

Optimum design of a soil improvement system by preloading with wick-drains

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Abstract

The design of a soil improvement system, by preloading with wick drains, is formulated as a constrained optimization problem. The drain spacing, length, embankment height, and time required to achieve a specified consolidation settlement are selected as design variables whereas, the total cost of the system is adopted as an objective function. The cost function includes excavation, sand blanket, engineering fill, surcharge, wick drains, instrumentations and observation cost components. For a given site dimensions, soil profile, targeted settlement, and maximum allowed time to achieve, a computer program is coded in Fortran-90 to solve the problem of consolidation in vertical and radial directions based on Hansbo's (1981) and Olson (1977) methods, with different options to include the effects of smear, well resistance, ramp loading, and wick drains characteristics. In conjunction with the modified Hooke and Jeeves optimization method, the program is applied to a real project under construction in Basra province-Iraq. The real site dimensions, soil profile, and soil characteristics, as obtained from the site investigation program, are adopted. For the unit prices assigned, the results support the capability of the optimization method in manipulating such a decision-making problem. They also revealed failure of decision taken of canceling the inclusion of wick drains and adopting preloading only as a technique to improve the site soil. Studying the effects of the values of coefficients of consolidation in two directions on the behavior highlighted the vital importance of conducting a preliminary site investigation to evaluate foundation proposals. After arriving to a decision regarding soil improvement, the detailed phase of site investigation should be oriented towards finding the first order soil parameters associated with the selected soil improvement method, instead of wasting the efforts and money through conducting an exaggerated number of traditional less important tests. It is concluded that increasing the coefficient of consolidation in the vertical direction and the ratio of its radial value to the vertical one will increase the optimum drain spacing and decrease the drain length, the time required to achieve a specified settlement, and the required cost of the system. Embankment height, time of consolidation and total cost are proportional to the required settlement.

Keywords: soil improvement, preloading, wick drains, optimization.

1. INTRODUCTION

Preloading is one of the most effective and economical methods to reduce the post construction settlement. It is usually combined with prefabricated vertical drains to speed up the consolidation process through shortening the drainage path by allowing the water to flow horizontally towards the drain, and drain out, Das (2011).

Optimization is to find the best possible solution among the many potential solutions satisfying the chosen criteria. Many optimization methods have been developed but, their application to new problems needs critical evaluation Rao (1979).

The research aims to utilize the available capabilities in the field of operations research to build a model to get the economical design of any soil improvement system by preloading with vertical

drains. It is intended to apply that model afterwards to a real life project in the city of Basra-Iraq.

2. CONSOLIDATION SETTLEMENT

The magnitude of consolidation settlement can be determined, depending on whether the soil is normally or preconsolidated, Das (2011). The average degrees of vertical consolidation (U_v) could be calculated based on Terzaghi's theory of one dimensional consolidation. The radial degree of consolidation (U_r) could be calculated using Hansbo's or Olson's equations, [as cited by Indraratna and Chu (2005)]. The combined average degree of consolidation (U_{vr}) can be found by using Carrillo's relationship (1942), which is defined as:

$$U_{vr} = 1 - (1 - U_v) \times (1 - U_r) \quad (1)$$

For partially penetrating drains, Zeng and Xie (1989) proposed the following equation to calculate the

average degree of consolidation (U) as, Ong et.al. (2012):

$$U = \frac{H_{\text{drain}}}{H} U_{\text{vr}} + \left(1 - \frac{H_{\text{drain}}}{H}\right) U_{\text{v}} \quad (2)$$

Where (H_{drain}) represents the drain length and (H) the total thickness of the clay layer.

3. CASE STUDY

3.1 General

Basra refinery upgrading-FCC project is located at Basra province in Iraq near the Main Outfall Drain, Figure (1). The site, is a (750 m x 1000 m) rectangular area. Most of the site is within a level of (+0.50 m) above mean sea level (MSL).

