Boiling resistant design of cofferdams regarding the 3-D effects of seepage

Batardeau résistant au bouillonnement concernant les effets en trois dimensions de fuite

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ABSTRACT: A new method for estimating the three-dimensional seepage force in a cofferdam is presented in this paper. A case study of the boiling failure is introduced; an actual failure occurred in a sheet pile cofferdam during the renovation of the Daiichi-Shinkawa Bridge over Shinkawa River in Hokkaido Prefecture, Japan. The significance of three-dimensional effect on the seepage force is demonstrated by a series of parametric calculations by using the finite element method. Finally a method for evaluating seepage force is derived based on another series of parametric calculations. A few charts and formulae are presented for the calculation of the factor of safety against the boiling failure in cofferdam.

RÉSUMÉ: Ce papier présente une nouvelle méthode d'estimation de la force de fuite en trois dimensions dans un batardeau. Une étude de cas de défaillance de bouillonnement est introduite ; une défaillance s'est réellement produite dans un batardeau à rideau de palplanches pendant les travaux de rénovation du pont Daichi-Shinkawa, sur la rivière Shinkawa dans la préfecture de Hokkaido au Japon. L'importance de l'effet trois dimensions sur la force de fuite est démontrée à travers une série de calculs en utilisant la méthode des éléments finis. Finalement, une méthode d'évaluation de la force de fuite est dérivée, basée sur une autre série de calculs parametriques. Quelques graphiques et formules sont présentés pour le calcul du facteur de sûreté en ce qui concerne la défaillance de bouillonnement dans les batardeaux.

1 INTRODUCTION

Cofferdams are temporary structures built to create dry conditions during construction under water such as in rivers and lakes. The collapse of cofferdams can occur due to the upward seepage force at the excavation base even when they are adequately designed to resist the lateral thrust of the soil and water. This is generally regarded as a boiling or piping failure. In this study, the finite element analysis was carried out to find the distribution of groundwater potential head inside and around the cofferdam. The steady state of seepage flow was concerned and quadrilateral element was employed with four Gaussian points for numerical integration. The applicability of this type of numerical analysis to groundwater potential distribution around a cofferdam was verified with field observation data by Furukawa (1993).

Then, two types of the definitions of the safety factor were employed. The first was derived from the balance of seepage force and gravity force on the prism of soil mass based on Terzaghi's proposal; see the schematic diagrams shown in Fig. 1, where the factor of safety F_{sa} can be defined as:

$$F_{sa} = W' / U = \gamma' V / h_a A \gamma_w \quad (1)$$

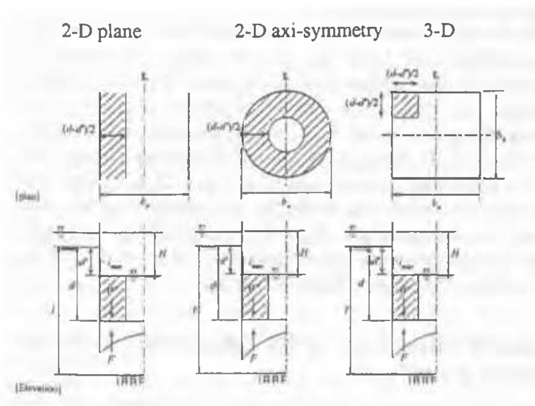


Fig. 1 Analytical condition for the determination of factor of safety against boiling failure

where V is the volume of soil prism, A is the base area of soil prism, and h_a is the average groundwater potential head which corresponds to the pressure applied to the bottom of soil prism.

The width of soil prism was assumed to be equal to $(d\text{-}d')/2$, as shown in Fig. 1; in 2-D plane, axial symmetric and 3-D conditions corresponding to the cofferdams with plan shapes of strip, circle and rectangle, respectively. The *Directions for Road and Earthworks* (JRA, 1976) simplified this method with the assumption of 'h_a is equal or less than $H/2$', and recommended the factor of safety F_{sa} = 1.5 for the design of cofferdams.

The second definition of the safety factor against boiling was derived from the comparison of maximum hydraulic gradient of groundwater i_{max} with its critical value i_c; as follows:

$$F_{sb} = i_c / i_{max} \quad (2)$$

The critical hydraulic gradient was given by Marsland (1953) as $i_c = \gamma'/\gamma_w$. And, the location at which the maximum hydraulic gradient (i_{max}) appeared on the surface is shown in Fig. 1.

