Case Study

Reducing the Economic Risk of LNG Tank Construction under Conditions of Fluctuating Resource Prices

Mitsuo Nagashima[1]; Masanori Tsuchiya[2]; and Motoyuki Asada[3]

Abstract: Fluctuating resource prices affect the costs of the materials used in the construction of LNG (liquid natural gas) tanks. In this paper, methods based on the field experience of the writers for the reduction of the cost of LNG tanks in general and in-ground LNG tanks in particular are discussed. Of the various components of the construction cost, the price of steel materials is a significant contributor. Using a newly defined cost impact index, the costs of construction of different types of LNG tanks are compared. Further, by considering actual examples of the construction of in-ground tanks, important issues relating to the use of steel materials are identified and, by using a cost reduction index, recommendations are made for the reduction of the cost risk during fluctuations in resource prices. **DOI:** 10.1061/(ASCE)CO.1943-7862.0000305.

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Introduction

Recent global fluctuations in the prices of resources, such as crude oil, iron ore, and others, are affecting the costs of construction of in-ground and above-ground liquid natural gas (LNG) tanks. Some recent changes in resource prices (2006–2008) are shown in Fig. 1 (The Asahi Shimbun 2008). Note that the price of iron ore began to rise in the second half of 2006; the prices of both iron ore and crude oil remained high despite much volatility and hit a historic high in July, 2008. The price of iron ore peaked in early 2008 at US\$200/t, which is approximately triple the price of early 2006—US\$70/t. Meanwhile, the price of crude oil also doubled from US\$70/barrel in early 2006 to US\$148/barrel in mid-2008. Although these prices subsequently dropped because of the sudden slowing of the global economy, the series of rapid price fluctuations considerably affected the construction market in Japan.

Meanwhile, amid a global call to combat global warming through the reduction of carbon dioxide (CO2) emissions, the use of LNG has been rapidly expanding because of its status as a clean, environment-friendly gas (Nakano 2001). In view of the violent fluctuation of the crude oil price, the demand for LNG with its promise of a stable supply is ever growing.

Fluctuating resource prices are likely to continue to present an economic risk in the coming years. In this socioeconomic environment, it has become essential to find methods for the construction of LNG tanks at a low, stable construction cost that takes the likely fluctuations of resource prices into consideration. Nagashima et al. (2009) and Nishizaki et al. (2003) tried to optimize the LNG tanks construction works from technical points of view. Sone et al. (1999) tried to evaluate the countermeasures of road construction cost reduction; however, there are few previous studies concerning cost evaluation of LNG tank construction.

In this research, the impact of the changing prices of steel materials, which are linked to the price fluctuations of resources (crude oil, iron ore, and others), on the construction cost of LNG tanks was analyzed by focusing on the differences between the structural specifications for in-ground tanks and those for above-ground tanks.

In addition to the comparison of the cost of these two types of LNG tanks, measures based on the actual work experience of the writers are identified that counteract the negative impact of steel price fluctuations on the construction of in-ground storage tanks. Several concrete measures for improving the economic efficiency of constructing with steel materials are proposed that aim to reduce the economic risk of construction during fluctuations in resource prices.

Summary of Characteristics of In-Ground and Above-Ground LNG Storage Tanks

The construction of LNG tanks in Japan has a history of nearly 40 years, and the number of in-ground and above-ground tanks has been steadily increasing (Nakano 2001). These tanks are generally constructed through collaboration between a general construction company and a mechanical engineering company. There are many models with different characteristics. Although in-ground tanks were once more expensive than above-ground tanks, the cost difference has shrunk because above-ground tanks require large quantities of steel materials, the prices of which have significantly increased. The characteristics of these two types of tanks are outlined in this section, with particular focus on their steel material specifications.

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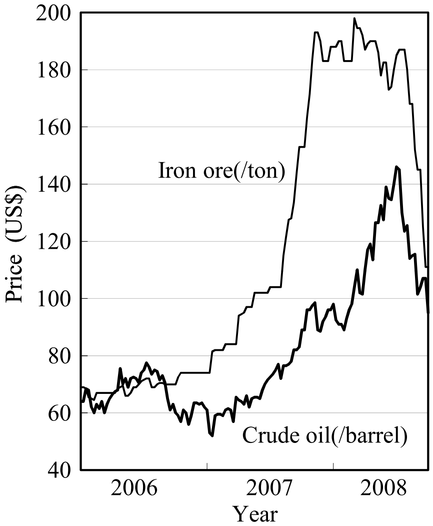

Fig. 1. Recent changes in crude oil and iron ore prices (Data source: The Asahi Shimbun 2008)

The storage capacity of the first in-ground tank was 10,000 kL. Following a series of technological developments in the design and construction of tanks that store extremely low-temperature liquids (approximately −162°C) deep underground, the storage capacity of the largest in-ground tanks has now reached 200,000 kL.

Above-ground tanks can be further classified into double-walled metal tanks and PC (precast concrete) LNG tanks with an integral PC cutoff wall. As a result of recent research into their rational design and construction, PCLNG tanks have become the standard above-ground LNG tank (Nishizaki et al. 2003), and their storage capacity has increased to 140,000 to 180,000 kL.

Fig. 2 shows the inner and outer configurations of an in-ground tank C (160,000 kL) as well as the specifications of its civil engineering structures. The reinforced concrete (RC) structures (RC continuous wall, bottom slab, side wall, and others) that protect the tank against the earth and water pressures below the ground surface are the principal civil engineering elements and require large quantities of reinforcing bars and concrete. The insulation material and inner tank membrane (SUS304; normal thickness 2 mm) are mechanical engineering elements that enable the absorption of displacement and so can efficiently store LNG and follow the temperature and pressure changes caused by the inflow and outflow of the LNG, while the fluid pressure of the LNG is contained by the bottom slab and side wall civil engineering structures (hereinafter referred to as "the body"). In addition, a pleated structure known as corrugation is present.

