LCC-based Multi-stage Decision Making Methodology for Quay Structure Design

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Abstract

Quay structures, one of the major components of port facilities, are embedded in undersea rubble mounds and reach above the sea level, thus exposing them directly to powerful wave forces such as tidal waves, typhoons and earthquakes. The design of quay structures requires careful selection of the type of structures concerning the external stability followed by a detailed structural design to determine geometry and associated dimensions of the structure. In this paper, a multi-stage decision-making methodology based on LCC (Life Cycle Cost)-based value analysis, structural reliability, and optimization techniques is proposed for the optimal design of a quay structure. The concept of this decision-making methodology is based on the gradual evolution of design details. Probabilistic approaches are taken to deal with the different characteristics of design stages rationally. The feasibility of the proposed decision-making methodology is also reviewed by applying it to a real-world case of port facility design.

Keywords: Quay Structure, Decision Making, Value Analysis, Life Cycle Cost, Port Facilities

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1. Introduction

Quay structures, used for mooring or tying vessels while loading or discharging cargo and/or passengers, are one of the major components of port facilities (Bruun 1976). They embed into undersea rubble mounds and reach above the sea level exposing themselves to powerful wave forces such as tidal waves and earthquakes. Stability against various failure modes should be secured so the quay structures serve their basic functions as part of port facilities. Caused by insufficient external stability, typical failure modes of quay structures include sliding, overturning, and bearing capacity failures (Oumeraci 1994, Kawai et al. 1997, Burcharth and Sorensen 1998). Therefore, the design of quay structures requires careful selection of the types of structures based on external stability followed by a detailed structural design to determine geometry and associated dimensions. Many design decisions are made throughout the design process.

The design of quay structures should consider not only functional aspects such as stability but also economic factors as other design problems. Decisions for selecting a design alternative, therefore, should be based on the 'value' of the considered alternatives. The value of a project alternative can be determined by the cost and the functional (non-economic) performance of the alternative such as stability, constructability and environmental impact. Performance evaluation of a design alternative requires selecting performance criteria, determining the weight of the selected criteria, and rating the performance of the design alternative with respect to the weighted criteria. The measure of value of an alternative for decision making becomes the ratio of the overall performance rating to the cost (Cal Trans 2003, Dell'Isola and Kirk 1997).

Economic feasibility analysis and alternative selections for the construction of harbor structures, including quays, have been limited to consideration of initial costs, such as design and construction cost, despite costs that can occur during the operation. These costs could be very high and even exceed the initial cost. Therefore, life cycle cost analysis (LCCA) is required for sound decision making when competing alternatives are considered for harbor construction projects. LCCA of constructed facilities must predict the cost, timing of operation, and maintenance activities to be performed over a long period of time. Therefore, it is important to properly manage the uncertainty and the variability of the input data for LCCA. Probabilistic or risk-based approaches can be used to make a rational assessment of life cycle cost (LCC), considering the effects of uncertainties. These approaches have been

used for LCCA of constructed facilities such as pavement systems and bridges (Ehlen and Marshall 1996, Walls and Smith 1998).

Once the available design alternatives have been reviewed and the type of quay structure is determined, a detailed structural design should be performed to determine the geometry and dimensions of the structural components. As a final step, this stage of the design can be optimized by reducing the life cycle cost after an alternative has been selected. Structural designs based on such optimization techniques are found in other applications of civil engineering (Vanderplaats 1987).

This paper proposes a four-stage decision-making methodology based on the utilization of various life cycle cost and value analysis techniques for the optimal design of quay structures. First, the applicable design alternatives are selected by screening initially considered designs based on the qualitative value analysis considering uncertainty and variability of the qualitative evaluation of alternatives. The preliminarily screened design alternatives are further investigated at the next stage based on the probabilistic LCC-based value analysis, and the candidate alternatives for a more detailed analysis are determined. For the next design decision, reliability analysis of the external stability of the quay structure is incorporated into the value analysis and the decision of the alternative selection is finalized. At the last stage, the geometry and dimensions of the selected alternative are designed through an optimization technique to reduce the LCC of the quay structure.

The approach of the multi-stage design decision making is based on the gradual evolution of design details and the consideration of uncertainties involved in the evaluation of design factors including life cycle cost and non-economic performance. The proposed methodology considers the characteristics and details of design variables and data of the different design stages for sound decision making. The applicability of this method is examined by applying the proposed multi-stage decision making methodology to a real-world case. It is believed that the methodology and the procedure proposed in this paper can be adapted for other design applications.

2. Multi-stage decision-making methodology

The design of quay structures requires evolutionary decision-making procedures to produce a final design as other design problems. This section describes the proposed multi-stage decision-making methodology. The method is composed of the following four stages:

1) Selection of applicable alternatives through qualitative performance analysis
2) Selection of alternatives for further consideration through LCC-based value analysis
3) Further design development of the selected alternative and selection of the optimal structure type through the structural reliability-based LCC analysis
4) Determination of the geometry and dimensions of the selected structure type through the LCC-based structural optimization technique.

The procedure of multi-stage decision-making methodology is described in detail in sections 2.1-2.4.

2.1 Preliminary stage analysis

In the preliminary stage analysis, statistical properties derived from questionnaire study data for the evaluation of the conceptual design are utilized for the rational decision-making. The preliminary stage analysis focuses on the evaluation of the qualitative performance of alternatives. Criteria for the performance evaluation are selected by analyzing the project owners' and/or users' needs and requirements. At this stage, the economic performance of design alternatives is included in the qualitative evaluation criteria instead of performing quantitative LCC analysis due to the conceptual features of the alternatives at the preliminary stage analysis. Once the performance evaluation criteria are determined, weights of criteria ($\boldsymbol{WC}$) are established by applying relatively simple matrix methodology (Dell'Isolla and Kirk 1997) to consider rigorously the importance of different criteria. The rank index ($\boldsymbol{RI}$) of the alternatives is evaluated with respect to the selected performance criteria. The performance index ($\boldsymbol{PI}$) of a design alternative is the sum of the products of the weights of criteria ($\boldsymbol{WC}$) and the rank index ($\boldsymbol{RI}$) with respect to the criteria.

The proposed methodology considers the probabilistic characteristics of the $\boldsymbol{PI}$ of alternatives. The $\boldsymbol{PI}$ of each alternative is treated as a random variable. Therefore, $\boldsymbol{PI}$ values are represented by probability or occurrence rates rather than by a fixed or deterministic value. In order to compare the $\boldsymbol{PI}$ values of two alternatives (e.g. $\boldsymbol{ALT.1}$ vs. $\boldsymbol{ALT.2}$) based on the probabilistic evaluation, the reliability concept is applied. The reliability analysis for probabilistic performance evaluation is then based on the following limit state equation.

$$g(\cdot) = PI_{ALT.2} - PI_{ALT.1} = \left[\sum\left(WC \times RI_{ALT.2}\right) - \sum\left(WC \times RI_{ALT.1}\right)\right] \quad \text{Eq. 1.}$$

where $PI_{ALT.1}$, $PI_{ALT.2}$ = performance index of alternative 1 and alternative 2

WC = weights of performance criteria

$RI_{ALT.1}$, $RI_{ALT.2}$ = rank index of alternative 1 and alternative 2

WC and RI in Eq. 1 are random variables with specific types of probability distributions such as normal and log-normal. They have statistical properties such as mean values (Mean) and coefficients of variation (COV), a ratio of the standard deviation and mean values. The reliability analysis of the proposed limit state equation produces the probability that the performance index of alternative 2 is higher or lower than alternative 1. Fig. 1 describes the reliability analysis conceptually. The dotted and solid lines of Fig. 1-(a) represent PDF_s (Probability Density Functions) of PI for alternative 1 and alternative 2, respectively. The limit state equation in Equation 1 would have a combined PDF shown in Fig. 1-(b) and the area under the combined PDF on the negative side represents the probability that the limit state equation produces negative values, meaning the PI of alternative 2 is higher than that of alternative 1. Therefore, the proposed methodology considers the uncertainty and the randomness of the input data related to the performance evaluation in order to reach a rigorous decision for design alternative selection.

(a) separate PDF_s of PI of $ALT.1$ & $ALT.2$ (b) combined PDF of the limit state equation

Figure 1. Reliability Analysis for PI Evaluation

2.2 First stage analysis

At this stage, qualitative (performance) and quantitative (LCC) evaluations on the applicable alternatives selected from the preliminary stage analysis are performed. Decision making through value analysis is then conducted based on reliability-based evaluation taking into consideration qualitative and quantitative properties as shown in Fig. 2.

Figure 2. First Stage Analysis

The first stage analysis is divided into three phases: 1) qualitative non-economic performance evaluation considering uncertainties, 2) probabilistic LCC analysis, and 3) decision making based on reliability-based evaluation. In the qualitative evaluation phase, the economic criterion should be excluded from the list of the performance criteria and the weights of performance criteria need to be re-evaluated without the economic criterion because LCC analysis is conducted separately. In establishing performance evaluation criteria, Saaty's analytic hierarchy process (AHP) standard (Saaty 1994) is applied to determine the weights of performance criteria ($\boldsymbol{WC}$). The uncertainties involved in the performance evaluation are considered through statistical analysis as in the preliminary stage analysis. The consistency of AHP analysis results can be examined by a consistency ratio, CR, suggested by Saaty. The rank index ($\boldsymbol{RI}$) is derived from a questionnaire study and the uncertainty and/or variability that can be induced while conducting the questionnaire is considered in the statistical analysis.