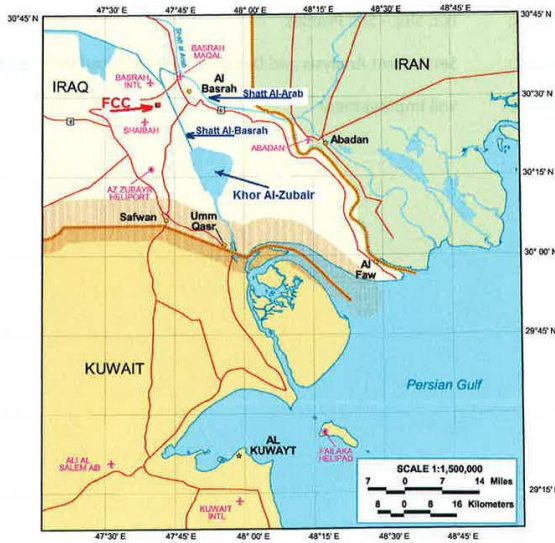


Fig. 1. Geographic location of the FCC project

3.2 Site investigation program

The soil exploration program included drilling (70) boreholes to depths of about (15m-30m) from the natural ground level, Andrea (2011). Extensive statistical data analyses were performed regarding soil properties. Although, the coefficient of consolidation and soil permeability have vital roles in predicting the rate of consolidation, a single value was assigned for the former and no value was given for the latter. Also, no consolidated undrained tests were conducted to trace the expected improvement of shear strength. The general configuration of the project is shown in Figure (2). It was recommended to use pre-loading with wick drains at (2 m) spacing, Al-Ani (2011).

3.3 EXECUTION STEPS

The site preparation works was divided into four steps, SRC (2011):

- Step 1: Topsoil removal of (300 mm) thickness.
- Step 2: Furnish a sandy layer of minimum (300 mm) thickness.
- Step 3: Raise the site elevation up to (+1.50 m MSL) with compacted structural fill material.

Step 4: Raise the site elevation up to (+6.00 m MSL) with uncontrolled and uncompacted backfill material.

An area of about (160000 m²) around the flare is excluded from steps (3 and 4). The surcharge load should be applied for a duration of about (14 months). The construction time is also about (14 months). The wick drains were decided to be cancelled.

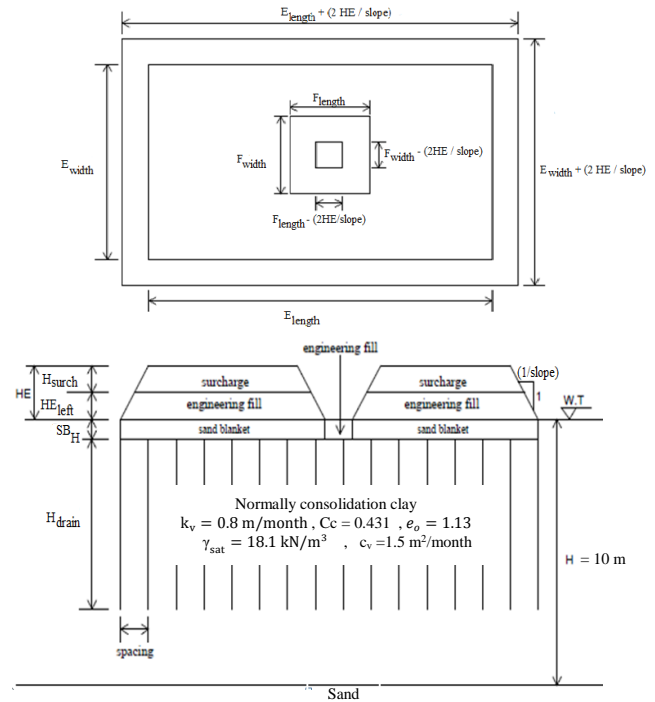


Fig. 2. Soil Profile showing preload configuration

3.4 Monitoring program

(150) settlement plates, installed after step- 2, are required. After the construction of the structural fill, monitoring settlements should be realized. (25) inclinometers and (25) piezometers should be installed at the end of step-4. The readings should begin after installation of piezometers and inclino-meters, SRC (2011). It should be mentioned that the commencement of readings after step-4 will not cover the considerable construction period. In addition to that, the inclinometers and piezometers would be inefficient as shear failure indicators, since they would be activated after constructing the full height of embankment. The commencement of installation and monitoring of inclinometers and piezometers were modified by the first author to be after step-3.