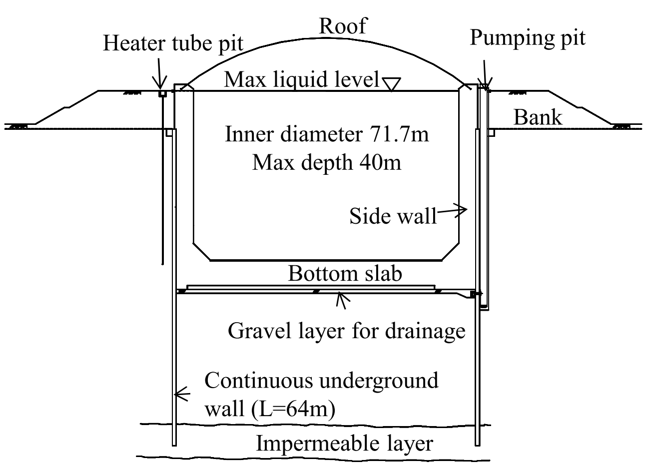

Fig. 2. Standard cross section of in-ground Tank C (160,000 kL)

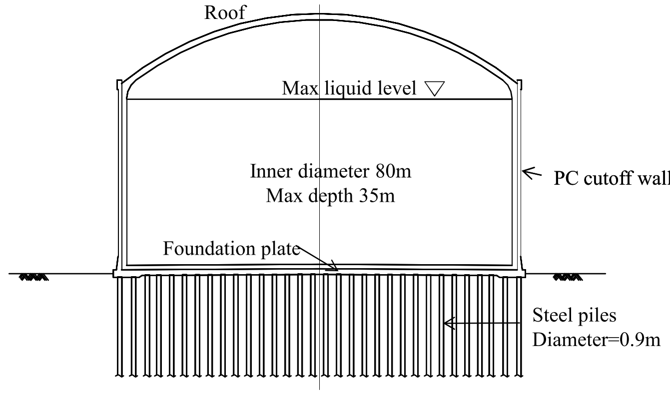

Fig. 3. Standard cross section of above-ground PCLNG Tank H (180,000 kL)

Fig. 3 shows the inner and outer configurations of an above-ground tank H (180,000 kL) as well as the specifications of the civil engineering structures. The principal civil engineering elements are the foundation piles extending to the bearing layer of the tank itself, the bottom slab, and the PC cutoff wall. The fluid pressure of the LNG is directly contained by the inner steel plate (9% Ni); a larger quantity of steel is required than in an in-ground tank to make the steel plate thicker (the normal thickness is 40–50 mm). Cold/heat resistance moderation materials and insulation materials are used to store the LNG efficiently and also to follow the temperature and pressure changes caused by the inflow and outflow of the LNG.

Survey of Impacts of Steel Prices on Construction Cost and Analysis Method

The construction costs of LNG tanks were surveyed over recent years with a view to assessing the importance of the cost of the main construction steel materials. In addition, measures to deal with increases in the prices of the steel materials used in the civil engineering structures of in-ground tanks were examined.

Selection of LNG Tanks for Analysis

In-ground tanks have become the standard type of LNG tanks; many have been constructed in recent years. The selected type of in-ground tank for analysis is the rigid bottom slab type, which resists the uplift pressure of groundwater beneath the bottom slab with a continuous sheathing and waterproofing wall. The selected type of above-ground tank for analysis is the PCLNG tank.

Four tanks that were completed after 1998 or that are under construction or at the planning stage were selected for analysis from each category, as listed in Table 1.

Study and Analysis Methods

LNG Tank Cost and Impact of Steel Price Changes

First, the costs of construction of the in-ground and above-ground tanks were studied to determine whether there are any significant differences according to year of tank construction, type of tank, tank capacity, and civil or mechanical engineering requirements. A more detailed analysis of LNG tank construction costs was then conducted.

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Table 1. List of Subject Tanks for Analysis

Tank name		Storage capacity (1000 kL)	Commencement year of construction work	Analysis items				
				Cost	Steel	Reduction of quantities	Review of specifications	Change of construction method
In-ground tank	A	125	1998					×
	B	200	2005	×				
	C	160	2006	×	×	×	×	×
	D	200	2009	×				
Above-ground tank	E	140	2006	×				
	F	140	2008	×				
	G	160	2008	×				
	H	180	2009	×	×			

In this cost analysis, the overall construction cost [10,000 million yen (¥); civil engineering cost + mechanical engineering cost] and the tank capacity (160,000 kL) were used as parameters, and the cost index was defined as shown in Eq. (1). The actual cost performance of Tank C was used as the reference cost index of 100 ($¥10,000$ million $\div 160,000$ kL $= ¥62.5/\mathrm{L}$).

$$\text{Cost Index} = \frac{[\text{ConstructionCost(in yen)} \times 100]/62.5(\text{in yen})/\mathrm{L}}{\text{TankCapacity(kL)}} \tag{1}$$

The actual cost was used for Tank A, whereas estimated costs were used for tanks under construction or at the planning stage.

The impact of steel price changes on construction cost was also studied by using the specifications, quantities, and prices of the principal steel materials used, and the proportion of the steel cost with respect to the overall construction cost, i.e., the cost ratio, was calculated. To establish the extent of the impact of changes in prices of different steel materials on the overall construction cost, the cost impact index was defined as shown in Eq. (2) by using the cost ratio, the price fluctuation rate, and the procured quantity ratio of steel materials in the assumed price fluctuation period as the parameters. The assumed price fluctuation periods were fiscal year (FY) 2006 for cryogenic steel (9% Ni steel, SUS304) and FY 2008 for structural steel (H-section steel and others).

The overall construction cost (civil and mechanical engineering costs) of a LNG tank is given as 100% of cost impact index (the overall construction cost of Tank C was ¥10,000 million ($¥5,000$ million $+ ¥5,000$ million), so 1% of the cost impact index is equivalent to approximately ¥100 million)

$$\text{Cost Impact Index} = (\mathrm{C}) \times (\mathrm{E}) \times (\mathrm{Q}) \tag{2}$$

where C (cost ratio) = ratio of material cost to estimated construction cost, in %); E (price fluctuation rate) = assumed price fluctuation rate, in %); and Q (procured quantity ratio) = ratio of procured quantity of steel in assumed price fluctuation period, in %).

