AN EXPERIMENTAL STUDY OF LOCAL SCOUR AROUND CIRCULAR BRIDGE PIERS IN COHESIVE SOILS

KAI TZE KHO, ERIC VALENTINE AND STEPHANIE GLENDINNING

School of Civil Engineering and Geosciences, University of Newcastle upon Tyne, Newcastle upon Tyne, NE1 7RU. UK..

An experimental investigation of local scour around circular bridge piers in soils of cohesive/non-cohesive mixtures is presented. Synthetic soils of different clay content, prepared by mixing Kaoline with sand at optimum moisture content to achieve maximum dry density, were tested. Pier Reynolds Number and clay content were found to have a significant effect on the development of the scour hole. An empirical equation was developed to predict the equilibrium scour depth. A comparison between the predicted equilibrium scour depth and existing equations reveals that these equations underestimate the equilibrium scour depth in cohesive soils at higher flow velocities. The side slope of the scour hole was also found to increase with the increase of clay content.

1 Introduction

Pier scour is the greatest single cause of bridge failures. With the prospect of more severe and more frequent floods due to climate change, reducing the risk of bridge failure is becoming increasingly important.

Bridge pier scour in sand and gravel river beds is relatively well understood. However, very few studies have been carried out on the scouring of cohesive soil. The scour of cohesive materials is fundamentally different from that of non-cohesive materials. The erosion of non-cohesive sediments depends on factors such as the grain size distribution, the shape and the density of individual grains. The resistance of cohesive sediments to erosion is related to electrochemical bonding between individual particles. Natural sediments rarely consist of only sand or mud. Many alluvial channels are made up of a mixture of cohesive and non-cohesive soils. Since many structures are founded on cohesive materials, there is a need to improve our understanding of their behaviour.

In order to clarify the effect of cohesive material on local scour, a series of experiments was carried out on circular piers in synthetic soils with various proportions of clay content, C, in which the depth of scour, d_s, was monitored as the scour hole developed. The dimensions of the scour hole, that is side slope, Z, and width, W, were measured at the end of the test. It took several days for these tests to reach their equilibrium scour depth, d_{se}. Therefore, a hyperbolic function shape model, as explained by Gudavalli (1997), was used to extrapolate the measurements to predict the equilibrium scour depth. This predicted equilibrium scour depth was used in this study.

2 Experimental Set Up And Procedure

The experiments were carried out in a recirculating metal flume located in the Fluid Dynamics Laboratory of the school of Civil Engineering and Geosciences, University of Newcastle upon Tyne.This flume is 6m long, 0.6m wide and 0.45m deep. A false bottom made of plywood was installed 0.15m above the original flume bed to create a recess for the soil bed. The slope of the false bed was 0.001m/m.

Soil samples with clay content 0, 5, 10, 15, 20, 30, 40 & 50% by dry weight were mixed with sand and tap water. The silt content of the material is equal to the clay content in this project, e.g. 30% clay content soil would have 30% silt size material and 40% sand. Both clay and silt are cohesive material. Therefore, by testing clay samples in the range of 0-50% clay content, this covered soils from 0% (sand) to 100% cohesive material (50% clay and 50% silt). The experiments were conducted by using three types of soils: synthetic Supreme Kaoline, Grade E Kaoline and sand. Kaoline was used to ensure that the soil parameters were well controlled. Supreme Kaoline is mostly made up of clay size particles (<0.002mm) and Grade E Kaoline is mostly made up of silt size particles ($0.002mm<d<0.06mm$). The very fine silica sand (non-cohesive component) used in this series of experiments had a mean diameter, d_{50}, of 0.14mm. The soil properties of each mixture, i.e. plastic index, optimum moisture content, shear strength and permeability were investigated.

Soil samples were prepared to the optimum moisture content and compacted to the maximum dry density in the flume. Circular piers of 25mm and 50mm diameter, b, were placed in the soils. Soil density and strength were obtained before each test. Various flow velocities, U, in the range of 0.26 m/s to 0.52 m/s were established in the flume. Flow velocities higher than 0.6m/s were found to be unrealistically erosive. Water flow depth, y_o, was set to 150mm in most experiments so that the influence of water depth on scouring may be neglected. Melville and Sutherland (1988), Ettema (1980), Chiew & Melville (1987) and Sheppard (1999) have shown that water depth has a negligible effect on scour when y_o/b reaches 2.5-3.0.

