sections of water mains to be replaced or rehabilitated.

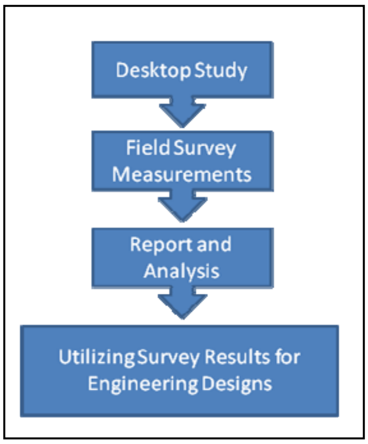

Figure 1: Framework of Pipe Condition Survey Works

2.1 Desktop Study

Desktop study was carried out to analyse the characteristics and locations of mains in the preliminary stage. Basic pipe information such as the pipe sizes, pipe materials, coating materials, operating pressures and year of installations was collected to provide key input parameters to the algorithms of the assessment. The related historical failure records between 1992 and 2007 were thoroughly studied in order to have a better understanding of the performance of the pipelines. Locations of non-buried water mains laid on slopes or embodied in the existing nullahs and box culverts were identified at this stage for arranging the subsequent visual inspection. The steps are crucial to the whole condition assessment as all the information obtained forms the fundamental part of the analysis.

2.2 Field Measurement

Non-destructive field measurements including Coating Defect Survey (CDS), soil corrosivity test, pipe wall thickness measurement (PWTM), stray current measurement and visual inspection to non-buried mains were carried out for the pipe condition assessment.

2.2.1 Coating Defect Survey (CDS)

The extent of deterioration of the exterior coating, such as coal tar enamel wrap along the water main, can be determined by the CDS technique using Pipe Current Mapping (PCM). The CDS technique operates by impressing current into a pipeline. For current to flow through the metal pipe and not to dissipate into the ground, its insulated exterior coating needs to be intact. Hence the length of unprotected area of a pipe section can be estimated from the rate of current loss. The degree of the coating deterioration can thus be found. [2] The basic principles are illustrated in Figure 2.

The CDS were undertaken over the full length of all water mains groups under the project, except for those non-buried water mains sections where CDS method could not be applied. In general, the length of sections is defined by the changes of pipe diameter, rates of current drop, and the locations of access points etc.

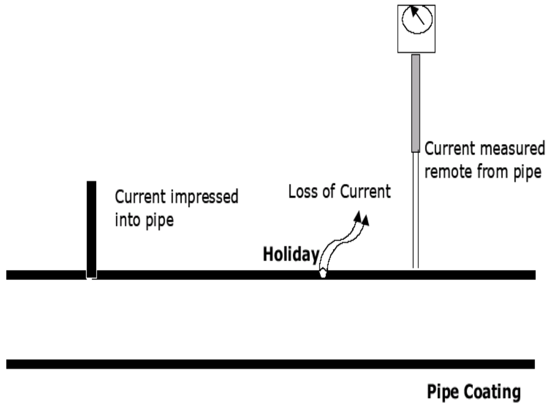

Figure 2: Schematic of Coating Defect Survey **Photo 1: Field Measurement of Coating Defect Survey**

2.2.2 Soil Corrosivity Test

Soil corrosivity test was conducted by Linear Polarisation Resistance (LPR) technique. LPR testing is an indirect, non-invasive technique to determine the corrosivity of soil using a laboratory electrochemical method. Soil samples were obtained from as close to the buried mains as practicable, and then packed into a cell between two electrodes. Direct current is applied at increasing magnitude in both the positive and negative directions, and the resulting change in potential is measured against a reference electrode. [2] The greater the "resistance", the less corrosive is the soil. A strong correlation exists between the polarisation resistance and the maximum pitting corrosion rate of bare pipe. Initial results obtained are polarisation resistance values, Rp, a measure of soil corrosivity. They are then transformed into pitting rates. The value of maximum pit depth exhibited by a pipe is obtained from a combination of empirical relationship between pitting rate of unprotected metal pipe and Rp, age of main, original pipe wall thickness and area of bare pipe on the coated main. [3]

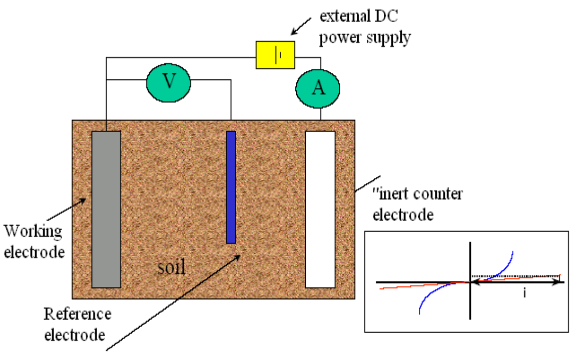

Figure 3: Schematic of Soil Testing (LPR) **Photo 2: Soil Sample Collected Near Pipeline**

A total of 218 numbers of soil samples were collected along the surveyed pipelines to determine the soil corrosivity for the assessment.

