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RESEARCH ARTICLE

Structural Integrity Assessment on the Sustainability of an LNG Export Terminal

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ABSTRACT - Natural gas reserves were discovered at offshore of Bintulu, Sarawak in late 1960s. First Liquefied Natural Gas (LNG) project begin operation since 1983. Currently there are nine (9) LNG production trains with an export terminal of three (3) berths in operation. This paper presents structural integrity assessment of an LNG export terminal to ensure sustainability and continuous safe cargo delivery, which was originally intended to operate up to 2021. Extension of service life avoid demolition of existing jetty, minimise construction activities and material used thus reduce CO2 and waste generation. Various inspection techniques such as visual inspection, underwater inspection, detail inspection with destructive test (DT) and non-destructive test (NDT) were conducted. Detail analysis with StaadPro V8i software was performed to assess the jetty structure integrity at current stage and prediction on safe operation in future. The field inspection results show that 62% of concrete pile jackets experienced moderate to severe defects. Generally, the jetty concrete structure was found to be still in good condition with minor defects. DT and NDT on the concrete structure indicated that the test results are within acceptable limits. Surface corrosions were observed on miscellaneous steel structure. Structural analysis result indicates that the berthing velocity need to be reduced from 115 mm/s to 100 mm/s for safe berthing of 80,000 DWT vessel unless the piles capacity is reinstated. The study concluded that through proper repair and rehabilitation of existing piles and structures, jetty service life can be further extended for 20 years.

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1.0 INTRODUCTION

Substantial natural gas reserves were first discovered in the late 1960s at Central Luconia gas fields, about 125-250 kilometres offshore of Bintulu, Sarawak. LNG Task Force had been established by Malaysian Government in 1975 to undertake implementation of Malaysia's first Liquefied Natural Gas (LNG) project [1]. The plant has been in operation since 1983 with three (3) trains initially, further expanded to 9 trains with a current total production capacity of 29.8 Million Tonne Per Annum (MTPA). To date, more than 12,000 LNG cargo shipments have been successfully delivered to various customers in East Asia and around the world.

Bintulu Port Authority (BPA) commenced its operation on 1 January 1983 and currently handles approximately 450 LNG cargoes annually from PETRONAS LNG Complex (PLC), Bintulu through three (3) LNG berths constructed between 1983 to 2002. Each of the existing LNG berths comprise of key elements, i.e., LNG loading platform, access trestle, pipe way, breasting dolphins, mooring dolphins, fendering system, mooring hooks, capstans and the berthing aid system as shown in Figure 1.

Figure 1. Aerial view of Berth 1

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The brief information of LNG berths is summarized in Table 1.

Table 1. Brief information of LNG berths

LNG berth	Year built	Design capacity		Water depth (m)	Breasting dolphin (BD)	Mooring dolphin (MD)
		DWT	m^3			
Berth 1	1983	65,000	75,000-130,000	15	4	4
Berth 2	1993	65,000	18,000-130,000	15	5	7
Berth 3	2002	75,000	75,000-145,000	15	4	4

Note: The design service life of the above LNG berths is 20 years.

The first LNG berth was in operation and in service since 1983. A comprehensive technical integrity assessment was carried out in 1999 [2] as part of the requirement for gas sales agreement renewal and as assurance for continuous reliable operation for another 20 years [3].

Based on the above integrity assessment, the inspection findings and recommendations for LNG Berth 1 were as follows:

- The structural integrity of the LNG Berth 1 is basically sound, and the state of repair is in a fair and reasonable condition.
- No significant deterioration observed on the jetty concrete superstructure.
- Approximately 52% of pile jackets are in severe or moderate condition due to prolonged exposure to severe marine conditions and the remaining 48% of the piles are in fair condition.
- The unjacketed portion of steel pipe piles underwater is generally in satisfactory condition.
- Repairs and/or replacement are required to rectify miscellaneous corroded and defective steel structure; M&E related items, facilities for the cathodic protection system and pneumatic fenders accessories.
- Continuous monitoring of the jetty condition especially the pile at closer frequencies (every 2 years).