All experiments had live bed scour conditions. The minimum flow velocity was higher than the critical mobility velocity of the sand (0.22m/s from Neill (1968)). The eroded clay material was in suspension. Owing to the different clay contents and flow velocities involved in each run, the test duration, t, varied from a few hours in sand to 59 hours for the 50% clay content soil bed.

The experimental data are shown in Table 1. Based on the flow velocities, the experiments were divided into four Series: A, B, C and D.

3 Analysis Of Experimental Data

The initial scour occurred in either the wake, or at the sides of the pier and then migrated to the upstream edge of the pier. With lower clay content scouring started very quickly, whereas it took much longer for this to initiate with highly cohesive material.

Table 1. Experimental Data

Exp no.	C (%)	b (mm)	y_s (mm)	Q (l/s)	U (m/s)	t (hour)	d_s (mm)	d_{se} (mm)
A1	50	50	150	21	0.26	59	0	-
A2	40	50	150	21	0.26	38.5	0	-
A3	30	50	150	21	0.26	20	0	-
A4	20	50	150	21	0.26	50	0	-
A5	20	50	150	21	0.26	23	0	-
A6	15	50	150	21	0.26	20	0	-
A7	10	50	150	21	0.26	46	75	78
A8	5	50	150	21	0.26	23	76	77
A9	0	50	150	21	0.26	11	73	75
A10	0	50	150	21	0.26	9	73	76
A11	0	25	150	21	0.26	6	34	34
B1	20	50	150	31	0.34	43	86	89
B2	15	50	150	31	0.34	11	85	87
B3	10	50	150	31	0.34	16	96	99
B4	5	50	150	31	0.34	12	94	94
B5	0	50	150	31	0.34	5.5	81	83
B6	10	25	150	31	0.34	6.3	51	52
C1	50	50	161	39.5	0.41	37	113	132
C2	40	50	161	39.5	0.41	27.5	118	127
C3	30	50	161	39.5	0.41	30	111	113
C4	20	50	161	39.5	0.41	7.7	96	99
C5	15	50	161	39.5	0.41	6	92	94
C6	10	50	161	39.5	0.41	12	106	108
C7	5	50	161	39.5	0.41	6	98	100
C8	30	50	161	39.5	0.41	22	112	114
C9	30	25	161	39.5	0.41	14	51	55
D1	50	50	205	67.8	0.52	3.5	130	185
D2	40	50	205	67.8	0.52	3	115	159
D3	30	50	205	67.8	0.52	3.5	131	151

The maximum scour depth was found upstream of the pier in all experiments at the end of the test. However, in soils with clay content at or above 20%, the scour depth on both sides and in the wake of the pier was found to be about the same as the maximum scour depth. The scoured sand in the soil mixtures deposited downstream and formed a bar, while the clay particles were suspended during the scouring process.

Fig. 1 shows that the equilibrium scour depth, d_{se}, correlates very well with Pier Reynolds Number, Re_p. This finding agrees with Guvadalli (1997). A regression relationship between d_{se} and Re_p was developed:

$$d_{se}=0.0044Re_p^{1.0234} \quad (1)$$

As most of the soil properties (plastic index, optimum moisture content, shear strength and permeability) depend on the proportion of clay, the clay content was chosen as the