In the quantitative analysis phase, all the variables for LCC analysis are considered as random variables with certain statistical distributions in accordance with data types. The probabilistic LCC model can be represented by Eq. 2, 3 and 4. The necessary cost and timing data for construction, operation and maintenance activities should be collected. After the basic parameters for LCCA including the discount rate and the alternatives' life (planning horizon) are determined, the LCC of a design alternative can be evaluated in terms of present worth by discounting the future cost with the discount rate.

$$E\left[LCC_{Total}\left(x,T\right)\right] = C_{INI} + \sum_{t=1}^{T}\left[E\left(C_{OMR}\left(x,t\right)\right)\right] \qquad \text{Eq. 2.}$$

where $E\left[LCC_{Total}\left(x,T\right)\right]$ = present value of LCC
C_{INI} = initial cost
$E\left(C_{OMR}\left(x,t\right)\right)$ = present value of operation/maintenance

$$C_{INI} = C_{DES} + C_{CSV} + C_{CON} + C_{ISI} \qquad \text{Eq. 3.}$$

where C_{DES} = design cost
C_{CSV} = supervision cost of design & construction

C_{CON} = construction cost
C_{ISI} = cost for initial inspection

$$C_{OMR} = C_{MAI} + C_{REH} + C_{DIA-I} + C_{DIC-II} \quad \text{Eq. 4.}$$

where C_{MAI} = maintenance cost
C_{REH} = rehabilitation cost
$C_{DIA-I,II}$ = periodical/precision safety inspection cost

In the decision making phase, the probabilistic value analysis is performed by considering the result of the performance evaluation and the LCC evaluation simultaneously. The value of an alternative for project decision making is defined as the ratio of non-economic performance rating to cost (Dell'Isola and Kirk 1997, Cal Trans 2003). Therefore, the value index of an alternative can be calculated as the performance index (PI) divided by LCC. To compare the value index of two alternatives probabilistically ($ALT.1$ vs. $ALT.2$), reliability-based evaluation is applied based on the limit state equation in Eq. 5.

$$g(\cdot) = VI_{ALT.2} - VI_{ALT.1} = \left[PI_{ALT.2} / LCC_{ALT.2}\right] - \left[PI_{ALT.1} / LCC_{ALT.1}\right] \quad \text{Eq. 5.}$$

where $VI_{ALT.1}$, $VI_{ALT.2}$ = value index of alternative 1 and alternative 2
$PI_{ALT.1}$, $PI_{ALT.2}$ = performance index of alternative 1 and alternative 2
$LCC_{ALT.1}$, $LCC_{ALT.2}$ = LCC of alternative 1 and alternative 2

In Eq. 5, which is similar to Eq. 1 for the performance evaluation of the preliminary stage analysis, $LCC_{ALT.1}$, $LCC_{ALT.2}$ are also considered as random variables along with the performance related variables $PI_{ALT.1}$, $PI_{ALT.2}$. $VI_{ALT.1}$, $VI_{ALT.2}$ represent the value of two alternatives. The MCS (Monte Carlo Simulation)-based reliability analysis can quantify the probability that the VI of one alternative is higher or lower than the other alternative.

2.3 Second stage analysis

In the second stage analysis, the qualitative and quantitative analyses are conducted after the design of the selected alternative from the first-stage analysis is further developed. At this stage, the failure probability of quay structures exposed to natural disasters such as earthquakes, storms, and tidal waves is considered for LCC analysis through structural reliability analysis of the external stability of the quay structure.

Similar to the first stage analysis, the second stage analysis consists of the qualitative evaluation of non-economic performance, the quantitative evaluation of LCC, and value oriented decision making. The qualitative evaluation procedure follows the same procedure as in the first stage analysis. All the input values for the LCC analysis are random variables and the Reliability-based Life Cycle Cost Analysis (RLCCA) is conducted on the stability of quay structures. RLCCA of this stage is different from the reliability-based evaluation of the value explained in the preliminary and the first stage analyses, where it was utilized to conduct the probabilistic comparison of two alternatives for decision making. The term 'Reliability' in this section means the structural reliability analysis to identify the failure probability of quay structures against the external loads. The life cycle cost model for RLCCA is given in Eq. 6, 7 and 8. In these equations, the failure probability derived from the examination of stability through the structural reliability analysis is converted to the annual equivalent failure probability. An extra LCC term for the possible structural failure is then calculated as an expected monetary amount. Since it is almost impossible to estimate the timing of an actual failure, the extra cost item is based on the annual equivalent failure probability.

$$E\left[LCC_{Total}(x,T)\right] = C_{INI} + \sum_{t=1}^{T}\left[E\left(C_{OMR}(x,t)\right) + E\left(C_{FAIL}(x,t)\right)\right] \qquad \text{Eq. 6.}$$

where $E\left[LCC_{Total}(x,T)\right]$ = present value of LCC
C_{INI} = initial cost
$E\left(C_{OMR}(x,t)\right)$ = present value of operation/maintenance cost
$E\left(C_{FAIL}(x,t)\right)$ = present value of failure cost

$$C_{FAIL} = P_{FLC} \cdot \left[C_{FREH} + C_{OIL}\right] \qquad \text{Eq. 7.}$$

where P_{FLC} = maximum failure probability of life cycle (Uni-modal bounds)
C_{FREH} = present value of reconstruction cost

C_{OIL} = present value of operating loss cost

$$P_{FAIL/AN} = 1 - \left(1 - P_{FAIL/LC}\right)^{1/L} \qquad \text{Eq. 8.}$$

where $P_{FAIL/LC}$ = failure probability of life cycle
$P_{FAIL/AN}$ = equivalent failure probability
L = life cycle

Structural reliability is generally defined as the capability to satisfy the design objectives, such as function and stability of the structure during the service life, or the probability that a structure is able to play its role without failure under any unfavorable conditions. In the case of the quay structures, stability analysis should be conducted under various loading conditions such as sliding, overturning, and bearing capacity against normal, earthquake and tidal wave situations (Sekiguchi and Kobayashi 1994, Nagao et al. 1997, 1998, Kawai et al. 1997, Takahashi et al. 2000). The reliability analysis based on a Uni-modal bound methodology (Ang and Tang 1984, Cho et al. 2000) is adopted to determine the representative failure probability caused by insufficient stability against the external loads.

The limit state function determining the failure probability in the stage of structural reliability analysis concerns the external stability conditions such as sliding, overturning and bearing capacity. MCS is commonly utilized due to the unrestricted use of limit state analysis in any random distributions, the conformance of calculated failure probability and the probability of selecting samples from the actual failure area. @Risk (Palisade 2002) is utilized for the structural reliability analysis mentioned above and the credibility of the reliability analysis result is examined by comparing it with the result of RELSYS (Estes 1997).

Meanwhile, the value analysis for decision making in this stage uses the same limit state function of the reliability analysis as in the first stage analysis. Decisions are then made based on the estimation of the reliability level produced by comparing alternatives. @Risk (Palisade 2002) is also used to consider the random variables of PI and LCC .

2.4 Third stage analysis

In the third stage analysis, the last stage for the design of quay structures, the geometry and dimensions of the selected alternative are determined through a structural optimization technique to reduce LCC. As shown in Fig. 3, the third stage analysis can be defined as a process for structural optimization for deriving the design variables that minimize the objective function, LCC for this analysis, and satisfy the constrained conditions. The general form of optimization is represented in Eq. 9 (VanderPlaats 1987-b).

Figure 3. Third stage analysis

$$
\begin{aligned}
&\text{Find vector} && \boldsymbol{X} \\
&\text{minimize} && \boldsymbol{F(X)} \\
&\text{subject to} && \boldsymbol{g_i(X) \le 0} \qquad \boldsymbol{i = 1,2,.....n_i} \\
& && \boldsymbol{h_j(X) = 0} \qquad \boldsymbol{j = 1,2,.....n_j} \\
& && \boldsymbol{X_k^l \le X_k \le X_k^u} \qquad \boldsymbol{k = 1,2,.....n_k}
\end{aligned}
\qquad \text{Eq. 9.}
$$

where $\boldsymbol{X}$ = design variables

$\boldsymbol{F(X)}$ = objective function for LCC

$\boldsymbol{g_i(X)}$ = inequality constraints

$\boldsymbol{h_i(X)}$ = equality constraints

$\boldsymbol{X_k^l \le X_k \le X_k^u}$ = side constraints

Non-linear optimization techniques are required in order to solve the above equations because $\boldsymbol{F(X)}$ and $\boldsymbol{g_i(X) \le 0}$ usually consist of non-linear functions for structural optimization problems. Although a certain optimization technique cannot provide the optimal solution, optimal solutions can be derived by iteratively solving Eq. 10 (Vanderplaats 1987-b).

$$X_q = X^{q-1} + a*_q \cdot S_q \qquad \text{Eq. 10.}$$

where X = design variables

q = iteration number

S = vector search direction in the design space

$a*_q$ = distance that we wish to move in direction S

Once the direction vector, S, is derived from Eq. 10, the optimization problem becomes a matter of finding variable a with regard to variable X. a can be obtained from the linear detection algorithm and eventually the value of the improved design variable is obtained.

X_q, obtained as an optimal solution, is required to satisfy the constraints. Many numerical methods using computer programming have been devised. These methods can be categorized into two types: the primal method and transformation method (Vanderplaats 1987-a). In this paper, the ALM (Augmented Lagrange Multiplier) method, a transformation method superior to other methods in the reliability of optimal solutions, is adopted. Once the constrained optimization problem is converted to the unconstrained problem using ALM methodology, multi-variable and unconstrained optimization methods can be used. Unconstrained optimization techniques can be categorized into direct search methods and descent methods. The Broyden-Fletcher-Goldfarb-Shanno (BFGS) method, one of the variable metric methods in the descent method category, is applied for this research. After a directional search based on the BFGS method is finished, the linear detection algorithm is conducted. The golden section method is selected for linear detection. Verified optimization software, ADS (Vanderplaats 1987-a), was used for the aforementioned optimization method. Figure 4 shows the flow diagram for the optimization of the quay structures. If caisson is the selected structure type, for example, the design variables considered for optimization could be the length of caisson, the thickness of caisson, and the reinforcement as shown in Fig. 4.

Figure 4. Flow diagram for the optimization of the quay structures

3. Application

A real-world case study of the proposed multi-stage decision making methodology for the optimal design of quay structures is presented in this section. The methodology proposed in the previous sections is applied to the design of a harbor container terminal facility recently completed in Korea. The case study presented here had an original design created previously. Therefore, the effort made to develop a better design than the original is explained in this section. Table 1 shows the summary of the original design.

Table 1. Original design

3.1 Preliminary stage analysis

3.1.1 Determination of performance evaluation criteria and indices

A questionnaire study was performed to identify performance criteria and their weights. The designer explained the design conditions to 10 selected specialists including designers, contractors and value engineering specialists. Based on the specialists' opinions and all the design-related information, the performance evaluation criteria were selected and the weights of criteria ($\boldsymbol{WC}$) were determined. Table 2 represents the results of the questionnaire study.

Table 2. Performance evaluation criteria and weights of preliminary stage analysis

Matrix method (Cal Trans 2003) was used to analyze the questionnaire study to determine the weight of the performance evaluation criteria. Durability and stability were the major performance criteria selected for the project as shown in Table 2.