In 2001, the jetty undergone its first major rehabilitation, i.e., repair of pile jackets, replacement of sacrificial anode for cathodic protection, repair of defective concrete components, replacement of miscellaneous defective steel structure and recoating of corroded structural steel components to extend the jetty service life for another 20 years.

In view of the requirement to operate beyond 2021, BPA has commissioned another technical integrity assessment in 2019 to study the jetty conditions and to evaluate the possibility of further extending its services life. This is in line with the sustainability development strategies, cost optimization and waste minimization, at the same time to avoid the need for asset replacement thus avoiding substantial carbon emission due to construction activities and materials used.

Originally Berth 1 was designed to cater for 65,000 Deadweight Tonnage (DWT) [4,5,6] tanker; whereby DWT is a vessel's weight carrying capacity excluding the empty weight of the ship. Due to the increase in LNG tanker size over the year, the capacity of the existing berth to accommodate larger tanker up to 80,000 Deadweight Tonnage (DWT) need to be assessed.

2.0 METHODOLOGY

A comprehensive methodology was developed based on jetty maintenance and inspection guide [7] to assess and evaluate integrity for the key structure components of existing LNG berths to ensure safe operation and service for extended period. Various inspection techniques, i.e., visual inspection, underwater inspection, detail inspection with non-destructive test (NDT) and destructive test (DT) had been adopted. Detailed structure analysis was performed to determine the jetty structural integrity at the time of inspection and its potential for service life extension. Options for rehabilitation considering economics and constructability factors were explored. Finally, the maintenance and monitoring system are proposed to ensure the most cost effective and fit for purpose solution in sustaining the jetty to meet its intended purposes for another 20 years [8].

The adopted methodology and scope coverage are as shown in Table 2.

Table 2. Methodology and scope coverage

Scope	Purpose	Coverage
Visual inspection for concrete structure	Identification of surface defects and anomalies	100%
Visual inspection for steel structure	- ditto -	100%
Above water pile inspection	- ditto -	10% (62 piles)

Table 2. (cont.)

Scope	Purpose	Coverage
Underwater pile inspection	- ditto -	67% (403 piles)
Destructive (DT)	See Table 3 for details	Yes
Non-destructive test (NDT)	See Table 3 for details	Yes
Engineering evaluation and analysis of jetty structure	Assessment of current and prediction of future structures capacity vs design condition	Yes
Rehabilitation options and strategy	Recommendation of repair options and strategy	Yes
Maintenance management system	Recommendation of long-term maintenance strategy	Yes

2.1 Destructive Test (DT) / Non-Destructive Test (NDT)

Various DT/NDT performed for integrity assessment were tabulated as per Table 3. The scope was identified for comprehensive coverage to provide fit for purpose assessment to draw a conclusive result. The site inspection and field test were conducted without interruption to jetty operation. The photos of underwater ultrasonic steel pile wall thickness measurement, above water ultrasonic steel pile wall thickness measurement, rebound hammer test for concrete structure and concrete sample coring are shown in Figure 2, 3, 4 and 5 respectively.

Table 3. Destructive and non-destructive test (DT/NDT)

Test	DT/NDT	Purpose	Test number [Location]
Rebound Hammer Test	NDT	Determination of concrete strength	13 [BD (7 nos), LP (6 nos)]
Concrete Coring	DT	Extraction of concrete sample for further determination of properties such as strength and composition	4 [BD]
Carbonation Test	DT	Determination of concrete carbonation depth	4 [BD]
Chloride Content Test	DT	Determination of chloride attack on concrete	4 [BD]
Sulphate Content Analysis	DT	Determination of sulphate content in concrete	4 [BD]
Cement Content Analysis	DT	Determination of cement content in concrete	4 [BD]
Ultrasonic Wall Thickness Testing	NDT	Determination of steel pipe pile wall thickness	62 [LP (8 nos), BD (9 nos), MD (4 nos), TR (40 nos), CS (1 no)]