4. FORMULATION OF THE PROBLEM

4.1 Design variables

There are four design variables to be optimized namely; spacing between drains (spacing), length of drain (H_{drain}), the total height of embankment (HE)

and the time of consolidation (t). The properties of sand blanket and materials of embankment are treated as constant quantities. A single ramp loading is assumed with a maximum embankment height of (5.5 m) constructed in (14 months).

4.2 Objective function

A formula representing the total cost of the system (COST), is considered as the objective function. It consists of the following cost components; excavation (C_{EX1}), sand blanket (C_{SB}), fill type-1 (C_{Fill1}) (engineering fill material), fill type-2 (C_{Fill2}) (additional surcharge), removing of surcharge (C_{EX2}), wick drain (C_{WD}), instrumentation (C_{Ins}) and monitoring (C_{Mon}).

$$COST = C_{EX1} + C_{SB} + C_{Fill1} + C_{Fill2} + C_{EX2} + C_{WD} + C_{Ins} + C_{Mon} \quad (3)$$

The excavation works include the base of embankment only.

$$C_{EX1} = V_{EX} \times EX_{cost} \quad (4)$$

where:

V_{EX} = volume of excavation work (m^3)

EX_{cost} = unit cost of excavation work (ID/ m^3)

$$V_{EX} = \left(E_{width} + \frac{2HE}{slope} \right) \times \left(E_{length} + \frac{2HE}{slope} \right) \times SB_H \quad (5)$$

The purpose of the sand blanket is to conduct the expelled water away from the drains and to provide a sound working mat.

$$C_{SB} = (V_{EX} - V_{EXF}) \times SB_{cost} \quad (6)$$

where:

V_{EXF} = an excluded volume to be replaced by engineering fill (m^3)

SB_{cost} = unit cost of sand blanket [material, labor and quality control] (ID/ m^3)

$$V_{EXF} = \left(F_{width} - \frac{2HE}{slope} \right) \times \left(F_{length} - \frac{2HE}{slope} \right) \times SB_H \quad (7)$$

The cost of engineering fill equals

$$C_{Fill1} = V_{Fill1} \times Fill1_{cost} \quad (8)$$

where:

V_{Fill1} = volume of filling by engineering fill material (m^3)

$Fill1_{cost}$ = unit cost of engineering fill [material, labor and quality control] (ID/ m^3)

$$V_{Fill1} = V_{EXF} + \left(E_{width} + \frac{HE+H_{surch}}{slope} \right) \times \left(E_{length} + \frac{HE+H_{surch}}{slope} \right) \times HE_{left} - \left(F_{width} - \frac{HE+H_{surch}}{slope} \right) \times \left(F_{length} - \frac{HE+H_{surch}}{slope} \right) \times HE_{left} \quad (9)$$

The cost of filling by any material as additional surcharge (which will be removed at the end of the project) is calculated as;

$$C_{Fill2} = V_{Fill2} \times Fill2_{cost} \quad (10)$$

where:

V_{Fill2} = volume surcharge (m^3)

$Fill2_{cost}$ = unit cost of filling by surcharge material [material & labor] (ID/ m^3)

$$V_{Fill2} = \left(E_{width} + \frac{H_{surch}}{slope} \right) \times \left(E_{length} + \frac{H_{surch}}{slope} \right) - \left(F_{width} - \frac{H_{surch}}{slope} \right) \times \left(F_{length} - \frac{H_{surch}}{slope} \right) \times H_{surch} \quad (11)$$

The cost of removing the additional surcharge is:

$$C_{EX2} = V_{Fill2} \times EX_{cost} \quad (12)$$

The cost of one drain is:

$$C_{WD1} = H_{drain} \times WD_{cost} \quad (13)$$

where:

WD_{cost} = unit cost of wick drain [materials & installation] (ID/m)

The number of drains can be calculated as :

$$N_{drain} = INT \left[\left(E_{width} + \frac{2HE}{slope} \right) \times \frac{1}{spacing} + 1 \right] \times INT \left[\left(E_{length} + \frac{2HE}{slope} \right) \times \frac{1}{spacing} + 1 \right] - INT \left[\left(F_{width} - \frac{2HE}{slope} \right) \times \frac{1}{spacing} - 1 \right] \times INT \left[\left(F_{length} - \frac{2HE}{slope} \right) \times \frac{1}{spacing} - 1 \right] \quad (14)$$

where:

INT = stands for integer conversion of the result.

