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OPTIMUM ASEISMIC DESIGN OF EMBEDDED STEEL PLATE CELLULAR BULKHEADS

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SUMMARY

The embedded steel plate cellular bulkhead has been developed as a new type of sea wall, for it is applicable even for poor sea beds and in deep water sites. As the sea wall is a wide and huge structure, economical design and construction are needed. The sea wall structure has relatively little design variables, which makes it a suitable structure for optimization. In this study, the authors develop the optimum aseismic design method of embedded steel plate cellular bulkheads including the ground improvement cost, and to clarify the relationship between the design factors and the response constraints of these structures.

INTRODUCTION

In recent years, there has been an increasing amount of construction work of artificial islands and seawalls. Due to a shortage of area, the sites are found at deeper and poorer seabeds which have brought difficulties for construction. To cope with such difficulties, a system named embedded steel cellular bulkhead shown in Fig. 1 was developed. Because it is economical and has easy workability, it is regarded as very prospective. As the sea wall is a wide and huge structure, it has been our greatest concern as to how to optimize and simplify the aseismic design. We regard the systems of sea walls as very attractive objects for the study of optimization, because of less design variables.

This study intends to develop an optimization program to minimize the total cost of embedded steel cellular bulkheads, to demonstrate the optimum aseismic design on four cases of ground conditions, to clarify effects of design variables on the objective function or constraints.

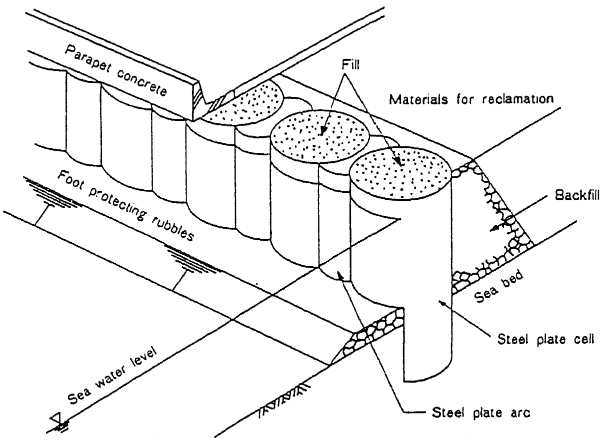

Fig. 1 Embedded steel plate cellular bulkhead system

FORMULATION OF OPTIMUM DESIGN

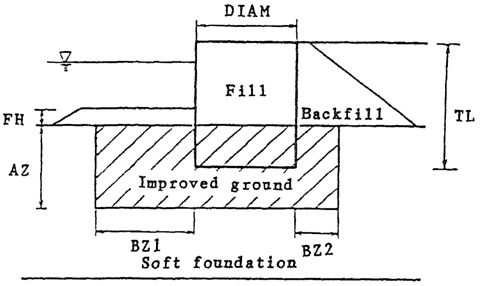

Fig. 2 Design Variables

The optimum design problem of the embedded steel plate cellular bulkhead is formulated as follows:

$$C = F\ (X) \longrightarrow \min \qquad (1)$$

$$g_i\ (X) \leqq 0 \ (i=1,\ 2,\ 3 \ldots n) \qquad (2)$$

where, C indicates the objective function, which is the unit construction cost of the sea wall divided by the cost of standard design. The construction cost is itemized in six items;
(a) cell & arc fabrication cost and transportation cost, (b) cell & arc equipment cost and driving work cost, (c) cell & arc filling cost, (d) sea bed improvement cost, (e) foot protection cost, (f) backfilling cost. X is a design variable vector, and as is shown in Fig. 2, six variables such as cell diameter (DIAM), cell height (TL), foot protection height (FH), sea bed improvement depth (AZ), front sea bed improvement width (BZ1), and back sea bed improvement width (BZ2) are considered. Consequently, this problem attained the optimization problem of six variables formulated as:

$$X = (\mathrm{DIAM},\ \mathrm{TL},\ \mathrm{FH},\ \mathrm{AZ},\ \mathrm{BZ1},\ \mathrm{BZ2})^T \qquad (3)$$

g_i indicates constraints, and thirteen constraints such as safety factor of circular sliding, cell deformation, static and seismic displacement, static and seismic bearing capacity, safety factor of static and seismic sliding, constraints of front and back sea bed improvement width, constraints of static and seismic propagation stress, constraints of vibro-hammer, and also the upper and the lower limit constraints of these design variables are considered. The number of the vibro-hammers employed for the construction is checked in the analytical program, and is not an active constraint.

Constraints

1) Deformation of cell

The steel plate cells are required to satisfy Eq.(4) so as not to be deformed by such external forces as earth pressure, residual water pressure, etc; working against the sea wall.

$$F \leqq M_{rd} \ / \ M_d \qquad (4)$$

where, M_{rd} denotes the deformation resistance moment of sea wall (tf·m/m), M_d denotes the deformation moment (tf·m/m), and F denotes the safety factor ($\geqq$1.2).

