DOI:10. 13434/j. cnki. 1007-4546. 2014. 0302

Materials Selection of Marine Seawater Pipelines Based on Life Cycle Costing

GENG Jun-bao[1], Michael Pecht[2]

[1]College of Power Engineering, Naval University of Engineering, Wuhan 430074, P. R. China;

[2]Center for Advanced Life Cycle Engineering (CALCE), University of Maryland, College Park, MD 20742, United States

Abstract: Marine seawater pipelines can be manufactured from different materials that vary in their purchase costs and lifetimes, thus presenting a challenge when selecting proper materials for a particular project. To solve this problem, a life cycle cost model for marine seawater pipelines was developed after identifying key corrosion features of pipeline materials. An offshore oilfield ship was used as a case study to compare the differences in the life cycle costs of marine seawater pipelines made of plain-carbon steel, seamless galvanized steel, stainless steel, stainless galvanized steel, and copper-nickel alloy. It was found that the seamless galvanized steel pipeline was a robust and economic choice for marine seawater pipelines for the offshore oilfield ship. The results showed that the proposed life cycle cost model was efficient and could be used in the design phase of ships.

Key words: life cycle costing; seawater pipeline; material selection; corrosion rate

1 Introduction

Marine seawater pipelines help ensure the normal operation of ships by providing cooling water, fire protection, and cleaning functions for many machines. However, seawater pipelines corrode under long-term exposure to seawater. The ability to resist corrosion depends on the performance of the pipeline material, but there are large differences in price between the various materials. The price of an expensive material may be ten times that of a cheap material. Additionally, while the purchase cost of a material may be low, its life may be very short, so the pipelines may need to be replaced several times over the lifetime of a ship, and the total replacement cost may be high. On the other hand, the purchase cost of a material may be high, but its anti-corrosion performance may be excellent, so its lifetime will be long and the cost of replacement for the pipelines will be low. Therefore, a material should not be chosen only because its purchase cost is the lowest. The life cycle cost of seawater pipelines over the life of a ship should also be considered.

The term "life cycle costing" was first used in a 1965 report titled "Life Cycle Costing in Equipment Procurement."[1]. Life cycle costing is a method of economic analysis for all costs caused by a product or a service during its entire life cycle, including the purchase of raw materials and components and the

Received 05 July 2014

cost of production, usage, operation, maintenance, and waste management. Life cycle costing is a tool to determine the most cost-effective option among different competing alternatives for a project.

Life cycle costing has been applied in many fields, such as transportation, energy, structure, and environmental protection. Santos and Ferreira conducted a life cycle cost analysis to compare different pavements in terms of global costs to select a pavement for a national road or highway[2]. McDonald and Madanat presented an optimization formulation for mechanistic-empirical pavement design that minimized the life cycle costs associated with the construction and maintenance of flexible pavements[3]. Zhu et al. compared deterministic and probabilistic life cycle cost analyses of ground source heat pump applications in heat and humidity[4]. Tahkamo et al. conducted a life cycle cost analysis to assess how light emitting diode (LED) technology affected the life cycle costs of street lighting in Finland[5]. Lagaros and Magoula conducted life cycle costing to assess the optimum designs for steel and steel-reinforced concrete composite designs[6]. Wang et al. developed a method to estimate the life cycle cost of base-isolated reinforced concrete structures in nuclear power plants[7]. Wee et al. studied the optimal replenishment policy for a deteriorating green product using life cycle cost analysis to improve the design of a green supply chain[8]. For ships, Turan et al. studied the effect of a change in structural weight on life cycle cost[9]. Lahar et al. optimized ship machinery maintenance scheduling through risk analysis and life cycle cost analysis[10].

Life cycle costing has been widely used, but there are few cases of life cycle costing being applied in ships. In particular, there is no life cycle cost model for marine seawater pipelines. One reason is that it is challenging to select materials for marine seawater pipelines because they can be made of different materials that vary in their purchase costs and lifetimes.

This paper presents a method of materials selection for marine seawater pipelines by life cycle costing. A life cycle cost model for marine seawater pipelines that considers different materials was developed. An offshore oilfield ship was employed as a case study to obtain the most suitable material for seawater pipelines and to confirm the feasibility of the life cycle cost model.

