

FINAL REPORT

**LARGE SCALE AND LIVE BED LOCAL PIER SCOUR
EXPERIMENTS**

**PHASE 2
LIVE BED EXPERIMENTS**

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SUBMITTED BY:

**D. MAX SHEPPARD
Department of Civil and Coastal Engineering
365 Weil Hall
P.O. Box 116580
University of Florida
Gainesville, FL 32611-6580**

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LIVE BED EXPERIMENTS

Introduction

The accurate prediction of sediment scour depths near bridge piers under design storm conditions is very important in bridge design. Under-prediction can result in costly bridge failure and possibly the loss of lives, while over-prediction can result in millions of dollars wasted on the construction of a single bridge. The physical processes involved are very complex and difficult to analyze, and thus most design scour depth predictive equations are based on laboratory scale experimental results. An ongoing bridge scour research program at the University of Florida is directed at increasing the understanding of scour processes and improving the accuracy of design scour depth predictions. Equations for predicting local scour depths were developed by the author early in this program. Additional data was needed to extend/verify these equations. Experiments to obtain this data were divided into two phases, 1) the large structure, clearwater scour phase and 2) the high velocity, live bed scour phase. The Phase 1 experiments were conducted by the author in the Hydraulics Laboratory at the Conte USGS-BRD Laboratory in Turners Falls, Massachusetts. The Phase 2 experiments were conducted by the author in the Hydraulics Laboratory at the University of Auckland in Auckland, New Zealand. Phase 1 has been completed and a technical paper on the results accepted for publication in the ASCE Journal of Hydraulic Engineering. A more complete description of this work can be found in a University of Florida Coastal Engineering Technical Report [Sheppard et al. (2002)]. Phase 2 of this work is the topic of this report.

Research Objectives

The research described in this report is part of a larger local sediment scour research effort being conducted by the author with funding from the Florida Department of Transportation. Early in this program predictive equations for local scour at single structures in cohesionless sediments were developed based on laboratory data obtained by the author at the University of Florida and data obtained by other researchers. Since the range of conditions (structure size, sediment size, flow velocity, etc.) used in the development of these equations was somewhat limited, additional data was needed to extend/verify the equations. To the knowledge of the author no single flume exists with

the capability of producing all of the conditions needed to verify the equations. That is, no existing flume can test large, prototype size structures, produce high velocity flows and recirculate the sediment. For this reason a research plan consisting of two phases was proposed. The first phase was directed at the geometric scale issues (i.e. the size of the structures tested) and relatively low velocity, clearwater scour conditions. The maximum size structure that can be tested is a function of the width of the flume (the structure width should not exceed ~15% of the flume width). The Hydraulics Laboratory at the USGS-BRD Laboratory in Turners Falls, Massachusetts has a large (20 ft wide, 21 ft deep, 126 ft long) flow-through type flume that is used for fisheries research. A cooperative agreement was established between the University of Florida and the Conte USGS-BRD Laboratory to conduct clearwater local scour experiments with three different circular piles ranging in size from 4.5 inches to 36 inches in diameter. Three sediment sizes were used in the tests ($D_{50} = 0.22$ mm, 0.8 mm and 2.9 mm) and a range of water depths and flow velocities. These tests achieved their objectives by providing data at large structure to sediment size ratios for a range of clearwater flow conditions.

Phase 2 of this research, which is the subject of this report, had three primary objectives: 1) to provide live bed scour data at larger structures, 2) to investigate the existence of a maximum (limiting) value of normalized local scour depth with increasing depth-averaged velocity and 3) if such a maximum exists, investigate the conditions under which the maximum occurs (at least for the range of conditions examined).

A survey of flumes in the United States and abroad that are capable of recirculating sediment and producing high velocity flows in the live bed scour range indicated that a flume in the Hydraulics Laboratory at the University of Auckland (UA) in Auckland, New Zealand was the most appropriate for the Phase 2 work. Arrangements were made for the author to conduct live bed scour experiments in this flume with the assistance of UA graduate students over a four month period (January-April) in 2002. This report presents a description of the facilities, instrumentation, and procedures used and the test results.

Facilities and Instrumentation

Facilities

All of the tests were conducted in a 5 ft wide, 4 ft deep, 148 ft long, tilting flume, located in the Hydraulics Laboratory at the University of Auckland in Auckland, New Zealand. The flume has a maximum tilt of 1%. It has two pumps for recirculating the water with a combined capacity of 42 cfs and a sediment pump with adequate capacity. The bed load sediment (sediment moving along the bottom) is trapped and is pumped to the flume entrance with the sediment pump. Suspended sediment is pumped with the water to the entrance with either or both of the water pumps. A photograph of the building in which the flume is located is shown in Figures 1. Photographs of the flume are shown in Figures 2-5. A schematic drawing of the flume is presented in Figure 5.



Figure 1. University of Auckland Engineering Building where the Hydraulics Laboratory and the flume used for the live bed scour experiments is located.