The cost of all drains is:

$$C_{WD} = C_{WD1} \times N_{drain} \quad (15)$$

The settlement plates will be left in position whereas, the piezometers and inclinometers are properties of the contractor. A lump - sum price will be assumed for the project.

The cost of monitoring is:

$$C_{Mon} = t \times Mon_{cost} \quad (16)$$

where:

t = the time from the start of monitoring (months)

Mon_{cost} = unit cost of monitoring (ID/month)

4.3 Constraints

The spacing between drains should be more than the equivalent drain diameter (d_w).

$$Spacing > d_w \quad (17)$$

The length of wick drains must be non-negative and not more than the thickness of the clayey layer.

$$H \geq H_{drain} > 0 \quad (18)$$

The total height of embankment must not be less than height of engineering fill.

$$HE \geq HE_{left} \quad (19)$$

The time of consolidation must not be less than the construction period and not exceed the maximum allowed time for the project.

$$t_{\max} \geq t \geq t_{\text{const}} \quad (20)$$

The accomplished settlement should not be less than the required one which in turn must not exceed 90 % of the final consolidation settlement.

$$0.9 S_c \geq S_{c_{\text{acc}}} \geq S_{c_{\text{req}}} \quad (21)$$

The final optimization problem can be stated as: find $\{\text{spacing } H_{\text{drain}} \text{ HE } t\}^T$ to minimize the objective function described by equation (3) subjected to the constraints expressed by equations (17) to (21). Among the pattern direct search methods, Hooke and Jeeves is utilized to perform the minimization. The program performing the minimization process using that method has been drawn from Bundy (1984) and translated to Fortran-90. A program (wick_drain) is prepared to evaluate the objective function and constraints. It works as a sub-routine receiving the values of the design variables from the main optimization program.

5. OPTIMIZED DESIGN

5.1 Sample problem

This problem illustrates the application of Hooke and Jeeves optimization method to the soil improvement design problem, and the influence of the initial trial points on the results. Using Olsen's method and adopting square drain distribution, the values given to the input parameters of subroutine (wick-drain) are listed in Table (1). Note: 1 US\$ \approx 1200 ID.

Table (1) The values of input variables for subroutine "wick_drain"

dw (m)	k_h/k_s	C_h/C_v k_h/k_v	ds/dw	$S_{c_{\text{req}}}$ (m)	t_{max} (month)
0.066	3	1	2	0.6	28

Ex_cost (ID/m ³)	SB_cost (ID/m ³)	Fill1_cost (ID/m ³)	Fill2_cost (ID/m ³)
3,000	10,000	10,000	5,000

WD_cost (ID/m)	Ins_cost (ID)	Mon_cost (ID/month)
2,000	20,000,000	1,000,000

In the above, (dw) is the equivalent drain diameter, (k_h and k_s) horizontal coefficients of permeability away from and inside the smear zone, and (ds) represents the diameter of this zone. The initial and optimum values of the design variables and the objective function are

listed in Table (2). The convergence towards the minimum for each trial point is shown in Figure (3). The values of the objective function are nearly the same, which support the efficiency of the optimization method in locating the true global minimum.

