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Shallow Water Effect on Pier Scour in Clays

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ABSTRACT

Shallow water effect is a common phenomenon in pier scour evaluation. While extensive studies have been carried out on the shallow water effect in sands, studies in clays are practically inexistent. Systematic flume tests were conducted on porcelain clay to explore the shallow water effect. Test results indicate that pier scour in clays has a very similar discount factor for shallow water scour depth to that in sands. The results also show that a faster scour rate can be caused by shallow flow. Therefore in clays, the shallow water effect leads to a shallower scour depth which occurs faster than in deep water.

INTRODUCTION

Shallow water effect on pier scour is also called wide pier effect. It happens when the flowing water depth, H, is relatively small compared to the pier size, B. Observations show that the scour depth increases with the depth of flow until the deep-water case is reached, where the scour depth is almost independent of water depth. However no fixed value exists to define the shallow water range. Bonasoundas (1973) concluded that the effects of flow depth became insignificant when $H/B > 1$ to 3 for clear-water scour, where H is the water depth and B is the pier diameter. Ettema (1980) stated that the shallow water effect was affected by the relative size of the pier and sediment and that $H/B<3$ was a good range to define shallow water in coarse sands. Ettema also stated that, as summarized by Johnson (1999), three reasons accounted for the shallow water affect: (1) the portion of the approach flow available to be diverted into the scour hole diminishes, (2) the development of the scour hole is influenced by the formation of a sediment bar behind the pier, (3) the formation of a surface roller in opposite direction to the rotation of the horseshoe vortex and the down flow into the scour hole.

Consideration of the shallow water effect is important because it has an economic impact on the final depth of the foundation. In Lander and Mueller's (1992) bridge pier scour database, if only the 234 cases of single pier with 0° attack angle are counted, there are 57.7% piers with $H/B<3$, 15.4% the piers with $H/B<1$, and 8.1% for $H/B<0.5$. It should be also noted that even though some pier scour prediction equations have a water depth term embedded in the formula such as HEC-18 (Richardson and Davis, 2001), the shallow water effect may not be fully represented because the original equation may have been based on flume tests performed in relatively deep water cases. Furthermore, previous research on shallow water effect has been concentrated on sand beds and there is

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no corresponding study on clay beds. Due to the difference between clay and sand, it was the primary goal of this research to investigate the shallow water effect in clay.

CORRECTION FACTOR FOR SHALLOW WATER EFFECT IN SANDS

Research on shallow water effects in sand can provide a background to clay scouring. Among the well-known studies on shallow water effect in sands are the studies by Melville (1999) and Johnson (1999). Both of them considered shallow water effects in the form of a correction factor Kw. It was calculated as the ratio of the shallow-water maximum scour depth to the deep-water maximum scour depth, which is defined as the reference case in this study. Johnson (1999) defined shallow water as H/B<0.8 and low velocity as Fr<0.8 where Fr is the Froude number. She isolated the data that met these conditions in the original data set from CSU used in the HEC-18 equation and added data from other sources to derive a new equation for wide pier using the same parameters. The new equation accounting for shallow water effect in the HEC-18 equation is:

$$Kw = 1.04\left(\frac{H}{B}\right)^{0.15} Fr^{0.21} \qquad \textbf{(1)}$$

Water depth was already included in the HEC-18 equation which can be written:

$$Z_{\max} = 2.0K_1 K_2 K_3 K_4 H^{0.135} B^{0.65}\left(\frac{V}{\sqrt{g}}\right)^{0.43} \qquad \textbf{(2)}$$

So, the total term for water depth effect in Johnson's equation should be a combination of (1) and (2) as:

$$K_w = 1.04\left(\frac{H}{B}\right)^{0.15} Fr^{0.21} H^{0.135} \qquad \textbf{(1. A)}$$