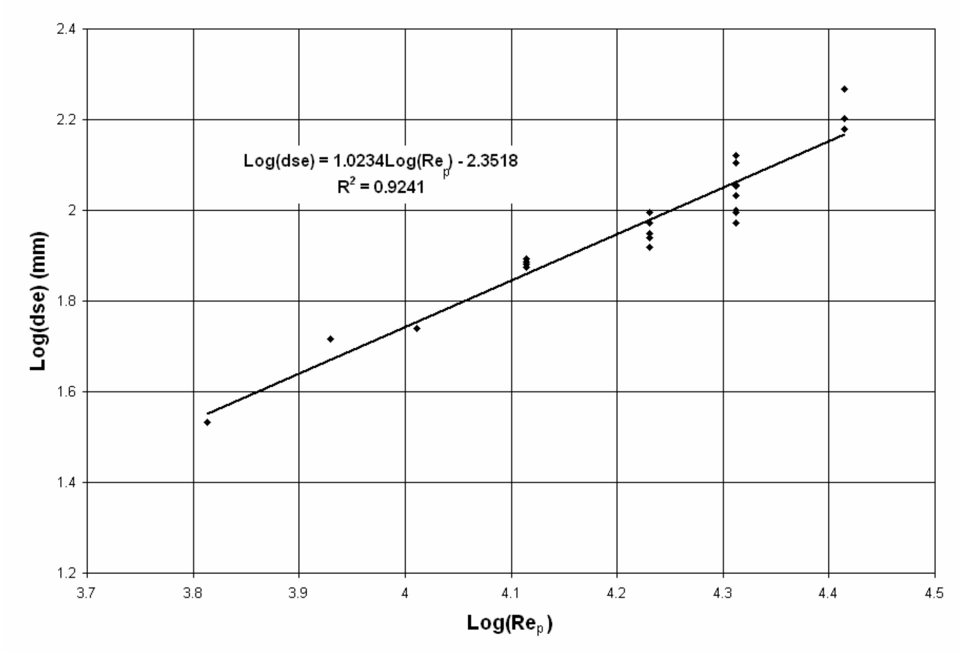

Figure 1. The regression between d_{se} and Re_p

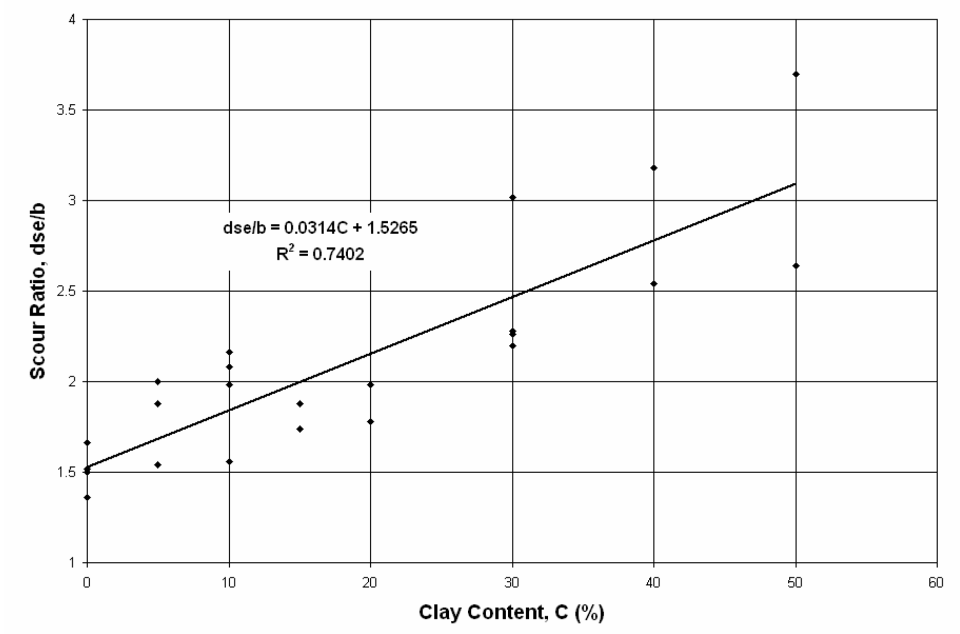

Figure 2. Scour ratio vs clay content

most representative parameter in this project. Scour ratio, d_{se}/b, and clay content correlate well (see Fig.2). The scour ratio increases with increasing quantities of clay in the soil. The scour depth is greater in soils with higher clay content because the lattice structure of the clay expands and the bonds between the clay particles break down with time in the presence of water, causing dispersion. Hence the clay material tends to be eroded more easily by even very low velocities. The linear regression equation from Fig.2 is:

$$d_{se}/b=0.0314C+1.5265 \qquad (2)$$

By combining both the effect of Pier Reynolds Number and clay content, an empirical equation was developed to predict the equilibrium scour depth in cohesive/non-cohesive mixtures:

$$d_{se}=0.0044Re_p^{1.0234}(1+C/100)^{0.5} \qquad (3)$$

Fig.3 shows the relationship between the d_{se} calculated by Eq. (3) and the hyperbolic model predicted value. The comparison is satisfactory. Eq. 3 underestimates the equilibrium scour depth by a maximum of 8%.

