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Briaud, Jean-Louis; Li, Ya; Chen, Hamn-Ching; Nurtjahyo, Prahoro; Wang, Jun

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Shear Stress Approach to Pier Scour Predictions

Ya Li[1], Jean-Louis Briaud[2], Hamn-Ching Chen[2], Prahoro Nurtjahyo[1], Jun Wang[1]

ABSTRACT

A shear stress approach for pier scour is developed based on the results of flume tests and numerical simulations: The final depth of pier scour, which might develop in a complex pier condition, is first correlated with the difference between the maximum shear stress and the critical shear stress of the eroding soil. Second, to simulate the time history of the scour development, a decay model of the boundary shear stress at the bottom of the scour hole is proposed. This model makes use of the erodibility function.

INTRODUCTION

One of the key yet unanswered questions in scour predictions is: "Is the maximum scour depth for a given pier subjected to a given constant velocity the same for all soils? Research at Texas A&M University (Briaud et al., 1999) indicated that the answer appeared to be Yes. The rate was drastically different for different soils but the maximum depth obtained in sand and in clay was the same in the flume experiments which were conducted. The present paper examines this question from the shear stress perspective. To begin, a shear stress approach is developed for the final pier scour prediction by integrating the maximum scour depth results from flume tests with the maximum boundary shear stress results from numerical simulations. Then, to simulate the time history of scour development, a decay model of the boundary shear stress on the bottom of the scour hole is proposed including the use of soil erodibility function.

SHEAR STRESS APPROACH FOR FINAL SCOUR DEPTH

The erosion process is assumed to be controlled by the shear stress acting on the water soil boundary of the scour hole. The shear stress on the river bottom is maximum at the beginning of the scour process and decays as the scour depth increases until an equilibrium scour depth or maximum scour depth, Z_{max}, is reached. At a certain time t during the scour process, the scour hole has a depth z and a pattern of shear stresses is distributed around the pier; the maximum value of these shear stresses for a given depth of the scour hole z is defined as the instantaneous maximum shear stress $\tau(z)$. The initial maximum shear stress (t = 0) just before scouring starts is called τ_{max} because it is the maximum shear stress among the $\tau(z)$ values.

[1] *Graduate student, Dept. of Civil Engineering, Texas A&M Univ., College Station, TX 77843, USA*

[2] *Professor., Dept. of Civil Engineering, Texas A&M Univ., College Station, TX 77843, USA*

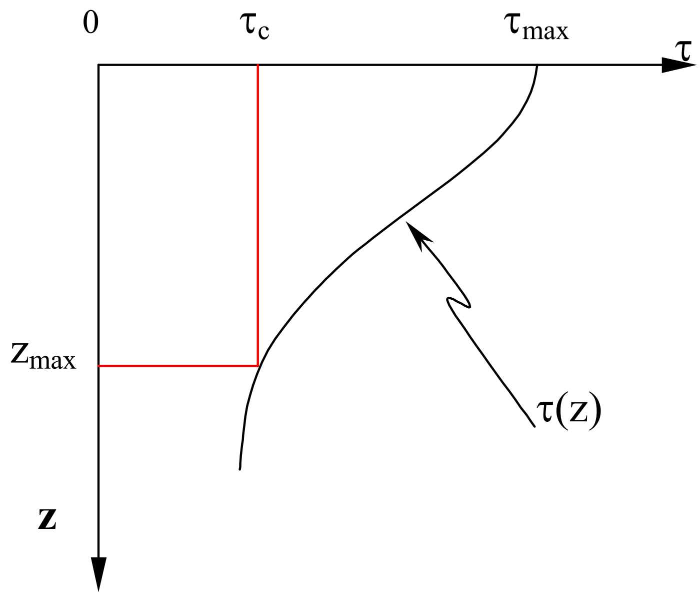

FIG 1 Diagram for Pier Scour Development

The threshold value for soil erosion is the critical shear stress τ_c, which means that scour happens only when the shear stress is larger than the critical shear stress. Unlike the decaying of the shear stress $\tau(z)$, τ_c will not change with the scour development, it is a property of the soil.