Table (2) Optimum values for different initial trial points

Initial point	S (m)	H_drain (m)	HE (m)	t month	Cost 10^{10} (ID)
1.0, 6, 2.5, 12	3.616	3.774	2.1	9.6	1.432632
1.5, 8, 2.5, 14	5.094	4.145	2.1	9.7	1.417220
0.5, 7, 2.0, 13	4.098	3.797	2.0	9.798	1.377092

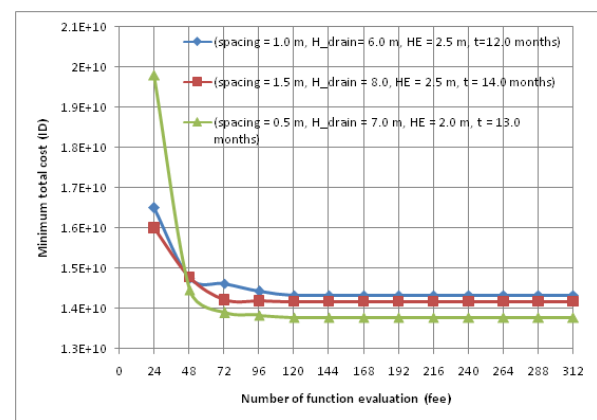


Fig. 3. Convergence towards the minimum for the three initial points

5.2 Parametric study

An extensive parametric study is performed regarding the effects of coefficients of consolidation, the unit cost of wick drains, and the required settlement. All constant values are similar to those enlisted in Table (1). The results are shown in Tables (3 to 8).

Table 3. Results of the parametric study
[$C_h/C_v = 1, 2$; $S_{c_{\text{req}}} = 0.4$ m; $WD_{\text{cost}} = 2000$ ID/m]

c_v m ² /month	spacing m	H_drain m	HE m	t month	cost 10^{10} ID
0.5	1.500	5.573	1.2	11.396	1.260625
	1.921	5.550	1.2	10.956	1.146108
1.0	2.937	4.754	1.2	9.778	1.034531
	3.160	4.330	1.2	9.352	1.020537
1.5	4.320	3.599	1.2	8.400	0.992328
	4.120	3.380	1.2	8.200	0.993046
2.0	4.520	2.975	1.2	7.400	0.9866061
	16.480	3.394	1.2	7.396	0.9708894
2.5	5.720	2.600	1.2	6.800	0.9787753
	17.240	2.776	1.2	6.796	0.9704590

Table 4. Results of the parametric study
[$c_h/c_v = 1,2$; $S_{c_{req}} = 0.5$ m ; $WD_{cost} = 2000$ ID/m]

c_v m ² /month	spacing m	H_{drain} m	HE m	t month	cost 10 ¹⁰ ID
0.5	1.500	5.936	1.6	11.98	1.471240
	1.700	5.377	1.6	10.978	1.379142
1.0	2.498	4.389	1.6	10.194	1.242540
	3.140	4.351	1.6	9.954	1.211609
1.5	6.480	4.174	1.6	9.000	1.171049
	4.357	3.379	1.6	8.780	1.180295
2.0	17.220	3.097	1.6	8.000	1.160307
	19.400	3.080	1.6	8.000	1.160016
2.5	5.300	2.196	1.6	7.396	1.168289
	63.700	2.376	1.6	7.396	1.158975

Table 5. Results of the parametric study
[$c_h/c_v = 1,2$; $S_{c_{req}} = 0.6$ m ; $WD_{cost} = 2000$ ID/m]

c_v m ² /month	spacing m	H_{drain} m	HE m	t month	cost 10 ¹⁰ ID
0.5	1.518	5.571	2.2	11.593	1.734897
	1.720	5.780	2.0	11.800	1.583019
1.0	2.495	4.904	2.0	11.196	1.444338
	2.893	4.578	2.0	10.592	1.415466
1.5	4.098	3.797	2.0	9.798	1.377092
	4.098	3.398	2.0	9.600	1.374241
2.0	5.100	2.794	2.0	8.796	1.362935
	5.340	2.599	2.0	8.800	1.360977
2.5	60.3	2.300	2.0	8.140	1.350014
	6.340	1.999	2.0	8.2	1.355957

5.2.1 Coefficients of consolidation

It can be realized from Tables and Figure (4) that the optimum spacing increases with the increase in coefficient of vertical consolidation. The effect of coefficients ratio is more pronounced beyond vertical coefficient values of [(1.5-2.0) m²/month]. Not imposing an upper limit on drain spacing resulted in high values for large consolidation coefficients which practically cancels the need for wick drains.