The period for cost ratio estimation was the first half of FY 2006 for in-ground Tank C and the second half of FY 2008 for above-ground Tank H. Therefore, the cost ratio represents the ratio of the steel cost to the overall construction cost in this period. In regard to the price fluctuation rate, the beginning of FY 2006 was provisionally set as the pre-price fluctuation reference point (100%), so the maximum price fluctuation rate in the subsequent one-year period was used to determine the extent of the cost impact based on the same price fluctuation rate. This approach was used because these tanks were either under construction (Tank C) or at the planning stage (Tank H). In other words, the full-year price fluctuations for cryogenic steel (9% Ni steel, SUS304, and others) in FY 2006 and for structural steel (H-section steel) in FY 2008 were checked to determine the maximum price fluctuation range (%) in each year in question.

The procured quantity ratio was provisionally estimated from 25% and 50%, based on the actual results for Tank C. The matters taken into consideration here were (1) the proportion of the site work involving steel during a period of approximately one year for both types of tank, and (2) leeway in terms of the time to finalize procurement after receipt of an order.

Measures to Counter Rising Prices of Materials for In-Ground Tanks (Civil Engineering Aspect)

Several measures are available for reduction of the cost of the principal steel materials, including quantitative reduction and modification of the specifications, both of which relate to the steel materials, and improvement of the cost-benefit performance by modifying the construction method.

In the case of in-ground Tank C currently under construction, the work commenced before the sharp rise in resources prices and has benefited from the cost reduction effects of conventional empirical measures such as the rationalization of the design and construction. The measures adopted for the construction of the actual in-ground tank were analyzed.

This analysis was conducted by defining the cost reduction index as shown in Eq. (3) to determine the extent of contribution of the cost reduction measures, particularly for the steel materials, which have the greatest influence on the overall construction cost, according to the study findings. The parameters for this estimation were the quantitative reduction rate of the construction work, the specification modification rate, and the construction method modification rate.

For the purpose of this analysis, a cost reduction index was estimated based on an index value of 50 for the total civil engineering work cost of an in-ground tank (as the total civil engineering work cost of in-ground Tank C is approximately ¥5,000 million, the index number value of 1 of the cost reduction index is equivalent to approximately ¥100 million)

$$\text{Cost Reduction Index} = (\mathrm{QR}) + (\mathrm{S}) + (\mathrm{M}) \tag{3}$$

where QR (quantitative reduction rate, in %) = rate of cost increase/decrease due to increased/decreased quantity of construction work; S (specification modification rate, in %) = rate of cost increase/decrease due to modification of specifications; and M (construction method modification rate, in %) = rate of cost increase/decrease due to modification of construction method.

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Quantitative Reduction of Construction Work

One way of reducing the quantity of steel materials (reinforcing bars and steel for temporary work) used in the construction of a tank is to reduce the quantity of such materials used in the principal body of an in-ground tank. When the inner diameter is increased, the excavation depth can be shallower. The resulting reduction in the uplift pressure of groundwater enables the use of a thinner bottom slab, although the side wall is exposed to higher loads. There can be an optimal inner diameter when all factors are taken into consideration. In the present analysis, attention was focused on the storage capacity, inner diameter, and banking height of the tank, and the impact of this approach on the overall construction cost (civil engineering cost + mechanical engineering cost) was estimated based on these three parameters.

An estimate of the overall cost was obtained by multiplying the unit cost (unit cost of construction work per m^3) of the stages of construction of an in-ground tank, namely continuous wall work, excavation work, bottom slab work, side wall work, and banking work, by the relevant work quantity. For the mechanical engineering stages, actual costs were used.

The specifications were as follows:

• Storage capacity:	~90, 000 kL–160, 000 kL (based on five cases)
• Inner tank diameter:	≦74 m (provisionally selected on basis of actual figures)
• Banking height:	4 m; 8 m
• Soil properties:	assumed presence of impermeable layer at ground level (GL) −60 m to −70 m

Modification and Review of Specifications

One feasible method for reducing the cost of structural reinforcing bars is to modify the specifications of existing reinforcing bars [mostly made of SD345 (steel deformed bar; yield point $= 345\ \mathrm{N/mm^2}$)]. Provided that the monetary value of the reduced quantity of reinforcing bars exceeds the increased cost of materials due to the use of a higher grade material (from SD345 to SD390 and further to SD490), it is possible to reduce the cost of the reinforcing bar work. An estimate was obtained of the impact of the use of higher grade reinforcing bars, such as SD390 or SD490 instead of the conventional SD345, on the cost of the reinforcing bar work for the body of an in-ground tank.

The cost increase rate by grade was estimated by using the price of reinforcing bars as the parameter, with the work cost fixed at ¥30, 000/ton.

The specifications were as follows:

• Reinforcing bar specifications:	three types (SD345, SD390, and SD490); extra cost due to use of higher grade material is set at ¥20, 000/ton for SD345, ¥22, 000/ton for SD390, and ¥35, 000/ton for SD490; extra cost results in cost increase due to use of material with higher grade than that of basic SD295 reinforcing bars
• Unit cost of reinforcing bar work:	¥30, 000/ton based on past results

Modification of Construction Method

An examination of the construction methods involving steel materials was conducted by analyzing the cost-benefit performance of two types of work: continuous wall work and side wall form work. The impact of the modification of the construction method on cost was evaluated for each of these two types of work.

The specifications were as follows:

• Storage tank capacity:	125, 000 kL × 2
• Continuous underground wall work:	analysis of two methods (partition method and cutting method) used at same time and at same site
• Side wall form work:	analysis of two conventional methods (segment method and wood form method)

Study and Analysis Results

LNG Tank Construction Cost

The construction costs and year of commencement of the construction of four in-ground and four above-ground LNG tanks are shown in Fig. 4. The results show that the cost index of tanks for which construction started after 1998 is similar for in-ground tanks at 100 ~ 150 and above-ground tanks at 110–140.