2) Vertical ground reaction force (q) (bearing capacity)

The vertical ground reaction force (q) at the bottom of the sea wall must be smaller than the allowable vertical bearing capacity that is obtained by the procedure shown in "Part 5, Chapter 2", of Explanatory Manual of the Technical Criteria for Port and Harbor Facilities (Ref.1).

3) Shearing reaction force (Q) at the bottom surface (sliding)

The shearing reaction force at the cell bottom surface (Q) must be smaller than the allowable shearing resistance force (Q_a) that originates between the sea wall bottom surface and the ground, and is obtained by the following formula:

$$Q_a = 1/F(W + P_v) \tan p \qquad (5)$$

where: W denotes unit weight of sea wall (tf/m), P_v denotes vertical component force of earth pressure working on the front and back side of sea wall (tf/m), p denotes the coefficient of the internal frictions of the fill at the bottom end of sea wall (degree), F denotes safety factor (static = 1.2, and seismic = 1.0)

4) Displacement at the top of the sea wall (displacement)

The horizontal displacement (D) at the top of the sea wall must not exceed the allowable displacement (D_a) obtained from past actual earthquake damage,

$$D_a = 0.015H \tag{6}$$

where H indicates the height of the sea wall and D_a takes the same value in both static and seismic condition.

5) Circular sliding

As occasions demand, circular sliding of the ground is studied under the conditions that the circular sliding surface does not cross the sea wall. The safety factor of circular sliding must be larger than 1.2.

6) Sea bed improvement width

When sea bed improvement is required, the lower limit constraints on sea bed improvement width and the constraints on the propagation stress working width must be satisfied, which are determined by the distance from the intersection of the grounds top surface and the cell to the active and passive collapse surface first originating at the cell bottom end.

Objective function

Each cost estimation basis is mentioned as follows; The bases of the unit prices adopted for construction cost estimation are from the "Ports and Harbors Civil Contract Works - the Ministry of Transport (Japan Ports and Harbors Institute)" and "Construction Prices Hand Book - 1985 edition". This cost estimation is based on the total construction length of 500m, cell transportation distance of 30km, construction ship operation ratio of 80%, and the sea bed improvement method by S.C.P. (70% improvement). The objective function used in this study is based on the sea wall construction cost per unit length divided by the cost of a certain standard design.

RESULTS OF THE OPTIMUM DESIGN

This optimization problem is formulated with 6 design variables such as DIAM, TL, FH, AZ, BZ1, and BZ2. The number of design variables is the important factor for the optimum design, and reduction of the number of design variables makes the optimization simpler. So, in this study, from the viewpoint of practical application, influence of each design variable on the objective functions and on constraints, and the possibility of reducing the number of the design variables are studied. The optimization sub-routine COPES (Ref.2) is used in this study to solve this optimization problem. Four cases of ground conditions are studied such as shallow soft ground (H = 5m), deep soft ground (H = 15m), and with or without ground improvement, respectively. The horizontal seismic coefficient (k_h) adopted for the design is 0.2.

Shallow soft-ground without ground improvement

Since sea bed improvement is not required, the design variables relating to sea bed improvement AZ, BZ1 and BZ2 can be omitted, and the problem is studied as a three variable problem of DIAM, TL, and FH. The results of solving this problem using the optimization sub-routine COPES is shown in Table 1. Figures marked with an asterisk (*) indicate the active constraints, and the three constraints of the lower limit of TL, seismic displacement, and seismic sliding are active. The optimum solution in this case is obtained as; DIAM = 20.66m, TL = 22.5m, FH = 1.77m, and C = 4.694.

As TL indicates the lower limit constraint, it is clear that the construction cost is reduced as the value of TL is made smaller, that is, in this case, to fix TL at 22.5 meters. After all, in the case where no sea bed improvement is required, the optimum design is formulated as a two-variable problem of DIAM and FH. The design space of the case is shown in Fig. 3.

Shallow soft-ground with sea bed improvement

There are six design variables such as DIAM, TL, FH, AZ, BZ1, and BZ2, and the optimization results obtained using COPES are shown in Table 1. The optimum solution shows that TL takes the lower limit and AZ takes the upper limit, and that seismic displacement, seismic sliding, and constraints on front and back sea bed improvement width are active. Each value of the optimum solution are: DIAM = 14.47m, TL = 18.5m, FH = 3.14m, and then C = 4.805.