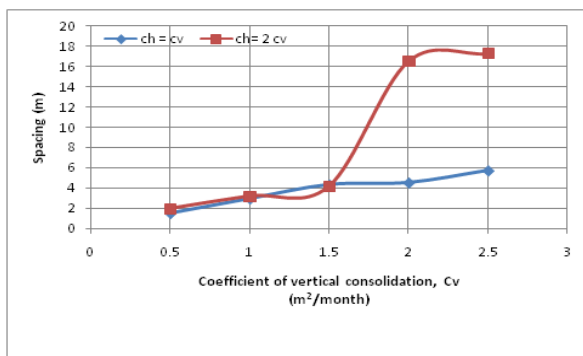


Fig. 4. Optimum spacing vs. coefficients of consolidation for (0.4 m) required settlement.

Figure (5) shows that the optimum drain length is inversely proportional to the coefficient of vertical consolidation. The coefficients ratio has a minor effect on the results.

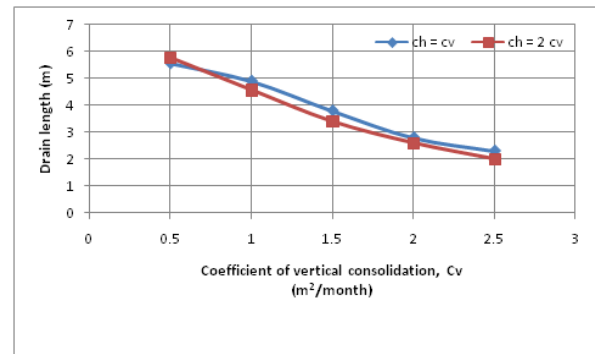


Fig. 5. Optimum drain length vs. coefficients of consolidation for (0.6 m) required settlement

It can be deduced from Tables (3) to (5) that the optimum embankment height is not sensitive to the variations in the coefficient of vertical consolidation or the coefficients ratio. Figure (6) reveals a reduction in the optimum time required to achieve a specified settlement with the increase in coefficient of vertical consolidation and coefficients ratio.

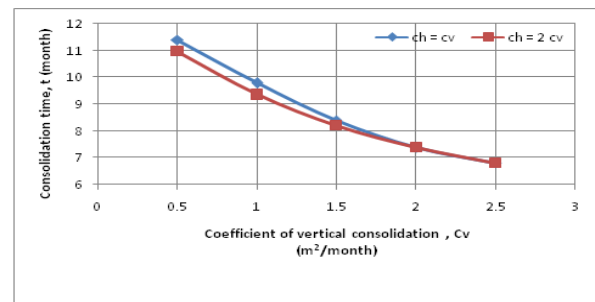


Fig. 6. Consolidation time vs. coefficients of consolidation for (0.4 m) required settlement

It is clear from Tables and Figure (7) that the total cost decreases as the coefficient of vertical consolidation increases. The rate of reduction and the effect of coefficients ratio are greatly reduced beyond a coefficient of vertical consolidation of 1.5 m²/month.

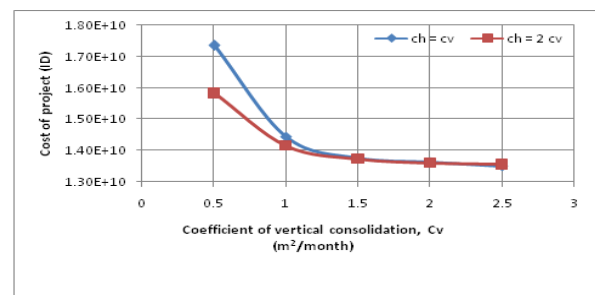


Fig. 7. Total cost vs. coefficients of consolidation for (0.6 m) required settlement

Table 6. Results of the parametric study
[$c_v = 1.5 \text{ m}^2/\text{month}$; $c_h/c_v = 1,2$; $S_{c\text{req}} = 0.4 \text{ m}$]