The variations of the cost index with the storage capacity for these tanks are shown in Fig. 5. There can be a significant difference between the costs of tanks of the same type despite a similar storage capacity. Such differences are present between Tanks B and D (200,000 kL in-ground tanks) and between Tanks E and F (140,000 kL above-ground tanks). Further examination of the sources of these differences found that, in the case of in-ground Tank D, the construction of which started after that of Tank B and for which the cost index is much lower than Tank B, the cost was much lower because of the rationalized design for the civil engineering work (a rigid connection between the bottom slab and side wall and other features) and improved construction technologies (the higher strength of the reinforcing bars and concrete, and other technological advancements).

In the case of the above-ground tanks, the cost index is higher for Tank F, for which the order was placed later (year of commencement of construction—2008) than that of Tank E. The high cost index of Tank F arises because the work commenced in the peak period for resources prices, so the cost of cryogenic steel (9% Ni steel, SUS304, and others) in the mechanical engineering work pushed up the overall construction cost.

As a result of the developments described above, the mechanical engineering cost for the recent construction of LNG tanks has increased, whereas the civil engineering cost declined, with the result that the cost indexes of these two types of work converge at around 125. The main reason for the decline of the construction cost is the rationalization of the design and construction work, while resource price increases are the reason for the increase in the mechanical

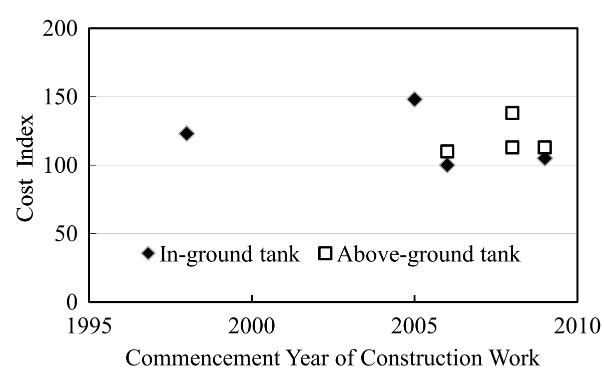

Fig. 4. Comparison of the cost index of LNG tanks according to year of commencement of construction

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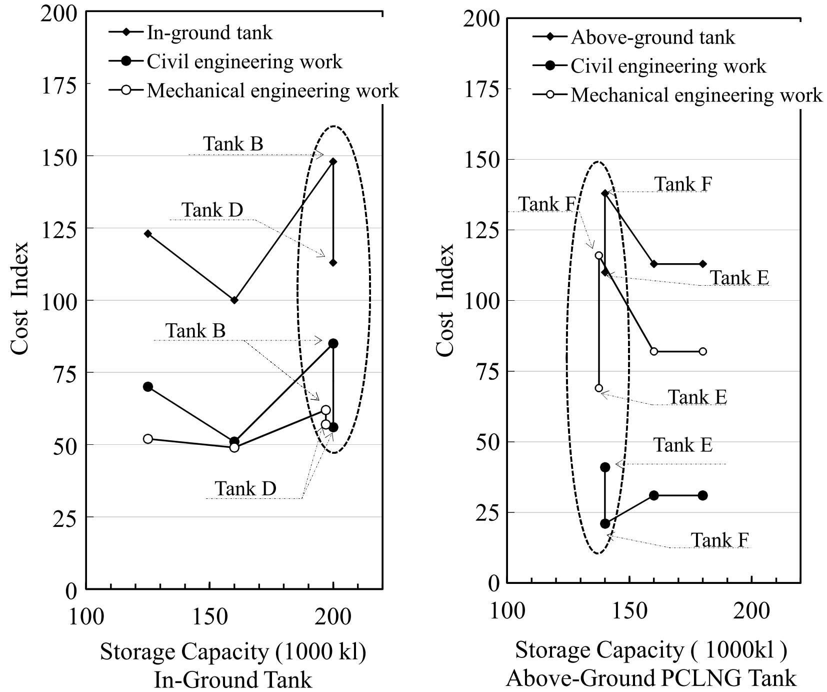

Fig. 5. Cost index of LNG tanks according to civil and mechanical engineering work

engineering cost; the latter is particularly relevant to the cost of above-ground tanks.

It was found that cost reduction was hampered by the procurement conditions for the materials required in the mechanical engineering work (the use of cryogenic steel such as 9% Ni steel and SUS304, for which the prices changed considerably).

Impact of Steel Material Price Changes on Overall Construction Cost for LNG Tanks

The specifications for the steel materials and the overall weights of in-ground Tank C and above-ground Tank H are shown in Table 2, and the cost ratios of steel in the overall construction costs of these tanks are shown in Fig. 6.

The estimated total weights of the steel in these tanks were 12,930 t for in-ground Tank C and 16,100 t for above-ground Tank H. For Tank C, the weight of the reinforcing bars for construction of the body (part of the civil engineering work) accounts for approximately 85% of the total steel weight, whereas the weight of the steel pipe piles (part of the civil engineering work) accounts for 76% of the total steel weight of Tank H.

Above-ground tanks use a much greater amount of steel in the mechanical engineering component: approximately 5,000 t per tank compared to approximately 780 t per tank for in-ground tanks. This requirement of a vast quantity of steel (especially cryogenic steel: 9% Ni steel) in above-ground tanks is dictated by the need to increase the thickness of the inner tank plate that, instead of a civil engineering body, supports the fluid pressure of the LNG.

The proportion of the steel cost to the overall construction cost is 36% for above-ground Tank H, which contains a large amount of cryogenic steel (9% Ni steel, SUS304, and others), compared to 15% for in-ground Tank C (Fig. 6).