Figure 2. Side and top views of the 5 ft wide, 4 ft deep, 148 ft long flume used for the local scour tests



Figure 3 Water (left picture) and sediment (right picture) return entrance sections.



Figure 4 Data acquisition computers (left) and test pile installation (right).

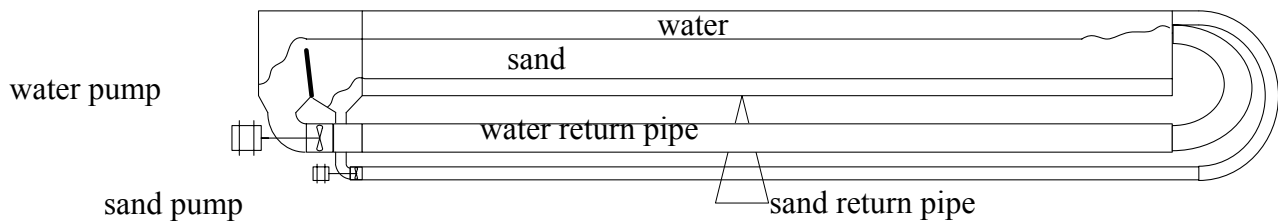
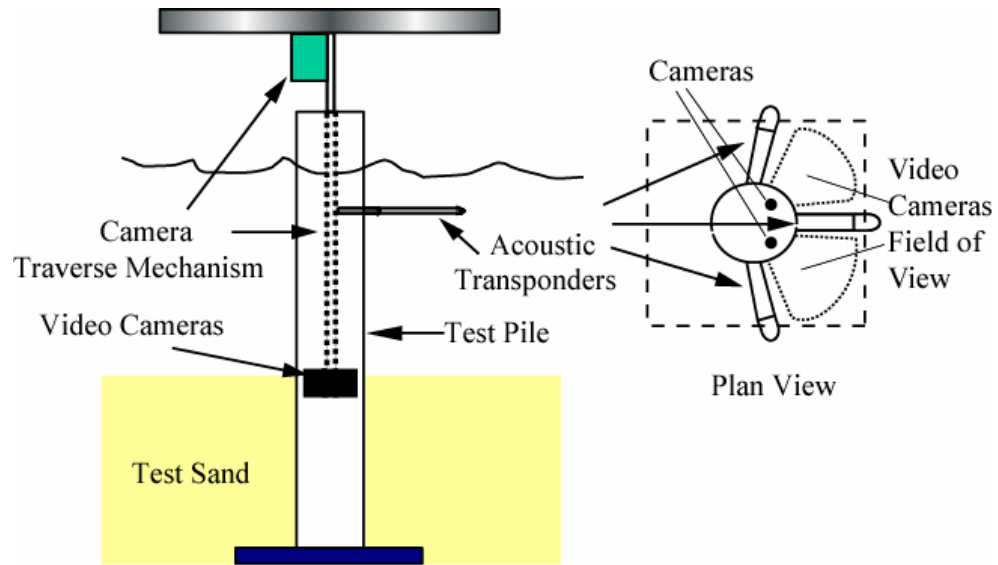


Figure 5. Schematic drawing of the flume used for this research.

Instrumentation

The instrumentation used in this research can be divided into two categories: 1) that which measures the flow parameters, and 2) that which measures scour depth. The flow parameters monitored were flow discharge (indirectly), velocity at specific locations, water depth, and temperature. The scour hole depth was monitored with internal video cameras and with arrays of acoustic transponders. The bed and water elevations at the walls of the flume were monitored with externally mounted cameras for some of the live bed tests.

Prior to starting the tests numerous vertical velocity profiles were measured and integrated to determine the flow discharge as a function of pump RPM (which can be precisely controlled). The velocity measurements were made with an acoustic Doppler velocimeter. During the tests the sectionally averaged velocity was estimated from the pump RPMs and the water depth at the section. Water temperature was measured with a glass thermometer. The water depth at the test section was measured using scales attached to the glass walls of the flume. A schematic drawing of the scour depth measuring instruments is presented in Figure 6. The 6 in diameter test cylinder with the scour depth instrumentation is shown in Figure 7. A photograph of the internal cameras and carriage is given in Figure 8 and a diagram of the external video cameras is shown in Figure 9. The external cameras were used to monitor the position of the bed on both sides of the flume during the live bed tests.



