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Effects of Cohesion on Bridge Scour

By

Albert Molinas[1], Sterling J. Jones[2]

ABSTRACT

This paper summarizes the comprehensive experimental study that was carried out at the Colorado State University Hydraulic Laboratory for the Federal Highway Administration to investigate effects of cohesion on bridge scour. In general, cohesive bridge scour experiments are classified as low clay content and high clay content experiments. In the presence of low clay contents, scour taking place around bridge piers and abutments exhibits characteristics observed in non-cohesive materials. In this case, the clay content is accounted for by the introduction of a scour reduction factor. As the clay content increases beyond a certain limit, cohesive material properties such as compaction, shear strength, initial water content, clay mineralogy, etc. dominate the scour process. For each class of experiments, results are summarized by equations using commonly measured parameters. The experimental study shows that for flows falling within the clear-water scour range, effects of cohesion may play a significant role in the magnitude of scour.

INTRODUCTION

In this paper effects of cohesion on local pier and abutment scour are investigated experimentally for Montmorillonitic and Kaolinitic clay mixtures using larger scale, 1.2 m, 2.4 m, and 5 m wide test flumes at the Colorado State University Hydraulics Laboratory housed in the Engineering Research Center. For low clay content soil mixtures with up to 12 percent clayey material, pier and abutment scour experiments show that the presence of a small amount of cohesive material may reduce scour considerably. To quantify the impact of clay content, scour in clayey sands is expressed as a fraction of scour measured in non-cohesive materials through a clay content reduction factor (K_{cc}). It is shown that K_{cc} is a function of clay content. It is also shown that different clay minerals have varying impacts on reducing bridge scour. For cohesive soils with significant clay content (30 percent for the present mixtures), soil parameters such as compaction, initial water content, degree of saturation, shear strength, and type of clay mineral dominate the abutment scour. In this study these effects are

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quantified for flow conditions with Froude numbers ranging from 0.2 to 0.9. Equations relating flow and selected cohesive soil parameters to bridge pier and abutment scour were developed to explain the variability of abutment scour with cohesion properties. These equations express bridge scour in cohesive soils relative to clear-water scour in non-cohesive material for the same flow and geometry conditions. Under the same geometric and flow conditions, measured scour in cohesive materials varies from 7 percent to 140 percent of that measured in medium sand.