The remainder of this paper is organized as follows. In Section 2, the anti-corrosion features of some materials in seawater are described. Section 3 develops a life cycle cost model for seawater pipelines made of different materials. Section 4 applies the life cycle costing to an offshore oilfield ship. Conclusions are given in Section 5.

2 Anti-corrosion features of materials used in marine seawater pipelines

Materials used in marine seawater pipelines mainly include plain-carbon steel, stainless steel, purple copper, copper-nickel alloy, titanium, and seamless galvanized steel. Titanium has excellent corrosion resistance in seawater, but it is very expensive and is seldom used in civilian ships. In addition, the velocity of the seawater has a significant impact on the corrosion rate of materials in seawater. Figures 1 to 5 describe the relationship between the material corrosion and the velocity of seawater for Q235 plain-carbon steel, Cr18Ni9Ti stainless steel, purple copper, 90/10 copper-nickel alloy, and seamless galvanized steel, respectively, in China's Bohai Bay [11].

In Figure 1, the corrosion rate of Q235 plain-carbon steel increases greatly as the velocity of seawater increases. In Figure 2, the corrosion rate of Cr18Ni9Ti stainless steel is less than 30 μm/a at a seawater velocity below 7.45 m/s. At a seawater velocity of 2.3 m/s, the corrosion rate reaches the maximum. As the velocity of seawater continues to rise, the corrosion rate slightly decreases. In Figure 3, when the velocity of seawater reaches 0.5 m/s, the corrosion rate of purple copper increases to about 0.25 mm/a from 0.07 mm/a in a static condition. When the velocity of seawater exceeds 2.3 m/s, the corrosion rate rapidly increases with the increasely of seawater velocity. In Figure 4, the corrosion rate of 90/10 copper-nickel alloy increases rapidly below seawater, a seawater velocity of 2 m/s, but the rate of corrosion is less than 0.1 mm/year below a seawater velocity of 7 m/s.

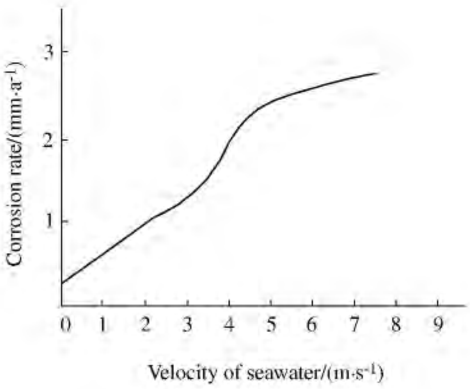

Figure 1 The relationship between the corrosion rate and the velocity of seawater for Q235 plain-carbon steel

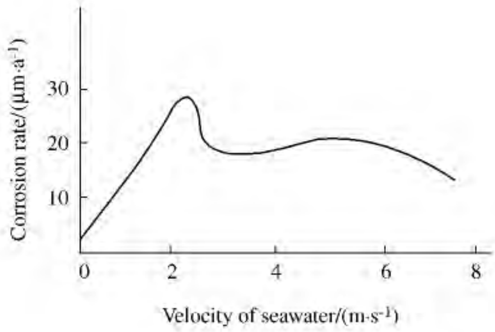

Figure 2 The relationship between the corrosion rate and the velocity of seawater for Cr18Ni9Ti stainless steel

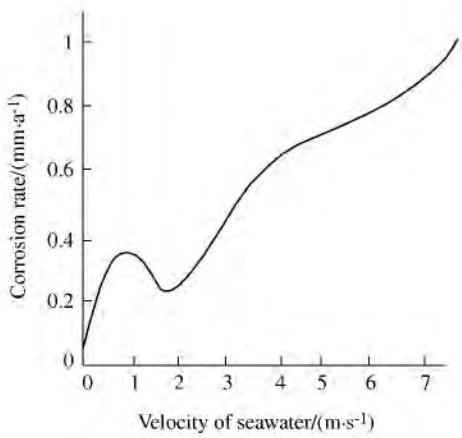

Figure 3 The relationship between the corrosion rate and the velocity of seawater for purple copper

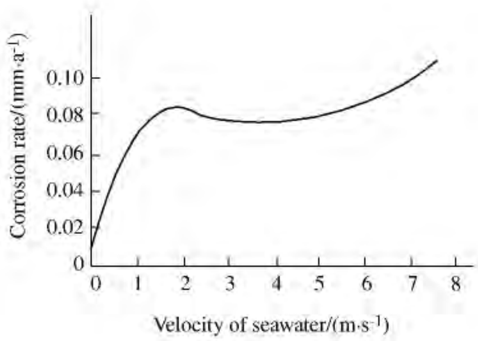

Figure 4 The relationship between the corrosion rate and the velocity of seawater for 90/10 copper-nickel alloy