Test Piles with Scour Depth Instrumentation

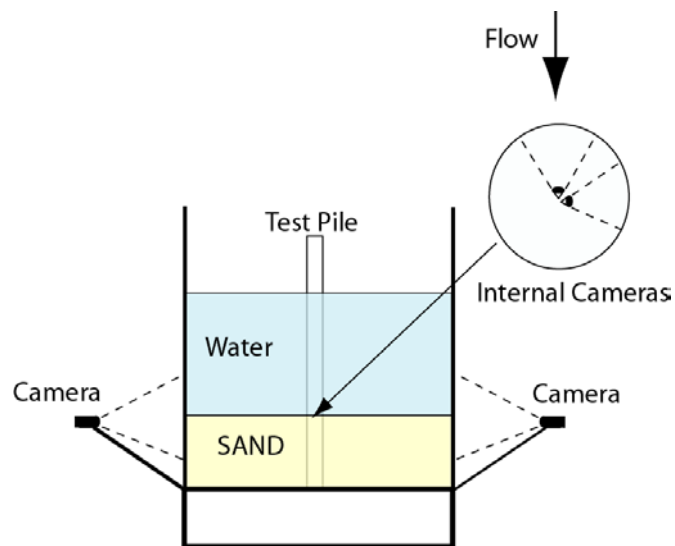
Figure 6. Schematic drawing of the local scour depth measuring instruments.



Figure 7. Photograph of the internal video cameras traversing mechanism and the acoustic transponders used to measure scour depth.



Figure 8. Internal video cameras and housing for the 6 in. diameter test cylinder.



Flume Cross-Section

Figure 9. Cross-section of flume showing location of external video cameras used for monitoring the bed elevation during the live bed tests. Three arrays of acoustic transponders were attached to the cylinder just below the water surface. Each array contained four crystals, which produced a 1 in. diameter acoustic

beam at the transducer. The spread angle of the beam was approximately 1.5 degrees. The footprint of the beam (area of the acoustic beam at the bed) varied with the water and scour hole depths. The time required for the acoustic pulse to travel to the bed and return to the transducer was measured and the distance from the transducer to the bed computed based on the speed of sound in water at that temperature. This system provided scour hole depth measurements at the 12 locations along three radial lines throughout the experiments.

For some of the tests an array of 22 acoustic transducers was used to measure the bedforms that propagated down the flume. A photograph of the array is shown in Figures 10 and 11. Personal computers were used to both control the instrumentation and to record the data.



Figure 10. Array of acoustic transducers used to measure bed forms (prior to installing drag reduction hydrofoils).



Figure 11. Bed form transducers with drag reducing hydrofoils during a live bed test.

Experimental Procedure

A summary of the experimental procedure used in performing the local sediment scour experiments is outlined below. The procedure is divided into the tasks performed before, during and after the experimental run.

Pre-experiment

1. Compact and level the bed in the flume.
2. Fill the flume slowly and allow to stand until the air trapped in the sediment has escaped.
3. Take pre-experiment photographs.
4. Check all instrumentation.

During experiment

1. Measure the scour depth as a function of time with acoustic transponders and video cameras.
2. Measure the velocity, water depth, and temperature.
3. Monitor bed elevation at flume walls in test section with external video cameras.
4. Monitor bed forms during live bed tests.

Post-experiment

1. Take post-experiment photographs.
2. Observe and note bed condition throughout the flume (presence of bed forms, etc.)
3. Survey the scour hole with a point gauge.
4. Reduce and analyze the data.

Results and Conclusions

Results

A significant quantity of local sediment scour data and bedform information were gathered during this research program. Even though most of the tests were performed in the live bed scour range a few tests were conducted in the clearwater scour range to fill in gaps in the existing data set. The structure, sediment and flow conditions under which the tests were conducted are summarized in Table 1. The scour results are given in Table 2. The experiments conducted as part of this work were relatively long in duration (for live bed scour tests) and thus the scour depths were near equilibrium at the end of the test. Two different sediment sizes were used, one with a $D_{50} = 0.27$ mm (and $\sigma = 1.33$) and one with a $D_{50} = 0.84$ mm (and $\sigma = 1.32$). Photographs of the test pile during some of the higher velocity live bed scour tests are shown in Figures 12 and 13.



Figure 12. Flow around test pile during a live bed test viewed from upstream.



Figure 13. Flow around test pile during a live bed test viewed from down stream.

Before and after photographs of a live bed scour test are shown in Figures 14 and 15. Typical bed forms that occur during the live bed tests are shown in Figures 15-17.



Figure 14. Photograph of test pile prior to live bed scour test taken through the water from outside the flume.



Figure 15. Scour hole after live bed scour test with large bedforms.