Table 2. List of Materials Used in In-Ground/Above-Ground Tanks

Category of work	Type of work		Name and specifications		Weight (t)
In-ground Tank C	Civil engineering	Continuous wall body	Steel (reinforcing bars)	SD295 to SD390	11,000
			Steel	SS	1,150
	Sub-total				12,150
	Mechanical engineering	Membrane	Cryogenic steel	(SUS304)	250
		Steel roof	Cryogenic steel	(9% Ni)	530
	Sub-total				780
	Total				12,930
Above-ground Tank H	Civil engineering	Foundation body	Steel pipe piles	SKK400	8,500
			Steel (reinforcing bars)	SD345 to SD490	2,400
			Steel	SS	200
	Sub-total				11,100
	Mechanical engineering	Inner tank steel plate	Cryogenic steel	(9% Ni)	3,500
		Steel roof, etc.	Steel	(SM)	1,500
	Sub-total				5,000
	Total				16,100

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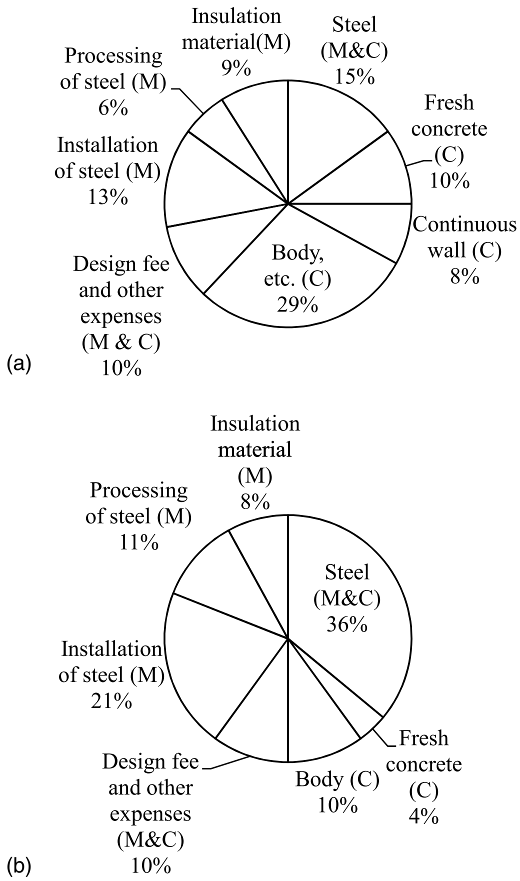

Fig. 6. Cost ratio of steel for (a) in-ground Tank C; and (b) above-ground Tank H; M = mechanical engineering; C = civil engineering

As shown in Fig. 7, the price fluctuation range within a single year was up to approximately 140% for nickel and SUS304, which had a large impact on the overall construction cost. In contrast, the maximum change in the price of steel (including steel pipe piles) within a single year was approximately 50%, much less than that of cryogenic steel.

Table 3 summarizes the estimation results. It can be clearly seen that the impact of price fluctuations on the relative construction cost in terms of the cost impact index is larger for above-ground Tank H (civil engineering work: 1.71–3.42; mechanical engineering work: 7.29–14.58; total: 9.0–18.0) than for in-ground Tank C (civil engineering work: 0.95–1.90; mechanical engineering work: 2.6–5.2; total: 3.55–7.10). Since each cost impact index point equates to ¥100 million, the difference can be as large as ¥1,090 million (18.0–7.1).

Measures to Decrease In-Ground Tank Construction Costs (Civil Engineering Work)

The breakdown of the construction cost of in-ground Tank C is shown in Fig. 8. The relationship between the storage capacity (inner tank diameter) and cost index is shown in Fig. 9 for a banking height of 4 m and in Fig. 10 for a banking height of 8 m.

In general, the unit cost tends to fall with increases in the inner tank diameter. However, the overall construction cost begins to increase when the inner tank diameter passes the optimal point because of an increase in the amount of roof work in the mechanical engineering portion. The range of variation of the cost index is approximately 1.25–1.75 for the same storage capacity.

It is clear that a greater banking height increases the cost merit. At the same time, surplus soil from the excavation work can be used for banking. In some cases, increases in the banking height can generate cost increase factors such as the problem of the tank becoming an eyesore or the need to reinforce nearby seawalls. With a change in the banking height from 4 m to 8 m, the range of variation of the cost index is approximately 0.75–1.25, according to the optimal value for each category of storage capacity.

The unit cost per kL decreases with increases in the storage capacity. A larger storage capacity and a greater banking height require an increased volume of relatively inexpensive earth work and a smaller volume of expensive reinforcing bar work and concrete work and a large cost reduction can be expected—the cost index can be reduced by up to 3.75. Based on the above analysis results, in the case of in-ground Tank C class tanks (160,000 kL), increases in the banking height from 4 m to 8 m and of the inner tank diameter to a maximum value of 70–72 m is likely to achieve a cost reduction of 0.75–1.0 in terms of the cost reduction index.

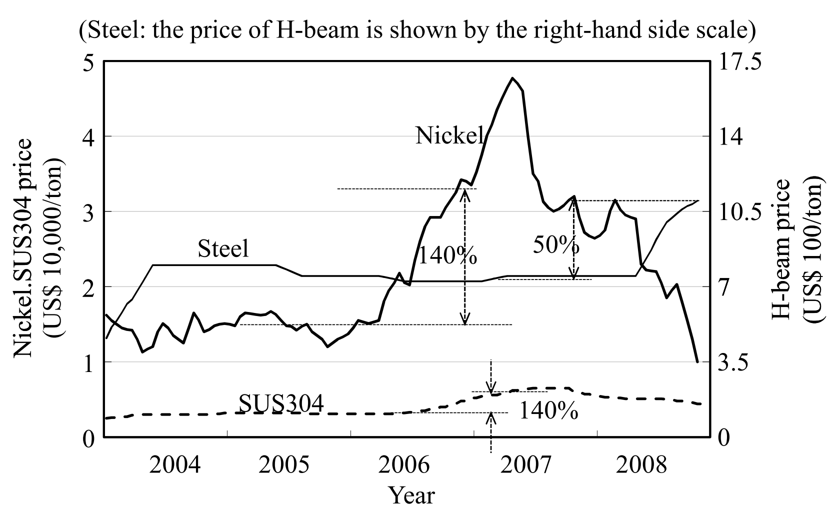

Fig. 7. Historical changes in prices of nickel, SUS304, and steel; sources: (nickel) *Nihon Keizai Shimbun*, Oct. 24, 2008; (SUS304) data from Tekko Shimbun (Japan Metal Daily), Oct. 2008; (H-sections) Construction Material Prices (published by the Construction Research Institute, Tokyo), Aug. 2008