3.1.2 Selection of applicable alternatives

A total of 7 design ideas were initially considered. They are the types of quay structures typically considered at the conceptual design stages and categorized into gravity type, shore-bridge type, and sheet pile type. Table 3 shows the developed design ideas.

Table 3. Design ideas of preliminary stage analysis

Through the questionnaire study based on the specialists' experiences and intuitive judgment, the rank indices (***RI***) of the 7 design ideas were investigated. The statistical distribution used for the values of the rank indices (***RI***) was triangular distribution, which is the most commonly used distribution for modeling expert opinion (Vose 2000). The statistical properties of the performance indices (***PI***) based on the performance evaluation criteria and the rank index for each alternative were utilized for the reliability-based performance evaluation for decision-making. A commercial MCS-based simulation software, @Risk (Palisade 2002), was used for the analysis. Table 4 represents the parameter (minimum, most-likely, maximum) values of the triangular distribution for the product of the weight and the rank index for each performance criteria, and MCS simulation results of the ***PI*** evaluation based on 10,000 simulations.

Table 4. MCS results for performance evaluation of preliminary stage

As shown in Table 4, the performance indices of steel-pipe pile, solid block, caisson, and composite steel have mean values of 92.22, 90.54, 89.65 and 87.71, respectively, and have higher reliability levels compared to other alternatives. The reliability level of design alternatives means the probability that the ***PI*** of an alternative is higher than that of the basis alternative which is the 'Panel of Steel Pile' type in this case. Therefore, steel-pipe pile, solid block, caisson and composite steel were selected as the applicable alternatives at the end of the preliminary stage analysis.

3.2 First stage analysis

3.2.1 Development of the basic design of the applicable alternatives

The basic design work to accommodate the site conditions was performed on the 4 alternative structure types that were selected from the preliminary stage analysis. The results are shown in Table 5.

Table 5. Structure types considered for the first stage analysis

3.2.2 Qualitative evaluation

(1) Determination of the performance evaluation criteria and weights of criteria

For the selection of the alternatives for further consideration, the performance evaluation criteria selected in the preliminary stage analysis, excluding the economy item, were used. The economic evaluation of the alternatives is replaced by a quantitative LCC analysis at this stage. Another questionnaire study by the same specialists who participated in the study at the preliminary stage analysis was conducted for the determination of the weights of the performance criteria without the economy item. Based on the questionnaire study, the weights were determined utilizing AHP methodology. The performance criteria and their weights are represented in Table 6.

Table 6. Performance evaluation criteria and weights of 1st stage analysis

The consistencies of the above results were examined by a consistency ratio (CR), suggested by Saaty (Saaty 1994). The consistency of the weight can be accepted in the case that the consistency ratio is within 10%. As shown in Table 7, the CR is 0.0076 and the stability and the connection capacity were the major performance criteria with higher weight points.

(2) Rank index and performance evaluation for each alternative

To determine the rank indices (***RI***) of alternatives with respect to the performance criteria, the designer explained the design details to the ten selected specialists, who were experts in port design, construction and value engineering. Rank indices of the alternatives were determined based on the specialists' opinions. Triangular distribution was used for the ***RI*** values. The results of the performance evaluation on each alternative are represented in terms of the performance index (***PI***) in Table 7. The performance index (***PI***) of alternative 2 has the highest mean value of 87.53.

Table 7. Performance evaluation of 1st stage analysis

3.2.3 Quantitative evaluation of LCC

(1) Basic parameters for life cycle cost analysis

A reference (Charkson Research Studies 2001) suggested that the service life of concrete quay structures should be 60 years. Considering the current technology level and the importance of the structures, the service life of the quay structures for the quantitative LCC analysis was assumed to be 80 years. The discount rate for the net present value analysis applied was 4.51% as suggested in the "Economic Statistics Yearbook (2003)" published by the Bank of Korea.

The statistical LCC analysis model suggested in Eq. 2, 3 and 4 was applied. The approximate construction quantities and the cost for the alternatives were estimated based on the basic design of each alternative. The cost for the regular and the precise safety investigations is based on the cost estimating standard of the Korea Infrastructure Safety and Technology Corporation (KISTEC 2000). For the calculation of the maintenance cost, 1.35%/year (COV=0.35) and 0.76%/year (COV=0.55) were selected for the repairing and reinforcing ratios, and 0.27%/year (COV=0.30) and 0.76%/year (COV=0.55) of the initial construction costs were used as the maintenance costs (UNCTAD 1985).

(2) Result of analysis

Based on the LCC model suggested in Eq. 2-4, the assumed parameters, and the cost/duration data, the life cycle cost analysis for the selected alternatives were performed. The statistical distributions selected for the cost and duration data were normal and triangular, respectively. ProLCC (KISTEC 2002), a probabilistic LCC analysis software, was used for the analysis. The result of the analysis, including the statistical properties and the probabilistic density functions of the alternatives' life cycle costs, are represented in Table 8.

Table 8. Result of life cycle cost analysis

As shown in Table 8, the statistical properties based on the PDF curves of the cost of alternatives 1 and 2 show very similar tendency to each other, and the same is true for alternatives 3 and 4. This is because alternatives 1 and 2 and alternatives 3 and 4 are made of concrete and steel, respectively. The statistical LCC analysis results shown in Table 8 are based on 100,000 times of MCS simulations. Alternative 2 was found to be the most economic with a mean value of 2,673.32 hundred million won. The cost of typical quay structures are governed by the initial cost rather than the expected maintenance cost during the service period of the structure. However, it should be noted that quay structures are exposed to various external loads such as tidal waves, typhoons, and clashes by ships, etc. Therefore, it is very important to consider the risk cost based on the structural reliability analysis against such disasters for the quantification of LCC of the alternatives. RLCC analysis that considers the risk cost is possible when the design is further detailed in the next stage analysis.

3.2.4 Value evaluation by reliability analysis

Value evaluations that combined the qualitative and quantitative evaluation results through a reliability analysis concept utilizing MCS methodology were performed and the results are represented in Table 9. The limit state function for the reliability analysis is given in Eq. 5 of Section 2.2.

Table 9. Value evaluation of alternatives

According to the simulation results of the value index (VI) in Table 9, the mean values of VI for alternative 1, 2, 3 and 4 are 0.0317, 0.0336, 0.0301 and 0.0287, respectively, and thus the average VI of alternative 2 is the highest. 100 million won was the unit of LCC for the calculation of VI values. The results of the decision making reliability analysis show that the probability that VI of alternatives 2, 1, and 4 are higher than alternative 3, which is the basis alternative for comparison, are 99.71%, 89.13%, and 13.28%, respectively. The reliability-based value evaluation was conducted using MCS methodology with 10,000 simulation times and 0.5% error range. As a result, alternative 2 was selected as the candidate alternative for further consideration in the first stage analysis.

3.3 Second stage analysis

3.3.1 Detailing the design of alternatives

The design alternative selected from the first stage analysis was the caisson type quay structure. Three types of caisson structures were considered and the design was further detailed at this stage. The original design was also compared to the three types of caisson structures. Reliability-based Life Cycle Cost Analysis (RLCCA) that considered the external stability of the quay structures was conducted and incorporated into the value analysis as suggested in Fig. 5. Table 10 shows the result of the developed designs for the selected caisson types.

Table 10. Developed design of alternatives at the 2nd stage

3.3.2 Qualitative evaluation

(1) Determination of performance evaluation items and weights of criteria

In this second stage analysis, external stability was not considered as a performance evaluation criteria because it is considered as a risk cost item. Therefore, the performance evaluation criteria were set again without items related to the external stability. Using the same methodology as in the first stage analysis, the weights of the criteria were determined for the following 6 items: serviceability, durability, environmental impact, constructability, connection with other facilities, and maintenance. The results are listed in Table 11.

Table 11. Performance evaluation criteria and weights of the 2nd stage analysis

As shown in Table 11, the consistency of the questionnaire survey was maintained because the CR is 0.0022. At this stage, the performance evaluation items of highest importance were constructability and connection with other facilities.

(2) Rank index and performance evaluation

Rank indices (***RI***) of the design alternatives with respect to the performance evaluation criteria were determined through the identical procedure of the first stage analysis. The results are listed in Table 12. As

explained in the first stage analysis, the statistical distribution used for the random variable ***RI*** is triangular. The mean values of the resulting PI are in the following order: alternative 1, alternative 2, original design and alternative 3. This is from the cumulative distribution curves for ***PI*** values of the considered alternatives.

Table 12. Results of ***PI*** evaluation at the 2nd stage

3.3.3 Structural reliability analysis considering external stability

The structural reliability analysis of the external stability (sliding, overturning and bearing capacity) is conducted to rationally evaluate the risk of the structure in terms of the life cycle cost.

(1) Statistical properties of design factors

The design factors treated as random variables are selected from those factors related to the external stability of quay structures. The statistical properties (nominal value & coefficient of variation) proper to the selected design factors are applied as shown in Table 13 (Nagao et al. 1995, 1997, 1998).

Table 13. Statistical properties of design factors

(2) Calculation of external load

As a standard for the calculation of the external load for this study, the variation of the unit weight with respect to the nominal value of the utilized material is considered for the self-weight of the structure. The unit weight of seawater is deterministic, but the variation caused by seawater levels is considered. The highest water level for this case study is 3.87. In the case of buoyancy, deterministic values are used for the unit weight of seawater, but the variation caused by the remaining water level is statistically considered. For dead loads except the self-weight, a fixed value is assumed due to the deficiency of the related data. The forces and moments caused by the soil pressure are random variables, but only the mean value of the water level in the soil is applied without considering the variance of the water level. The variance of filling material weight is considered with the coefficient of variation shown in Table 13. In the case of the inertial forces, the statistical properties of the seismic

intensity in Table 13 are applied to force and moment. For the dynamic water pressure, force and moment are based on the statistical properties of the seismic intensity in Table 13 under the average sea level condition. However, the variance of the sea level is not considered for the dynamic water pressure as in the case of the soil pressure. The statistical properties of the sea level and remaining water level are applied to quantify the remaining water pressure. Traction power is considered to be deterministic due to insufficient data. The statistical properties in Table 13 are applied to the friction force. The load calculations for the original design and all the selected alternatives in normal, earthquake and storm conditions were conducted based on the aforementioned external load calculation standard. Table 14 summarizes the data related to the external loading.