2 CASE STUDY OF THE TROUBLE IN THE CONSTRUCTION OF A COFFERDAM IN THE RIVER

The boiling failure occurred during the renovation of the Daiichi-Shinkawa Bridge in Otaru City, Hokkaido Prefecture, Japan. The failure was first reported with the field exploration by Imafuku et al. (1991). During this renovation work, the old bridge was replaced by two new bridges. The failure occurred in the cofferdam for casting of Pier No. 1 of the bridge on the downstream side, which was designed in accordance with the *Directions for Road and Earthworks* (JRA, 1976), The sheet pile was penetrated to a depth of 10 m below the riverbed, which consisted of homogeneous clean sand up to the elevation of -15.06 m, and then the inside water was pumped out. After that the ground inside was excavated to a depth of 4.7 m (see Fig. 2) and the steel piles of the old bridge were cut and removed in dry condition. Then six steel H-piles were driven with a 60 kW vibro-hammer in order to provide a temporary platform above the cofferdam (see Fig. 3). The installation of the H-piles was also carried out under dry conditions by continuous pumping; just after the completion of piling, a small amount of water leakage with sand and mud was found. However, owing to the

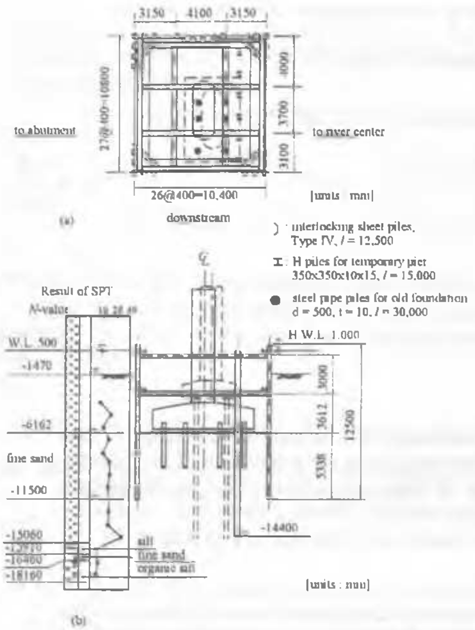


Fig. 2 Cofferdam for Pier No. 1 of Daiichi-Shinkawa Bridge
(a) plan view; (b) side view

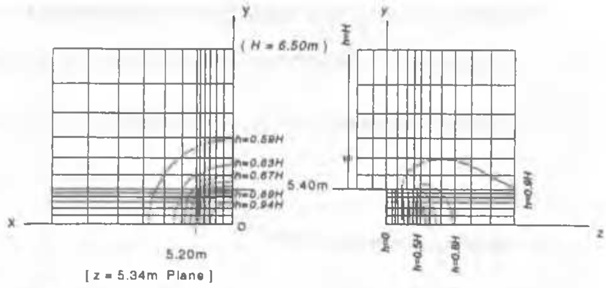
Fig. 3 The installation of H-pile in cofferdam

Fig. 4 Cofferdam just after the boiling failure occurred

judgment that the leakage was insignificant in amount and was not progressive, no treatment was provided and the inside of the cofferdam was kept dry over night with pumping. At 11.00 a.m. on the following day, 18 hours after the H-pile placement, the groundwater blew up and the cofferdam filled with muddy water within only 5 min (see Fig. 4). For more details, see Miura et al. (1999).

2.1 *Condition of the damaged ground*

The profile of damaged ground was explored with the Standard



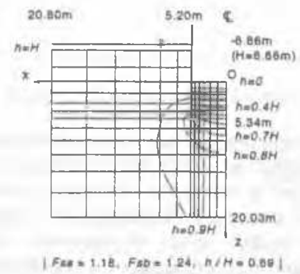


Fig. 5 Distribution of equi-potential line from 3-D FEM of cofferdam for Pier No. 1 of Daiichi-Shinkawa Bridge

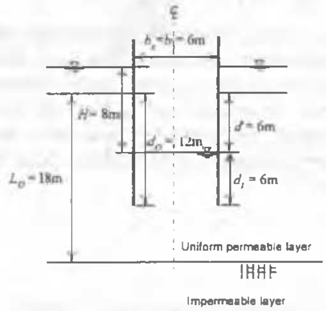


Fig. 6 Fundamental case employed in the parametric investigation

Penetration Test (SPT). The riverbed consisted of a rather uniform clean sand layer (D_{50} = 0.12-0.16 mm and U_c = 2), which was underlain by laminated silt layers. Due to the disturbance created by the failure, the foundation ground became loose and its bearing capacity reduced as indicated by the SPT values. The damaged cofferdam in Pier No. 1 was later recovered as follows: first, the sheet piles were penetrated to an additional depth of 0.2 m, and then the deep mixing method was employed to stabilize the soil layer in a range close to the level of the sheet pile tips.