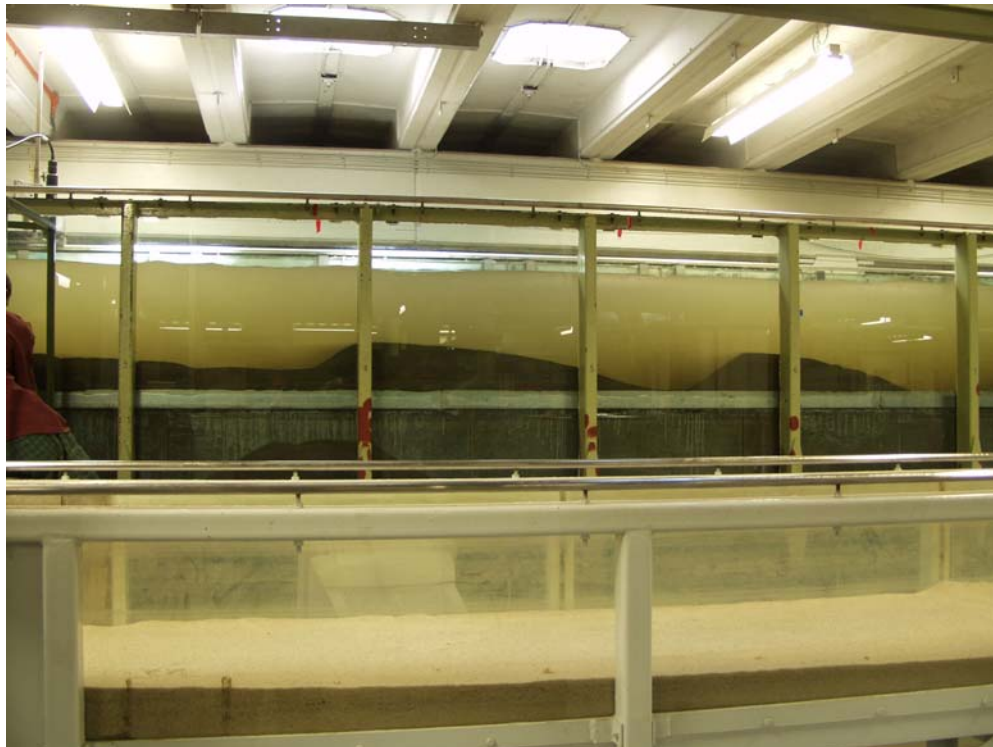


Figure 16. Bed forms at the end of a live bed scour test. Flow was from right to left.

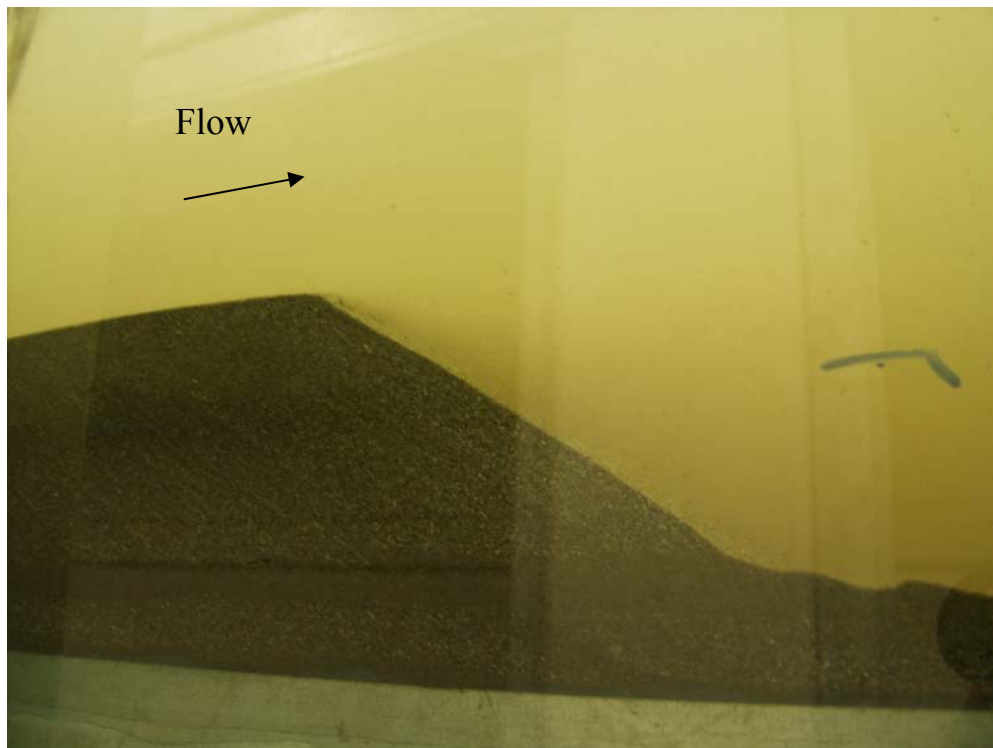


Figure 17. Downstream edge of a bedform during a live bed test.

Table 1. Flow, sediment and structure parameters for tests.