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Table 3. Cost Impact Index for In-Ground/Above-Ground Tanks

	Category of work	Material	(C) (%)	(E) (%)	(Q) (%)	Cost impact index
In-ground Tank C	Civil. engineering	Steel	7.6	50	25	0.95
					50	1.90
	Mechanical. engineering	SUS304	1.4	140	25	0.50
					50	1.00
		9% Ni	6.0	140	25	2.10
					50	4.20
	Total	—	15.0	—	25	3.55
					50	7.10
Above-ground Tank H	Civil. engineering	Steel pipe piles	13.7	50	25	1.71
					50	3.42
	Mechanical. engineering	9% Ni	20.0	140	25	7.00
					50	14.00
		SM	2.3	50	25	0.29
					50	0.58
	Total	—	36.0	—	25	9.00
					50	18.00

Note: Procured quantity ratio (Q) was provisionally estimated from 25% and 50%, based on actual results for Tank C.

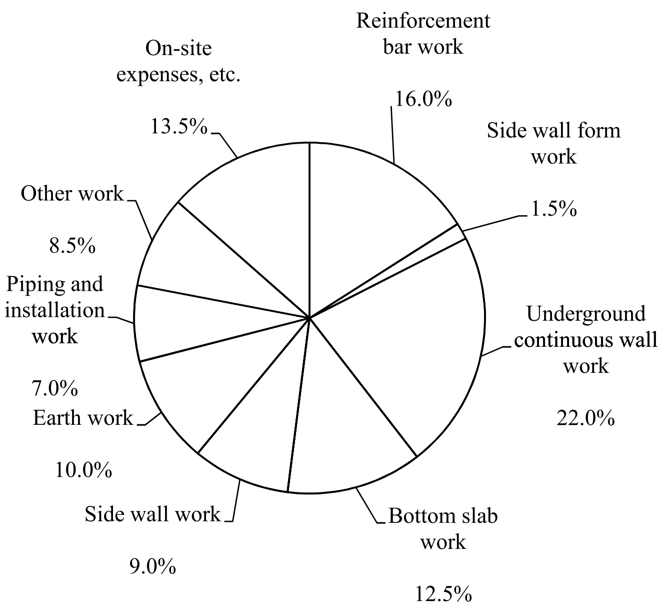

Fig. 8. Breakdown of cost of construction (civil engineering work) of in-ground Tank C

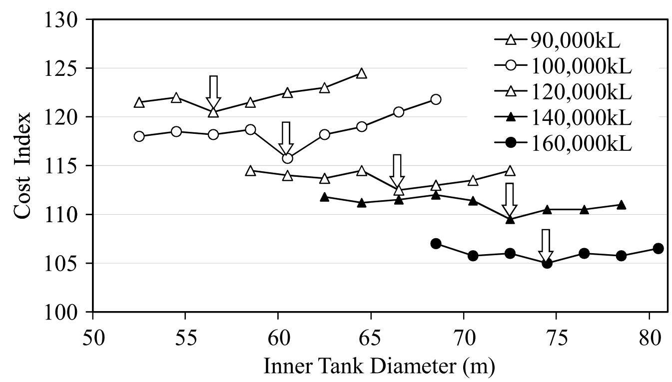

Fig. 9. Relationship between storage capacity (inner tank diameter) and cost index (banking height = 4 m); arrows = optimal diameter for minimizing cost index

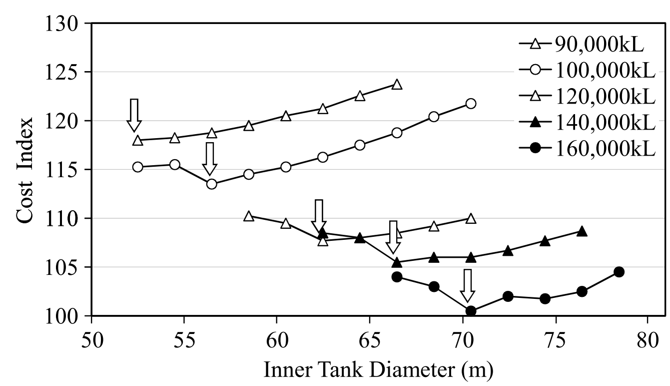

Fig. 10. Relationship between storage capacity (inner tank diameter) and cost index (banking height = 8 m); arrows = optimal diameter for minimizing cost index

Measures to Counter Increasing Material Prices for In-Ground Tanks (Civil Engineering Work)

Fig. 11 shows how the combined cost of materials and labor increases in accordance with changes in the prices of reinforcing bars due to higher standards. When the quality of the reinforcing bars is increased (from SD345 to SD390 to SD490), the unit cost of the materials increases. However, a reduction in the total weight of the reinforcing bars leads to cost reduction and a shorter duration of construction as well as a reduction in the labor cost.