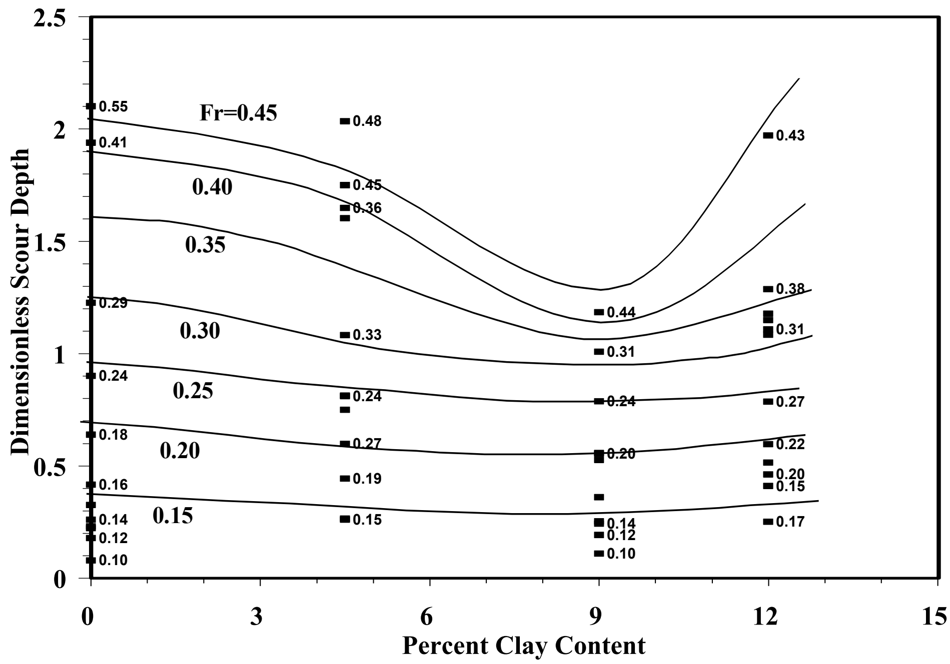

Fig. 1. Effect of clay content on abutment scour

LOW CLAY CONTENT EXPERIMENTS

Scour at bridges has been studied extensively in the past for non-cohesive sediments. The currently adopted scour estimation methodologies are developed from laboratory experiments conducted in sand or gravel beds. No expression for scour depth estimation is available to account for the presence of cohesive materials in cases where bridges are founded in clayey sands. Figure 1 illustrates the effect of varying cohesive material content on abutment scour. As shown in this figure, as the cohesive material content is increased, the depth of scour is reduced. However, beyond a certain threshold this behavior is reversed. The ultimate scour depth computations for the sandy clay materials are further complicated by the presence of different clay minerals. This section presents the results of experiments to quantify the presence of small amounts of clay on bridge scour. Results of these experiments are presented in terms of empirical relationships that relate scour in cohesive material to that observed in the non-cohesive material that was used in preparing the mixtures for the same flow and geometric conditions. The sand used in mixing with clayey soils had a median diameter of 0.55 mm and a gradation coefficient σ_g of 2.43. The properties of clays used in the mixtures are elaborated in the following section.

Pier Scour

Results of pier scour experiments in clayey sands are presented in figure 2. In deriving this figure, scour depths observed in Montmorillonitic clayey sand were normalized with the sand scour observed under similar flow and geometry conditions. In figure 2, pier scour results are expressed in terms of a reduction factor, K_{cc} , whose value ranges between 0 and 1; K_{cc} equal to unity denotes the depth of scour being equal to that observed in sand. Since the pier shape and width, flow depth, and sand properties were kept near constant, it was possible to identify the effects of clay content under various flow conditions. Figure 2 shows that for a given clay content, the clay content reduction factor (K_{cc}) is independent of approach flow conditions. The expression that best fits the data is given by:

$$K_{cc} = \frac{1}{1 + (\frac{CC}{11})^{0.9}}; \qquad 0 \leq CC \leq 11 \tag{1}$$

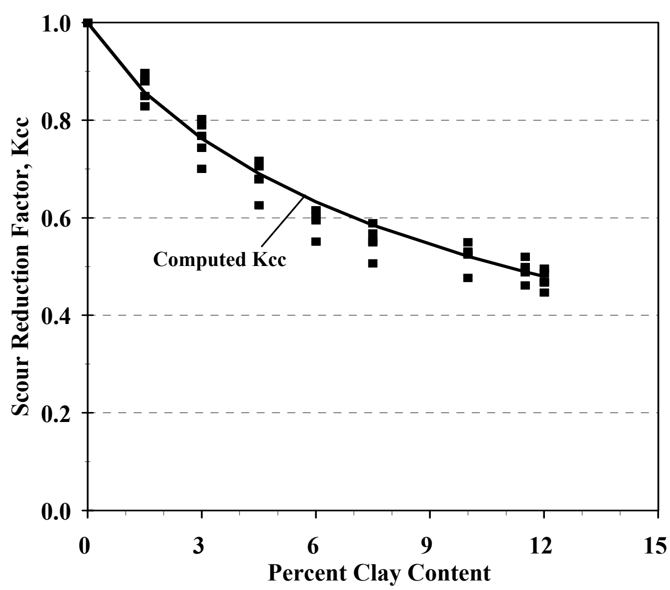

Fig. 2. Pier scour reduction factor for Montmorillonite clay mixtures.

Abutment Scour

Results of abutment experiments in clayey sands are summarized in figures 3 and 4. Similar to pier scour experiments, in deriving these figures scour depths observed in clayey sand were normalized with the scour observed in sand under similar flow and geometry conditions. In figures 3 and 4, abutment scour results are expressed in terms of a reduction factor K_{cc} whose value ranges between 0 and 1; K_{cc} equal to unity denotes the depth of scour being equal to that observed in sand. Since the abutment size and shape, flow depth, and sand properties were kept near constant, it was possible to identify the effects of clay content under various flow conditions. Figures 3 and 4 show that for a given clay content, the clay content reduction factor (K_{cc}) is independent of approach flow conditions. The expression that best fits the data for Montmorillonite clay mixtures is given by:

$$K_{cc} = \frac{1}{1 + (\frac{CC}{\alpha})^{\beta}}; \qquad 0 \leq CC \leq 11 \tag{2}$$

α, β = 16 and 1.5 for the best-fit line; and 22 and 1.8 for the envelop line that can be used as a design equation, respectively.