Figure 5 describes the relationship between the loss in corrosion thickness of zinc coating and the experiment time at a seawater velocity of 5 m/s. The zinc coating thickness decreased by about 40 μm in the first 1 000 h of the experiment. The zinc coating thickness then decreased by 20 μm in the next 3 000 h of the experiment, showing that zinc coating has good corrosion resistance. When the experiment time is up to 4 000 h, the corrosion rate of the zinc coating is less than 4 μm per 1 000 h.

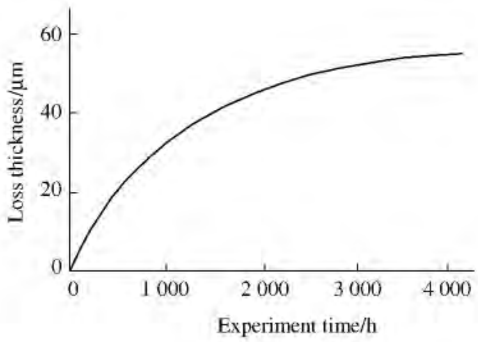

Figure 5 The relationship between the loss in thickness of zinc coating and the experiment time

3 Life cycle cost model for marine seawater pipelines

This section presents the details of the models used in the life cycle cost of marine seawater pipelines, which include life model, life cycle cost model, and replacement cost model.

3.1 Life model of the seawater pipeline

Factors, such as the corrosion rate of the material, the thickness of the pipeline wall, and its minimum allowable thickness, have a significant impact on the life of the seawater pipeline.

The mean life of the seawater pipeline can be given by:

$$ML = \frac{\delta - \delta_0}{v} = \frac{\Delta\delta}{v} \tag{1}$$

Where ML is the mean life of the pipeline in years, δ is the thickness of the pipeline wall in millimeters, δ_0 is the minimum allowable thickness of the pipeline wall in millimeters, v is the corrosion rate of the material in millimeters per year, and $\Delta\delta$ is the corrosion allowance of the pipeline in millimeters.

If there is a coating on the pipeline, such as zinc coating, the life model should include the life of the coating. Suppose that the average corrosion rate of the coating is ε in millimeters per year, and δ_1 denotes the thickness of the coating in millimeters. The mean life of the pipeline is given by:

$$ML = \frac{\delta - \delta_0}{v} + \frac{\delta_1}{\varepsilon} \tag{2}$$

3.2 Life cycle cost model of the seawater pipeline

The life cycle cost of the seawater pipeline consists of the initial investment cost, maintenance cost, loss due to the failure of the pipeline, and residual cost of the pipeline. The life cycle cost is given by:

$$LCC = CN_0 + \sum_{i=1}^{K} (CM_i + CF_i - CR_i) + \sum_{j=1}^{N} CO_j \tag{3}$$

Where LCC is the life cycle cost of the pipeline in RMB (Chinese currency); CN_0 is the initial investment cost in the ship's manufacturing phase (its calculation model is given in Section 3.3); CM_i is the cost for the i^{th} replacement of the pipeline (its calculation model is given in Section 3.3); CR_i is the cost of the residual value of the pipeline at the i^{th} replacement of the pipeline, set at 8% of the material cost in this paper; CO_j is the cost of the operation cost of the pipeline at the j^{th} year from the beginning service year; CF_i is the loss cost at the i^{th} replacement of the pipeline; N is the life of the ship in years; i is the index of the replacement for the pipeline; j is the number of the years the ship has serviced; and K is the total number of the replacements for the pipeline. K is given by:

$$K = \mathrm{int}\left(\frac{N}{ML}\right) \tag{4}$$

Where int( ) is the rounding function.

When considering inflation and the time value of currency, Equation (3) becomes:

$$LCC = CN_0 + \sum_{i=1}^{K}\left((CM_i + CF_i - CR_i) \times \left(\frac{1+\gamma}{1+\mu}\right)^{m_i}\right) + \sum_{j=1}^{N}\left(CO_j \times \left(\frac{1+\gamma}{1+\mu}\right)^{j}\right) \tag{5}$$

Where γ is the consumer price index, μ is the annual average interest rate, and m_i is the calendar year between the initial investment time and the i^{th} replacement time of the pipeline.