Test	Structure Diameter D (ft)	Sediment		Flow		Computed Parameters				
		D ₅₀ (mm)	σ	Water Depth y ₀ (ft)	Velocity V (ft/s)	Sediment Critical Velocity V _c (ft/s)	Live Bed Peak Velocity V _{lp} (ft/s)	y ₀ /D	V/V _c	D/D ₅₀
1	0.50	0.27		1.38	0.56	0.89	5.28	2.72	0.62	564.4
2	0.50	0.27		1.38	2.03	0.92	5.31	2.76	2.23	564.4
3	0.50	0.27		1.41	2.89	0.92	5.35	2.79	3.2	564.4
4	0.50	0.27		1.31	3.61	0.89	5.18	2.62	3.99	564.4
5A	0.50	0.27		1.31	4.13	0.89	5.18	2.62	4.59	564.4
5B	0.50	0.27		1.31	4.69	0.89	5.18	2.62	5.23	564.4
6	0.50	0.27		1.31	5.38	0.89	5.18	2.62	5.99	564.4
7A	0.50	0.27		0.66	1.80	0.82	4.03	1.31	2.18	564.4
7B	0.50	0.27		0.66	2.36	0.82	4.03	1.31	2.86	564.4
8	0.50	0.27		1.41	2.26	0.92	5.35	2.79	2.49	564.4
9	0.50	0.27		1.61	0.82	0.92	5.74	3.2	0.88	564.4
10	0.50	0.84		1.41	1.21	1.34	6.82	2.79	0.89	181.4
11	0.50	0.84		1.25	1.90	1.34	6.76	2.49	1.42	181.4
12	0.50	0.84		1.25	2.43	1.34	6.76	2.49	1.81	181.4
13	0.50	0.84		1.25	3.44	1.34	6.76	2.49	2.57	181.4
14	0.50	0.84		1.25	3.97	1.34	6.72	2.49	2.97	181.4
15	0.50	0.84		1.25	4.49	1.34	6.76	2.49	3.36	181.4
16	0.50	0.84		1.25	4.99	1.34	6.76	2.49	3.72	181.4
17	0.50	0.84		0.98	4.99	1.31	6.53	1.97	3.85	181.4
18	0.50	0.84		0.98	5.77	1.31	6.53	1.97	4.45	181.4
19	0.50	0.84		0.98	6.07	1.31	6.53	1.97	4.68	181.4
20	0.50	0.84		0.98	6.53	1.31	6.53	1.97	5.03	181.4
21	0.50	0.84		0.98	7.08	1.31	6.53	1.97	5.46	181.4
22	0.50	0.84		1.41	0.82	1.34	6.76	2.79	0.61	181.4

Table 2. Scour depth results.

Test	Scour Regime	y_0/D	V/V_c	D/D_{50}	Equilibrium Scour Depth y_{se} (ft)
1	Clearwater	2.72	0.62	564.4	0.42
2	Live Bed	2.76	2.23	564.4	0.71
3	Live Bed	2.79	3.2	564.4	0.75
4	Live Bed	2.62	3.99	564.4	0.82
5A	Live Bed	2.62	4.59	564.4	0.89
5B	Live Bed	2.62	5.23	564.4	0.87
6	Live Bed	2.62	5.99	564.4	0.98
7A	Live Bed	1.31	2.18	564.4	0.59
7B	Live Bed	1.31	2.86	564.4	0.71
8	Live Bed	2.79	2.49	564.4	0.72
9	Clearwater	3.2	0.88	564.4	0.50
10	Clearwater	2.79	0.89	181.4	0.85
11	Live Bed	2.49	1.42	181.4	0.56
12	Live Bed	2.49	1.81	181.4	0.83
13	Live Bed	2.49	2.57	181.4	0.82
14	Live Bed	2.49	2.97	181.4	0.75
15	Live Bed	2.49	3.36	181.4	0.82
16	Live Bed	2.49	3.72	181.4	0.85
17	Live Bed	1.97	3.85	181.4	0.85
18	Live Bed	1.97	4.45	181.4	0.86
19	Live Bed	1.97	4.68	181.4	0.87
20	Live Bed	1.97	5.03	181.4	0.92
21	Live Bed	1.97	5.46	181.4	0.97
22	Clearwater	2.79	0.61	181.4	0.64

There are a number of ways to present the data from the tests conducted as part of this study and to evaluate the scour prediction equations. Perhaps the best way is to plot normalized scour depth, y_{se}/D , versus normalized velocity, V/V_c for approximately constant values of y_0/D and D_{50}/D . All of the clearwater and live bed data from the New Zealand tests are presented in Figures 18-20. The scour prediction curves were evaluated and plotted along with the CSU equation presented in HEC-18 for the conditions of the experiments. These results are discussed in the conclusions section of this report.