Melville(1999) defined the water depth effect on scour depth by using data published by Chabert and Engeldinger(1956), Lausen and Toch(1956), Hancu(1971), Bonasoundas(1973), Basak(1975), Jain and Fisher(1979), Chee(1982), Chiew (1984), and Ettema(1980). He proposed that piers be classified according to H/B: narrow pier (deep-water), intermediate pier (intermediate-water), and wide pier (shallow-water). The maximum scour depth for narrow piers is controlled by pier width, for wide piers by water depth and for intermediate piers by both water depth and pier width. The corresponding correction factor is:

$$Kw = \begin{cases} 0.53(B/H) & B/H < 0.7 \\ 0.44\sqrt{B/H} & 0.7 < B/H < 5 \\ 1 & B/H > 5 \end{cases} \qquad \textbf{(3)}$$

FLUME TESTS

Systematic flume tests were conducted at Texas A&M University to investigate the shallow water effect on clay soils. The flume is a 1.5 m wide concrete tank and the water is circulated in a close system by pumps. Two different sizes of PVC piers were used: B=273mm and B=160mm. They were installed in a 1.2m×1.5m soil tank filled with porcelain clay. The soil properties of the porcelain clay are listed in Table 1. During each test, velocity and water depth were kept constant. The velocity was measured as the depth-average velocity with an ADV placed upstream of the pier where the pier had no influence on the velocity distribution. The instant scour depth z(t) (maximum depth of the scour hole at a given time) was recorded as a function of time t with a precise point gage without interrupting the flow. The primary parameters for each test are listed in Table 2.

Table 1: Soil Properties of Porcelain Clay

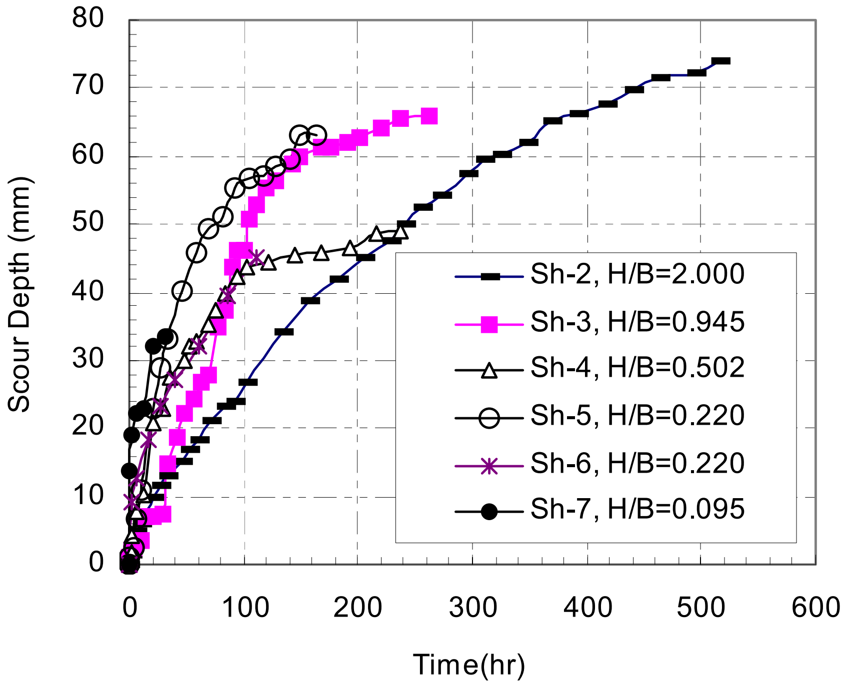
NO.	Property	Porcelain
1	Liquid Limit, %	40.23
2	Plastic Limit, %	19.17
3	Plastic Index (PI), %	21.06
4	Bulk Unit Weight (KN/m^3)	19.65
5	Water Content, %	27.35
6	Sand Content, %	0.0
7	Clay Content, %	100.0
8	Shear Strength, KPa	10.7

Table 2: Parameters and Major Results of Flume Tests (*bold one is the reference case in each group*)