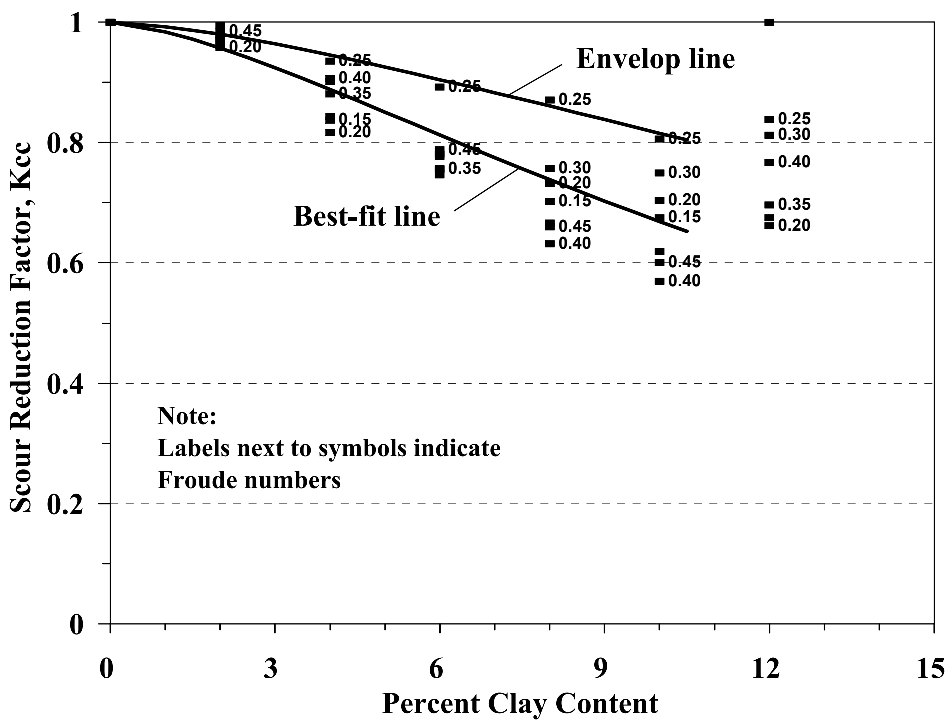

Fig. 3. Abutment scour reduction factor for Montmorillonite clay mixtures.

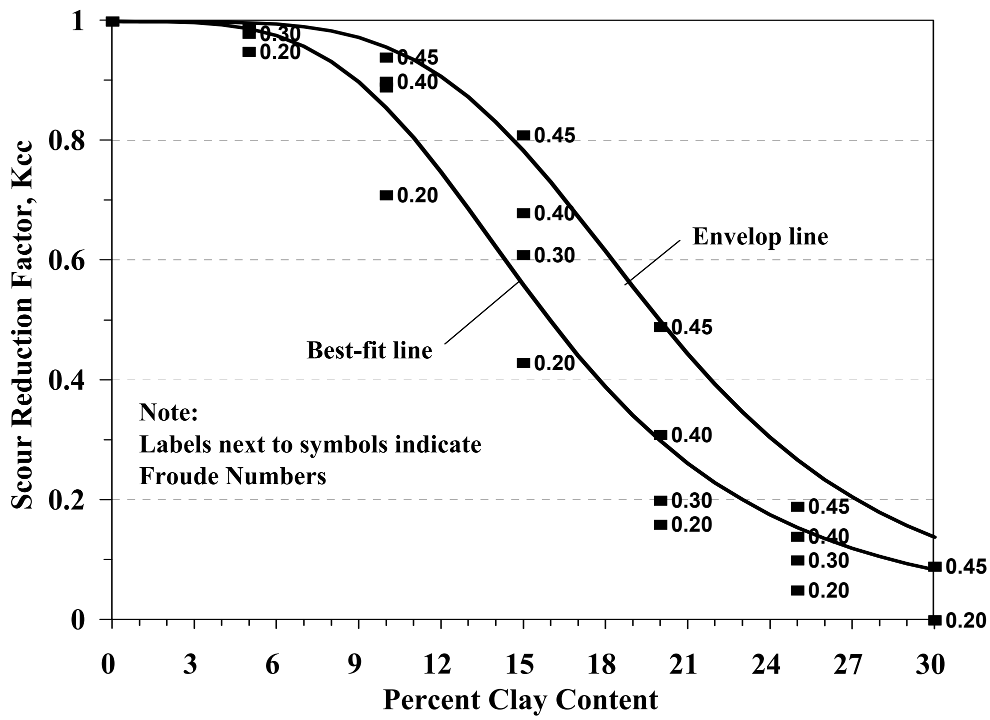

Fig. 4. Abutment scour reduction factor for Kaolonite clay mixtures.

For the Kaolinite clay mixtures the expression that best fits the data is:

$$K_{cc} = \frac{1}{1 + (\frac{CC}{\alpha})^{\beta}}; \qquad 0 \leq CC \leq 30 \tag{3}$$

where α,β = 16 and 3.8 for the best-fit line and 20 and 4.5 for the envelop line, respectively.