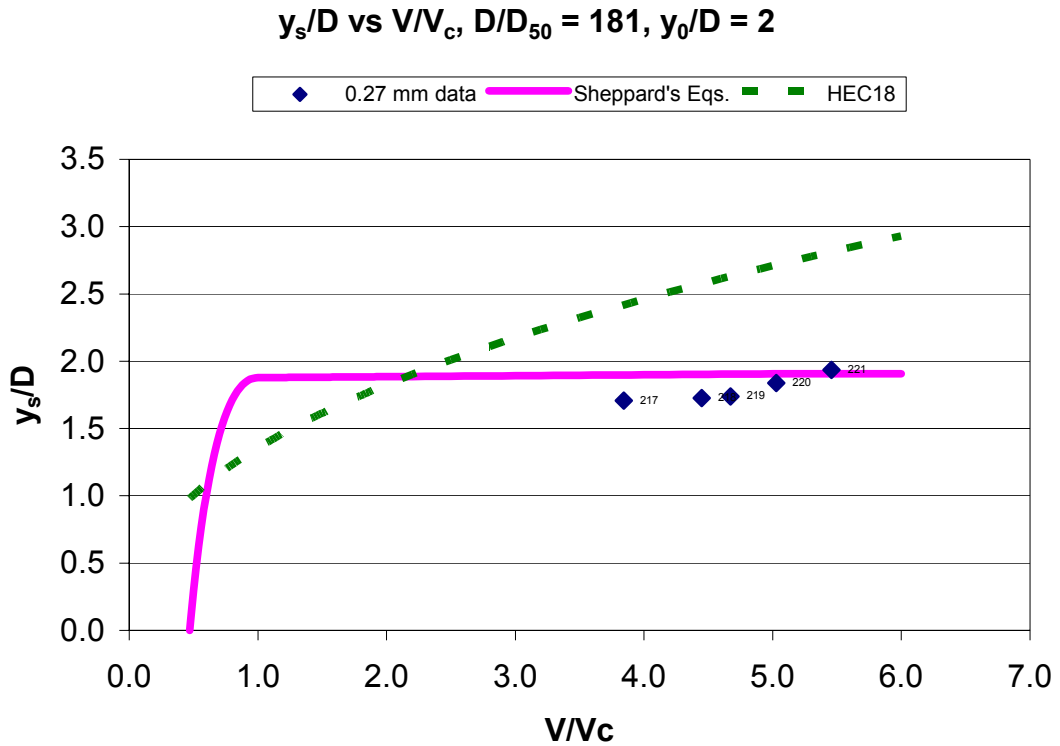


Figure 18. Normalized equilibrium scour depth versus normalized velocity for five of the New Zealand tests. Scour depth predictions using Sheppard's Equations and the CSU Equation are also shown.

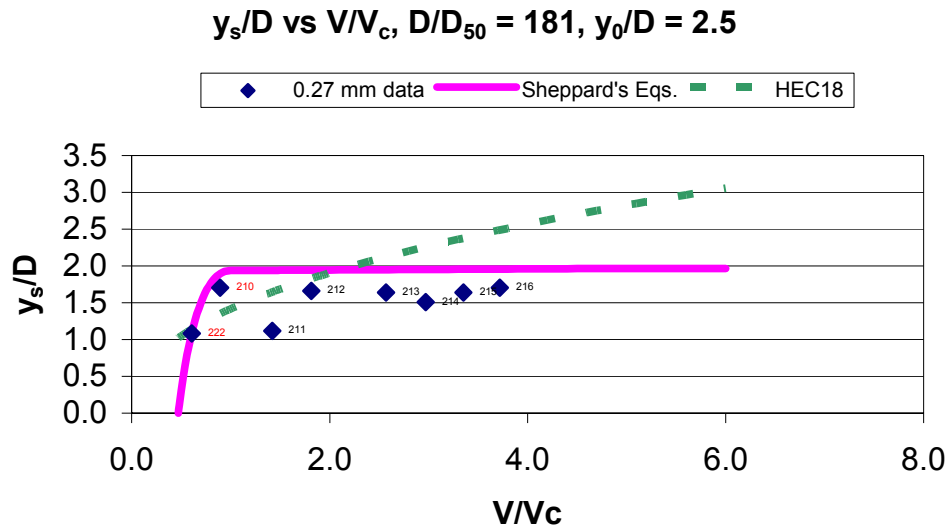


Figure 19. Normalized equilibrium scour depth versus normalized velocity for eight of the New Zealand tests. Scour depth predictions using Sheppard's Equations and the CSU Equation are also shown.

