PIER SCOUR AND EROSION CHARACTERISTICS AT CHOJI BRIDGE

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Scour involves the erosive potential of flowing water and the relative ability of soil to resist erosion. The scour phenomenon in fine-grained soils is much different from that in coarse-grained soils. Scour in fine-grained soils is much slower and more dependent on soil properties which resist erosion. Therefore, a scour analysis method for fine-grained soils needs to consider the time effect and the erosion characteristics of soil as well as hydraulic parameters. In this article, the SRICOS method which has been developed to predict the scour depth around bridge piers founded in fine-grained soils is verified against full-scale scour measurements and compared with other scour analysis models through a case study. The Choji Bridge is located in Kanghwa-Goon of Incheon Metropolitan City in Korea and connects Kanghwa-Goon and Kimpo City over the Yumha River. This bridge is an arch-type bridge opened to traffic in August 2002, which has 13 spans and is approximately 1,200 m long. First, scour depths around bridge piers are measured using an ultrasonic sensor driven from a boat. Second, undisturbed soil samples are collected using the Shelby Tubes from the bridge site. Through tests of the soil samples using an EFA(Erosion Function Apparatus), the erosion function of the bridge site showing the relationship between scour rate and shear stress is obtained. Third, the calculations and the results using the SRICOS method are presented. The calculated scour depth is compared to the measured one. Forth, the calculated and measured scour depths are also compared to the results which are predicted using other scour analysis models based on the experiments in coarse-grained soils. A discussion follows.

1 Introduction

The scour phenomenon involves the erosive potential of flowing water and the relative ability of the soil to resist erosion, and shows different mechanisms because of the various erodibility which depends on the types of the bed materials. Coarse-grained soils resist erosion by their buoyant weight and the friction between the particles. The soil particles are dislodged individually from the bed under the action of the eroding fluid. On the other hand, erosion of fine-grained soils also depends on the physical and chemical properties of the soil particles as well as the buoyant weight and the friction. Scour in fine-grained soils is much slower and more dependent on soil properties than that in coarse-grained soils. Applying the equations for coarse-grained soils to fine-grained soils regardless of time appears to be overly conservative. Therefore, a scour analysis method for fine-grained materials needs to consider the time effect and soil properties as well as hydraulic parameters.

The SRICOS method can consider the erosion characteristic of the soil in scour analysis as well as the hydraulic parameters in relation to the erosive potential, which suggests that the scour process is highly dependent on the shear stress τ imposed by the flowing water at the soil-water interface. In this study, the applicability of the existing scour analysis models including the SRICOS method are examined against the full-scale scour measurements in the field through a case study. The Choji Bridge is selected for the case study, where bed materials around the bridge consist of mostly silty clay. The scour depths around bridge piers are directly measured using an ultrasonic sensor driven from a boat. The undisturbed soil samples are collected using the Shelby Tubes from the bridge site. Through tests of the soil samples using an EFA(Erosion Function Apparatus), the erosion function of the bridge site showing the relationship between scour rate and shear stress is obtained. The pier scour depths are calculated using the existing scour analysis model as well as the SRICOS method. Through the comparison of the calculated and measured values, the applicability of each scour analysis model is examined to fine-grained soil.

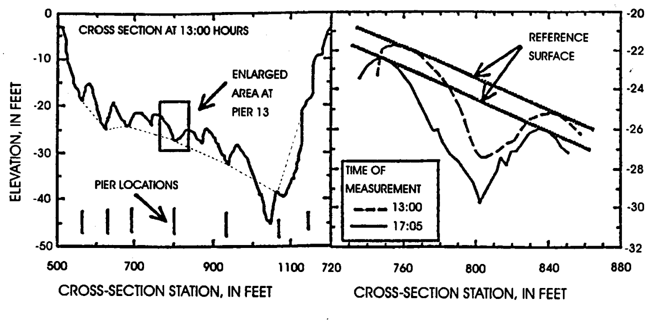
2 The Choji Bridge

The Choji Bridge is located in Kanghwa-Goon of Incheon Metropolitan City in Korea and connects Kanghwa-Goon and Kimpo City over the Yumha River. This bridge is an arch-type bridge opened to traffic in August 2002, which has 13 spans and is approximately 1,200 m long. The bridge piers are founded within the layers formed in the middle of the Proterozoic era. The soils below the main channel bed consist of alluvial deposits, weathered layer, and soft rock from the surface. The alluvial deposit and the weathered layer are mostly very soft silty clay.

The Yumha river comes across the West Sea at the location of the Choji bridge and flows very fast because of the ebb and flow of the tide. Therefore, the possibility of scour around bridge piers in the river bed is assumed to be relatively high. The difference between the ebb and flow of the tide is 9 m, the flow velocity is 4 m/s, and the average water depth is 12.4 m.