High Clay Content Experiments

Flow structure around bridge piers and abutments and the resulting local scour were studied in the past by numerous experimental, numerical, and analytical investigations for non-cohesive materials. As a result, series of empirical and semi-empirical prediction equations were developed to relate the local scour depth at bridge piers and abutments to different approach flow conditions, sediment size and gradations, and different structural types and size characteristics.

The mechanism of cohesive-material scour is significantly different from scouring of alluvial non-cohesive materials. The process involves not only the balancing of flow-induced shear stresses and the shear strength of soils to withstand scour, but also the chemical and physical bonding of individual particles and the properties of the eroding fluid. Cohesive materials, once eroded, remain in suspension. As a result, the phenomenon identified as clear-water local scour in non-cohesive materials always prevails. Along with the eroding fluid properties, the scour process in cohesive soils is strongly affected by the amount of cohesive material present in the soil mixture as well as the type of mineral clay, initial water content, soil shear strength, and compaction of the clay. The objectives of this paper are to apply the knowledge gained in the past in cohesive material scour to study local scour around piers and abutments and to analyze effects of compaction, initial water content, soil shear strength, and the approach flow conditions on local bridge scour. For this purpose two different types of clay mixtures were used. The first cohesive mixture was a naturally occurring soil that contained 32 percent Montmorillonite mineral clay with almost the same amounts of fine sand and silt. The second cohesive mixture was prepared by blending 30 percent pure Kaolinite clay with medium sand.

Details of experiments, tabulated results, and the initial analysis of data are presented by Molinas and Hosni (1998), Molinas and Reiad (1998), Molinas and Abdeldayem(1998), Molinas, Jones and Hosni (1999). In general terms, the pier and abutment scour experiments using Montmorillonite clay mixtures are classified as unsaturated and saturated clay experiments. The Kaolinite clay scour experiments were conducted under unsaturated conditions where compaction and initial water content of the mixture were varied.

Flumes

Experiments were conducted in two different larger scale test flumes housed at the Engineering Research Center at Colorado State University to achieve desired flow intensities. These flumes are identified as the Sediment Transport Flume and the Steep Flume. The Sediment Transport Flume is 2.4 m wide by 60 m long and the Steep Flume is 1.2 m wide by 12 m long. The flow depths used in the experiments varied between 0.12 m and 0.3 m, and approach Froude numbers ranged from 0.1 to 0.9.

Measurements

Flow and sediment parameters measured in experiments were velocity distribution (vertical, longitudinal, and lateral), depth of flow, depth of scour, initial water content of soil, Torvane shear strength, and degree of compaction. Velocity measurements were carried out by the use of a magnetic flowmeter. In the experiments, approach velocity to each pier and abutment was determined by depth- and width-integrated average of 7 vertical velocity profiles. Similarly, the approach depth was determined from a width- and length-averaged value of water surface and bed elevation measurements. The bed elevations were measured along flumes across the flow channel before and after each experiment. The depth of abutment scour was measured during and at the end of each experiment; it was determined by the difference between the minimum bottom elevation at the nose region of abutment and the maximum elevation away from the structure.

Cohesive Soil Types

In this study two cohesive soil mixtures were used. The first is a naturally occurring homogeneous soil containing 32 percent clay, 30 silt, and 38 percent fine sand particles. Utilizing the X-Ray Diffraction Test, the dominant clay mineral was found to be Montmorillonite. According to the USCS, the cohesive soil is classified as medium plasticity clay and the texture as clay loam. The second cohesive soil mixture was prepared by blending commercially obtained pure Kaolinite clay with medium sand. This mixture was composed of 30 percent clay and 70 percent sand.

Piers and Abutments

In pier scour experiments, 1-m-long cylindrical piers made of clear Plexiglas with 0.152-m and 0.102-m diameters were used. The scour depth development was measured against time utilizing three measuring tapes attached to the interior wall of each pier and a periscope manufactured by the use of a small inclined mirror.
In abutment scour experiments rectangular vertical-wall abutments constructed of clear Plexiglas with protrusion lengths of 0.22 m and 0.11 m were used. Lengths of these abutments in the direction of flow were 0.44 m and 0.22 m, respectively. The scour depth development was measured against time utilizing three measuring tapes attached to the interior wall of each abutment and by the use of a small inclined mirror.