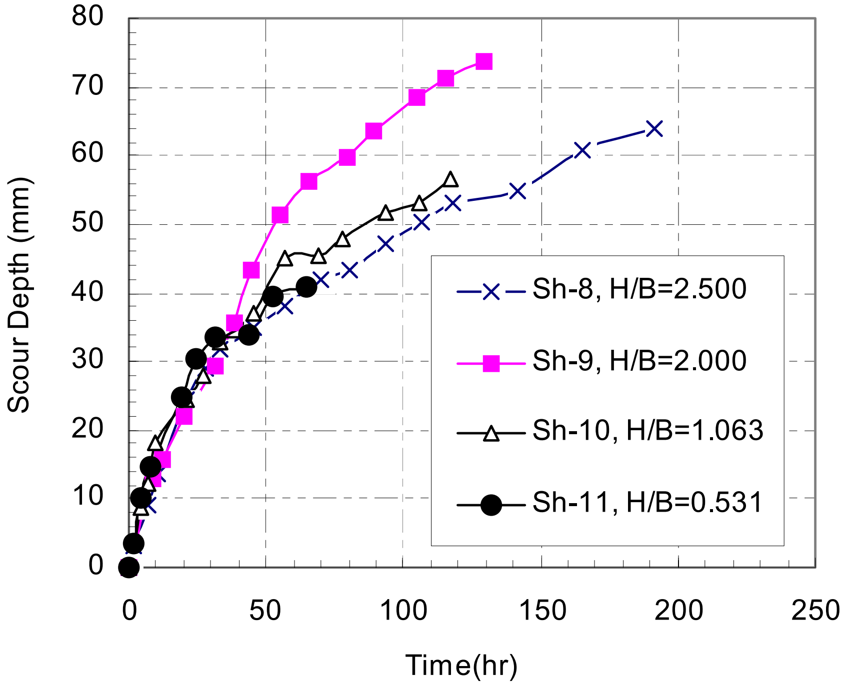
Test No.	H (mm)	B (mm)	V (m/s)	H/B	Time Lasting (hr)	$\dot{z}_i$ (mm/hr)	Zmax (mm)
Sh-1	**683.00**	**273.00**	**0.30**	**2.502**	**-----**	**----**	**112.94**
Sh-2	546.00	273.00	0.30	2.000	515.75	1.06	129.62
Sh-3	258.00	273.00	0.30	0.945	262.33	1.57	79.37
Sh-4	137.00	273.00	0.30	0.502	237.42	1.39	57.80
Sh-5	60.00	273.00	0.30	0.220	164.08	1.71	81.30
Sh-6	60.00	273.00	0.30	0.220	111.03	4.49	61.35
Sh-7	25.80	273.00	0.30	0.095	30.50	38.91	35.59
Sh-8	**400.00**	**160.00**	**0.40**	**2.500**	**191.33**	**1.50**	**76.92**
Sh-9	320.00	160.00	0.40	2.000	129.67	1.82	109.67
Sh-10	170.00	160.00	0.40	1.063	117.17	1.98	77.73
Sh-11	85.00	160.00	0.40	0.531	64.50	2.62	53.48

MAXIMUM SCOUR DEPTH AND INITIAL SHEAR STRESS CALCULATION

Clay scouring is really a time dependant process due to its extremely low erosion rate. Generally it takes several months to reach the equilibrium scour depth, Zmax, which is too time-consuming for a flume test. So in the current research, all the flume tests were terminated after a limited time, as shown in Fig 2, and a hyperbolic model (Briaud, 1999, 2001) was used to fit the data. The hyperbola model is:



(Pier: B=0.273m and V=0.3m/s)



(Pier: B=0.160m and V=0.4m/s)