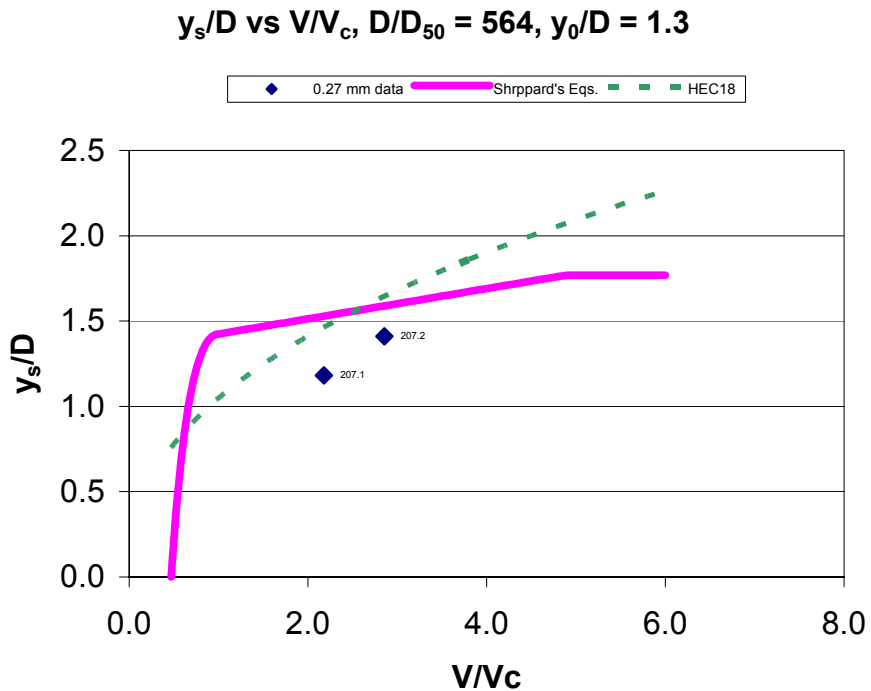


Figure 20. Normalized equilibrium scour depth versus normalized velocity for two of the New Zealand tests. Scour depth predictions using Sheppard's Equations and the CSU Equation are also shown.

Conclusions

The objectives of the project were achieved. A number of clearwater and live bed scour tests were successfully conducted and Sheppard's predictive equations verified in the live bed scour range (covered by the experiments). Even though it was not a direct component of the scope of work for this project, sediment bed form data was also obtained for a range of flow conditions. When analyzed the bed form data will be useful in improving the accuracy of design scour depth predictions for bridge foundations and other structures.

One of the main objectives of this work was to provide data for testing/verifying Sheppard's single structure, scour depth prediction equations in both the clearwater and live bed scour ranges. Minor adjustments to the equations were made as a result of the data obtained in this study. The adjustments were, however, in the clearwater scour range as opposed to the higher velocity, live bed scour range which was the main thrust of this work. The resulting single structure equilibrium scour depth prediction equations are presented below:

$$\text{Clearwater Scour} \quad 0.47 \leq \frac{V}{V_c} \leq 1.0$$

$$\frac{d_{se}}{D} = K_s 2.5 \left\{ \tanh \left[\left(\frac{y_0}{D} \right)^{0.4} \right] \right\} \left\{ 1 - 1.75 \left[\ln \left(\frac{V}{V_c} \right) \right]^2 \right\} \left\{ \frac{D/D_{50}}{0.4(D/D_{50})^{1.2} + 10.6(D/D_{50})^{-0.13}} \right\}$$

$$\text{Live Bed Scour} \quad 1.0 \leq \frac{V}{V_c} \leq \frac{V_{lp}}{V_c}$$

$$\frac{d_{se}}{D} = K_s f_1 \left(\frac{y_0}{D} \right) \left[2.2 \left(\frac{V - V_c}{V_{lp} - V_c} \right) + 2.5 f_3 \left(\frac{D}{D_{50}} \right) \left(\frac{V_{lp} - V}{V_{lp} - V_c} \right) \right]$$

$$\text{Live Bed Scour} \quad \frac{V}{V_c} \geq \frac{V_{lp}}{V_c}$$

$$\frac{d_{se}}{D} = K_s 2.2 \tanh \left[\left(\frac{y_0}{D} \right)^{0.4} \right]$$

where

D \equiv structure width at zero flow skew angle,

V_c \equiv sediment critical velocity,

K_s \equiv structure shape coefficient, and

V_{lp} \equiv velocity where the live bed peak scour occurs (flow and sediment conditions where the bed planes out).

These equations are intended for design and thus are, by design, conservative, especially at lower velocities in the live bed scour range. Figures 18-20 are plots of normalized scour depth (y_s/D) versus normalized velocity (V/V_c). It has long been known that, under most conditions, equilibrium scour depths decrease in magnitude as flow velocities go from clearwater to live bed scour conditions. The data obtained in this study shows the same behavior. To simplify the predictive equations and to provide a level of conservatism to the prediction, the clearwater peak (scour) is connected to the live bed peak (scour) with a straight line as shown in Figures 18-20. This must be kept in mind when comparing the predicted scour depths with the measured values.

As can be seen in Figures 18-20, Sheppard's equations give an accurate prediction of all of the experimental data obtained in this investigation. The slight over prediction in the range of velocities just beyond transition from clearwater to live bed scour conditions (i.e. for V/V_c just greater than 1) are for the reasons described above. The live bed peak scour depth in the equations was based on the hypothesis that local scour reaches a maximum in the live bed range at the point where the bed planes out. This was supported by data from small scale tests (2 inch diameter cylinder) conducted at the University of Auckland. The tests conducted in this research extended the live bed data to structure diameters three times that of the earlier work. High velocity, live bed tests with larger, prototype scale, structures are needed. But until such time that facilities where such tests can be conducted are available it is the opinion of the author of this report that the above

equations represent the best available method for local scour depth prediction in both the clearwater and live bed scour ranges.