2.2.3 Pipe Wall Thickness Measurement (PWTM)

Intensive Ultrasonic Thickness (IUT) Measurement was used to determine the residual pipe wall thickness of the surveyed mains because ultrasonic test provided the best resolution of the corrosion over the pipe wall. A comprehensive picture of the pitting condition on the pipe wall was obtained through measuring on a 50mm x 50mm grid to the whole circumference of the pipe body with 1m length for a typical measurement.

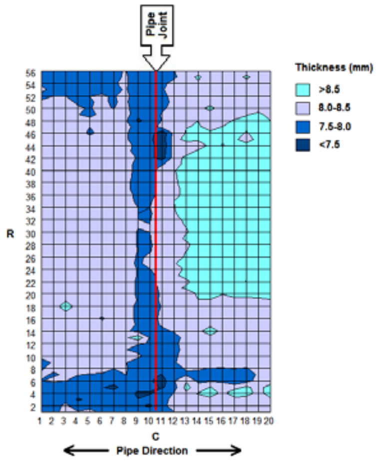

Figure 4: Illustrative Example of IUT Result of 50-year-old MS Pipe

Photo 3: Field Measurement of PWTM

In order to have a better understanding on the pipe joint conditions of the surveyed mains, IUT was carried out to pipe body in vicinity of pipe joints as far as practicable. Magnetic Particle Test (MPT) was also employed to examine the condition of the existing welded joints. In total, 117 numbers of PWTM were carried out and 30 numbers of pipe joints were scrutinized in this project.

2.2.4 Stray Current Measurement

Stray current corrosion is one of major causes for failures of water main. Stray current corrosion is caused by uncontrolled electrical current from extraneous sources through unintended paths. If current passes in and then out from a metal pipe, an electrolysis cell is set up. As a result, the area where the positive current exist the metal pipe is forced to react as an anodic site. This may lead to a rapid consumption of the metal and causes the local corrosion reaction on the pipe wall. The amount of metal lost from corrosion is directly proportional to the amount of current discharged from the affected pipeline. [4] In Hong Kong, the common sources of stray currents include electric railway system, cathodic protection of nearby pipelines and DC-driven elevators, etc. The stray current measurements were performed by measuring pipe-to-soil potential, using a high capacity digital Data Taker data logger and copper-copper sulphate electrode according to BS EN 50162:2004. Testing were conducted in 15 locations chosen based on preliminary evaluation of possible stray current interference, such as the water mains close to the existing MTR system, by using the configuration shown in the following diagram for periods between 11pm and 5am.

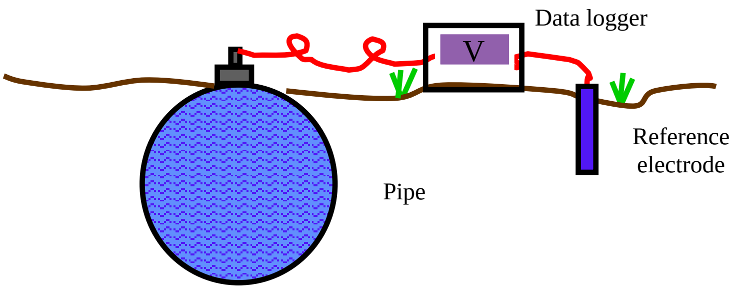

Figure 5: Schematic of Stray Current Monitoring

2.2.5 Visual Inspection to Non-buried Mains

Since CDS could not be carried out on the non-buried mains due to unavailability of electrical signal path, visual inspections were conducted to examine the pipe coating condition, pipe joint condition and the extent of external corrosion to the non-buried mains. It was also supplemented with pipe wall thickness measurements.

The exposed pipe condition have been categorised into 5 categories in accordance with Table 1. The category for a section of pipe is determined based on the worst condition prevailing at the pipe joint and/or pipe length. [2]

Category	Coating	Pipe	General Comments	Wall thickness/ Pit Depth Measurement
1	Good condition, little or no crazing, no bare metal	No corrosion	Very good condition, coating affording corrosion protection	Not required
2	Some lose coating /disbonding	No corrosion	Good condition. Some potential loss of corrosion protection of coating for underlying metal	Not required
3	Some small area of exposure	Some surface corrosion (minor pitting)	Poor condition of coating	Not required
4	Large area of exposure	General surface corrosion (minor pitting)	Very poor condition of coating	Optional
5	Large area of exposure	Significant corrosion	Significant level of pitting	Required