FIG 1 Scour Development in Shallow Water Case

$$z(t) = \frac{t}{at + b} \tag{4}$$

Where a is the inverse of the initial scour rate, $\dot{z}_i$, and b is the inverse of the maximum scour depth, Z_{max}. The hyperbola model can be written as:

$$\frac{t}{z(t)} = at + b \tag{5}$$

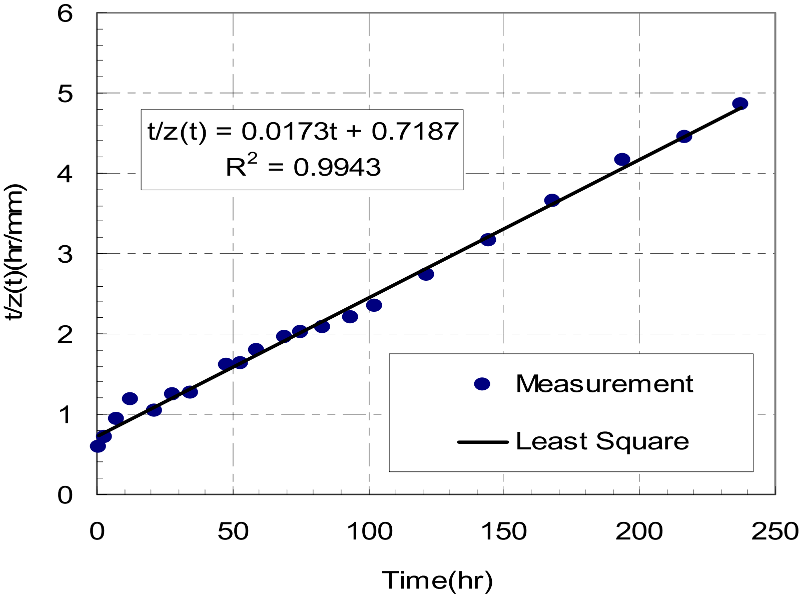


Fig 3 Least Square Method to determine a and b for Test Sh-4

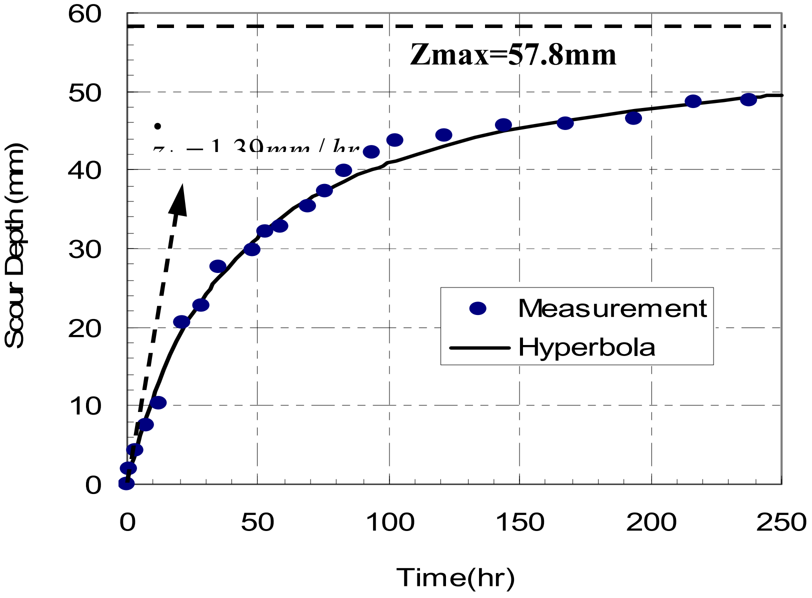


Fig 4 Comparison between Hyperbola Model and Measurement for Test Sh-4

Both a and b can be determined by a least square regression on the data z(t) and t. Test Sh-4 is used as an example to explain the above approach in Fig 4 and the scour depth vs. time curves obtained from the hyperbolic model and the measurement are compared in Fig 5.

Note that the hyperbolic approach gives not only the maximum scour depth Zmax but also the initial scour rate $\dot{z}_i$. For a given flume test, if one single hyperbola could not simulate the initial section and the final section of the scour curve with satisfactory precision at the same time, two separate hyperbolas were used: $\dot{z}_i$ was obtained by a hyperbola simulating the initial part while Zmax by simulating the final part of the measurements. The calculated results of Zmax and $\dot{z}_i$ are summarized in Table 2.