2.2 *Investigation of the factor of safety*

According to the *Directions for Road and Earthworks*, the factor of safety for the cofferdam for Pier No. 1 was equal to 1.60. However, the factors of safety based on the 3-D FEM were F_{sa} = 1.18 and F_{sb} = 1.24. The analytical results are shown in Fig. 5. Inside the cofferdam around the corner, equi-potential lines are dense; the average potential head associated with uplift seepage force h_a is larger than a half of the total head difference $H/2$, which resulted in the reduction of safety factor from the design. The analysis was carried out further as shown in Table 1. In many cases, the safety factor F_{sa} obtained from the 3-D analysis was less than 1.5. In the case of Daiichi-Shinkawa Bridge, the value of the submerged unit weight of $\gamma' = \gamma_w$ = 9.81 kN/m^3 was not a conservative selection, while the site exploration was not conducted in the riverbed for the determination of soil properties. For instance, the submerged unit weight γ' of 84% of γ_w could create a critical condition of F_{sa}=1.0.

2.3 *Parametric investigation of the influence factors on the boiling failure in a cofferdam*

Finite element seepage analysis was conducted in the fundamental case as shown in Fig. 6 and extended to cases shown in Table 2, in 2-D plane, axi-symmetric and 3-D

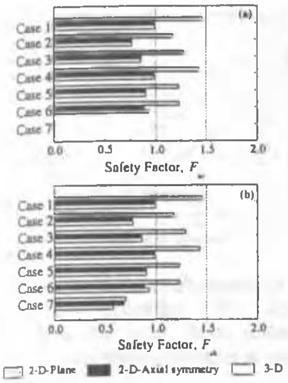


Fig. 7 Factor of safety against boiling in cofferdam for some influence factors

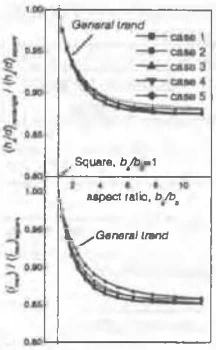


Fig. 8 Effect of the shape of cofferdam

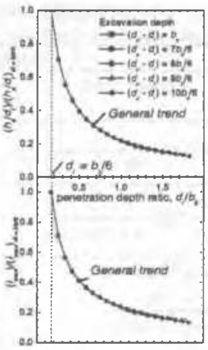


Fig. 9 Effect of the sheetpile penetration depth

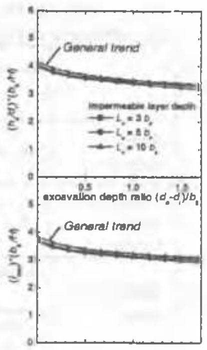


Fig. 10 Effect of the excavation depth

Table 1 Calculation results for boiling failure in some cofferdams for bridge construction in Japan

	Name of Bridge [Notaton]	Number of national road (place) [comment]	$\overline{\gamma'}$ kN/m³	Factor of safety 3-D FEM F_{Sa}	F_{Sb}	F_{Sd}**
1*	Daiichi-Shinkawa [DS]	route 337 (Otaru)	9.80	1.181	1.240	1.603
2*	Bridge A [A]		7.84	1.134	1.180	1.594
3*	Bridge B [B]	[see Suzuki (1990)]	8.82	1.085	1.113	1.543
4*	Bridge C [C]	[incomplete penetration]	(9.80)	1.058	1.153	1.200
5*	Bridge D [D]	[partly incomplete penetration under construction]	(9.80)	0.984	1.084	1.237
5'	" [D']	[result of the analysis in the design]	(9.80)	1.623	1.727	2.151
6*	Bridge E [E]	[incomplete penetration of sheet pile]	(9.80)	0.536	0.584	0.687
6'*	" [E']	[under construction of footing]	(9.80)		0.527	
7	Onopporo [ON]	route 12 (Sapporo)	8.82	1.074	1.100	1.556
8	Nopporo-River [NP]	route 12 (Sapporo)	5.88	1.092	1.117	1.586
9	Shintotsukawa (P2)	route 275 (Shintotsu kawa)	8.82	1.082	1.094	1.576
9'	" (P3)	" "	8.82	1.117	1.150	1.565