Table 14. Loading data of alternatives

(3) Limit state function

Limit state of a structure means a condition that a structure or its critical elements lose their structural function or stability during its service period. Eq. 11, 12 and 13 are used as the limit state function against the failure caused by external stability problems such as sliding, overturning and bearing capacity failure.

$$Z = \left(X_1 + X_2 + X_3 + X_4 + X_5 + X_6 + X_7 + X_8 - X_9\right) X_{10} - \left(X_{11} + X_{12} + X_{13} + X_{14} + X_{15} + X_{16} + X_{17} + X_{18}\right) \quad \text{Eq. 11.}$$

where

X_1	=	self load of reinforced concrete	X_2	=	self load of plain concrete
X_3	=	self load of rock	X_4	=	self load of seawater
X_5	=	static vertical earth pressure	X_6	=	dynamic earth pressure
X_7	=	surface load	X_8	=	vertical load of crane
X_9	=	buoyancy	X_{10}	=	coefficient of friction
X_{11}	=	static horizontal earth pressure	X_{12}	=	dynamic horizontal earth pressure
X_{13}	=	hydrodynamic pressure	X_{14}	=	self weight of inertial force
X_{15}	=	surface load of inertial force	X_{16}	=	residual water pressure
X_{17}	=	tractive force	X_{18}	=	horizontal load of crane

$$Z = (X_1 + X_2 + X_3 + X_4 + X_5 + X_6 + X_7 + X_8 - X_9) - (X_{10} + X_{11} + X_{12} + X_{13} + X_{14} + X_{15} + X_{16} + X_{17}) \quad \text{Eq. 12.}$$

where X_1 = moment of self load of reinforced concrete
X_2 = moment of self load of plain concrete
X_3 = moment of self load of rock
X_4 = moment of self load of seawater
X_5 = total static vertical earth pressure
X_6 = total dynamic vertical earth pressure
X_7 = total surface load
X_8 = total vertical load of crane
X_9 = total buoyancy
X_{10} = total static horizontal earth pressure
X_{11} = total dynamic horizontal earth pressure
X_{12} = total dynamic water pressure
X_{13} = total self load of inertial force
X_{14} = total surface load of inertial force
X_{15} = total residual water pressure
X_{16} = total tractive force
X_{17} = total horizontal load of crane

$$Z = X_1 - \left(\frac{1 + 6X_2}{B}\right)\frac{X_3 + X_4 + X_5 + X_6 + X_7 + X_8 - X_9 + X_{10} - X_{11}}{B} \quad \text{Eq. 13.}$$

where X_1 = internal force of mound
X_2 = eccentric
X_3 = self load of reinforced concrete
X_4 = self load of plain concrete
X_5 = self load of rock
X_6 = self load of seawater
X_7 = static vertical earth pressure
X_8 = dynamic vertical earth pressure
X_9 = surface load
X_{10} = load of crane
X_{11} = buoyancy
B = width of caisson including footing

(4) Result of analysis

There are several software programs for structural stability evaluations based on reliability analysis. For this case study, RELSYS (Estes 1997), a well-verified and commercialized reliability analysis program, was utilized. The reliability analysis on the quay structure was conducted with regard to all the possible combinations of sliding, overturning and bearing capacity failure. The result of the structural reliability analysis against all the loading combinations satisfied the safety factors of the current design specifications. Table 15 shows the result of the structural reliability analysis including failure probability of the representing failure mode. According to Table 15, reliability index of alternative 3 is the highest at 2.37, followed by alternative 1 at 2.09. The failure probabilities of alternatives 1 and 3 were analyzed to be 1.85% and 0.88%. The results are in the following order: alternatives 3, 1, 2 and the original design.

Table 15. Result of structural reliability analysis

3.3.4 Quantitative LCC Analysis

(1) Analysis conditions and data

The methodology used for the quantitative analysis of the first stage was utilized for this stage as well. However, the failure restoration and loss cost during the operation are separately calculated because they were already considered as the risk cost items through the structural reliability against failure analysis. Table 16 shows the failure probability and the calculated annual equivalent failure cost.

Table 16. Failure probability and annual equivalent failure cost

(2)Result of analysis

The statistical LCC analysis that considers the risk cost was conducted based on Eq. 6, 7 and 8 mentioned in the previous section. The results are shown in Table 17, Fig. 5.

Table 17. Result of RLCCA (Reliability-based life cycle cost analysis)

Figure 5. The statistical LCC analysis

According to Table 17 and Fig. 5, alternative 2 is the most economical option with respect to overall LCC and alternative 3 is the lowest risk cost.

3.3.5 Value evaluation by reliability analysis

The qualitative and quantitative evaluation results of the previous sections were analyzed for value in the same way as the first stage analysis. The results of the value analysis on the alternatives are shown in Table 18. Eq. 5 is utilized as the limit state function for the reliability-based value analysis.

Table 18. Value evaluation by reliability analysis

As shown in Table 18, the results of the VI simulation shows that the mean values of the VIs of the original design, alternatives 1, 2 and 3 are 0.0492, 0.0528, 0.0524 and 0.0386, respectively. The unit of LCC is 100 million won for analyzing VI. The probabilities that VI of the newly developed alternatives are higher than that of original design are 96.81%, 94.45% and 0.00% for alternatives 1, 2 and 3, respectively. MCS methodology was utilized for the decision making reliability analysis with 10,000 simulation times and an error range of 0.5%. Therefore, VI of the alternative 2 is selected as the best design alternative at this stage.

3.4 Third stage analysis

3.4.1 LCC based structural optimization

(1) Objective function

The optimization of structure aims to find the values of the design variables that satisfy the limited conditions and minimize the objective function. The objective function for the design of the selected caisson-type quay structure is represented with Eq. 14. The objective function in Eq. 14 considers the design factors (Concrete, Reinforcing bar, Forms) that influence the LCC of quay structure greatly.

$$F = C_c \cdot V_c + C_f \cdot A_c + C_s \cdot W_s \qquad \text{Eq. 14.}$$

where F = LCC of caisson

C_c = cost of concrete per unit volume V_c = volume of concrete

C_f	=	cost of form per unit area	A_c	=	surface area of concrete
C_s	=	cost of reinforcing bar per unit weight	W_s	=	weight of reinforcing bar

(2) Design variables

Design variables for the large-sized caisson quay structure for minimizing the objective function in Eq. 14 are shown Fig. 6. t_h, t_l, t_b are the thicknesses of the side wall, the thickness of the wall in length direction, the thickness of the wall in depth direction, respectively. $A_{sv1\sim4}$ are the vertical reinforcements for the wall and $A_{sh1\sim4}$ are the horizontal reinforcements of the wall.

(a) plan (b) cross section

Figure 6. Design variables for the large-sized caisson quay structure

(3) Constraints

The constraints are divided into properties related to stability, properties of the concrete section, and the maximum and minimum values of the design variables. The constraints related to the stability are sliding, overturning and stability of the foundation mound under normal, earthquake, and storm conditions. The constraints related to the properties of the concrete section are the reinforcement, the bending moment and the crack width. For the side wall, the rear and front wall, the length and width of the walls, the vertical and horizontal reinforcement, and the caisson length, the minimum and maximum values of the design variables were considered. All the constraints mentioned above are summarized in Table 19.

Table 19. Constraints for structural optimization

3.4.2 Result of analysis

The results of the LCC-based structural optimization of the newly selected alternative are shown in Table 20. As a result of the section optimization, the side, rear, and front wall may have thicknesses of 40 m and the diaphragm wall may have a thickness of 0.30 m. The amounts of horizontal and vertical reinforcement are 44.93 ㎠ and 27.93 ㎠, respectively. These are significantly reduced values from the original design. The length of caisson has been increased from 9.9 m to 31.6 m. The LCC of the original design and the optimized alternative are 117,195 million won and 111,403 million won, respectively. Therefore, the selected optimal alternative is preferable.

Table 20. Results of LCC-based structural optimization

3.5 Design suggestions

This case study was conducted based on the proposed multi-stage decision making methodology for quay structure design by considering the level of detail and the uncertainties of design decision factors of different design stages. In the preliminary stage analysis, solid block, caisson, steel pipe pile and steel composite types were found to be the applicable alternatives. In the first stage analysis, the caisson was found to be the candidate alternative as a result of the value analysis that considered the performance analysis and the statistical LCC analysis. In the second stage analysis, large-sized caisson, semi-hybrid caisson and wide caisson were considered as the candidate alternatives for further consideration. As a result of the reliability analysis on the 3 alternatives and the original design, the large-sized caisson was suggested as the final alternative. At this stage, the performance analysis and statistical LCC analysis were performed by considering the reliability analysis on the external stability. In the third stage analysis, the optimal geometries and dimensions of the large-sized caisson type quay structure were suggested through an LCC-based structural optimization.

4. Conclusion

A four-stage decision making methodology is suggested for the optimal design of quay structures of harbor container terminals. The suggested methodology is composed of the selection of applicable alternatives through qualitative performance analysis in the preliminary stage analysis, the selection of alternatives for further consideration through LCC-based value analysis in the first stage analysis, the selection of the optimal structure type through the structural reliability-based LCC analysis in the second stage analysis, and the determination of the geometry and dimensions of the selected structure type through the LCC-based structural optimization technique. The feasibility of the methodology was examined by applying it to a real-world project. Design decisions should be made with different levels of details as the design process evolves. The value of the design was improved by considering the performance and life cycle cost of the design. The backbone of the suggested methodology is based on the analysis of 'value' of the design alternatives. The risk from the external stability and the LCC-based optimization for the determination of the geometry and dimensions of the alternatives were specific design considerations for quay structures. It is, however, expected that the procedure and methodology suggested in this paper can be applied to the design of other types of facilities.