3 Measurement of local scour

Scour cannot be measured directly; it must be determined by interpretation of channel geometry data. The magnitude of scour for a scour data set is the vertical distance between the measured channel geometry and a surface, line, or point that represents the reference channel geometry for the baseline condition, i.e., for conditions in the absence of the bridge structure (Landers and Mueller, 1996). Reference surfaces should be selected so that the local, contraction, and general components of total scour may be quantified separately. The scour measurements could vary according to methods determining the reference surface. Field measurements of local scour which can fatally affect the stability of the structures, have generally used the concurrent ambient bed level as a reference(Fig.1).



(a) (b)

Fig.1. Definition of local pier scour (After Landers and Muellers, 1996)

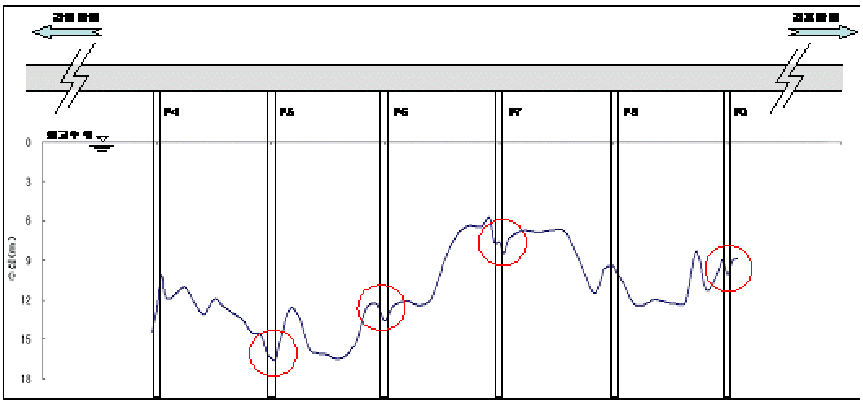


Fig.2. River Bed Profile(P4 ~ P9)

The scour depths around the bridge piers were measured using an ultrasonic sensor driven from a boat. In order to get the reasonable reference line for the exact pier scour depths, the water depths around the bridge piers were measured at the points as many as possible in all direction. The measured pier scour depths around the bridge piers were decided as the vertical distances between the measured channel geometry and the reference line. As shown in Table 1 and Fig.2, the location of maximum pier scour for each pier is not consistent but occurred in all direction. This phenomenon seems to reflect the influences of the tidal flow as well as the 1-dimensional stream flow. The maximum pier scour depth at the Choji bridge was 3.9m at P5.

Table 1. Max. Pier Scour at Each Pier

Pier	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**
Location	Back	Left	Front	Right	-	Left
Max. Pier Scour (m)	1.7	**3.9**	1.7	1.9	-	1.0

Table 2 Soil properties

Depth(m)	Specific Gravity	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)	Water Content (%)	Dry Unit Weight (kN/m^3)	Undrained Shear Strength (kN/m^2)	% Passing #200	Critical Shear Stress* (N/m^2)	USCS
1.0 ~ 1.5	2.47	25.4	20.9	4.5	49.1	11.0	98.0	54.1	30.7	CL-ML
1.5 ~ 2.0	-	-	-	-	46.6	11.3	132.4	-	12.3	-
2.0 ~ 2.5	2.45	25.4	21.7	3.7	43.1	11.7	215.7	41.8	16.5	ML
2.5 ~ 3.0	-	-	-	-	39.1	12.3	215.7	-	30.7	-
3.0 ~ 3.5	2.50	28.2	22.0	6.2	39.8	12.3	313.8	52.9	19.7	CL-ML
3.5 ~ 4.0	-	-	-	-	37.1	12.7	274.6	-	2.6	-
4.0 ~ 4.5	2.51	25.7	21.7	4.0	34.0	13.2	304.0	82.2	18.9	ML
4.5 ~ 5.0	-	-	-	-	34.7	13.1	289.3	-	20.1	-
5.0 ~ 5.5	2.48	24.7	19.7	5.0	37.3	12.6	245.2	94.1	70.0	CL-ML