A higher standard of reinforcing bars means that there are decreases in the total weight of the reinforcing bars and the density of the bar arrangement that improves both the productivity of the

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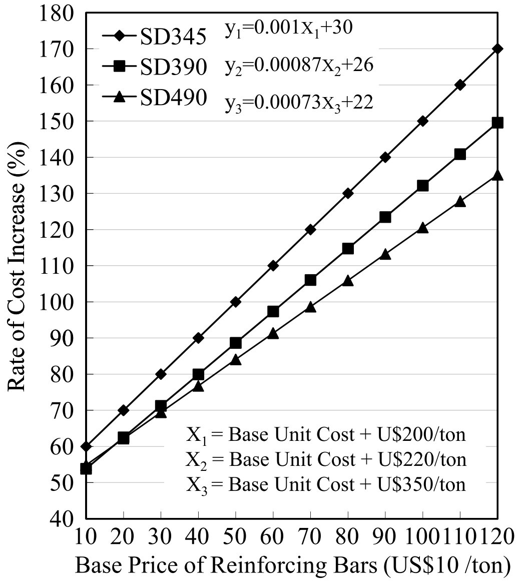

Fig. 11. Rate of cost increase in response to changes in prices of reinforcing bars owing to higher standards

bar arrangement work and the concrete filling performance. When SD345 and SD490 are compared, the use of SD490 could achieve a cost reduction of 16% in the case of a base unit cost of ¥50,000/ton or 22.7% in the case of a base unit cost of ¥80,000/ton.

The above results indicate that, in light of the cost ratio of the reinforcing bar work (16%) shown in Fig. 10, the cost impact index can be reduced by 1.0–1.5 or more when the base unit cost of the reinforcing bars is between ¥50,000/ton and ¥80,000/ton; this result means that when the price of steel increases, a higher cost reduction can be achieved by selecting reinforcing bars of a higher standard.

Construction Method for Continuous Underground Walls

Fig. 12 compares two different methods for the construction of a continuous wall joint structure, i.e., the partition method and the cutting method. When the soil and water pressures acting on a continuous wall are nearly uniformly distributed, the circumferential continuous wall stress takes the form of a full-face compression, which eliminates the need to join the reinforcing bars in the circumferential direction. In this case, the cutting method can be used. When a high level of uneven soil pressure can occur, employment of the partition method is necessary.

The partition method usually requires a steel plate partition. Compared to the cutting method, a larger quantity of reinforcing bars and steel materials (steel plate platforms) is required and increases the cost. The results for the cost-benefit performance of these two methods are shown in Fig. 13. The overall cost of both methods is identical, and the duration (D) of the two methods of approximately four months is also similar.

As the shape of an element in the cutting method is determined by the horizontal dimension (approximately 2.8 m) of the excavator (to cut the leading elements), the number of elements (vertical connection joints) in the cutting method is higher than that in the partition method by approximately 40–50%. Because of the need for cutting work, the selected excavator must have multiple horizontal spindles. Further, the plant for the cutting method needs to be much more heavily equipped than that required by the partition method. All of these special requirements of the cutting method also increase the demands on quality management.

Compared to the cutting method, the partition method involves more site work processes because of the need for partition work, foot protection work (to prevent sliding of the partitions at the time of concrete placement), and canvas sheet work (to prevent leakage

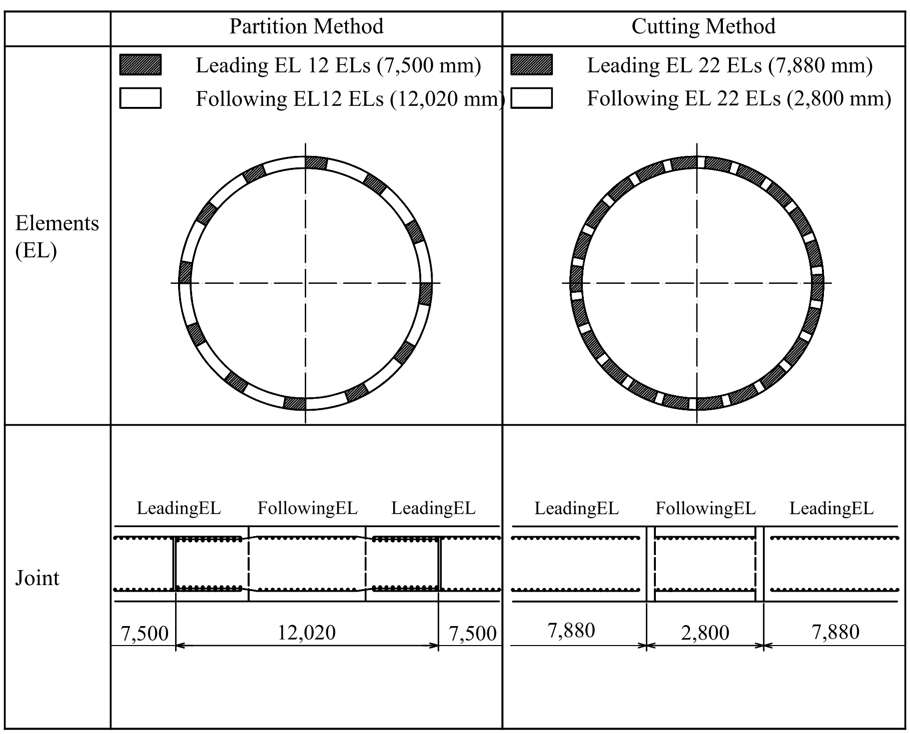

Fig. 12. Comparison of different continuous wall structures

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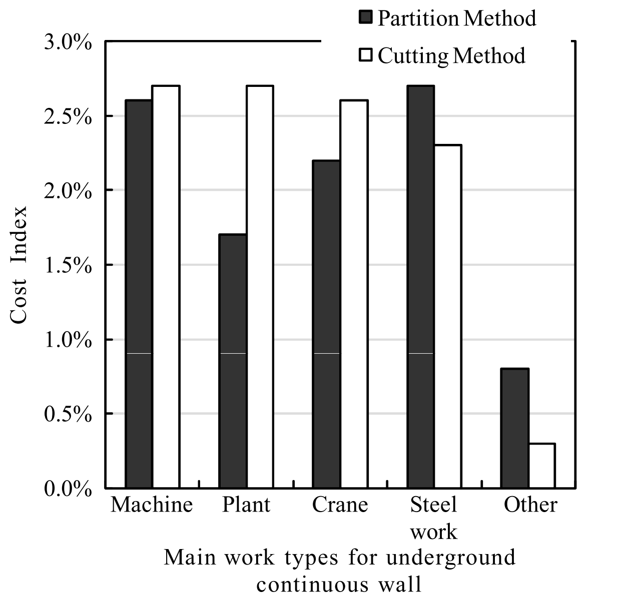

Fig. 13. Comparison of cost indexes of different joint structures

of the concrete at the time of concrete placement), all of which increase the labor participation rate. The unit weight of the reinforcing bar cage per element is also high for the partition method and makes it necessary to use a larger crane.