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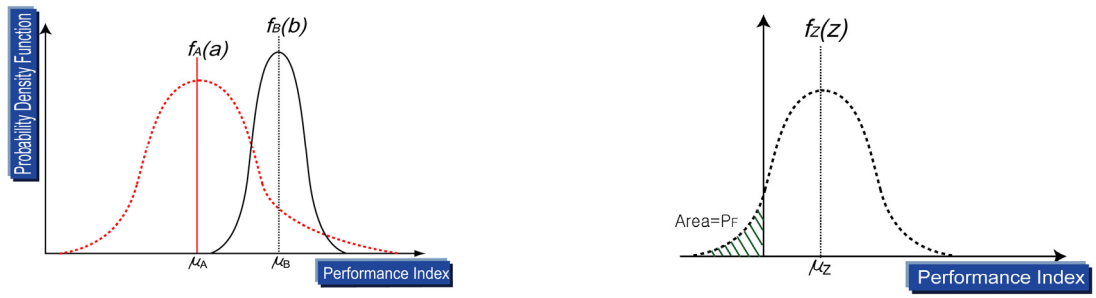


(a) separate $\boldsymbol{PDF_s}$ of $\boldsymbol{PI}$ of $\boldsymbol{ALT.1}$ & $\boldsymbol{ALT.2}$ (b) combined $\boldsymbol{PDF}$ of the limit state equation

Figure 1

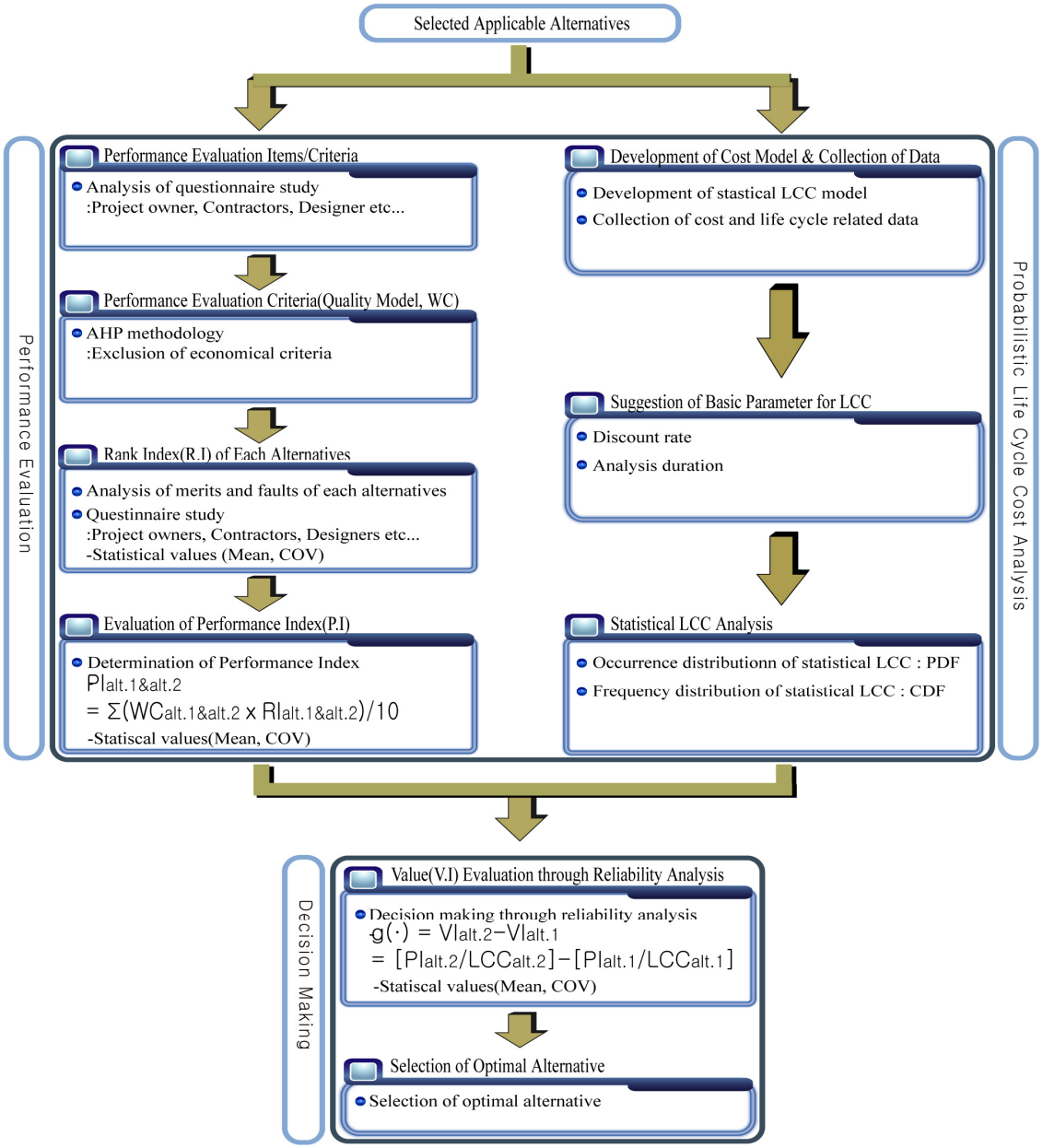

Selected Applicable Alternatives
Performance Evaluation
Performance Evaluation Items/Criteria
Analysis of questionnaire study
:Project owner, Contractors, Designer etc...
Performance Evaluation Criteria(Quality Model, WC)
AHP methodology
:Exclusion of economical criteria
Rank Index(R.I) of Each Alternatives
Analysis of merits and faults of each alternatives
Questinnaire study
:Project owners, Contractors, Designers etc...
-Statistical values (Mean, COV)
Evaluation of Performance Index(P.I)
Determination of Performance Index
PIalt.1&alt.2
= Σ(WCalt.1&alt.2 x RIalt.1&alt.2)/10
-Statiscal values(Mean, COV)
Development of Cost Model & Collection of Data
Development of stastical LCC model
Collection of cost and life cycle related data
Suggestion of Basic Parameter for LCC
Discount rate
Analysis duration
Statistical LCC Analysis
Occurrence distributionn of statistical LCC : PDF
Frequency distribution of statistical LCC : CDF
Probabilistic Life Cycle Cost Analysis
Decision Making
Value(V.I) Evaluation through Reliability Analysis
Decision making through reliability analysis
g(·) = VIalt.2−VIalt.1
= [PIalt.2/LCCalt.2]−[PIalt.1/LCCalt.1]
-Statiscal values(Mean, COV)
Selection of Optimal Alternative
Selection of optimal alternative

Figure 2

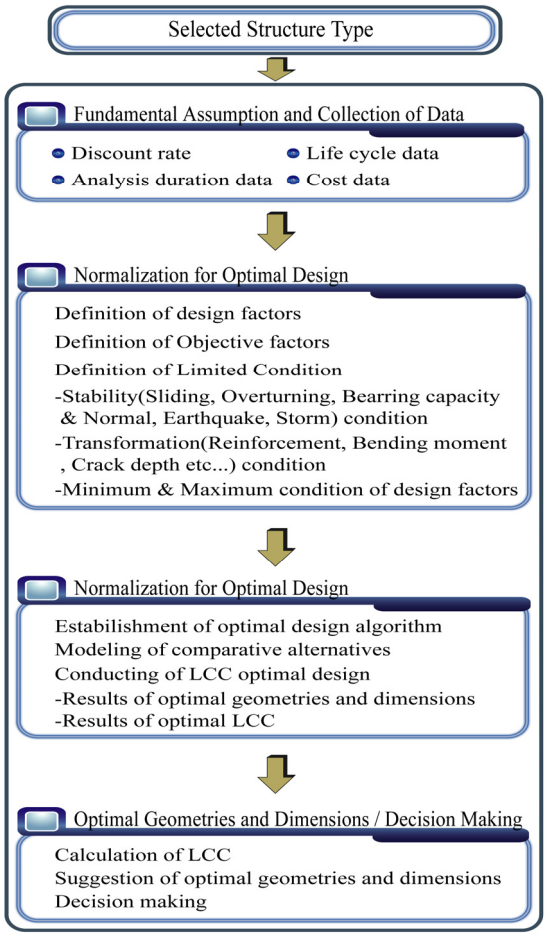

Selected Structure Type
Fundamental Assumption and Collection of Data
Discount rate
Life cycle data
Analysis duration data
Cost data
Normalization for Optimal Design
Definition of design factors
Definition of Objective factors
Definition of Limited Condition
-Stability(Sliding, Overturning, Bearring capacity & Normal, Earthquake, Storm) condition
-Transformation(Reinforcement, Bending moment , Crack depth etc...) condition
-Minimum & Maximum condition of design factors
Normalization for Optimal Design
Estabilishment of optimal design algorithm
Modeling of comparative alternatives
Conducting of LCC optimal design
-Results of optimal geometries and dimensions
-Results of optimal LCC
Optimal Geometries and Dimensions / Decision Making
Calculation of LCC
Suggestion of optimal geometries and dimensions
Decision making

Figure 3

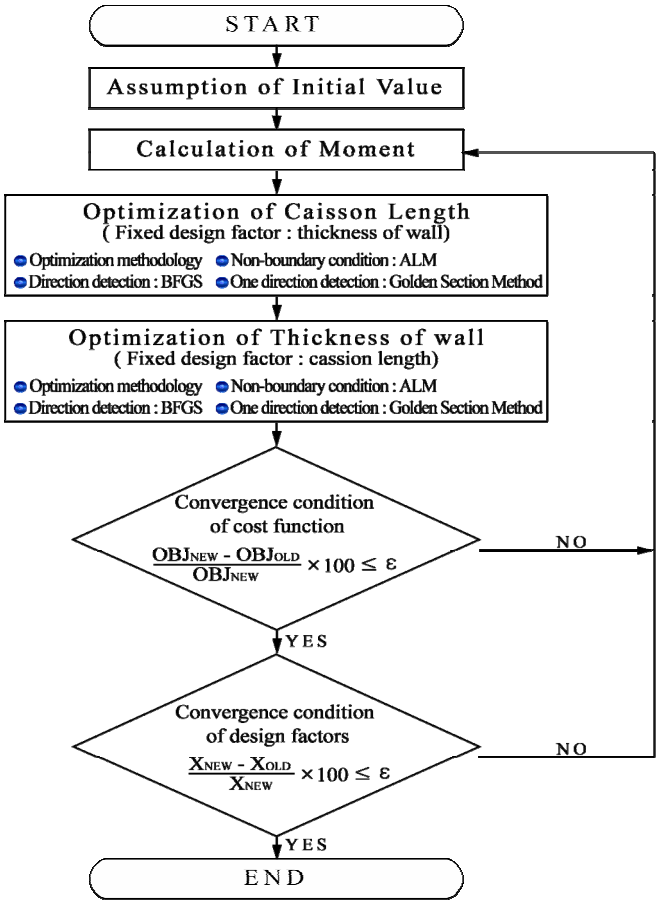

START
Assumption of Initial Value
Calculation of Moment
Optimization of Caisson Length
(Fixed design factor : thickness of wall)
Optimization methodology
Non-boundary condition : ALM
Direction detection : BFGS
One direction detection : Golden Section Method
Optimization of Thickness of wall
(Fixed design factor : cassion length)
Optimization methodology
Non-boundary condition : ALM
Direction detection : BFGS
One direction detection : Golden Section Method
Convergence condition
of cost function
$\frac{OBJ_{NEW} - OBJ_{OLD}}{OBJ_{NEW}} \times 100 \leq \varepsilon$
NO
YES
Convergence condition
of design factors
$\frac{X_{NEW} - X_{OLD}}{X_{NEW}} \times 100 \leq \varepsilon$
NO
YES
END