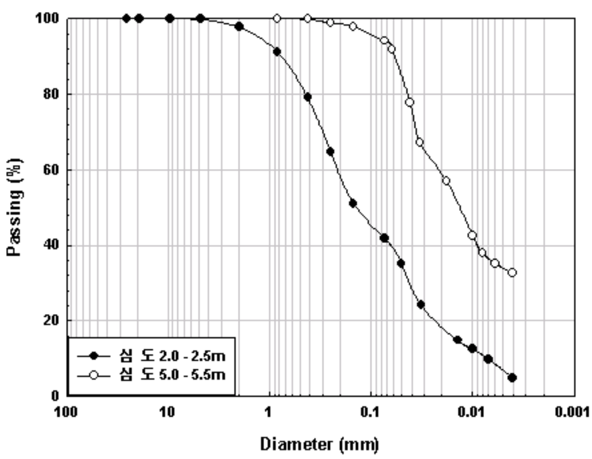


Fig.3. Particle-Size Distribution Curves

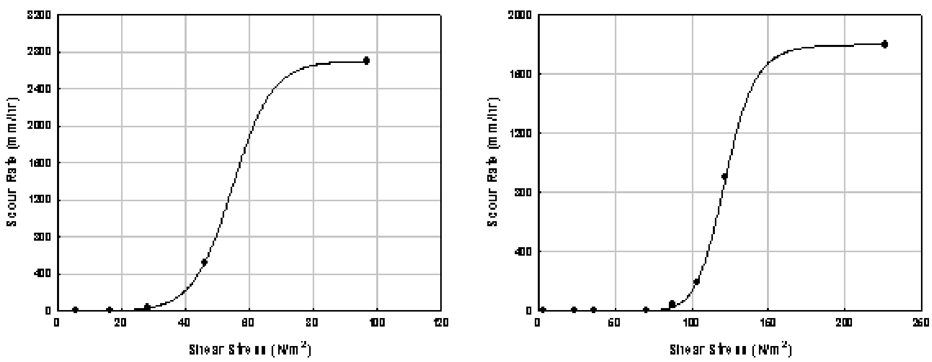
4 Geotechnical Properties

4.1. Physical Properties

In order to consider the erosion characteristics of the fine-grained soils at the Choji bridge site, the undisturbed soil samples were collected at the location of P3 using Shelby tubes with 76.2mm outside diameter and 0.8m length. A series of 5 tube samples were taken from 1m depth of the river bed. Before performing the EFA tests, the basic soil properties are obtained by lab tests, which may influence the scour phenomenon. The results of soil property tests are shown in Table 2 in detail. Most of soils consist of clay including sand or silt, which are classified as ML or CL-ML using the USCS (Unified Soil Classification System). The examples of particle-size distribution curves of silty clay (Depth 5.0 – 5.5m) and sandy silt (Depth 2.0 – 2.5m) are shown in Fig.3.

4.2. Erosion Characteristics

The EFA was developed to determine the scour rate of soils (Briaud et al., 1999). The purpose of the EFA test is to obtain the curve that shows the relationship between the scour rate and shear stress induced by flowing water. The water flows over the sample at a chosen velocity and the sample is advanced 1 mm as soon as it is eroded. These experiments are performed repeatedly for six or seven different velocities varying between 0.1 m/s to 6 m/s on each Shelby tube. The corresponding range of τ values is approximately 0.1 N/m^2 to 100 N/m^2. The flowing water generates an average bed shear stress over the soil sample in the test section. The hydraulic shear stress imposed by the water on the soil is calculated by using Moody Chart (Moody, 1944, Briaud et al., 2001 a). The scour rate is considered to be zero if it is less than 1 mm/hr. Therefore, the critical shear stress is considered to be the shear stress right before the scour rate becomes to be higher than 1 mm/hr. This number is used as a practical definition of the critical shear stress



(a) Sandy Silt (Depth 2.0 ~ 2.5m) (b) Silty Clay (Depth 5.0 ~ 5.5m)

Fig.4. Relationships between Scour Rates and Shear Stresses

The EFA tests were performed for the Shelby tube samples collected from the bridge site. The examples of EFA test results for silty clay (Depth 5.0 – 5.5m) and sandy silt (Depth 2.0 – 2.5m), which show the relationships between scour rates and shear stresses imposed by flowing water, are shown in Fig.8. In the case of silty clay which is more cohesive than sandy silt, the scour rates corresponding to the same shear stresses are a lot less and the critical shear stress is much higher as shown in Fig.8. The relative ability of silty clay to resist erosion which has cohesion is assumed to be higher than that of sandy silt.

5 Pier Scour Analysis

The pier scour depths for the P5 where the maximum pier scour occurred are calculated using the existing scour analysis models, which were based on the experiments conducted on the coarse-grained soils, as well as the SRICOS method. The parameters for the pier scour analyses are presented in Table 3. In this case, the caisson width instead of the pier width is used for the calculation because the water surface is about 1m below the top of the caisson.