Table 1: Non-buried Pipe Categorization by Visual Inspection

2.2.6 Summary of Field Measurements

The overall field measurements conducted in the project are summarized in the table below:

Method	Summary of Conducted Field Measurement
Coating Defect Survey	Approx. 78 km (Full Length)
LPR Soil Testing	218 nos.
Pipe wall thickness measurement	117 nos.
Stray Current Measurement	15 locations (approx. 3km of water mains covered)
Visual Inspection	30 locations

Table 2: Summary of Conducted Field Measurements

2.3 <u>Data analysis and reporting</u>

The outcomes of the probability of failure were determined by using the survey data via proprietary deterministic algorithms – ***Envirostat*** and ***PipeFail***: [2]

PipeFail is a series of algorithms developed by the condition survey specialist to estimate the most likely time to failure of a pipeline or individual pipelines. It is a function of maximum pitting rates using Polarisation Resistance (**Rp**) values, age, length and original wall thickness of main, length of pipes, maximum operating pressures and coating condition of pipes as determined by CDS. ***Envirostat*** is the spatial extrapolation of a physical quantitative measurement, such as residual pipe wall thickness, pit depth, or Polarisation Resistance (Rp) from a relatively small number of field measurements to the entire length of mains.

Values of probability of failure and first time of failure are generated using the ***PipeFail*** algorithm on the basis of the empirical condition data and the ***Envirostat*** spatial extrapolation of condition. The relationship between probability of failure and first time of failure is explained by the following formula:

$$T = 1/P \quad \text{(1)}$$

Where P = Probability of failure

T = Estimated time between the installation and the first failure occurred

The probability of failure data depicts the likelihood of at least one individual pipe length belonging to that section of pipeline failing in a 12-month period. Values greater than 10% can be considered very high, with failure expected within 10 years. The probability of failure is determined by considering the extent of corrosion through coating condition and the remaining wall thickness, type of material and pressure regime. Each section of pipeline is assigned with a condition category based on its current probability of failure shown in Table 3 below.

Grade	Class	Probability of Failure
1	Very Good	<2.5%
2	Good	2.5-5%
3	Fair	5.0-10%
4	Poor	10-20%
5	Very Poor	>20%

Table 3: Condition Classification of Pipeline Section

3. OVERALL RESULTS

According to the condition survey reports and the prediction of the probability of failure, the survey results for the water mains groups in Kowloon areas are summarised in Table 4 below.

Results	Percentage	Length (km)
Grade 1	52.7%	41.1
Grade 2	19.1%	14.9
Grade 3	5.0%	3.9
Grade 4	6.9%	5.4
Grade 5	16.3%	12.7
Total	100%	78

Table 4: Results of Pipe Condition Survey

4. ENGINEERING DESIGN CONSIDERATIONS

4.1 Recommendation for Grades 1, 2 & 3

There is about 76.8% (approximate 59.9 km) of the surveyed mains classified as "Very Good', "Good' and "Fair" according to the survey report. The pipe conditions were found to be in good condition with the support by inspection pits verification. The coating conditions of the water mains in the inspection pits were found intact and also no significant external corrosion on the bare pipe body and pipe joints was observed. Pipe wall thickness measurement results also exhibited no prominent wall reduction on the mains.

Taking into account the low oxygen content and neutral pH value for the potable water, internal corrosion was considered minor in the fresh water mains. In addition, no prominent external corrosion was identified as aforementioned. The structural integrity and operation condition of the concerned mains are remained in good conditions since its installation. It is therefore reasonable to recommend that neither structural rehabilitation nor replacement is necessary at this stage from a perspective of cost effectiveness.

Notwithstanding the estimated probability of failure is relatively low, it is proposed to install a cathodic protection system, which serves as a protective measure against pipe corrosion, and to replace the aged sectional valves along the pipelines. These proposed upgrading measures are very cost-effective with involvement of minimum excavation. These measures could further improve the overall durability of the water mains and enhance the reliability of the whole system.

It is also proposed to conduct detailed inspection to the internal pipe coating if the isolation of water mains is feasible. This inspection would comprise a general CCTV inspection or man-entry survey to inspect the internal coating condition of the pipelines via construction of access pits/ openings to the water mains. Such inspection can enable the designer to assess the existing conditions of the internal bitumen coating as well as to further verify the results of earlier non-destructive condition survey. If the condition of the internal coating is found unsatisfactory, pipe rehabilitation such as spray epoxy lining rehabilitation with local internal repairs would be carried out to improve the pipe condition.