Figure 4

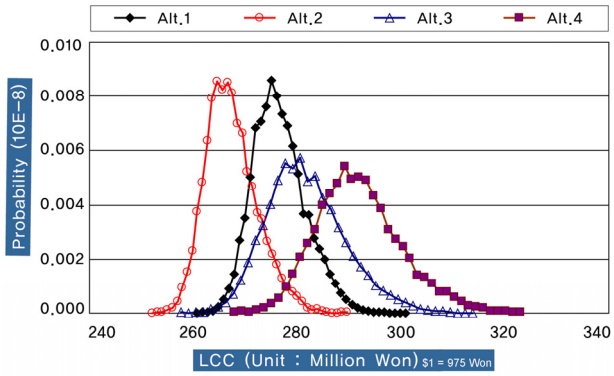
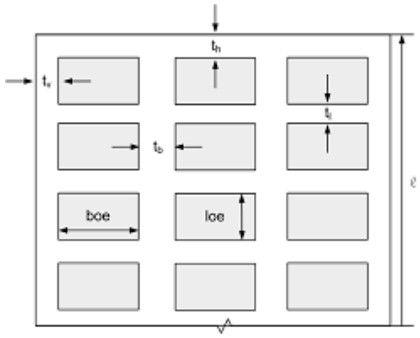
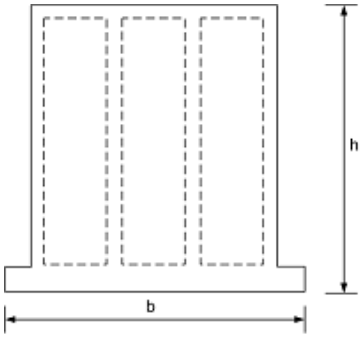

Alt.1
Alt.2
Alt.3
Alt.4
0.010
0.008
0.006
0.004
0.002
0.000
Probability (10E−8)
240
260
280
300
320
340
LCC (Unit : Million Won) $1 = 975 Won

Figure 5



(a) plan



(b) cross section

Figure 6

Table 1

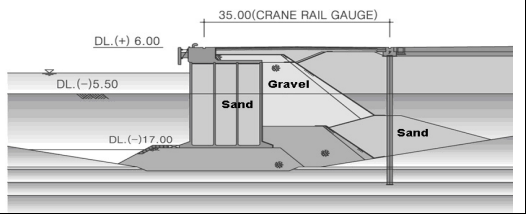
	Original Design	Cross Section	
Structure Type	Small Caisson		
Weight	1,631 tonf/Caisson		
Size	13.6(B)*9.9(L)*20.1(H)		
Number of Caisson	130		
Stuffing	Sea-sand for all Partition Chamber		

Table 2

Performance Evaluation Criteria		Quality Model
Criteria	Required Function	Mean
Serviceability	Level of accommodation of associated docking facility	6
Stability	Stability & adaptability for docking	16
Durability	Resistance to salt damage & service period	15
Environmental Impact	Level of environmental pollution during construction	13
Constructability	Convenience of construction method & equipment usage	14
Connection with Other Facilities	Consideration of master plan	9
Economy	Initial & follow-on cost	20
Maintenance	Frequency & convenience of maintenance activities	7

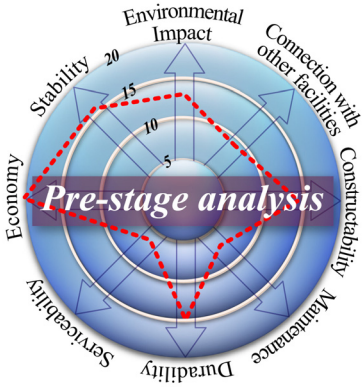


Table 3

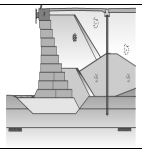
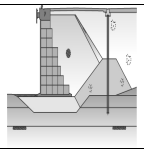
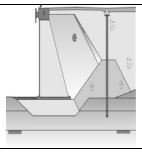
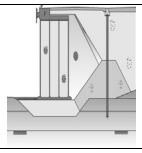
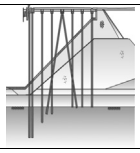
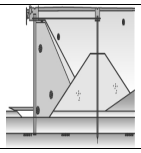
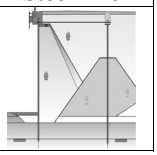
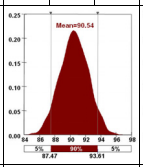
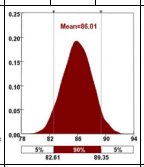
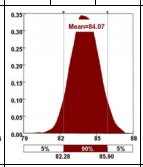
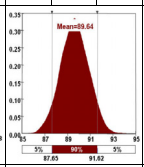
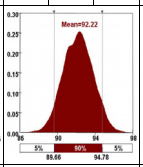
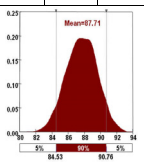
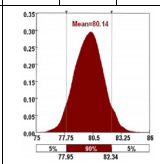
	Alt. 1	Alt. 2	Alt. 3	Alt. 4	Alt. 5	Alt. 6	Alt. 7
Structure Type	Gravity				Shore-Bridge	Sheet Pile	
	Solid	Cell	L-Type	Caisson	Steel Pipe	Composite Steel	Panel of Steel Pile
							

Table 4

	Alt. 1			Alt. 2			Alt. 3			Alt. 4			Alt. 5			Alt. 6			Alt. 7		
	Solid			Cell			L-Type			Caisson			Steel Pipe			Composite Steel			Panel of Steel Pile		
	Min	M.L	Max	Min	M.L	Max	Min	M.L	Max	Min	M.L	Max	Min	M.L	Max	Min	M.L	Max	Min	M.L	Max
Serviceability	4.68	5.24	5.75	4.43	4.85	5.28	3.85	4.36	4.92	4.42	4.80	5.18	5.52	5.95	6.37	5.02	5.40	5.78	4.45	4.96	5.52
Stability	12.48	13.97	15.33	9.23	12.40	14.99	11.87	13.23	14.72	13.55	15.33	16.90	14.08	15.57	16.93	12.48	13.97	15.33	13.39	14.40	15.41
Durability	12.70	14.38	15.85	12.55	13.50	14.45	12.57	13.62	14.70	13.80	14.88	15.93	12.55	13.50	14.45	12.70	14.38	15.85	10.80	11.88	12.93
Environmental Impact	10.89	11.80	12.74	10.88	11.70	12.52	10.88	11.70	12.52	9.59	10.50	11.44	10.66	11.60	12.51	11.44	12.65	13.75	8.84	10.05	11.15
Constructability	9.50	12.60	15.70	10.92	12.23	13.41	10.33	11.31	12.32	11.73	12.71	13.72	10.69	12.95	15.73	10.92	12.23	13.41	10.33	11.31	12.32
Connection with Other Facilities	6.68	7.44	8.28	6.63	7.20	7.77	7.53	8.10	8.67	7.02	7.86	8.62	6.68	7.44	8.28	7.53	8.10	8.67	5.78	6.54	7.38
Economy	16.94	19.17	21.13	15.27	18.50	22.46	14.74	16.00	17.26	16.74	18.00	19.26	16.40	17.84	19.24	11.54	15.50	18.73	12.79	14.89	17.27
Maintenance	5.46	6.11	6.71	5.16	5.60	6.04	5.17	5.65	6.16	5.17	5.65	6.16	6.04	7.18	8.56	5.22	5.88	6.63	5.27	6.02	6.68
PI Distribution Chart																					

PI	Min.	84.19	79.19	79.74	85.54	86.22	80.87	75.45
	Mean	90.54	86.01	84.07	89.64	92.22	87.71	80.14
	Max.	96.86	92.57	87.71	94.23	97.60	93.97	85.05
Reliability Level		99.99%	99.33%	98.86%	99.99%	99.99%	99.99%	Basis
Decisions		○			○	○	○	

Table 5

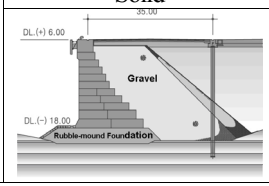
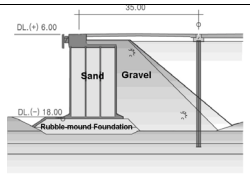
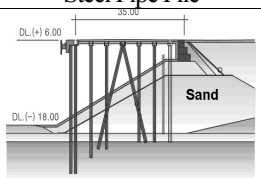
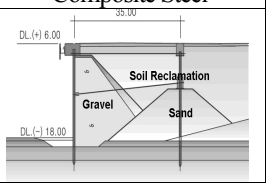
	Alt. 1	Alt. 2	Alt. 3	Alt. 4
Structure Type	Gravity		Shore-Bridge	Sheet Pile
	Solid	Caisson	Steel Pipe Pile	Composite Steel
				

Table 6

Items		A	B	C	D	E	F	G	Weight	Normalized
A	Serviceability	1.0	0.5	3.0	3.0	2.0	0.5	1.0	0.3436	15
B	Stability		1.0	4.0	4.0	3.0	1.0	2.0	0.5883	22
C	Durability			1.0	1.0	0.5	0.25	0.33	0.1236	6
D	Environmental Impact				1.0	0.5	0.25	0.33	0.1236	9
E	Constructability					1.0	0.33	0.5	0.2032	11
F	Connection with Other Facilities						1.0	2.0	0.5883	22
G	Maintenance							1.0	0.3436	15
									2.3142	100