SHALLOW WATER EFFECT ON PIER SCOUR DEPTH

To compare the shallow water effect between these flume tests and other research results in sands, two approaches were taken based on different normalization methods.

Zmax/B vs. H/B

When both scour depth and water depth were normalized with respect to pier size, the relative scour depth, Zmax/B, increases with increasing relative water depth, H/B, in the shallow water range. Even though the tendency of the curve in Fig 5 is consistent with the result in sands, there is some variation in the magnitude of the Zmax/B for a given value of H/B. This is possibly because the shallow water effect depends on the soil properties and on the water velocity. For example, Zmax/B can be 0.7 to 2 when the soil bed changes from medium sand to coarse sand under the corresponding critical velocity (Melville and Colleman, 1999). It indicates that this kind of normalization is not a good way to get a unique solution for shallow water effect.

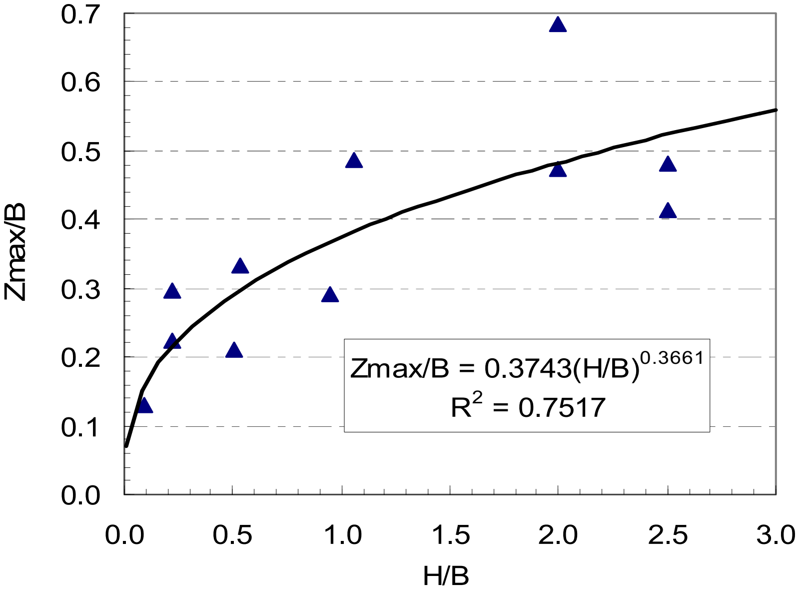


Fig 5 Influence of Flow Shallowness on Pier Scour Depth

Correction Factor Kw vs. H/B

The correction factor, Kw, is calculated as the ratio of the shallow water scour depth to the scour depth for a reference case where the water depth has no longer any noticeable influence on the scour depth. In this research, the maximum scour depth under the deepest relative water depth, H/B=2.5, was used as the reference case. Test Sh-1 was used as the reference for the tests where B=0.273m and V=0.3m/s, and test Sh-9 was used as the reference for the tests where B=0.160m and V=0.4 m/s. In Fig 6, the Kw values obtained in this study are compared with Melville and Johnson's results. Johnson's correction factor depends on both pier size and velocity. So "Johnson 0.273/0.3, Equ (1)" represents the correction factor for the condition of B=0.273m and V=0.3m/s according to Equation (1), and ditto for "Johnson 0.160/0.4, Equ (1)". Because Johnson did not provide the equation for very shallow water, a straight line connects the origin to the first point on Johnson's curve. As mentioned previously, the combined effect of Johnson's Kw and the water depth effect included in the HEC-18 equation is represented by Equation (1.A). The Kw for Equation (1.A) is plotted in Figure 6 under the label "0.273/0.3, Equ (1.A)" and "0.160/0.4, Equ (1.A)" with H/B =2.5 as the reference cases for B=0.273m, V=0.3m/s and B=0.160V=0.4m/s respectively.