Table 1 Optimum results (k_h=0.2)

			Soft foun. 5m		Soft foun. 15m	
			No imp.	Imp.	No imp.	Imp.
Objective Function			4.694	4.805	7.922	7.545
Design Variables	DIAM	(m)	20.66	14.47	23.52	18.19
	TL	(m)	22.50*	18.50*	32.50*	18.57
	FH	(m)	1.77	3.14	4.00*	3.11
	AZ	(m)	-	5.00*	-	13.00
	BZ1	(m)	-	9.80	-	15.40
	BZ2	(m)	-	2.00	-	5.10
Constraints	Circular Sliding		1.577	1.480	1.827	1.202*
	Deformation of Cell		3.569	2.325	5.279	3.340
	Static Displacement		0.184	0.061	0.160	0.042
	Static Bearing Capacity		0.630	0.308	0.544	0.278
	Static Sliding		2.806	5.378	3.415	5.593
	Front Improvement Width		-	1.009*	-	0.997*
	Back Improvement Width		-	1,000*	-	1.000*
	Static Propagation Stress		-	0.308	-	0.909
	Seismic Displacement		1.474*	1.477*	1.495*	0.344
	Seismic Bearing Capacity		0.772	0.562	0.460	0.266
	Seismic Sliding		1.000*	1.007*	2.630	1.078*
	Seismic Propagation Stress		-	0.562	-	0.966*

* : Active

To make the situation of the optimum solution clearer, each design variable is studied as follows through the graphical method, like the above. First, the feasible region delineated by constraints is shown in Fig. 4 with DIAM as the ordinate and AZ as the abscissa. As is evident from the figure, when the propagation stress constraints are not considered, the feasible region exists on

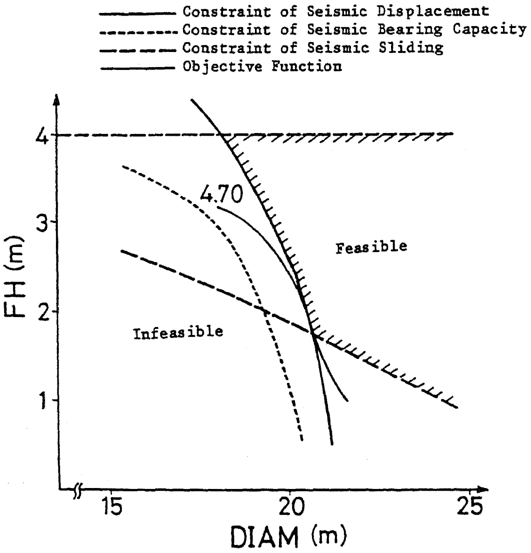

Fig. 3 Design space expressed by DIAM and FH (TL=22.5m)

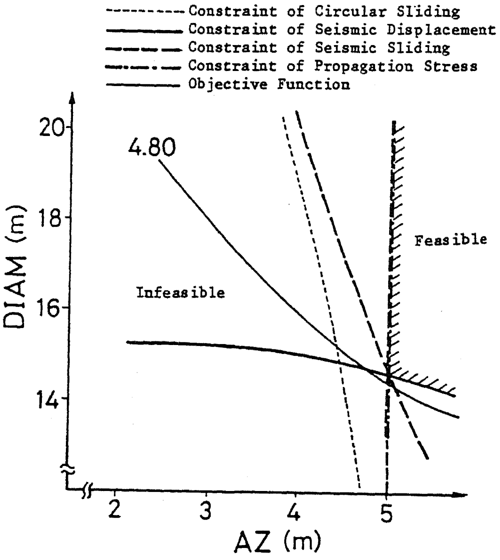

Fig. 4 Design space expressed by AZ and DIAM (TL=18.5m, FH=3.14m, BZ1=9.8m,BZ2=2.0m)

the right hand top in the figure but when considered, the feasible region is allocated to the domain of AZ = 5.0m, then, all of the soft ground is needed to be improved. Thus, the design variable AZ is determined as 5.0m, and the remainders are the optimization problem of five variables. And since the two variables of BZ1 and BZ2 are safe enough judging from Table 1 with respect to the circular sliding constraints, and AZ has been determined already, the optimization problem is considered to be the function of only TL. It is clear from Table 1, like the case where no sea bed improvement is required, that the adoption of the lower limit constraints value (18.5m) of TL makes it economical. In the result, this problem becomes the optimization problem of the two variables of DIAM and FH. This problem is also formulated properly as the optimization problem of two variables, though the six variables are concerned at first, and the solution is obtained without difficulty.

According to Table 1, the construction cost index of the shallow soft-ground without sea bed improvement is C = 4.694, and is smaller than that with sea bed improvement (C = 4.805) by about 2.3%, however from the viewpoint of engineering, it makes no significant difference either way. Adoption of the sea bed improvement should be left to the competent engineer's discretion. In this study, since the construction cost is considered except for the element of the construction term, and also the construction term is much shorter in practice in the case where no sea bed improvement is required than in the case where required, then the construction term should be taken into consideration in the course of the construction planning.