The equation developed in this project is compared to those developed by Gudavalli (1997), Hosny (1995), Shen (1969) and Richardson and Davis (CSU) (1995). The comparisons (Fig.4) show the same trend for the Gudavalli, Shen and CSU equations. However, the equilibrium scour depth obtained by Eq. 3 is smaller at low velocities and larger at high velocities when compared to these equations. The equilibrium scour depth from Eq. 3 is dramatically different from the Hosny prediction.

The Gudavalli equation was developed mainly from clay material. However, it does not take into account the soil properties. Only Pier Reynolds Number is considered. It is impractical to neglect the soil properties in scour prediction in cohesive material as scouring of cohesive sediments involves the chemical and physical bonds of the individual particles.

The Shen and CSU equations show very similar results, even although the Shen equation is a function of Reynolds Number and the CSU equation is a function of Froude Number. It is noted that both equations are developed from non-cohesive soils and Fig.4 suggests that it is not suitable for scour depth prediction of cohesive material, especially at high velocities. The values of scour depth predicted by the Shen and CSU equations are smaller than those predicted by Eq. 3 at high velocities. This is probably due to the refilling of the scour hole by sand during the live bed scouring. Some non-cohesive scour depth prediction equations suggest that the maximum scour depth is only equal to 2.4b (Raudkivi and Ettema (1983), May and Willoughby (1990)).

Hosny also investigated the scour in the soil of cohesive and non-cohesive mixtures. However, his equation shows very different results from Eq. 3. A reason may be that the definition of clay content is different from this project. Hosny defined the clay content as the amount of cohesive soil by dry weight in the soil mixtures. The cohesive soil used was made up of 24% sand, 44% silt and only 32% of clay. However, the clay content defined in this study is the amount of clay size material by dry weight in the soil mixtures. The maximum clay content that Hosny investigated was 40% (only 12.8% clay content by the definition of this project). Hosny concluded that scour depth decreases with the increase of clay content, which is contrary to the findings of this project.