Note: BD: Breasting Dolphin, LP: Loading Platform, MD: Mooring Dolphin, TR: Trestle, CS: Catwalk Support

Figure 2. Ultrasonic wall thickness testing for underwater pile

Figure 1. Ultrasonic wall thickness testing for above water pile

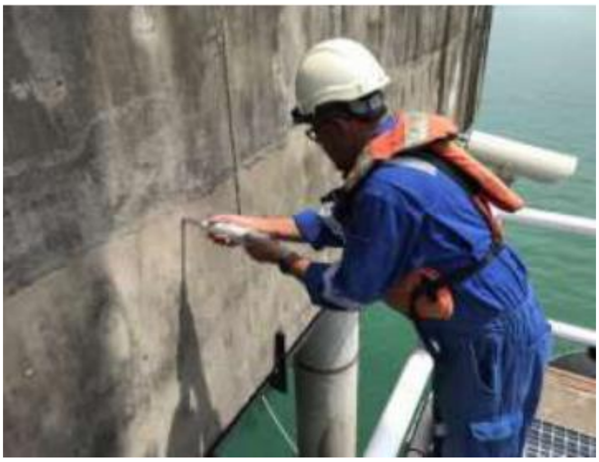

Figure 4. Rebound hammer test for concrete structure at loading platform

Figure 5. Concrete coring (100 mm ϕ x 150 mm length) for compressive strength test

3.0 CONDITION OF BERTH

3.1 Jetty Piles

In total, there are 600 steel pipe piles for Berth 1 supporting breasting dolphins (88 nos), mooring dolphins (40 nos), loading platform (78 nos), approach trestle (390 nos) and catwalk (4 nos). The installed steel pipe pile size is 610 mm dia. x 12.7 mm thick completed with above water concrete jacket extending to 1 m below Lowest Astronomical Tide (LAT) for fire protection.

From visual inspection, cracks and spalling were observe on the above water pile concrete jackets. Typical defects of pile concrete jacket are as shown in Figure 6. This is mainly due to prolonged exposure to severe marine conditions with high chloride content in the seawater causing steel reinforcement corrosion. In general, defect is more severe on seaward piles due to direct wave impact. 62% of concrete pile jackets were found with moderate to severe defects that requires rectification. Heavy presence of barnacles and other marine growth can be seen at submerged section as shown in Figure 7.

The result of visual inspection findings for steel pipe piles and underwater pile thickness measurement is summarised in Table 4.

Table 4. Steel pipe pile wall thickness for Berth 1

Jetty element	Average pile wall thickness (mm)
Loading platform	9.15
Breasting dolphin	9.25
Mooring dolphin	9.35
Trestle	9.50

Figure 6. Major crack and spalling of concrete jacket due to chloride attack of steel reinforcement

Figure 7. Presence of barnacles at submerged section

3.2 Concrete Structures

The visual inspection was carried out as preliminary assessment on the general physical condition of the structure involving all the structural components of the LNG Berth 1 and related facilities. These includes trestle, loading platform, breasting dolphins, mooring dolphins and intermediate catwalk support.

The trestle constructed of inverted 'U' precast concrete panels bolted together and resting on the pile caps. Water marks and stains were observed at about 30% of soffits of the trestle and surface of pile caps. Water was noted to have seeped through the joints of the precast panels and from the discharge holes on some of the precast panels. There were no concrete delamination or spalling found on the under-deck soffits of the trestle. Generally, the concrete structure was found to be still in good condition. Typical defects of concrete structures such cracks and spalling are as shown in Figure 8 and under deck soffit still in good condition as shown in Figure 9.