Analysis

(a) Pier Scour

In pier-scour experiments, the effects of compaction on unsaturated cohesive soils were studied by compacting the material around piers at 58, 65, 73, 80, 87, and 93 percent degree of compaction; and the effects of initial water content on saturated cohesive soil erosion were examined by saturating the soils at initial water contents of 32, 35, 40, and 45 percent.
Dimensional analysis that has been used for correlating the variables affecting the local scour depth at bridge piers has been extended to include cohesive soil properties in order to account for the cohesive bed material. The variables used in the analysis are parameters defining the soil, the fluid, and the geometry of the modeled system. Depth of pier scour, D_s, which is the dependent variable in this analysis, can be expressed as a function of the following independent variables:

$$D_{sc} = f(Y, b, V, D_{50}, \sigma_g, \phi, \rho, t, g, \upsilon, S, CC, Mn, C, IWC) \qquad (4)$$

in which D_{sc} = depth of scour; Y = depth of approach flow; b = pier width; V = velocity of approach flow; D_{50} = mean sediment diameter; σ_g = standard deviation of sediment size; ϕ = pier shape factor; t = time; g = gravitational acceleration; ρ = fluid density; υ = fluid kinematic viscosity; S = soil shear strength; CC = clay content; *Mn* = origin of clay minerals (e.g. Kaolinite, Illite, Montmorillonite); *C* = degree of compaction; and *IWC* = initial water content.

Applying the dimensional analysis using b, V, and ρ as repeating variables, and using appropriate simplifications, the following set of dimensionless parameters can be obtained:

$$\frac{D_{sc}}{b} = f\left(F_r , IWC \ , \frac{S}{\rho V^2} , C \right) \tag{5}$$

in which F_r is the approach Froude number.

In the derivation of equation 5, the clay content (*CC*) was eliminated as a variable since the effects of this parameter was found to be an independent factor up to 12 percent clay content. In the pier scour experiments using Montmorillonite-clay mixtures, clay content was kept constant at 32 percent. In these experiments, the variation of scour with time was measured. This relationship was shown to be an asymptotic function with a sharp initial scour development followed by a gradual increase (Molinas, Jones, and Hosni, 1999). The initial rate of scour hole development is generally controlled by the nature of the clay mineral and other cohesive material parameters such as compaction, initial water content, etc. Past experimental and theoretical studies have shown that the velocity at the nose region of a circular pier is amplified by a factor of 1.6 to 1.7 times the approach velocity, *V*. Accordingly, the bottom shear stresses that are related to V^2 are also amplified and cause local scour in the affected zone. If approach velocities are increased beyond a threshold value, defined as critical velocity, the entire approach channel bottom becomes subject to general scour in addition to the local scour. Under these conditions, the scour hole development process continues until equilibrium slopes are attained for the entire reach and may last indefinitely. The experimental study presented in this report limited itself to conditions in which the oncoming flows do not scour the approach reach (clear water conditions). Under these conditions, as soon as the scour hole reaches a depth where the shear stresses within the hole become equal to the critical shear stress of the cohesive material, local scouring ceases. The duration of experiments in the study were long enough to maintain the equilibrium condition for at least 4 hours. The final scour depth values obtained under these conditions are independent of time, and therefore in deriving equation 5 the time parameter, *t*, is eliminated.

Pier scour analysis in this study was conducted under two major categories: 1) unsaturated Montmorillonite clay scour and 2) saturated Montmorillonite clay scour. The distinction is made since for saturated cohesive materials, parameters such as Torvane shear strength and compaction have no physical significance; whereas these parameters are important in unsaturated cohesive material scour.

UNSATURATED CONDITIONS

The measured values of (D_s /b) were regressed against the remaining dimensionless groups in equation 5. The best-fit regression equation resulting from the statistical analysis of experimental data is:

$$\frac{D_{sc}}{b} = 24715.49\,(IWC)^{-0.36} F_r^{\,1.92} C^{-1.62} \qquad (6)$$

where the initial water content (*IWC*) and compaction (*C*) are in percent. In deriving this expression, the initial water content ranged from 15 to 50 percent, and compaction ranged from 50 to 100 percent. The development of equation 6 is based on laboratory tests in which Froude numbers ranged from 0.18 to 0.37 and soil shear strength values ranged from 0.1 to 0.45 kg/cm^2. The higher value of the correlation coefficient, $R^2 = 0.95$, between the observed and predicted scour ratio indicates the strong correlation between measured scour depths and the parameters selected for defining flow and sediment properties. The plot of equation 6 with observed data is presented in figure 4. Pier scour corresponding to Froude numbers less than 0.2 and for compaction ratios higher than 85 percent is zero (scour threshold conditions).