* places that boiling occurred
**based on the *Directions of Road and Earthworks*

conditions. The comparison of factors of safety against boiling for each case is shown in Fig. 7. Some comments are given below:

- The effect of analytical condition on the seepage force is remarkable. While the value of the safety factor in the 2-D plane condition is almost the same as that calculated according to the *Directions for Road and Earthworks*, the safety factor in axi-symmetric and 3-D conditions are approximately only two thirds of that in the 2-D plane condition (Cases 1 to 6).
- Although the amount of water flow into a cofferdam is dependent on the depth of the impermeable base or the thickness of a permeable layer, the safety factor is nearly independent (Case 1 and 4). It can be said that even with no reliable information about the impermeable base, the numerical calculation is effective for the estimation of the safety factor.
- The effects of excavation area and anisotropic permeability are also notable (Cases 1, 5 and 6). For narrower excavation areas and/or higher degrees of anisotropy, where the riverbed is more permeable in a horizontal direction, the safety factor becomes smaller. In the case of an actual sheet pile cofferdam, the frictional force mobilized between soil mass and sheet piles is expected to be more effective in the narrower excavation and may stabilize the excavation floor and the cofferdam; however, from the hydraulic point of view, the narrower excavation is not necessarily safer.
- The weight of a constructed footing is expected to improve the stability of an excavation floor; however, the highly concentrated upward hydraulic gradient appears in the narrow space between footings and sheet piles (Case 1 and 7). This concentrated hydraulic gradient actually caused the boiling failure in Bridge E listed in Table 1.

3 SIMPLIFIED ESTIMATION METHOD TO DETERMINE THE FACTOR OF SAFETY AGAINST THE BOILING FAILURE

The effects of each influence factor on the boiling failure were examined by series of parametric calculations under 3-D condition. From Eqs. 1 and 2, the factors of safety could be calculated as: $F_{sa} = (\gamma'/\gamma_w)/(h_a/d_t)$ and $F_{sb} = (\gamma'/\gamma_w)/i_{max}$. And, the values of (h_a/d_t) and i_{max} are given as:

$$h_a/d_t = (h_a/d_t)_0 * N_{sh} * N_{ph} \tag{3}$$

$$i_{max} = (i_{max})_0 * N_{si} * N_{pi} \tag{4}$$

The values of the coefficients were derived from the parametric calculation as follows:

Table 2 Analytical conditions for case study of the influence factors on boiling type of failure in the cofferdams for bridge construction

Fundamental Condition :
(Size and Shape of Model):
excavation width; $b_a = b_b = 6$m,
sheet pile installation depth ; $d_o = 12$m,
excavation depth ; $d' = 6$m,
permeable layer thickness ; $l = 18$m,
water head difference ; H = 8m
(Parameter of Soil) :
$k_h = k_v = 1.0*10^{-8}$ m/sec,
$\gamma_w = 9.8$ kN/m³, $\gamma' = 9.8$ kN/m³

	Analytical Condition	Comment
Case 1	fundamental condition	F_s (Direction) = 1.5
Case 2	$d' = 7$m, $H = 9$m	deeper excavation
Case 3	$d_o = 11$m	shallower penetration depth
Case 4	$l = 24$m	thicker permeable layer
Case 5	$b_a = b_b = 4$m	narrower excavation
Case 6	$k_h = 4k_v = 4.0*10^{-8}$ m/sec	anisotropic permeability
Case 7	$a_a = a_b = 5$m	with footing of square base

Table 3 Values of shape factors, penetration depth factors, and reference value of seepage force and maximum hydraulic gradient

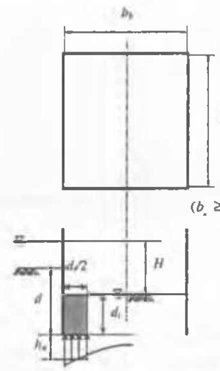
	Approach	
	Seepage force	Maximum hydraulic gradient
Shape factors	$N_{sh} = 0.88 + \frac{1}{2(1+b_a/b_b)^2}$	$N_{si} = 0.84 + \frac{1}{2+4.2*b_a/b_b}$
Penetration depth factors	$N_{ph} = 0.03 + \frac{5}{1+25*d_i/b_b}$	$N_{pi} = 0.05 + \frac{5.6}{1+28.5*d_i/b_b}$
Reference value	$(h_d/d_i)_o*(b_b/H) = \frac{1+d'/b_b}{0.24+0.33*d'/b_b}$	$(i_{max})_o*(b_b/H) = \frac{1+d'/b_b}{0.26+0.36*d'/b_b}$

The first series of calculations was conducted with cases 1 to 5 listed in Table 2 with the variable aspect ratio b_a/b_b of the cofferdam. Then, the ratio h_d/d_i and the maximum hydraulic gradient i_{max} were numerically calculated and normalized by the value of the corresponding square cofferdam (See Fig. 8). These normalized values were defined as shape factors N_{sh} and N_{si}, in Eqs. 3 and 4.