Quality

Model

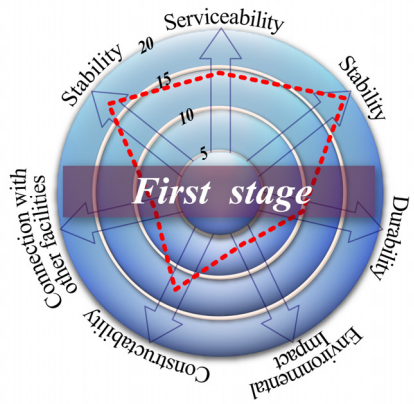


Table 7

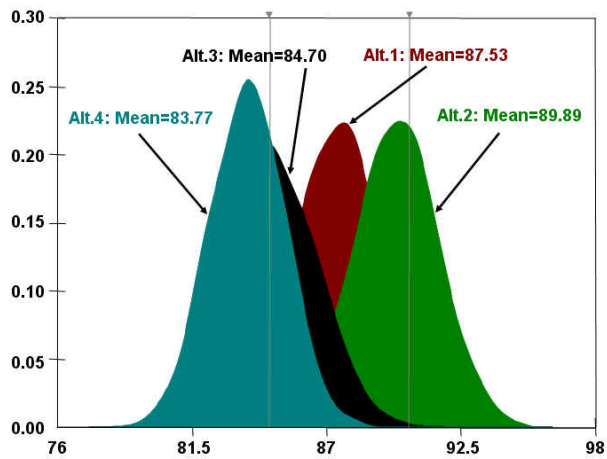
		Alt. 1			Alt. 2			Alt. 3			Alt. 4		
		Solid			Caisson			Steel Pipe Pile			Composite Steel		
		Min.	M.L.	Max.	Min.	M.L.	Max.	Min.	M.L.	Max.	Min.	M.L.	Max.
Serviceability		7.40	8.44	9.63	8.17	9.00	9.83	7.17	8.00	8.83	7.36	8.00	8.64
Stability		8.37	9.00	9.63	8.53	9.60	10.54	7.17	8.28	9.48	7.46	8.40	9.47
Durability		7.51	8.69	10.10	7.57	8.61	9.53	8.17	9.00	9.83	9.36	10.00	10.64
Environmental Impact		6.97	8.22	9.55	7.17	8.28	9.48	8.17	9.00	9.83	7.36	8.00	8.64
Constructability		8.17	9.00	9.83	8.57	9.61	10.53	7.80	8.73	9.58	7.36	8.00	8.64
Connection with Other Facilities		7.57	8.70	9.74	7.80	8.73	9.58	7.17	8.28	9.48	7.37	8.10	8.86
Maintenance		8.20	8.92	9.62	7.80	8.73	9.58	7.80	8.73	9.58	8.14	8.90	9.63
PI	Min.	81.42			83.61			77.24			78.21		
	Mean	87.53			89.89			84.70			83.77		
	Max.	93.86			96.33			91.72			89.72		
PI Probability Distribution Function													

Table 8

			Alt. 1	Alt. 2	Alt. 3	Alt. 4
			Solid	Caisson	Steel Pipe	Composite Steel
Life Cycle Cost (100M Won, $1=975 Won)	Initial Cost		2,580.61	2,494.28	2,590.45	2,69.91
	Operation / Maintenance Cost		185.41	179.04	226.10	249.59
	Total	Mean	2,7766.02	2,673.32	2,816.55	2,919.50
		COV	0.0428	0.0415	0.0589	0.0558

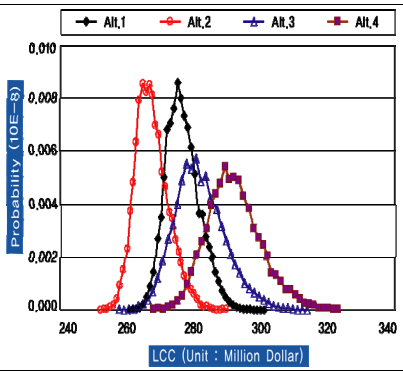


Table 9

		Alt. 1	Alt. 2	Alt. 3	Alt. 4
		Solid	Caisson	Steel Pipe Pile	Composite Steel
Value Index (VI)	Min.	0.0288	0.0308	0.0267	0.0259
	Mean	0.0317	0.0337	0.0302	0.0288
	Max.	0.0351	0.0369	0.0339	0.0319
	Std. Dev.	0.0008	0.0009	0.0010	0.0008
	Skewness	0.1081	0.0861	0.0770	0.1552
Decision Making	Min.	-0.0036	-0.0009	Basis	-0.0058
	Mean	0.0015	0.0089		-0.0014
	Max.	0.0062	0.0035		0.0039
	Reliability Level	89.13%	99.71%		13.28%
Optimum Alternative			○		

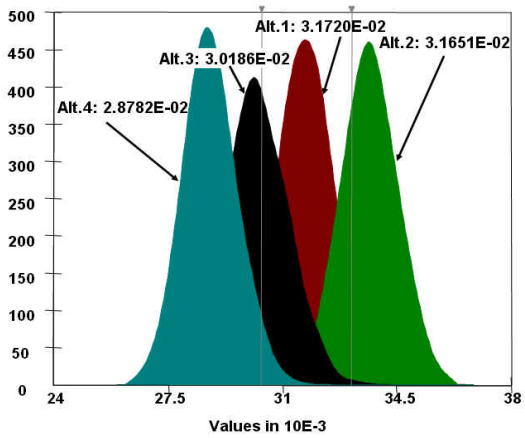
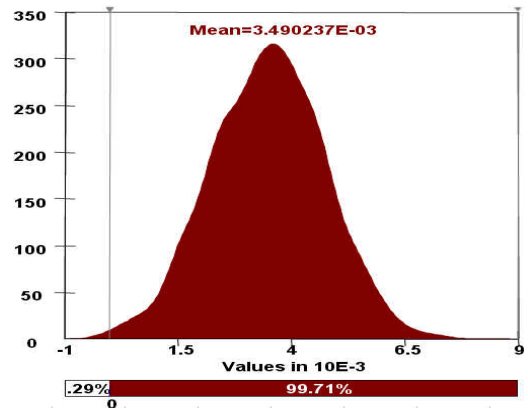
VI Distribution Chart	g(.) = VI(Alt. 2)-VI(Alt. 3)
	

Table 10

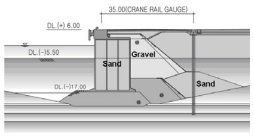
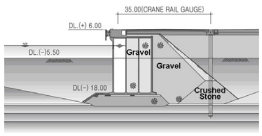
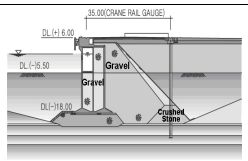
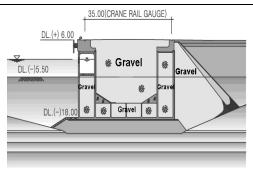
Classification	Original Design	Alternative		
		Alternative 1	Alternative 2	Alternative 3
	Small Caisson	Wave Breaking Caisson	Semi-Hybrid Caisson	Wide-Width Caisson
Design				
	13.6B*9.9L*20.1H Water line : 15.26m Weight : 1,631 tonf/Caisson	14.9B*31.6L*21.6H Water line : 14.2m Weight : 5,000 tonf/ Caisson	9.7B*28.2L*21.6H Water line : 16.8m Weight : 4,194 tonf/ Caisson	38.7B*26L*22.1H Water line : 15.49m Weight : 6,558 tonf/ Caisson

Table 11

Items		A	B	C	D	E	F	Weight	Normalized
A	Serviceability	1.0	2.0	1.0	0.5	0.5	1.0	0.3073	15
B	Durability		1.0	0.5	0.33	0.33	0.5	0.1699	10
C	Environmental Impact			1.0	0.5	0.5	1.0	0.3073	15
D	Constructability				1.0	1.0	2.0	0.5864	22
E	Connection with Other Facilities					1.0	2.0	0.5864	22
F	Maintenance						1.0	0.3037	16
								2.2646	100

Quality Model

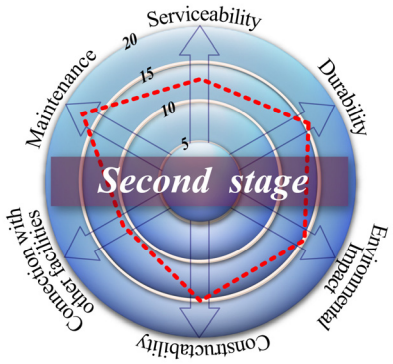


Table 12

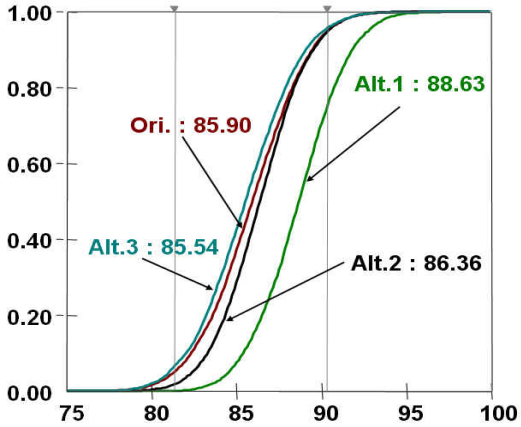
		Original			Alternative 1			Alternative 2			Alternative 3		
		Small Caisson			Wave Breaking Caisson			Semi-Hybrid Caisson			Wide-Width Caisson		
		Min.	M.L.	Max.	Min.	M.L.	Max.	Min.	M.L.	Max.	Min.	M.L.	Max.
Serviceability		9.55	11.33	12.90	11.05	12.83	14.40	12.55	14.33	15.90	12.55	14.33	15.90
Durability		7.37	8.56	9.60	7.16	8.50	9.68	6.37	7.56	8.60	6.37	7.56	8.60
Environmental Impact		11.05	12.83	14.40	11.05	12.83	14.40	11.05	12.83	14.40	11.05	12.83	14.40
Constructability		18.41	21.02	23.33	18.41	21.02	23.33	16.21	18.82	21.13	16.15	19.80	23.45
Connection with Other Facilities		16.21	18.82	21.13	18.41	21.02	23.33	16.21	18.82	21.13	13.95	17.60	21.25
Maintenance		11.79	13.69	15.36	10.15	12.80	15.45	11.75	14.40	17.05	11.79	13.69	15.36
PI	Min.	76.26			80.40			77.07			75.80		
	Mean	85.90			88.63			86.36			85.54		
	Max.	95.55			97.65			94.42			98.19		
PI Cumulative Distribution Function													