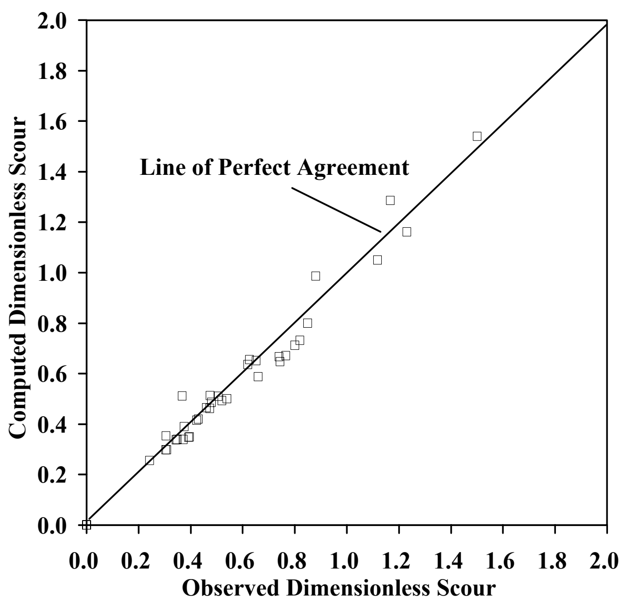

Fig. 4. Computed vs. measured dimensionless pier scour depth for unsaturated Montmorillonite clay.

SATURATED CONDITIONS

For saturated Montmorillonite clay soils, equation 5 can be further simplified by eliminating the dimensionless soil shear strength parameter, ($S/\rho V^2$), since this term has no physical meaning for saturated clays at high initial water contents (it approaches to 0). Also, for saturated conditions the compaction of cohesive soils, C, is mainly related to the water content and can therefore be removed from the list of independent variables. Introducing the pier scour initiating Froude number, F_i, to define threshold conditions for pier scour and replacing F_r by $(F_r\text{-}F_i)$, equation 5 becomes:

$$\frac{D_{sc}}{b} = f(IWC, F_r - F_i) \qquad (7)$$

Using the results of experimental study, F_i and D_s/b are determined as:

$$F_i = \frac{350}{(IWC^2)} \qquad (8)$$

$$\frac{D_{sc}}{b} = \begin{cases} 0 & \text{for} \quad F_r < F_i \\ 0.0288(IWC)^{1.14}(F_r - F_i)^{0.6} & \text{for} \quad F_r < F_i \end{cases} \qquad (9)$$

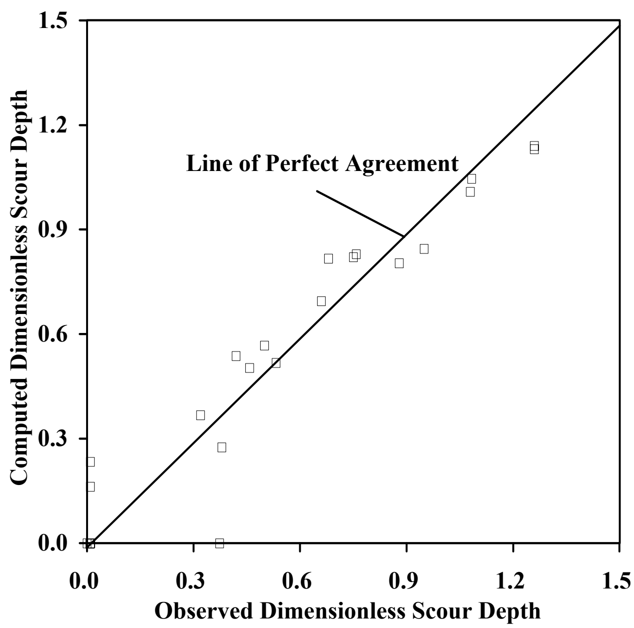

Fig. 5. Computed and measured dimensionless pier scour depth for saturated Montmorillonite clay.

For supercritical approach conditions, the value of experimental coefficient 0.0288 was found to be 0.0131. The plot of equation 9 with observed data is presented in figure 5.

(b) Abutment Scour

The functional relationship between the maximum depth of abutment scour and the parameters defining the soil, fluid, and the geometry of the abutment is derived through dimensional analysis. The depth of abutment scour in cohesive material (D_{sc}) can be expressed as a function of the following independent variables:

$$D_{sc} = f(D_s, Y, a, L, V, IWC, C, CC, S, Mn, T, t, g, \alpha, \phi, \rho, \upsilon) \quad (10)$$

in which D_s = depth of abutment scour in noncohesive material for conditions corresponding to D_{sc}; Y = depth of approach flow; a = abutment protrusion length; L = length of abutment in the direction of flow; V = velocity of approach flow; IWC = initial water content; C = compaction related to the optimum compaction; CC = clay content; S = Torvane shear stress, Mn = type of clay (e.g., Kaolinite, Illite, Montmorillonite); T = water temperature; t = duration of experiment; g = gravitational acceleration, α = angle of attack; ϕ = pier shape factor; ρ = fluid density; and υ = fluid kinematic viscosity.