3.3 Replacement cost model of the seawater pipeline

The initial investment cost in the pipeline during the manufacture phase of the ship includes the material cost and labor cost. It is given by:

$$CN_0 = W \times C_W + S_1 \times L \times C_L \tag{6}$$

The i^{th} replacement cost in the operation phase, without considering inflation and the time value of currency, is given by:

$$CM_i = W \times C_W + L \times C_L \tag{7}$$

Where CN_0 is the initial investment in RMB; CM_i is the i^{th} replacement cost in RMB; W is the weight of the material in tonnes; C_W is the price per unit weight of the material in RMB per tonne; L is the length of the pipeline in meters; S_1 is the coefficient of the installment cost of the pipelines without the demolition of old pipelines, which is usually set at 0.4; and C_L is the ship replacement labor cost of some nominal diameter pipeline at unit length in RMB per meter. The value of C_L can be gained by the ship repair price regulation, such as the ship repair price list published by China Transportation Technology Press in 2006.

The weight of the material is given as:

$$W = \pi\left(\left(\frac{d}{2} + \varphi\right)^2 - \left(\frac{d}{2}\right)^2\right) \times \rho \times L \times 10^{-9} \tag{8}$$

Where d is the nominal diameter of the pipeline in millimeters; φ is the thickness of the pipeline in millimeters; ρ is the material density in kilograms per cubic meter.

4 Case study

Life cycle costing is applied in the design phase of an offshore oilfield ship to select an optimal material for the seawater pipelines. First, a preliminary screen of materials is conducted, resulting in five feasible pipeline schemes. Next, the corrosion allowance of each pipeline is determined. The life and weight of each pipeline are then determined according to the dimensions, the corrosion features, and the corrosion allowance. The life cycle cost of each pipeline is estimated based on the mean consumer price index and annual average interest rate from 2000 to 2011. Finally, sensitivity analysis of life cycle cost is conducted for each scheme according to the consumer price index, the annual average interest rate, and the material unit price. It is assumed that the velocity of seawater is 2 m/s and the ship is intended to be in service for 33 years.

4.1 Preliminary screen of the materials

Because the corrosion rate of purple copper increases rapidly as the velocity of seawater increases, purple copper is seldom used as a material for seawater pipelines. The unit price of titanium is about RMB 400 000 per tonne, which is very expensive, so it is also not commonly used in civilian seawater pipelines. Based on the cost and corrosion features, plain-carbon steel pipeline, seamless galvanized steel pipeline, stainless steel pipeline, stainless galvanized steel pipeline, and 90/10 copper-nickel alloy pipeline are the alternative materials for seawater pipelines. Thus, there are five possible materials.

4.2 Determination of the corrosion allowance

According to standards such as GJB 4000-2000(6), the corrosion allowance of seawater pipelines made of steel materials, including plain-carbon steel, stainless steel, seamless galvanized steel pipeline, and stainless galvanized steel, is set to 3 mm[12]. For 90/10 copper-nickel alloy, the pipeline is designed for no-replacement in the life of the ship. Therefore, the corrosion allowance of the copper-nickel alloy pipeline is the product of the mean corrosion rate and the service life of the ship. The service life of the ship is 33 years. At a seawater velocity of 2 m/s, the mean corrosion rate of 90/10 copper-nickel alloy is about 0.08 mm/a, so the corrosion allowance, denoted by c_2, is $c_2 = 0.08 \times 33 = 2.64$ mm. The corrosion allowance ensures that the 90/10 copper-nickel alloy pipeline will not be replaced in the lifetime of the ship.

4.3 Determination of the mean life of the pipeline

The mean corrosion rate of the plain-carbon steel at a seawater velocity of 2 m/s is about 1 mm per year. The corrosion allowance is 3 mm. Therefore, if the plain-carbon does not use corrosion protection, such as galvanization, the life of the plain-carbon steel pipeline would be about 3 years. The thickness of galvanization for the seamless galvanized steel pipeline was about 200 ~ 300 μm. Based on the corrosion rate of zinc coating presented in Figure 5, the life of the zinc coating would be about 8 years. Including the life of the plain-carbon steel pipeline, the life of the seamless galvanized steel pipeline would be up to about 11 years.