Based on the above analysis, a diagram is shown in FIG 1 to represent the scour development. The boundary and initial conditions for pier scour in clay or clear water scour in sand are:

(1) Scour starts from: ($t = 0$, $z = 0$, $\tau = \tau_{max}$)

(2) Scour terminates at: ($t = t_{final}$, $z = Z_{max}$, $\tau = \tau_c$)

To satisfy these two boundary conditions, the maximum (final) scour depth must be a function of ($\tau_{max} - \tau_c$), which means:

$$Z_{max} = \text{function of } (\tau_{max} - \tau_c) \quad \textbf{(1)}$$

In Equation (1), the maximum shear stress can be calculated numerically (Wei, 1997, Nurtjahyo, 2002) and a summarized equation is given below:

$$\tau_{\max} = K_w K_{sh} K_{sp} K_a \times 0.094 \rho V^2 \left(\frac{1}{\log \mathrm{Re}} - 0.1 \right) \quad \textbf{(2)}$$

Where, K_w, K_{sh}, K_{sp}, K_a are the correction factors for water depth effect, pier shape effect, pier spacing effect, and attack angle effect on τ_{max}. The exact equations for these factors can be found in Nurtjahyo (2002). The critical shear stress of the soil can be measured in the Erosion Function Apparatus (Briaud et al, 2001). The maximum scour depth Z_{max} was measured in a number of flume tests conducted by Gudavalli (1997) and Li (2002). These tests included pier scour tests in different clays and sands, and different complex pier scour configurations. By using the flume test data with equation (1), the best fitting function of (τ_{max} - τ_c) was found to be:

$$\frac{Z_{max}}{B'} = 20\left(\frac{\tau_{max} - \tau_c}{\rho g B'}\right)^{0.4} f\left(\frac{H}{B'}\right) \quad \textbf{(3)}$$

with an upper boundary envelope of:

$$\frac{Z_{max}}{B'} = 40\left(\frac{\tau_{max} - \tau_c}{\rho g B'}\right)^{0.4} f\left(\frac{H}{B'}\right) \quad \textbf{(4)}$$

and a lower boundary envelope of:

$$\frac{Z_{max}}{B'} = 10\left(\frac{\tau_{max} - \tau_c}{\rho g B'}\right)^{0.4} f\left(\frac{H}{B'}\right) \quad \textbf{(5)}$$

where, B' is the pier projection width perpendicular to the flow and H is the water depth. The function $f\left(H/B'\right)$ is the correction function for the shallow water effect in the shear stress approach and it can be represented as (Li, 2002):

$$f\left(\frac{H}{B'}\right) = \begin{cases} 0.075e^{\left(1.88\frac{H}{B'}\right)} & H/B' < 1.383 \\ 1 & H/B' > 1.383 \end{cases} \quad \textbf{(6)}$$

SHEAR STRESS DECAY MODEL

Scour, especially in cohesive soil, is a time dependant process. Therefore a shear stress decay model is necessary to develop the time history for the progression of the scour hole. Of course the erodibility function will also be necessary to transform the shear stress information into an erosion rate parameter. The Erosion Function Apparatus (Briaud et al 2001) can provide that erodibility function. If $\tau(z)$ is the instantaneous maximum shear stress value when the scour hole is z deep, and if the erosion function for the soil is $f(\tau - \tau_c)$, then the finite difference scheme for scour development is:

$$\begin{cases} z_1 = 0 \\ z_{i+1} = z_i + \Delta t \cdot f\left(\tau\left(z_i\right) - \tau_c\right) & i = 1,2,3,\cdots\cdots \end{cases} \quad \textbf{(7)}$$

As discussed before, the shear stress decay model must pass through the initial point $\left(\tau_{max}, 0\right)$ and the terminal point $\left(\tau_c, z_{max}\right)$ as shown in FIG 2. Accordingly, there are several possible shear stress decay models. By fitting the scour depth versus time curves obtained in the flume tests (Gudavalli 1997, Li 2002), it was found that the shear stress on the bottom of the scour hole decays in a curve which is first concave and then convex as the scour depth increases. This reverse curvature model was chosen to describe the decay curve (FIG.3):

$$\frac{\tau - \tau_c}{\tau_{max} - \tau_c} = e^{-4\left(\frac{z}{z_{max}}\right)^2} \quad \textbf{(8)}$$