Figure 8. Minor cracks and spalling of concrete on loading platform

Figure 9. Under deck soffit (good condition)

In-situ and laboratory test to the concrete samples from the inspection are summarized in Table 5.

Table 5. Summary of DT and NDT result

Test	Result	Threshold limit	Finding
In-situ test			
Rebound hammer	40-70 N/mm^2	≥ 20 N/mm^2	Within design limit (BS 1881-202: 1986) [9]
Laboratory test			
Chloride content	0.1%	< 0.2%	Within allowable limit (BS 1377-3: 1990) [10]
Sulphate content	0.1%	< 4%	Within allowable limit (BS 812-118: 1988) [11]
Carbonation test	17-25mm	> 75mm	Within allowable limit (BS 1881-201: 1986) [12]
Compressive test	30-74.5 N/mm^2	≥ 20 N/mm^2	Within design limit (BS 1881-120: 1983) [13]

3.3 Miscellaneous Steel Structures

The steel structure inspection for staircases, ladders, catwalks and miscellaneous supports found general corrosion, minor rust stains and surface corrosion which require minor repairs and recoating. Typical surface corrosion defects of handrail are as shown in Figure 10. In general, catwalks are still in good condition is as shown in Figure 11.

Figure 10. Surface corrosion on handrail

Figure 11. Catwalk between mooring dolphins is still in good condition

4.0 STRUCTURAL ANALYSIS

Over the years, the structures have experienced deterioration due to prolonged exposure to the extreme marine environment. The piles have undergone corrosion with the reduction in wall thickness. Present pile wall thickness was determined from the field measurement. The linear analysis on existing jetty structure and pile capacity of the berth was modelled and analyzed using StaadPro V8i design software based on 80,000 DWT vessel [14,15,16,17]. Additional assessment on future pile capacity in the next 20 years was also made based on predicted reduced wall thickness due to corrosion. Berth 1 pile analysis model is as shown in Figure 12 and structural modelling output for loading platform is as shown in Figure 13.

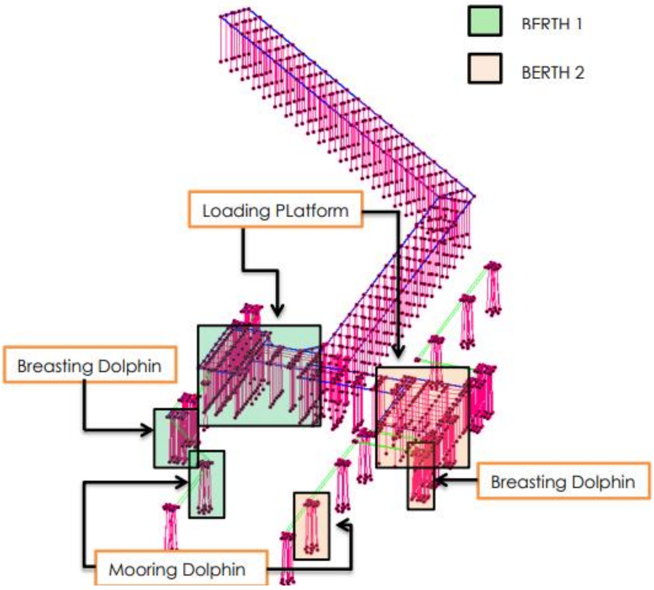

Figure 12. Berth 1 pile analysis model

The outcomes of the analysis are summarized in Table 6.

Table 6. Summary of pile analysis

Jetty component	Pile structural capacity	
	At presence (2019)	Future (2039)
Loading Platform	Overstress	Overstress
Breasting Dolphin	Adequate	Overstress
Mooring Dolphin	Overstress	Overstress

Note: The piles for Berth 1 structures are made up of 610 mm diameter with thickness 12.7 mm, grade STK50 (500 Mpa) steel pipe pile.