The water effect factor for the cohesive soil of this study is very close to the one for sand (Fig. 6). The correction factor for clay is somewhat smaller than Melville's result at very shallow water depth when H/B<1.12 and reaches 1.0 for H/B=1.62. For H/B> 1.62, the flow in clay is treated as a deep water flow and the correction factor is truncated at 1.0. By regression, the expression of the current correction factor is:

$$Kw = \begin{cases} 0.85\left(\frac{H}{B}\right)^{0.34} & H/B < 1.62 \\ 1 & H/B > 1.62 \end{cases} \tag{6}$$

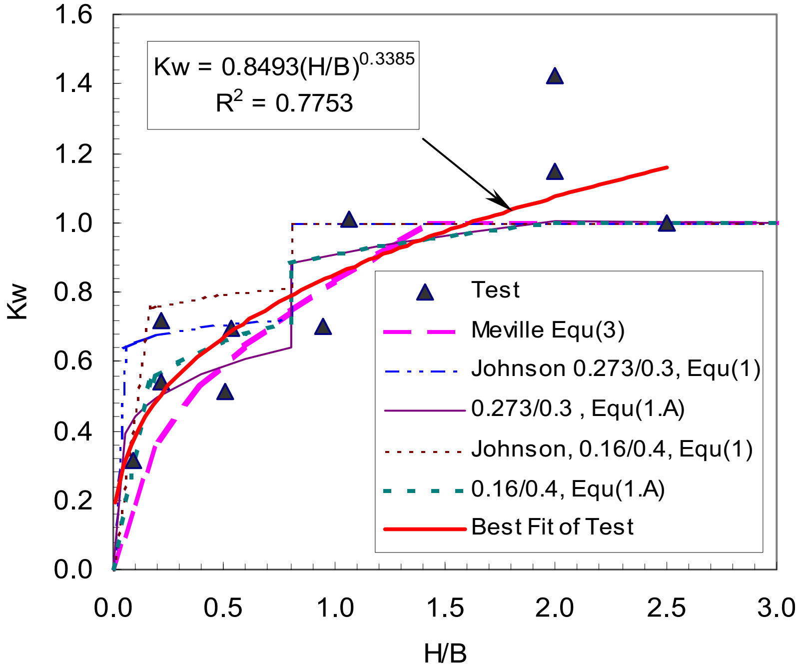


Fig 6 Correction Factor for Shallow Water Effect on Pier Scour Depth

SHALLOW WATER EFFECT ON INITIAL SHEAR STRESS

Scouring in clays is a time-dependant process compared to scouring in sands, so the scour rate becomes a critical issue. For a given scour flume test, the initial scour rate is one of the two parameters obtained from the hyperbolic model. The two groups of initial scour rates are plotted in Fig 7. Because Test Sh-8 has a much higher initial scour rate, the data including Test Sh-8 are plotted in the small upright figure. Fig.7 indicates that the initial scour rate decreases as the water depth increases within the shallow water range. There is a more pronounced increase in the initial scour rate when H/B< 0.5. The scour rates for the pier with B=0.273m are smaller than the ones for the pier with B=0.160m because the larger pier induces a smaller shear stress.