The mean corrosion rate of stainless steel at 2 m/s velocity of seawater is about 0.02 mm per year, but the main failure modes of stainless steel are pitting and crevice corrosion, so the life of a stainless steel pipeline is mainly determined by pitting and crevice corrosion. Different types of stainless steel have large differences in maximum pitting and crevice corrosion. For example, the maximum pitting of 2Cr13 stainless steel is 1.6 mm if it is exposed to seawater for one year. The maximum pitting of F179 (000Cr17) stainless steel is 3.1mm, and its maximum crevice corrosion depth is 3.1 mm if exposed to seawater for four years[11]. If the corrosion allowance of stainless steel is designed to be 3 mm and is not given other corrosion protection, the pipeline will be replaced in four years. Because of the differences in the maximum pitting and crevice corrosion depth in different types of stainless steels, the life of the stainless steel pipeline is set at 8 to 10 years.

If the stainless steel is galvanized, the life of the stainless galvanized steel pipeline increases by about 8 years, so the life of the stainless galvanized steel pipeline can be up to about 15 years. The 90/10 copper-nickel alloy pipeline will not be replaced in the service life of the ship.

4.4 Determination of the weight of the material

Using the values of the nominal diameter, thickness, length, and material density of the different pipelines in the ship design book, the weight of all the seawater pipelines in the ship can be estimated by Equation (8). Due to space limitations, the dimensions of the seawater pipelines are not listed in this paper. If a steel material is used, the weight of the material is about 5.226 tonnes. If copper-nickel alloy is used, the weight is about 5.495 tonnes.

4.5 Life cycle cost of the seawater pipelines with different materials

A ship is not in a continuous work state, because there are other ships. Once the seawater pipelines of a ship fail, the other ships can do temporary work to replace it. So, the loss because of pipeline failure is set to zero. In the operation phase, the mean operation cost is small and is set to zero. The life cycle cost includes the material cost, labor cost, and residual value of the pipeline. The labor cost includes the demolition cost of the old pipelines and the installation cost of the new pipeline.

The average unit price of each material for 2013 is investigated by the market. The plain-carbon steel pipeline averages RMB 4 500 per tonne; the seamless galvanized steel pipeline is RMB 5 200 per tonne; the stainless steel pipeline is RMB 28 000 per tonne; the stainless galvanized steel pipeline is about RMB 28 700 per tonne; and the 90/10 copper-nickel alloy pipeline is RMB 95 000 per tonne. According to the nominal diameter and length of the pipeline in reference to the book Ship Repair Price, the labor cost for making one replacement of a seawater pipeline is about RMB 80 000, including the demolition of the old pipeline [13]. The labor cost for making one installment of a new pipeline is about RMB 32 000. The total labor cost of the pipeline over the life of the ship is the sum of the labor cost of initially installing the new pipeline and the labor cost of replacing the pipeline in the operation phase.

If plain-carbon steel is used as the material for the seawater pipeline, it will be replaced 10 times during the lifetime of the ship. If seamless galvanized steel is used, it will be replaced 3 times. Stainless steel will also be replaced 3 times, and stainless galvanized steel will be replaced 2 times. If the 90/10 copper-nickel alloy is used, it will be not replaced. If the number of replacements is 3, the ship needs 4 times the amount of materials of the pipeline in its life. The residual value of the waste pipeline is 8 percent of the material price.

According to the National Bureau of Statistics in China, from 2000 to 2011, the mean consumer price index was about 2.8% ($\gamma = 2.8\%$). The annual average interest rate for an RMB lump deposit for lump withdrawal from 2000 to 2011 was 2.5% ($\mu = 2.5\%$.). The result of life cycle costing for each scheme is shown in Table 1.