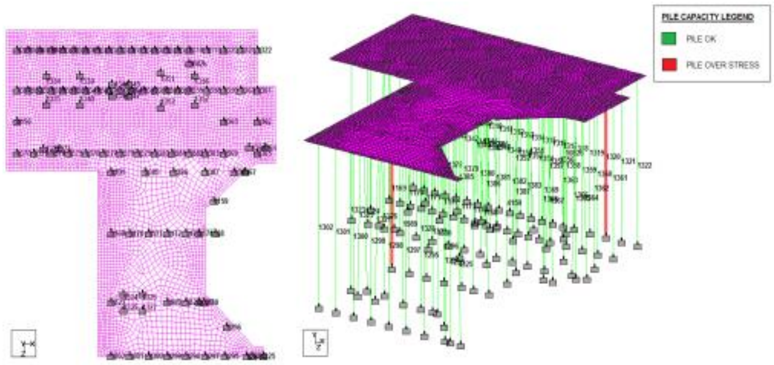

Figure 13. Structural modelling output for loading platform (future-2039)

From the structural analysis with original designed pile thickness of 12.7 mm, the jetty structure can accommodate 80,000 DWT vessel [18,19,20]. However due to reduction in wall thickness over the years, piles at some structures as indicate in Table 6 were found overstress. Further assessment found that there is a need to reduce the designed berthing velocity from 115 mm/s to 100 mm/s for safe berthing of LNG tanker up to 80,000 DWT unless the piles capacity is reinstated.

5.0 MITIGATION STRATEGY

From the inspection findings, to enable the existing Berth 1 continue to serve its function safely, it is essential that major rehabilitation and refurbishment on the defective components of the jetty as identified to be implemented. This will restore the jetty structure and its installations to top notch conditions as expected of an important facility which have major economic significance. Some of the mitigation measures including:

- Provide cathodic protection and/or ensleeve of piles below water.
- Repair of jacketing and/or ensleeve of piles above water. Typical concrete jacket sleeve and HDPE sleeve are as shown in Figure 14.
- Repair and rehabilitation of reinforced concrete structure.

To address the reduction in pile capacity due to corrosion, mitigation through operational control by reducing berthing speed or major rehabilitation via strengthening of piles to reinstate to its original design capacity have been adopted.

For long term, condition-based maintenance strategy shall be continued to ensure all assets are periodically monitored and inspected for safe and reliable operation at optimal cost.

Figure 14. Concrete jacket sleeve and HDPE sleeve

6.0 CONCLUSION

Berth 1 is the oldest LNG export terminal in Malaysia which is still in service since 1983. In 2001, the jetty has undergone a major rehabilitation exercise for continue safe operation. To determine the feasibility of further extension of service life, another integrity assessment was conducted in 2019. Visual inspection, DT, NDT and structure analysis were performed to determine the current and future conditions of the berth. The outcome of the field inspection results shows that 62% of concrete pile jackets experienced moderate to severe defects that requires rectification. Generally, the jetty concrete structure was found to be still in good condition with minor defects. DT and NDT on the concrete structure indicated that the test results are within acceptable limits. Surface corrosions were observed on miscellaneous steel structure, which require minor repairs and recoating. Outcome of structural analysis indicates that the berthing velocity need to be reduced from 115 mm/s to 100 mm/s for safe berthing of 80,000 DWT vessel unless the piles capacity is reinstated. This structural integrity assessment concludes that Berth 1 service life can be further extended with another major rehabilitation on the identified jetty elements.

7.0 AUTHOR CONTRIBUTIONS

Ting Kang Lung: Writing- Conceptualization and Editing

Ting Ding Sie: Writing- Reviewing and Editing

Siti Haida Yusop: Writing – Original draft preparation

Abg Afzanizam Syam Abg Junaidi: Data curation and reviewing

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9.0 DATA AVAILABILITY STATEMENT

The data used to support the findings of this study are included within the article.

10.0 ACKNOWLEDGEMENT

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11.0 CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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