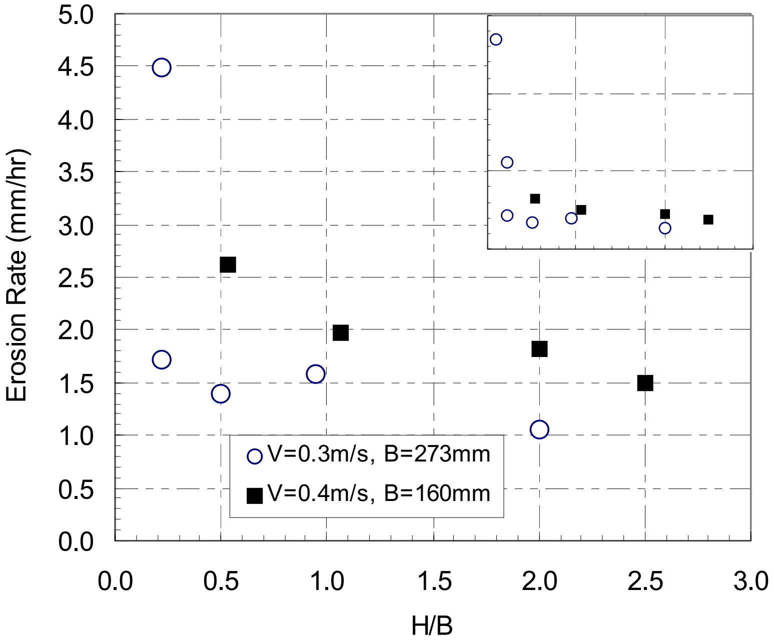


Fig7 Initial Scour Rate for Shallow Water Effect on Pier Scour

SCOUR MODEL FOR SHALLOW WATER EFFECT

Based on the above experiments and data analysis of shallow water effect on the maximum scour depth and initial scour rate in clay, a summarized scour model is developed in Fig 8. For a pier under shallow water flow such as C, the scour depth develops more rapidly than in the deep-water case and results in a deeper scour depth at the beginning. But the scour rate decays quickly and converges to the maximum scour depth, which is smaller than deep water one. This trend increases with the shallowness of the flow as A→B→C in Fig 8.

This model demonstrates that it is important for cohesive soils to include time effects in scour depth calculations.

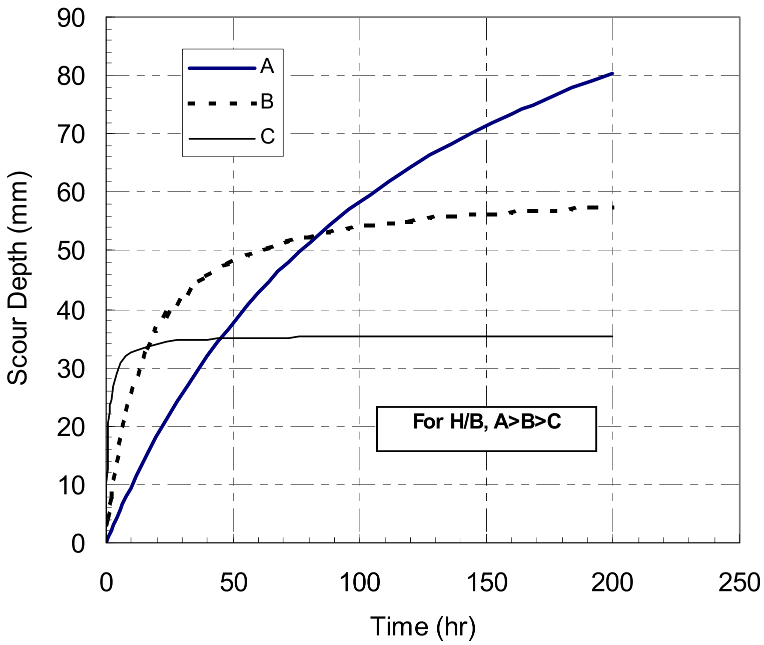


Fig 8 Scour Model for Shallow Water Case

SUMMARY

A correction factor for scour depth was developed for clay scouring under shallow water conditions. The value is close to the correction factors given by Melville and Johnson in sands. The water depth limit for the shallow water effect in clay is around 1.6 times the pier size.

The initial scour rate decreases with increasing water depth within the shallow water range. A summary scour model shows that the scour depth in shallow water may be larger at first but smaller in the long term than the deep water case.

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SYMBOL INDEX

a	Parameter in hyperbola model, inverse of maximum scour depth Zmax (1/mm)
b	Parameter in hyperbola model, inverse of initial scour rate $\dot{z}_i$ (hr/mm)
B	Pier diameter, m
Fr	Froude number $=V/\sqrt{gH}$
g	Gravity acceleration, 9.81m/s^2

Kw	Correction for scour depth under shallow water case
V	Upstream depth-average velocity (m/s)
$\dot{z}_i$	Initial scour rate (mm/hr)
$Z_{\max}$	Maximum scour depth or equilibrium scour depth (mm)

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