Table 1 Life cycle costing of seawater pipelines with different materials

Scheme	Pipeline material	Initial investment cost/RMB	Material cost for one replacement/RMB	Number of replacements	Life cycle cost/RMB
1	Plain-carbon steel	55 517	23 517	10	1 234 350
2	Seamless galvanized steel	59 175	27 175	3	393 235
3	Stainless steel	178 328	146 328	3	861 144
4	Stainless galvanized steel	181 986	149 986	2	647 705
5	90/10 copper-nickel alloy	554 025	522 025	0	554 025

From Table 1, Scheme 1, the plain-carbon steel has the lowest initial investment cost, but it also has the highest life cycle cost. This shows that the scheme with the lowest initial investment cost is not necessarily the scheme with the lowest life cycle cost. Scheme 5, the 90/10 copper-nickel alloy, has the highest initial investment cost, but not the highest life cycle cost, showing that the material with the highest initial investment is not necessarily the material with the highest life cycle cost. Moreover, Scheme 5 has no replacement of the pipeline over the life of the ship, which will increase the availability of the ship. Scheme 2, the seamless galvanized steel, has the lowest life cycle cost, and the initial investment cost is neither the highest nor the lowest. The results demonstrate that life cycle costing is beneficial for selecting the optimal material for the seawater pipeline in a particular ship. This result shows that Scheme 2 is more economic than the other schemes.

4.6 Sensitivity analysis

Some factors, such as the mean consumer price index, the annual average interest rate, and the material unit price, have a significant impact on life cycle cost of the seawater pipelines. In order to examine the impact of the mean consumer price index, we first set the annual average interest rate as 2%, and change the mean consumer price index from 0 to 9%. The relation between the life cycle cost of each scheme and the mean consumer price index is described in Figure 6. To determine the impact of the annual average interest rate, we set the mean consumer price index at 5%, and changed the annual average interest rate from 0 to 9%. The relation between the life cycle cost of each scheme and the annual average interest rate is described in Figure 7. Finally, to examine the effect of a changing material unit price, we set the mean consumer price index as 2.8%, the annual average interest rate as 2.5%, and the material unit price in 2013 as the standard price. We separately estimated the life cycle cost of each scheme when the material unit price ranges from 70% to 130% of the standard price at a 10% rate increase. The relation between the life cycle cost of each scheme and the degree of the change in material price is described in Figure 8.

Figure 6 Change in life cycle cost with the mean consumer price index

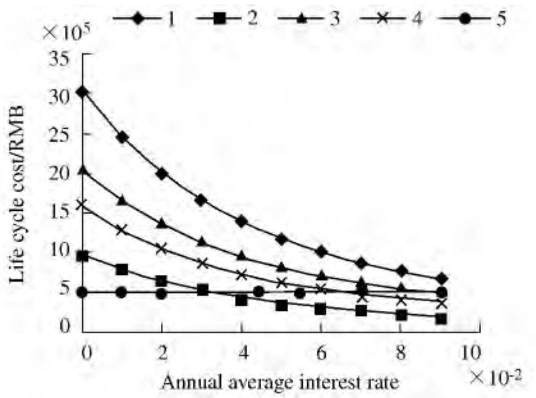

Figure 7 Change in life cycle cost with the annual average interest rate

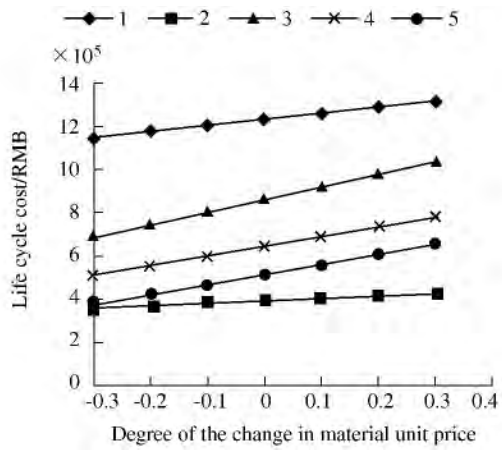

Figure 8 Change in life cycle cost with the degree of the change in material unit price

In Figure 6 and Figure 7, the life cycle costs of Schemes 1, 2, 3, and 4 increase with the increase in average consumer price index and decrease with the increase in the annual average interest rate. The life cycle cost of Scheme 5 remains the same because there is no pipeline replacement during the life of the ship. Under the condition that the annual average interest rate is 2% and the mean consumer price index is less than 4%, the life cycle cost of Scheme 2 is smaller than that of Scheme 5. Under the condition that the annual average interest rate is 2% and the mean consumer price index is more than 4%, the life cycle cost of Scheme 2 is larger than that of Scheme 5. Under the condition that the mean consumer price index is 5% and the annual average interest rate is less than 3.5%, the life cycle cost of Scheme 2 is larger than that of Scheme 5. Under the condition that the mean consumer price index is 5% and the annual average interest rate is more than 3.5%, the life cycle cost of Scheme 2 is smaller than that of Scheme 5. In Figure 8, the life cycle costs of the schemes, except for Scheme 2, increase sharply with the increase in material unit price. The life cycle cost of Scheme 2 is less than that of the other schemes. The change in the material unit price has little impact on the life cycle cost of Scheme 2. This shows that Scheme 2 is more robust than the other schemes.