Deep soft-ground without ground improvement

In this case the optimization is studied as a three-variable problem of DIAM, TL, and FH. The results solved using COPES are shown in Table 1. The three active constraints are the lower limit constraints of TL, the upper limit constraints of FH and the constraints of seismic displacement, and the optimum solution is: DIAM = 23.52m, FH = 4.0m, TL = 32.5m, and the cost index C = 7.922. It is proven from Table 1, like the case of shallow soft-ground with no ground improvement, that TL takes the lower limit value. Consequently, in this case, like the case of shallow soft-ground, the problem results in the two-variable optimization problem of DIAM and FH excepting TL.

Deep soft-ground with sea bed improvement

The results of a six-variable problem optimized using COPES are shown in Table 1. The active constraints are circular sliding, seismic sliding, front and back ground improvement width, and seismic propagation stress, all these are related with ground improvement measurement. In the optimum solution, considering that BZ1, BZ2 are the minimum values determined by passive collapse angle, that AZ is allocated halfway in the soft ground, and that the safety factor constraints of circular sliding is active, then, it is known that the optimum solution is to improve the ground in the depth where AZ satisfies the circular sliding safety factor under the minimum required BZ1 and BZ2 values.

In this six-variable problem, as each design variable is mutually related and the essence of the optimization problem is not clear, the study is conducted as follows using the graphical solution. First, the contour line of the feasible region delineated by the constraints and the contour line of the objective function are shown in Fig. 5 with AZ and DIAM as the coordinate axes. The feasible region of the constraints is almost parallel to the ordinate, and the contour line of the objective function is a very steep gradient. This means that AZ is dominant over the objective function as well as over the constraints. The figures delineated with AZ and FH, or AZ and TL as the coordinate axes show the same tendency, and the decision of AZ is the most significant design factor in this optimization problem.

In this case, since BZ1, BZ2 and TL take the lower limit values, only AZ is required to be determined, and consequently this optimization problem can be studied as a two-variable problem of DIAM and FH. As has been clarified throughout this case, the optimization becomes a very difficult problem in the case of deep soft-ground and with ground improvement, since the constraints are mutually related. Even when the optimization is studied using COPES, remarkably different results are obtained depending on the choice of initial values, therefore, as have been studied herein, the combined use of the graphical solution is required to solve the complicated optimization problem simply and surely.

And since the difference of the cost is as small as about 5% between the cases of ground improvement and no improvement, adoption of the ground improvement should be left to the engineer's discretion. And as already mentioned, the objective function in this study is considered except for the construction term, this matter is required to be considered when adoption of the ground improvement is decided.

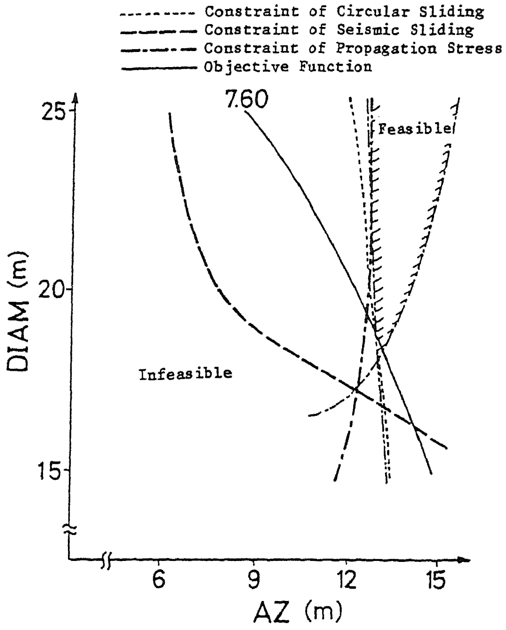

Fig. 5 Design space expressed by AZ and DIAM (TL=18.57m, FH=3.11m, BZ1=15.40m, BZ2=5.10m)

CONCLUSIONS

In this study, the optimization programs of the embedded steel plate cellular bulkheads as a new type of sea wall have been developed, which is to minimize the construction cost including the ground improvement cost, the optimum design has been demonstrated on four cases of ground conditions, furthermore, the effect of the design variables on the constraints or the objective function has been clarified using the sensitivity analysis or the graphical solution, mapping out the contour lines of the objective function and the constraints, and thus the characteristics of the optimum solution has been studied.

This study shows that the problem is formulated as the optimization problem of only two design variables of DIAM and FH, thus the problem is solved easily. Under the design conditions in this study, no distinct cost difference is recognized between the cases of sea bed improvement and of no improvement, adoption of ground improvement must be decided from the synthetic viewpoint.

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