Table 13

Classification		Nominal Value	Coefficient of Variation	Classification	Nominal Value	Coefficient of Variation
Unit Volume Weight	Reinforced Concrete	0.98	0.02	WL (water level)	2.32	0.30
	Plain Concrete	1.02	0.02	RWL (remaining water level)	2.55	0.36
	Sand	1.02	0.04	Seismic intensity of design	1.00	0.25
	Rock	1.00	0.03	Coefficient of Friction	1.06	0.15
Earth Pressure	Static	1.00	0.10	-	-	-
	Dynamic	1.00	0.25	-	-	-

Table 14

		Original				Alternative 1				Alternative 2				Alternative 3			
		Small Caisson				Wave Breaking Caisson				Semi-Hybrid Caisson				Wide-Width Caisson			
		V	H	Mv	Mh	V	H	Mv	Mh	V	H	Mv	Mh	V	H	Mv	Mh
Self Load	Reinforced Concrete	212.64		1701.63		212.64		1701.63		212.64		1701.63		212.64		1701.63	
		4.25		34.03		4.25		34.03		4.25		34.03		4.25		34.03	
	Plain Concrete	10.02		88.15		10.02		88.15		10.02		88.15		10.02		88.15	
		0.20		1.76		0.20		1.76		0.20		1.76		0.20		1.76	
	Rubble mound	514.46		5044.09		426.69		5097.27		291.31		2978.66		403.37		8205.16	
		15.43		151.32		15.43		151.32		15.43		151.32		15.43		151.32	
Buoyancy		305.79		2690.94		349.40		3127.17		232.16		1822.42		359.82		6962.54	
		12.90		113.53		12.90		113.53		12.90		113.53		12.90		113.53	
Surface load		22.80		271.32		25.80		295.41		8.20		95.12		69.90		1482.48	
		0.00		0.00		0.00		0.00		0.00		0.00		0.00		0.00	
Earth Pressure		20.57	76.79	362.03	680.24	22.11	82.50	395.77	759.97	20.84	82.56	327.25	731.07	55.41	109.28	2144.37	1022.65
		1.91	7.14	33.66	63.28	1.91	7.14	33.66	63.28	1.91	7.14	33.66	63.28	1.91	7.14	33.66	63.28
Residual Water Pressure			37.02		343.92		37.02		343.92		37.02		343.92		37.02		343.92
			5.39		50.04		5.60		54.83		5.74		56.25		5.62		55.12
Traction Force			15.15		365.87		6.33		159.20		6.67		167.68		11.54		283.85
			0.00		0.00		0.00		0.00		0.00		0.00		0.00		0.00
Load of Crane		57.37	5.74	269.64	135.46	57.37	5.74	269.64	135.46	57.37	5.74	269.64	135.46	57.37	5.74	269.64	135.46
		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Upper : Mean Value, Lower: Standard Deviation																	

Table 15

		Upper & Lower Bound	Failure Probability (P_f)	Reliability Index (β)	Decision
Original	Small Caisson	$3.77E-02 \le P_f \le 3.90E-02$	3.84E-02	1.77	OK
Alternative 1	Wave Breaking Caisson	$1.79E-02 \le P_f \le 1.91E-02$	1.85E-02	2.09	OK
Alternative 2	Semi-Hybrid Caisson	$4.20E-02 \le P_f \le 4.36E-02$	4.28E-02	1.72	OK
Alternative 3	Wide-Width Caisson	$8.14E-03 \le P_f \le 9.46E-03$	8.80E-03	2.37	OK

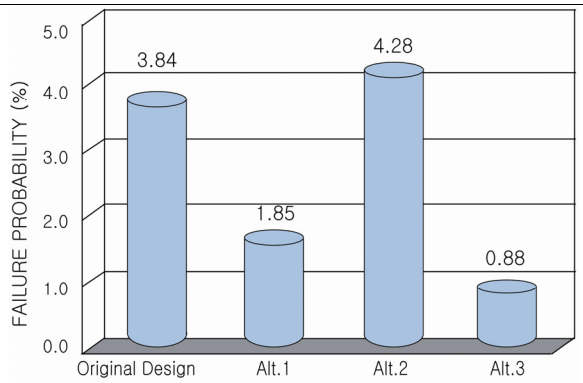


Table 16

		Original	Alternative 1	Alternative 2	Alternative 3
		Small Caisson	Wave Breaking Caisson	Semi-Hybrid Caisson	Wide-Width Caisson
Frequency	Failure Probability	3.84E-02	1.85E-02	4.28E-02	8.80E-03
	Equivalent Failure Probability	4.893E-04	2.334E-04	5.466E-04	1.105E-04
Cost (Won)	Reconstruction Cost	209,024,114	203,334,995	195,397,124	269,533,428
	Operate Loss Cost	942,857,140	942,857,140	942,857,140	942,857,140
Equivalent Failure Cost (Won, $1=975Won)		563,615	267,521	622,169	133,969

Table 17

			Original	Alternative 1	Alternative 2	Alternative 3
			Small Caisson	Wave Breaking Caisson	Semi-Hybrid Caisson	Wide-Width Caisson
Life Cycle Cost (100M Won, $1=975Won)	Initial Investment Cost		1,099.59	1,047.37	597.09	1,595.53
	Operation & Maintenance Cost	Operation & Maintenance	172.36	166.66	170.76	232.32
		Risk Cost	475.58	464.55	521.98	387.28
	Total	Mean	1,747.53	1,678.58	1,649.83	2,215.13
		COV	0.0248	0.0223	0.0268	0.0222

Table 18

		Original	Alternative 1	Alternative 2	Alternative 3
		Small Caisson	Wave Breaking Caisson	Semi-Hybrid Caisson	Wide-Width Caisson
Value Index (VI)	Min.	1,099.59	1,047.37	597.09	1,595.53
	Mean	172.36	166.66	170.76	232.32
	Max.	475.58	464.55	521.98	387.28
	Std. Dev	1,747.53	1,678.58	1,649.83	2,215.13
	Skewness	0.0248	0.0223	0.0268	0.0222
Decision Making	Min.	Basis	-0.0034	-0.0039	-0.0169
	Mean		0.0037	0.0032	-0.0105
	Max		0.0128	0.0100	-0.0028
	Std. Dev		.0020	0.0020	0.0019
	Skewness		0.0638	0.0064	0.0348
	Confidence Interval		96.81%	94.45%	0.00%
Optimum Alternative			○		

Table 19.

		Constraints	Contents
Stability-related Constraints	Sliding (3ea)	$g(x)=\frac{F_s^s}{S\cdot F_s}-1\le 0$	F_s^s : Allowable Safety Rate of Ordinarily Load $S\cdot F_s$: Rate of Ordinarily Load
	Overturning (3ea)	$g(x)=\frac{F_s^{sto}}{S\cdot F_{sto}}-1\le 0$	F_s^{sto} : Allowable Safety Rate of Storm $S\cdot F_{sto}$: Safety Rate of Storm
	Soil Pressure of Ground (3ea)	$g(x)=\frac{q_{sto}}{S\cdot q_a^{sto}}-1\le 0$	q_{sto} : Sub-grade Reaction of Strom Load q_a^{sto} : Allowable Sub-grade Reaction of Strom Load
		$g(x)=\frac{q_{sqe}}{S\cdot q_a^{sqe}}-1\le 0$	q_{sqe} : Sub-grade Reaction of Seismic Load q_a^{sqe} : Allowable Sub-grade Reaction of Seismic Load
	Soil Pressure of Foundation (3ea)	$g(x)=\frac{F_s^{sto}}{S\cdot F_{sto}}-1\le 0$	F_s^{sto} : Allowable Safety Rate of Storm Load $S\cdot F_{sto}$: Safety Rate of Storm Load
		$g(x)=\frac{F_s^{eq}}{S\cdot F_{eq}}-1\le 0$	F_s^{eq} : Allowable Safety Rate of Storm Load $S\cdot F_{eq}$: Safety Rate of Storm Load
Concrete Behavior-related Constraints	Steel Weight (2ea)	$g(x)=\frac{A_s^{min}}{S\cdot A_{suse}}-1\le 0$	A_s^{min} : Minimum Steel Weight A_{suse} : Using Steel Weight
	Bending Strength (1ea)	$g(x)=\frac{M_r}{\psi M_r^a}-1\le 0$	M_r : Ultimate Bending Moment of Load ψ : Strength Capacity Reduction Factor M_r^a : Nominal Strength of Section
	Crack Width (1ea)	$g(x)=\frac{W}{W_a}-1\le 0$	W : Allowable Crack Width W_a : Crack Width
Minimum & Maximum Constraints	Thickness (6ea)	$g(x)=\frac{T_{in}^{min}}{T_{in}}-1\le 0$	T_v^{min} : Minimum Thickness of Side Wall T_v : Using Thickness of Side Wall
		$g(x)=\frac{T_h}{T_h^{max}}-1\le 0$	T_h : Using Thickness of Before & Behind Wall T_h^{max} : Maximum Thickness of Before & Behind Wall
		$g(x)=\frac{T_{in}^{min}}{T_{in}}-1\le 0$	T_{in}^{min} : Minimum Thickness of Bulkhead T_{in} : Using Thickness of Bulkhead

Table 20

Design Data & LCC Components					Original Design	Optimum Design
					Small Caisson	Wave Breaking Caisson
Result of Alternative Design of Profile	Thickness of Side Wall				0.40	0.40
	Thickness of Before & Behind Wall				0.40	0.40
	Thickness of Bulkhead (Length)				0.30	0.30
	Thickness of Bulkhead (Width)				0.30	0.30
	Steel Weight (Horizontality)				53.49	44.93
	Steel Weight (Verticality)				32.78	27.54
	Length of Caisson				9.90	31.60
Result of Optimum Estimate of LCC	Initial Cost	Design / Supervision Cost			83.60	79.63
		Construction cost	Stem	Manufacturing of Caisson	278.85	261.20
				Transport / Install / Loading	9.67	1.89
				Incidental expenditure etc.	5.11	2.76
			Pier, Super-structure, Crane		720.94	700.54
		Initial Safety Inspection			1.42	1.35
		Subtotal			1,0099.59	1,047.37
	Operation & Maintenance Cost	Repair & Reinforcement Cost			67.37	64.16
		Periodical Inspection / Scrutiny / Safety Scrutiny			4.99	2.50
		Subtotal			72.36	66.66
	Total				1,171.95	1,114.03