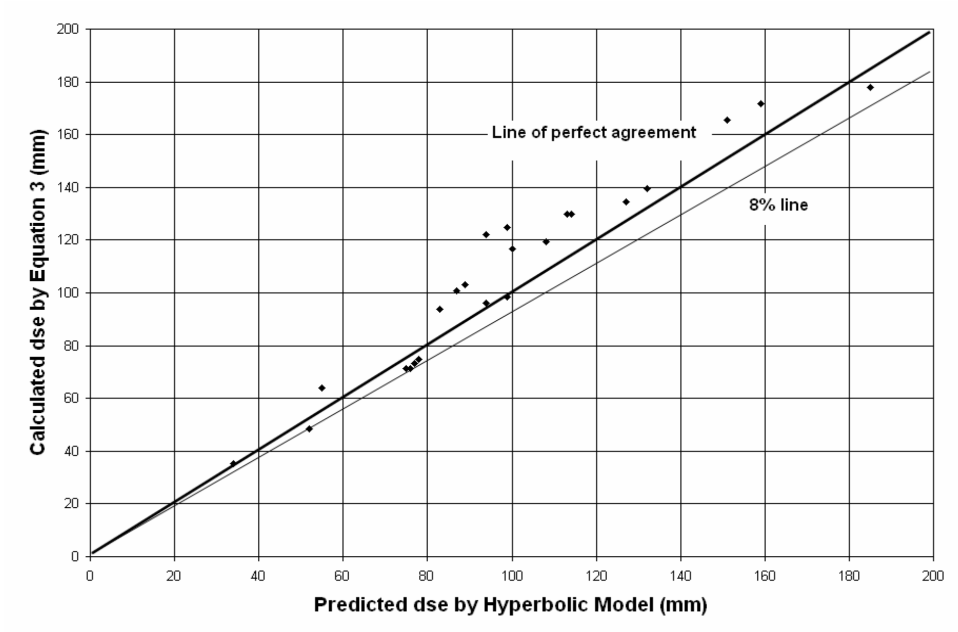

Figure 3. Comparison of d_{se} by equation 3 and d_{se} by hyperbolic model

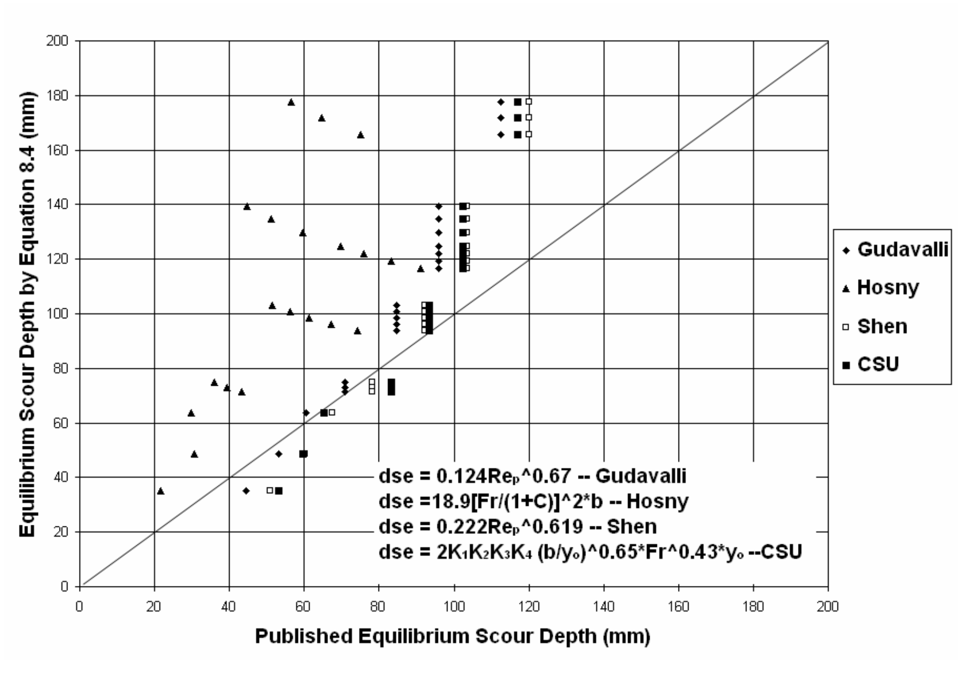

Figure 4. Comparison of equilibrium scour depth

After the test, the side slope, Z, and Width, W, of the scour hole upstream of the pier were measured. This slope is plotted against clay content in Fig. 5. The plot suggests that the slope angle increases with the increasing quantity of clay content. The result is consistent with the finding of Hosny (1995). A regression line (R^2 =0.95) was fitted to the data and the regression equation obtained is:

$$Z=0.3205C+30.84 \tag{4}$$

The width of the scour hole, W measured from the edge of the pier to the edge of the scour hole can be estimated by:

$$W=ds/\tan(Z) \tag{5}$$

As the slope is steeper in soil with higher clay content, the width of the scour hole is smaller. It was also observed that the volume of scour hole upstream of the pier decreased with the increase in clay content. Therefore the flow velocity in the scour hole of soil with higher clay content is expected to be higher as the flow is more contained and a deeper scour hole is created.