Then, the second series of calculations was conducted with the square cofferdams to find the effect of sheet pile penetration depth by varying the value of sheet pile penetration depth. The ratio h_d/d_i and the maximum hydraulic gradient i_{max} were numerically calculated and normalized by the value corresponding to a cofferdam with a sheet pile penetration depth of $b_b/6$ (See Fig. 9). These normalized values are defined as penetration depth factors N_{ph} and N_{pi} in Eqs. 3 and 4, respectively.

Finally the excavation depth was parametrically varied in the case of a square cofferdam with a sheet pile penetration depth of $b_b/6$ by varying the excavation depth and depth of the impermeable layer. The calculation results show that the depth of an impermeable layer has relatively small effect on the calculation results. So, the effect can be neglected in the estimation of the hydraulic safety of the cofferdam. The ratio h_d/d_i and the maximum hydraulic gradient i_{max} are plotted as shown in Fig. 10 and referred to as the reference seepage force $(h_d/d_i)_o$ and reference maximum hydraulic gradient $(i_{max})_o$.

The values of the derived coefficients are given in Table 3.



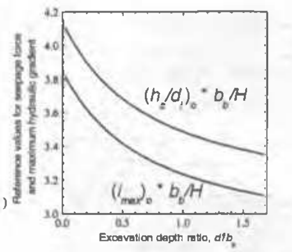


Chart A Seepage force and hydraulic gradient of cofferdam with penetration depth, d_i = b_b/6 as a function of excavation depth ratio

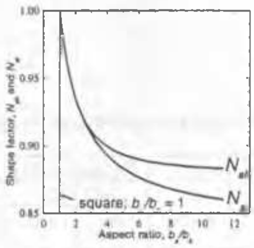


Chart B Influence of shape of cofferdam

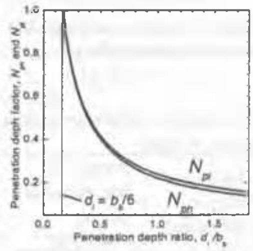


Chart C Influence of depth of penetration

Fig. 11 Design chart to evaluate the influence of 3-D Seepage in the cofferdam

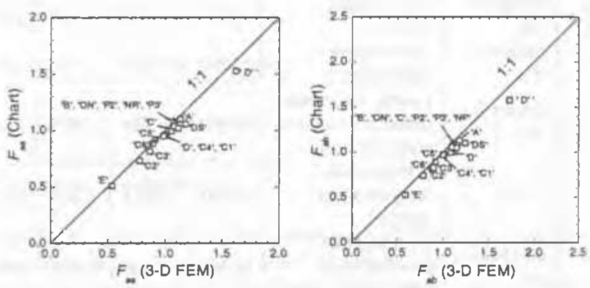


Fig. 12 Comparison of factors of safety by design chart and 3-D FEM

3.1 *Simplified design chart for Cofferdam*

The design chart, as shown in Fig. 11, was derived for the estimation of the factor of safety against the boiling failure. The comparison of the factors of safety between the simplified design chart and the 3-D Finite element method are shown in Fig. 12 for some models and actual cofferdams (see Tables 1 and 2). The factors of safety obtained from the simplified design chart and the 3-D finite element method are in good agreement; the values obtained from the simplified design chart are conservative.

4 CONCLUSIONS

The results of this study showed that the effect of analytical conditions is notable; the factor of safety obtained under 3-D condition was much lower than that proposed by the *Directions for Road and Earthworks*. Then, the simplified design chart proposed in this paper was derived from the comparative examination of some series of parametric calculations with the 3-D finite element method for steady seepage behavior. With the design chart, the effects of the shape of a cofferdam, sheet pile penetration depth, excavation depth, and the depth of an impermeable base layer can be taken into account properly, and relatively conservative values can be obtained.

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