Table 3. Parameters for Pier Scour Analysis

Parameters			
Pier	Pier Width	b	5 m
	Caisson Width	b^*	13 m
Bed Material	Median Particle Size	d_{50}	0.02 ㎜
	Maximum Particle Size	d_{90}	0.1 ㎜
Flow	Channel Shape		Straight
	Attack Angle of Flow	θ	0
	Water Depth	y_1	12.4 m
	Velocity	V_1	4 m/s

5.1. Existing Scour Analysis Models

The pier scour equations applied in this case study are presented as follows. These equations are recommended for pier scour analysis in River Design Standards in Korea.

(1) CSU Equation (1995)

$$\frac{y_s}{y_1} = 2.0 K_1 K_2 K_3 K_4 \left(\frac{b}{y_1} \right)^{0.65} Fr^{0.43} \qquad (1)$$

where y_s is the scour depth, y_1 is the flow depth directly upstream of the pier, b is the width of pier, the K's are the correction factors for the various influences such as pier nose shape, attack angle, bed configuration, and size of bed material, and Fr is the

Froude number, $v/(gy)^{0.5}$, v is the approach average velocity, and g is the gravitational acceleration.

(2) Froehlich Equation

$$d_s = 0.32K_*\left(\frac{b'}{b}\right)^{0.62}\left(\frac{y}{b}\right)^{0.46} Fr^{0.2}\left(\frac{b}{D_{50}}\right)^{0.08} + 1 \quad (3)$$

(3) Laursen Equation

$$\frac{b}{y} = 5.5\frac{y_s}{y}\left[\left(\frac{y_s}{11.5y}+1\right)^{1.7} - 1\right] \quad (4)$$

(4) Neill Equation

$$\frac{y_s}{b} = 1.5\left(\frac{y}{b}\right)^{0.3} \quad (5)$$

5.2. SRICOS Method

The steps of the SRICOS method are shown as follows(Briaud et al., 2001 b):

1) Obtain the erosion function showing the relationship between erosion rates and shear stresses through the EFA tests,
2) Calculate the maximum shear stress $\tau_{\max}$ and the maximum scour depth $z_{\max}$ by eq. (6) and (7),

$$\tau_{\max} = 0.094\rho \cdot v^2\left(\frac{1}{\log \mathrm{Re}} - \frac{1}{10}\right) \quad (6)$$

$$z_{\max}(mm) = 0.18\,\mathrm{Re}^{0.635} \quad (7)$$

where ρ is the density of water (kg/m^3) , v is the mean flow velocity, $\mathrm{Re} = vD/\nu$ is the pier Reynolds number, D is pier diameter, and ν is the kinematic viscosity of water (10^{-6} m^2/s at 20°C).

3) Obtain the initial scour rates $\dot{z}_i$ corresponding to $\tau_{\max}$ from the erosion function,
4) Calculate the equivalent time t_e by eq. (8), and

$$t_e(hrs) = 73t_{life}^{0.126}(yrs) \cdot v^{1.706}(m/s) \cdot \dot{z}_i^{-0.200}(mm/hr) \quad (8)$$

5) Calculate the scour depth y_s by eq. (9).

$$y_s(mm) = \frac{t_e(hrs)}{\dfrac{1}{\dot{z}_i(mm/hr)} + \dfrac{t_e(hrs)}{z_{\max}(mm)}} \quad (9)$$

5.3. Comparison

The predicted pier scour depths for P5 using the various pier scour equations are compared with the measured pier scour depth in Table 4. The Equations recommended in River Design Standards, which don't consider the erosion characteristics of the soil, highly overestimated the pier scour depth, on the other hand, the SRICOS method shows reasonable value 6.7m if it is compared with the measured scour depth 3.9m.

Table 4 Compariosn of Pier Scour Depths at P5

구 분	Predicted Scour Depth (m)	Measured Scour Depth (m)
SRICOS Method	6.7	3.9
CSU Equation	16.5	
Froehlich Equation	19.7	
Laursen Equation	13.9	
Neill Equation	19.2	

6 Conclusion

A case study of the pier scour analysis has been performed to examine the applicability of the various bridge pier scour models for the bridge piers founded in fine-grained soils. The undisturbed soil samples were collected using the Shelby tubes and tested using the EFA to determine the erosion function of the bridge site. The scour depths around the Choji Bridge piers were directly measured and compared with the predicted values using the various pier scour equations including the SRICOS method. The Equations recommended in River Design Standards, which don't consider the erosion characteristics of the soil, highly overestimated the pier scour depths, on the other hand, the SRICOS method showed reasonable value. It is shown that the scour analysis for fine-grained soils needs to consider the erosion characteristics of soil as well as hydraulic parameters.

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