When the required excavation depth for a continuous wall is relatively shallow (less than 70 m deep), it is essential to carefully select the excavator and a suitable method for construction and, in particular, to take the soil conditions of the site into consideration.

For a steel price increase of 50%, the cost of the partition method in terms of the cost ratio of a continuous wall is approximately 6% higher than the cutting method because of the use of more steel materials.

In short, when steel prices are stable, there is little cost difference between the two methods for a 160,000 kL class in-ground tank such as Tank C. When steel prices increase, however, the cost of the partition method is higher than that of the cutting method with a cost impact index (M1) of approximately 0.7 based on the cost ratio of the continuous wall work (22%) shown in Fig. 8.

Examination of Side Wall Forms

There are two types of construction methods for side wall forms. One is the segment method (precast concrete; approximate dimensions: 2.5 m in length, 5 m in width, and 15 cm in thickness). The other is the wood form method employed for construction work in general.

When focusing on the use of steel, the segment method requires reinforcing bars and various types of metalware. These steel items are not required by the wood frame method. At first glance, the wood frame method might appear to be much more economical. However, the segment method has been popular for the construction of in-ground tanks in recent years because of safety considerations as well as the dimensional accuracy of the inner face.

It is clear that the segment method is more advantageous than the wood form method except from the viewpoint of cost. Because of its heavy use of reinforcing bars and steel joints, the cost burden of the segment method increases with rises in steel prices. The cost ratio is approximately 1.5% in the case of the wood form work for Tank C (Fig. 8).

The cost ratio of the segment method is approximately 3%. When steel prices are high, it is anticipated that the overall construction cost will be increased by approximately 0.5%.

Based on the preceding analysis, the segment method is approximately 1.5% more expensive than the wood form method for Tank A (125,000 kL). If the wood form method had been used for this tank, the cost impact index (M2) could have been lowered by approximately 0.75 points. The wood form method can offer a cost reduction of approximately 0.25 points in terms of the cost impact index when steel prices are high. However, in the actual selection of a suitable method, it is necessary to consider the likely cost-benefit performance of each method based on the foreseeable economic and market conditions and the required quality of the tank.

Reduction of Economic Risk of In-Ground Tank Construction

Measures for the reduction of the cost of steel materials were applied to in-ground Tank C, the construction of which commenced prior to the rise in the resource prices. A subsequent estimate established that a cost reduction of at least 0.75–1.0 points in terms of the cost reduction index could have been achieved by reducing the quantity of the construction work through a greater banking height and the selection of the optimal inner tank diameter and liquid depth. It was also found that the positive cost reduction effects of scale can be achieved by increasing the storage capacity. In the case of reinforcing bars, a change in the specifications to upgrade the strength of the bars would have achieved a cost reduction of at least 1.0–1.5 points within the range of the base price fluctuations for reinforcing bars (¥50,000/t to ¥80,000/t).

When the different construction methods, i.e., the continuous wall joint method and the side wall form method, are compared, the adoption of the cutting method for the continuous wall construction can achieve a cost reduction of up to 0.7 points in terms of the cost reduction index (M1). In contrast, the adoption of the segment method for the side wall form construction increases the cost by approximately 0.75–1.0 points in terms of the cost reduction index (M2).

Based on the above results, the actual cost reduction index is presented in the following equation for the construction conditions of in-ground Tank C (reinforcing bar specification: from SD345 to SD390; partition method for continuous wall; wood form method for side wall forms):

$$\text{Cost Reduction Index} = (\text{QR}) + (\text{S}) + (\text{M1}) + (\text{M2})$$

$$= (0.75 \text{ to } 1.0) + (1.0 \text{ to } 1.5) + (0 \text{ to } 0.7) + (0)$$

$$= (1.75 \text{ to } 3.2)$$

The above figures show that because of the actual implementation of these measures for Tank C, the tank cost was decreased by 1.75–3.2 points in terms of the cost reduction index. Accordingly, it is now clear that even if a rise in the material cost is anticipated to have a negative impact on the overall construction cost, a positive economic effect that compensates for such negative impact can be achieved by combining the several measures proposed in this paper.

Conclusions

Cost Evaluation for Above-Ground and In-Ground Tanks

The costs of constructing these two types of LNG tanks were evaluated by using the cost index and the cost impact index. While

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the cost index was found to be similar for both types of tanks at around 125, a fairly large difference in cost impact index was found: the overall variation ranges from 3.55 to 7.10 points for in-ground tanks and from 9.0 to 18.0 points for above-ground tanks.

This difference in cost impact index results from the different characteristics of the civil engineering and mechanical engineering tasks for these tanks. When the fluctuations of resource prices are taken into consideration, above-ground tanks are associated with a higher economic cost risk than in-ground tanks because of their heavy use of cryogenic steel.

Reduction of Economic Risk of In-Ground Tanks

Based on the above results, the actual cost reduction index value was calculated by using the construction conditions for in-ground Tank C (reinforcing bar specification: from SD345 to SD390; partition method for continuous wall; wood form method for side wall forms). The cost reduction index was found to decrease by 1.7–3.2 points with the implementation of certain cost reduction measures. Even if a rise in the material costs is anticipated to have a negative impact on the overall construction cost, a positive economic effect that compensates for such negative impact can be achieved by combining the several measures proposed in this paper.

Acknowledgments

This paper compiles the findings of a study by the writers of cost risk reduction for the construction of LNG tanks that was triggered by the actual fluctuations beyond normal expectations of resource prices during our involvement in the construction of in-ground tanks since 1982 and above-ground tanks since 2006. The writers would like to express their utmost gratitude to the members of Shizuoka Gas and Shimizu LNG for their kind guidance and assistance.

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