Applying the dimensional analysis using D_s, V, and ρ as repeating variables, and using appropriate simplifications, the following set of dimensionless parameters can be obtained:

$$\frac{D_{sc}}{D_s} = f\left(IWC, \frac{S}{\rho V^2}, C, Mn \right) \quad (11)$$

In the derivation of equation 11, the clay content (CC) was eliminated as a variable since the effects of this parameter was found to be an independent factor up to 12 percent clay content. In cohesive bridge-scour experiments, the clay content was kept above 30 percent. In local scour experiments, the variation of scour with time was measured. This relationship was shown to be an asymptotic function with a sharp initial scour development followed by a gradual increase (Molinas and Reiad, 1998). The initial rate of scour hole development is generally controlled by the nature of the clay mineral and other cohesive material parameters such as compaction, initial water content, etc. Experimental and theoretical studies have shown that the velocity at the nose region of a vertical wall abutment is amplified by a factor of 1.2 to 1.8 times the approach velocity, V. Accordingly, the bottom shear stresses that are related to V^2 are also amplified (by up to 11 times) and cause local scour in the affected zone (Molinas, Kheireldin, and Wu, 1998). If approach velocities are increased beyond a threshold value, defined as critical velocity, the entire approach channel bottom becomes subject to general scour in addition to the local scour. Under these conditions, the scour hole development process continues until equilibrium slopes are attained for the entire reach and may last indefinitely. The experimental study presented in this report limited itself to conditions in which the oncoming flows do not scour the approach reach (clear water conditions). Under these conditions, as soon as the scour hole reaches a depth where the shear stresses within the base become equal to the critical shear stress of the cohesive material, local scouring ceases. The duration of experiments in the study were long enough to maintain the equilibrium condition for at least 4 hours. The final scour depth values obtained under these conditions are independent of time, and therefore in deriving equation 11 the time parameter, *t*, can be eliminated. Additionally, the dimensionless shear strength, *S*, can be related to *C* and *IWC*, further reducing the number of parameters. The local abutment scour analysis in this study was conducted separately for the two clay types. This distinction is made since the type of clay mineral (*Mn*) was found to have a dominant effect on the scour resistance of bed material.

MONTMORILLONITE SCOUR

Montmorillonite-clay mixture experiments studied the effects of compaction, initial water content, and shear strength for unsaturated and saturated soil conditions. This was achieved by compacting the cohesive material placed around the abutments at various degrees of compaction and by using soils of different initial water content. The measured values of (D_{sc}/D_s) were regressed against the remaining dimensionless groups in equation 11 using nonlinear multiple regression analysis through the use of a commercially available SAS computer package. The best-fit regression equations resulting from the statistical analysis of experimental data are:

For **unsaturated** clays with initial water content less than 25 percent:

$$\frac{D_{sc}}{D_s} = (2.186 - 0.05342\ IWC)(15.407 - 0.522\ C + 0.006087\ C^2 - 0.0000235\ C^3) \quad (12)$$

where initial water content (*IWC*) and compaction (*C*) are in percent.

For **saturated** clays with initial water content in the range of 28 to 45 percent:

$$\frac{D_{sc}}{D_s} = (4.76 - 0.451\ IWC + 0.01361\ IWC^2 - 0.000126\ IWC^3)(-0.339 + 0.01744\ C) \quad (13)$$

In deriving equations 12 and 13, IWC ranged from 12 to 45 percent, and C ranged from 58 to 89 percent. Equations 12 and 13 were developed based on laboratory tests in which Froude numbers ranged from 0.1 to 0.6 and soil shear strength values ranged from 0.1 to 0.63 kg/cm^2. The plot of equations 12 and 13 with observed data is presented in figure 6.

KAOLINITE SCOUR

Kaolinite-clay experiments investigated the effects of initial water content on unsaturated clay erosion by preparing mixtures with varying initial water contents. In these experiments compaction was varied over a narrow range of conditions.

For **unsaturated** Kaolinite clay soils, the basic form of equation 13 was retained. For the cohesive soil consisting of 30 percent Kaolinite clay and 70 percent medium sand with a median diameter of 0.81 mm, the best-fit regression equation from the statistical analysis of experimental data is:

$$\frac{D_{sc}}{D_s} = (0.12 + 0.014\ IWC - 0.00205\ IWC^2 - 0.000057\ IWC^3)(-0.4 + 0.017\ C) \qquad (14)$$

Scour initiating velocities for the Kaolinite clay mixture were experimentally determined to be 0.6 m/s. For velocities smaller than this value, the scour ratio is zero. The plot of equation 14 with observed data is presented in figure 7.