WD _{cost} ID/m	spacing m	H _{drain} m	HE m	t month	cost 10 ¹⁰ ID
2000	4.320	3.599	1.2	8.400	0.992328
	4.120	3.380	1.2	8.200	0.9930462
4000	4.320	3.599	1.2	8.400	1.015189
	4.120	3.380	1.2	8.200	1.016636
6000	4.320	3.599	1.2	8.400	1.038031
	4.120	3.380	1.2	8.200	1.040226
8000	4.320	3.599	1.2	8.400	1.060900
	4.120	3.380	1.2	8.200	1.063815
10000	63.300	3.358	1.4	7.198	1.064476
	78.700	3.936	1.4	6.956	1.064367

Table 7. Results of the parametric study
[$c_v = 1.5 \text{ m}^2/\text{month}$; $c_h/c_v = 1,2$; $S_{c\text{req}} = 0.5 \text{ m}$]

WD _{cost} ID/m	spacing m	H _{drain} m	HE m	t month	cost 10 ¹⁰ ID
2000	6.480	4.174	1.6	9.000	1.171049
	4.357	3.379	1.6	8.780	1.180295
4000	6.480	4.174	1.6	9.000	1.182972
	4.357	3.379	1.6	8.780	1.201485
6000	6.480	4.174	1.6	9.000	1.194894
	4.357	3.379	1.6	8.780	1.222675
8000	6.480	4.174	1.6	9.000	1.206816
	4.357	3.379	1.6	8.780	1.243865
10000	6.480	4.174	1.6	9.000	1.218738
	4.357	3.379	1.6	8.780	1.265055

Table 8. Results of the parametric study
[$c_v = 1.5 \text{ m}^2/\text{month}$; $c_h/c_v = 1,2$; $S_{c\text{req}} = 0.6 \text{ m}$]

WD _{cost} ID/m	spacing m	H _{drain} m	HE m	t month	cost 10 ¹⁰ ID
2000	4.098	3.797	2.0	9.798	1.377092
	4.098	3.398	2.0	9.600	1.374241
4000	4.098	3.797	2.0	9.798	1.404057
	4.098	3.398	2.0	9.600	1.398378
6000	4.098	3.797	2.0	9.798	1.431022
	4.098	3.398	2.0	9.600	1.422513
8000	4.098	3.797	2.0	9.798	1.457986
	4.098	3.399	2.0	9.600	1.446667
10000	63.500	3.380	2.2	8.960	1.446522
	5.282	2.997	2.2	8.800	1.510651

5.2.2 Unit cost of the drain

Proportional trends between the total cost and the drain unit cost are observed.

5.2.3 Targeted consolidation settlement

The required settlement has minor effects on the drain spacing and length. The embankment height, consolidation time, and total cost are proportional to the required settlement.

For (8000 I.D./m) drain unit cost, the total cost and time of the project are around (14.60 Billion I.D.) and (9.8 months), respectively, compared to (31.60 Billion I.D.) and (28 months) for the project without drains.

6. CONCLUSIONS

1. For large projects, it is necessary to activate the preliminary phase of site investigation to evaluate foundation proposals. This will help to direct the detailed site investigation towards predicting the first order parameters.
2. The construction period should be taken into consideration in the rate of settlement analysis, especially for large projects.
3. The optimization method of Hooke and Jeeves proved to be powerful to arrive to the economical design through locating the optimum values of the design variables and the minimum cost of the project.
4. Total cost reduces as the coefficient of vertical consolidation increases. The rate of reduction and the effect of coefficients ratio are greatly decreased beyond a specified value ($1.5 \text{ m}^2/\text{month}$) of the vertical consolidation coefficient.
5. The total cost is proportional to the variation of drain unit cost and the required settlement.
6. Based on the adopted unit costs, the use of wick drains resulted in around (54%) reduction in total project cost and about (65%) reduction in time compared to the project without drains.
7. Due to the limited thickness of soft soil and inclusion of vertical consolidation, the application of the optimization method revealed necessity of short drains at moderate spacing.
8. The decision to cancel the wick drains was found to be inappropriate.

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