4.2 Recommendation for Grades 4 & 5

There are approximate 18.1km (about 23.2%) of the mains categorized as Grades 4 & 5, i.e. in "Poor" and "Very Poor" conditions and replacement or rehabilitation works are proposed for those mains. For mains which can be isolated, rehabilitation works are preferred to replacement to minimize the areas of road opening and disruption to the public. Otherwise, off-line open-cut or trenchless replacement will be employed depending on actual site conditions.

It is anticipated that the pipe joint areas and locations of the pipe fittings are at a high risk of corrosion attack leading to water leakage. Detailed investigations were to be carried out on the conditions of pipe fittings, such as tee branches and air valves along the mains to be rehabilitated as far as practicable. Replacement of defective or less-than-satisfactory valves and fittings is proposed to further enhance the reliability of the supply system.

4.3 Operation Consideration

Since it is not always practicable and cost-effective to provide temporary mains for isolation of large diameter water mains, the feasibility of isolation of water mains must be assessed for proposed rehabilitation works in advance. With detailed discussion among WSD Regional Operations Divisions, the isolation schemes were developed based on the best information available at the design stage. The isolation schemes have to be programmed in a logical order with minimal disruption to normal water supply. For example, simultaneous isolation of various large diameter mains within the same supply zone must be avoided. Primary and secondary contingency supply plans have also been developed in formulating isolation schemes to cater for any unforeseen event such as mal-functioning of valves during isolation. Trial isolations and advance exercising of critical valves will also be conducted before full implementation for rehabilitation to ensure that disruption of normal water supply to the public during the construction could be avoided.

4.4 Programme Consideration

To facilitate the necessary rehabilitation works and the inspection works to be completed on time during construction stage, a comprehensive project programme has been developed. The anticipated duration of rehabilitation/inspection for each water mains group is given in the project programme. Site constraints, such as the working in areas with congested traffic, interfacing with other projects and working within restricted working hours or even night works have been identified and factored into the programme. Water mains isolation schemes to tie in with the programme of the rehabilitation works have been developed based on the feasibility of the modification of the water supply patterns and the changing of the related water supply zones. Whilst the detailed project programme is intricate and difficult to prepare, it is the most important part in the implementation of the proposed works to minimize unnecessary delays during construction and avoid complicated contractual matters.

4.5 Cost Benefits

The final recommendations after the adjustments[4] to suit operation needs are summarised in Table 5 below.

What if	Proposed Recommendation	Approx. Length (km)	Approx. percentage
The current pipe condition rated in Poor & Very Poor condition (Grades 4 & 5)	Mains to be replaced or rehabilitated	31	40%
The current pipe condition rated in Fair, Good & Very Good condition (Grades 1, 2 & 3)	Mains to be upgraded or rehabilitated subject to inspection	47	60%

Table 5: Summary of Recommendations on R&R Works

The pipe condition survey helps identify about 60% of water mains requiring upgrading works in lieu of substantial and costly replacement and rehabilitation works. Table 6 below shows a high level comparison on the construction cost under R&R Stage 3 project in Kowloon areas. Compared with full-scale replacement and rehabilitation, pipe condition survey leads to a cost-effective R&R design with significant saving over HK$550 million.

	Length (km)	Total (HK$ million)
(1) Replacement/Rehabilitation without Pipe Condition Survey	78	**1110**
(2) Replacement/Rehabilitation with Pipe Condition Survey		**556**
- Pipe Condition Survey		30
- Proposed Replacement/Rehabilitation	31	441
- Proposed upgrading works	47	85
Saving (1) – (2)		**554**

Table 6: High Level Comparison on Construction Cost under R&R Stage 3 in Kowloon area

Apart from saving in the construction cost, the excavation areas and the construction period for upgrading works would be reduced significantly. Hence, the traffic impact, environment nuisance and water supply suspension during construction would be greatly minimized as a result.

5. CONCLUSIONS

The conditions of the large diameter pipelines were found satisfactory in general and only 23.2% of the surveyed mains were graded "Poor" and "Very Poor". It was indicated that the original coating has contributed significantly in protecting the pipeline. After reviewing the feasibility of water mains isolation and the concerns of continuity, it is determined that about 40% of the surveyed mains in Kowloon area require substantial replacement or rehabilitation works.

With the different applications of the pipe condition survey, a cost-effective solution can be arrived by identifying problematic sections of water mains and selecting appropriate replacement, rehabilitation or upgrading works to be carried out in the construction phase of the third stage of the R&R Programme. Pipe condition survey not only brings about significant saving in construction cost but

[4] Apart from the grading of the water mains, the exact extent of R&R works has been adjusted to suit operation and to maintain water supply. For example, the whole section of water mains between isolation valves would have to be rehabilitated even though some sections are in Grades 1, 2 & 3.

also reduces disruption to the general public as compared with a full-scale replacement or rehabilitation of the water mains which might otherwise be required.

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