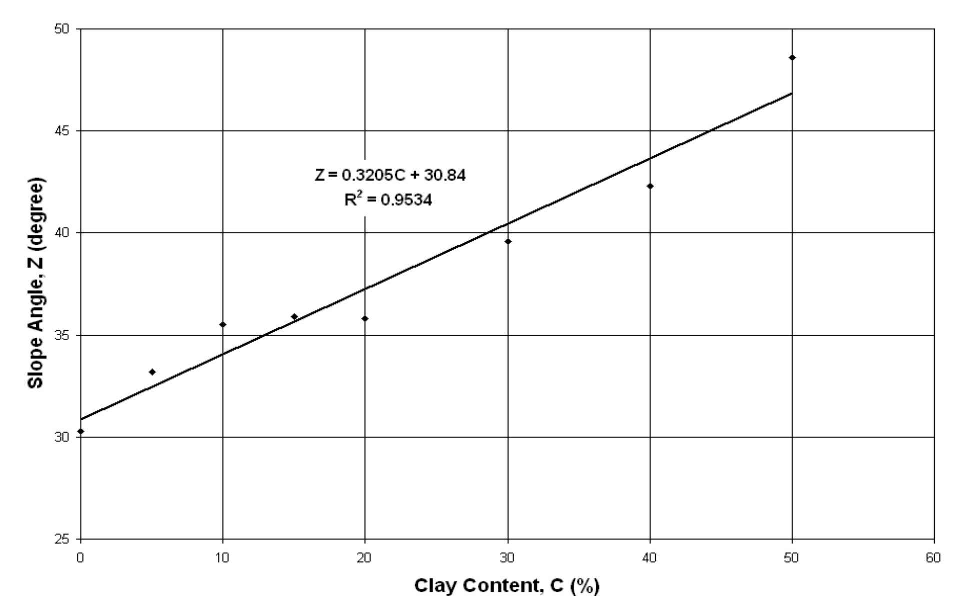

Figure 5. Slope v clay content

4 Conclusions

1. The wake vortex was found to have a more significant effect in initiating scour in cohesive materials.
2. Maximum scour depth was observed to occur at the upstream of the pier in all experiments. However, in soils with clay content at or greater than 20%, the scour depth on both sides and even in the wake of the pier was found to be about the same as the maximum scour depth.

3. Local scour in soils of cohesive/non-cohesive mixtures is a function of Pier Reynolds Number and clay content. The equilibrium scour depth increases with an increase in both parameters.
4. Values of scour depth predicted by non-cohesive scour depth prediction equations are smaller than those predicted by the equation developed in this project for soils of cohesive/non-cohesive mixtures at high velocities. This is probably due to the refilling of the scour hole by sand during the high flow live bed scour.
5. The side slope of the scour hole increases with the increasing clay content. However, the width and volume of scour hole upstream of the pier are inversely proportional to the clay content.

References

Chiew, Y.M. & Melville, B.W. (1987), "*Local Scour Around Bridge Piers*", Journal of Hydraulics Research , IAHR, Vol.25, January, 15-26.

Ettema, R. (1980), *Scour at Bridge Piers*, Ph.D Dissertation, Civil Engineering Department, University of Auckland, New Zealand.

Gudavalli, S.R. (1997), *Prediction Model for Scour Rate Around Bridge Piers in Cohesive Soil on the Basis of Flume Tests*, Ph.D Dissertation , Civil Eng. Department, Texas A & M University.

Hosny, M.M. (1995), *Experimental Study of Local Scour Around Circular Bridge Piers in Cohesive Soil,* Ph.D Dissertation , Civil Engineering Department, Colorado state University.

May, R.W.P. & Willoughby, I.R. (1990), *Local Scour Around Large Obstructions*, HR Wallingford, Report SR 240.

Melville, B.W. & Sutherland, A.J. (1988), "*Design Method for Local Scour at Bridge Piers*", Journal of Hydraulic Engineering, ASCE, Vol.114, October, 1210-1226.

Neill, C.R. (1968), "*Note on Initial Movement of Coarse Uniform Bed Material*", Journal of Hydraulics Research, IAHR, Vol.17, February, 247-249.

Raudkivi, A.J. & Ettema, R. (1983), "*Clear Water Scour at Cylindrical Piers*", Journal of Hydraulic Engineering, ASCE, Vol.109, March, 338-350.

Richardson, E.V, & Davis, S.R. (1995), *Evaluation Scour at Bridges, 3rd edition, (HEC-18), Report Number: FHWA-IP-90-017*, Federal Highway Administration, Washington DC.

Shen, H.W., Schneider, V.R. & Karaki, S. (1969), "*Local Scour around Bridge Piers*", Journal of Hydraulics Division, Proceedings of the ASCE, Vol.95, No.HY6, 1919-1940.

Sheppard, D.M. (1999), "*Conditions of Maximum Local Structure-induced Sediment Scours*", Stream Stability and Scour at Highway Bridges: Compendium of Papers ASCE Water Resources Engineering Conferences 1991 to 1998, Ed: Richardson, E.V. & Lagasse, Reston, VA, ASCE 1999, 347-364.