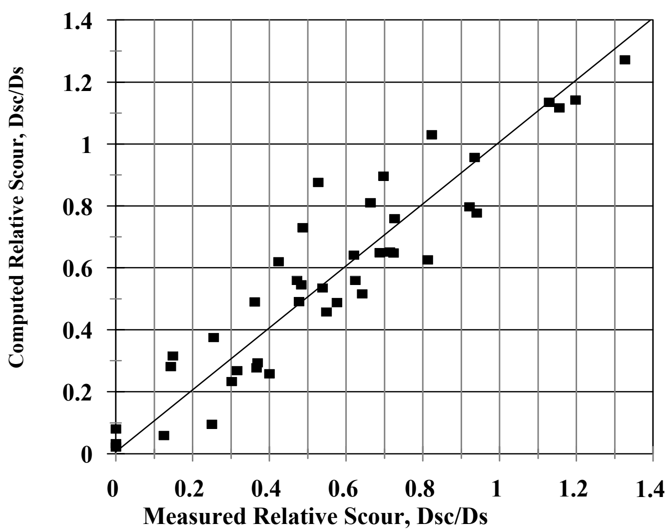

Fig. 6. Computed vs. measured relative abutment scour for Montmorillonite clay.

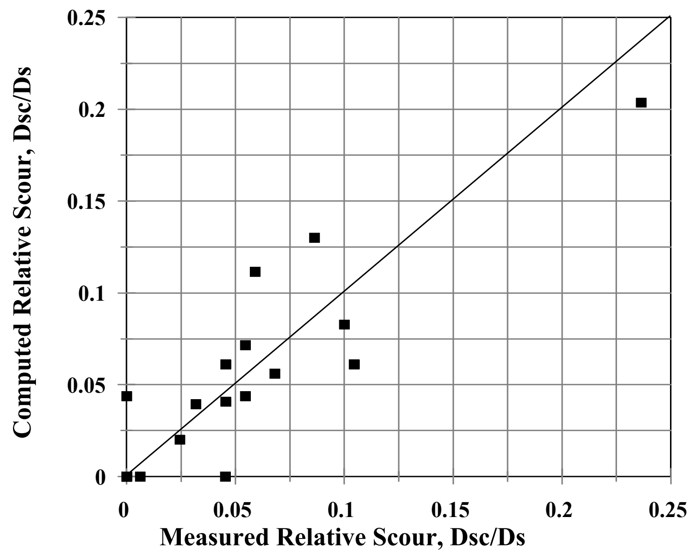

Fig. 7. Computed vs. measured relative abutment scour for Kaolinite clay.

CONCLUSIONS

Conclusions from the study can be listed as:

1. Bed material mixtures that are predominately sand with low clay content can be analyzed using the traditional non-cohesive soil parameters for scour with a reduction factor to account for the cohesive effects from the clay fraction. The experimentally determined reduction coefficients found from the present study are given by equations 1 through 3 for Montmorillonite and Kaolinite clays, respectively. Two sets of coefficients are given for equations 2 and 3 to represent the best-fit line through the data and the envelop-line that can be used as a design equation. Bed material mixtures with high clay contents are governed by cohesive soil properties. There is no clear clay content percentage that determines where the shift occurs from non-cohesive to cohesive properties. For the present study this limit was found to be around 12% and was affected by the clay mineralogy.
2. There is a distinction between pier scour taking place in unsaturated compacted clayey soils and saturated clayey soils. This differentiation affects parameters controlling local pier scour. For unsaturated compacted Montmorillonite clay soils, a new scour depth predictor is proposed in terms of initial water content, Froude number, soil shear strength, and degree of compaction. The pier scour depth and volume decrease as the compaction of cohesive soils increases. For saturated cohesive soils, the scour depth can be expressed as a function of initial water content and excess Froude number,

(F_r-F_i). Under saturated conditions, the scour depth is directly proportional to excess Froude number and is inversely proportional to initial water content.

3. Abutment scour in cohesive soils shows a wide range of variability depending on properties of soils. In the present experiments, under the same geometric and flow conditions, measured scour in cohesive materials varied anywhere from 7 percent to 140 percent of that measured in medium sand. This is due to initial water content, soil shear strength, degree of compaction, and type of clay mineral present in the soil. For Montmorillonite-clay soils, the relative scour depth is expressed in terms of initial water content and degree of compaction. For unsaturated Montmorillonite-clay mixtures, abutment scour depth decreases as the compaction and initial water content increases. For saturated cohesive soils, however, the scour depth is mainly a function of the initial water content and is inversely proportional to initial water content. For unsaturated Kaolinite-clay mixtures, the initiation of scour takes place under higher flow intensities, and under same flow conditions the total scour is up to a factor of five times smaller.

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