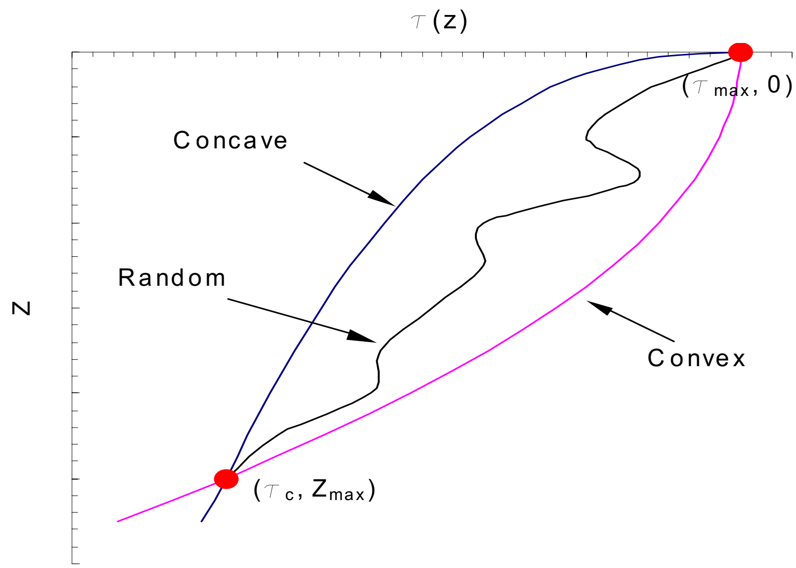

FIG 2 Different Shear Decay Curves

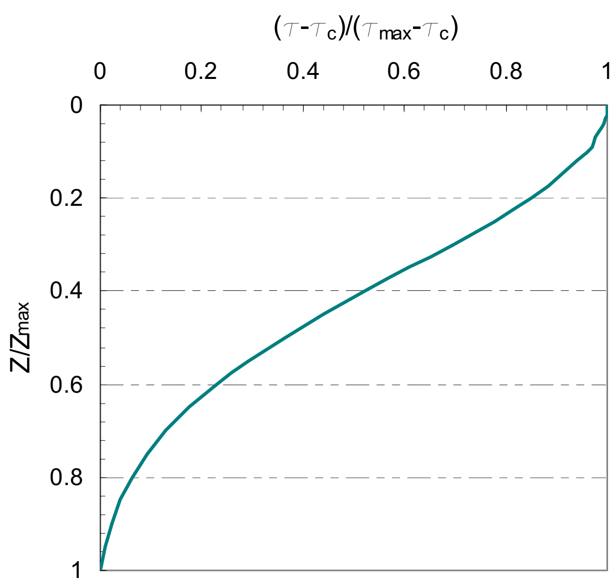

FIG 3 Normalization of Shear Decay Curve

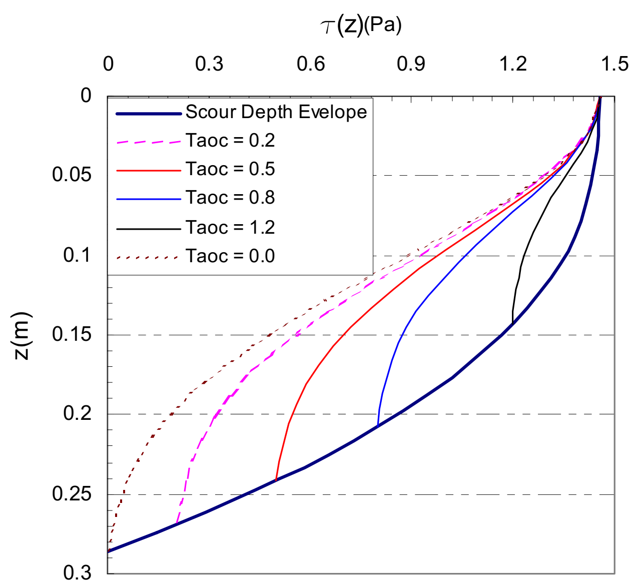

FIG 4 Relationship between Shear Stress Decay Curves and Maximum Scour Depths

An interesting relationship exists between the shear stress decay curve in Equation (8) and the shear stress approach for the maximum pier scour depth in Equation (3). As shown in FIG 4, for the same scour condition but on soils with different critical shear stresses, scour starts from the same origin but follows different tracks as defined by the decay model leading to different maximum scour depths. The envelope of the maximum scour depths is exactly described by Equation (3).

The shear stress approach introduced in this paper for a constant water velocity can also be used for a multi-flood hydrograph and a layered soil system. The reasoning used is similar to the one proposed by Briaud et al (2001) and can be found in Li (2002).

CONCLUSIONS

A shear stress approach is proposed to predict complex pier scour depth, where the scour depth is a function of the difference between the maximum shear stress and the critical shear stress of the eroding soil. The method is limited at this time to pier scour developed in cohesive soils or clear water pier scour in sands. To simulate the time histrory of scour development, a shear stress decay model which gives the evolution of the shear stress at the bottom of the scour hole as the hole deepens is proposed. The shape of that decay model has a reverse curvature with depth.

Previous work at Texas A&M University showed that sands and clays scoured to the same depth but got there at very different rates. This article argues that not only is the rate different for different soils but so is the maximum scour depth. The reason is that different soils have different critical shear stresses. The fact that previous work did not show differences between sand and clay is explained by the fact that the critical shear stresses of the sands and clays used in the flume tests were similar.

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