In Figures 6 to 8, the life cycle costs of Schemes 1, 3, and 4 are always larger than that of Scheme 2. From the results in Table 1, the life cycle cost of Scheme 5 is larger than that of Scheme 2. Thus, Scheme 2, seamless galvanized steel, is more economic than the other schemes in the current situation. Thus, it is obvious that Scheme 2, seamless galvanized steel, is the most suitable material for the seawater pipelines, because Scheme 2 is more economic and robust than the other schemes.

5 Conclusions

Life cycle costing is a method that has been applied to different systems, such as the houses, bridges, pumps and so on. In this paper, the life cycle cost model was used to solve the selection in the material of seawater pipelines for an offshore oilfield ship. The results showed that the model of life cycle cost found in this paper can be used to select the optimal material for seawater pipeline in the design phase of ship construction. This method of selecting materials based on life cycle costing is more scientific and rational than the method base on the purchase price.

The authors would like to thank Kelly Smith and Mark Zimmerman for their edits.

References

[1] Logistics Management Institute (LMI). Life cycle costing in equipment procurement [R]. Report No. LMI Task 4C-5, Washington, D. C., 1965

[2] Santos J, Ferreira A. Life-cycle cost analysis system for pavement management at project level [J]. International Journal of Pavement Engineering, 2013, 14(1):71-84

[3] McDonald M, Madanat S. Life-cycle cost minimization and sensitivity analysis for mechanistic-empirical pavement design [J]. Journal of Transportation Engineering, 2012, 138(6):706-713

[4] Zhu Y, Tao Y, Rayegan R. A comparison of deterministic and probabilistic life cycle cost analyses of ground source heat pump (GSHP) applications in hot and humid climate [J]. Energy and Buildings, 2012, (55):312-321

[5] Tahkamo L, Ylinen A, Puolakka M, *et al.* Life cycle cost analysis of three renewed street lighting installations in Finland [J]. International Journal of Life Cycle Assess, 2012, 17(2):154-164

[6] Lagaros N D, Magoula E. Life-cycle cost assessment of mid-rise and high-rise steel and steel-reinforced concrete composite minimum cost building designs [J]. The Structural Design of Tall and Special Buildings, 2013, 22(12):954-974

[7] Wang H, Wang D, Lu X, *et al.* Life-cycle cost assessment of seismically base-isolated structures in nuclear power plants [J]. Nuclear Engineering and Design, 2013, 262: 429-434

[8] Wee H M, Lee M C, Yu C P, *et al.* Optimal replenishment policy for a deteriorating green product: life cycle costing analysis [J]. International Journal Production Economics, 2011, 133(2):603-611

[9] Turan O, Olcer A I, Lazakis I. Maintenance/repair and production-oriented life cycle cost/earning model for ship structural optimisation during conceptual design stage [J]. Ships and Offshore Structures, 2009, 4(2):107-125

[10] Lahar B, Hidetoshi A, Kenji I. Optimizing ship machinery maintenance scheduling

through risk analysis and life cycle cost analysis [C] // 25th International Conference on Offshore Mechanics and Arctic Engineering, Hamburg, Germany, June 4-9, 2006

[11] Zhu X R, Wang X R. Metallic materials marine corrosion and protection [M]. Beijing: National Defense Industry Press, 1999 (in Chinese)

[12] GJB 4000-2000(6). General specification for naval ships in China, Part 5 auxiliary systems [S]. 2000 (in Chinese)

[13] China association of the national shipbuilding industry. Ship repair price list [M]. Beijing: Transportation Technology Press, 2006 (in Chinese)

Brief Biographies

GENG Jun-bao is now an associate professor in College of Power Engineering, the University of Naval Engineering. His research interests include life cycle costing, reliability and maintainability. gengjb2002@163.com

Michael Pecht is now a Chair Professor in Mechanical Engineering and a Professor in Applied Mathematics, the University of Maryland, College Park, USA. His interests include reliability, prognostics and health management, supply chain policies. pecht@calce.umd.edu