Acknowledgements

The success of this research project is due to the effort and hard work of many people. The facilities and laboratory support staff at the University of Auckland were excellent. Dr. Bruce Melville, Chairman of the Civil and Environmental Engineering Department and Director of the Hydraulics Laboratory was most helpful throughout the project. He not only provided office space, assisted with the UF/UA agreement, housing, and management of the project but also made numerous technical contributions as well. Dr. Stephen Coleman contributed to the project by providing instrumentation and data reduction software as well as helpful suggestions. Doctoral student Sjoerd van Ballegooy and undergraduate student Thomas Macdougall Clunie worked long and hard to make the project a success. Both are very capable students and their work is appreciated. University of Florida doctoral student, William Miller, helped with the data reduction and analysis. University of Auckland departmental manager, Magdalene Woo, was most helpful with administrative matters throughout the project. Laboratory staff members Jim Bickner and Raymond Hoffmann were very helpful in the preparation for and operation of the tests. Sidney Schofield in the Coastal Engineering Laboratory at the University of Florida provided assistance with the instrumentation and Jim Joiner assisted with preparation of the equipment for shipment. The author is grateful to all of these individuals for their hard work and assistance with this project.

BIBLIOGRAPHY

- Ahmad, M. 1953. "Experiments on design and behavior of spur dikes." *Proc. of International Hydraulics Convention*, St. Anthony Falls Hydraulic Laboratory, Minneapolis, MN, 145-159.
- Ahmad, M. 1962. "Discussion of 'Scour at bridge crossings' by E.M. Laursen." *Trans. of ASCE*, 127, pt. I(3294), 198-206.
- Baker, R.E. 1986. "Local scour at bridge piers in non-uniform sediment." *Report No. 402*, Department of Civil Engineering, University of Auckland, Auckland, New Zealand.
- Basak, V. 1975. "Scour at square piers." Devlet su isteri genel mudulugu, Report No. 583, Ankara, Turkey.
- Blench, T. 1962. "Discussion of 'Scour at bridge crossings' by E.M. Laursen." *Trans. of ASCE*, 127, pt. I(3294), 180-183.
- Blevins, R.D. 1984. *Applied Fluid Dynamics Handbook*. Van Nostrand Reinhold, New York.
- Bonasoundas, M. 1973. "Non-stationary hydromorphological phenomena and modelling of scour process." *Proc. 16th IAHR Congress*, Vol. 2, Sao Paulo, Brazil, 9-16.
- Breusers, H.N.C., Nicollet, G., and Shen, H.W. 1977. "Local scour around cylindrical piers." *Journal of Hydraulic Research*, 15(3), 211-252.
- Chabert, J., and Engeldinger, P. 1956. "Etude des affouillements autour des piles des ponts." Laboratoire National d'Hydraulique, Chatou, France.
- Chiew, Y.M. 1984. "Local scour at bridge piers." *Master's Thesis*, Auckland University, Auckland, New Zealand.

- Chitale, S.V. 1962. "Discussion of 'Scour at bridge crossings' by E.M. Laursen." *Trans. of ASCE*, 127, pt. I(3294), 191-196.
- Cunha, L.V. 1970. "Discussion of 'Local scour at bridge crossings' by Shen, H.W., Schneider, V.R. and Karaki, S.S." *Trans. of ASCE*, 96(HY8), 191-196.
- Ettema, R. 1976. "Influence of material gradation on local scour." *Master's Thesis*, Auckland University, Auckland, New Zealand.
- Ettema, R. 1980. "Scour at bridge piers." *PhD Thesis*, Auckland University, Auckland, New Zealand.
- Froehlich, D.C. 1988. "Analysis of on-site measurements of scour at piers." *Proc. of the 1988 National Conference on Hydraulic Engineering*, ASCE, New York, 534-539.
- Gao, D.G., Posada, G., and Nordin, C.F. 1992. "Pier scour equations used in the People's Republic of China." Draft, Department of Civil Engineering, Colorado State University, Fort Collins, CO.
- Garde, R.J., Ranga Raju, K.G., and Kothyari, U.C. 1993. *Effect on unsteadiness and stratification on local scour*. International Science Publisher, New York.
- Graf, W.H. 1995. "Local scour around piers." *Annu. Rep.*, Laboratoire de Recherches Hydrauliques, Ecole Polytechnique Federale de Lausanne, Lausanne, Switzerland.
- Gust, G. 1976. "Observations on turbulent-drag reduction in a dilute suspension of clay in sea-water." *Fluid Mechanics*: 75 (1), 29-47.
- Hancu, S. 1971. "Sur le calcul des affouillements locaux dans la zone des piles de ponts." *Proc. 14th IAHR Congress*, Vol. 3, Paris, France, 299-313.
- Hanna, C.R. 1978. "Scour at pile groups." *Master of Engineering Thesis*, University of Canterbury, Christchurch, New Zealand.
- Henderson, F.M. 1966. *Open Channel Flow*. Macmillan, New York.

- <http://vortex.spd.louisville.edu/BridgeScour/whatis.htm>. 1998. Bridge scour internet site, Department of Civil Engineering at the University of Louisville.
- Inglis, S.C. 1949. "The behavior and control of rivers and canals." *Central Water Power Irrigation and Navigation Report*, Publication 13, part II, Poona Research Station, Poona, India.
- Jain, S.C., and Fischer, E.E. 1979. "Scour around circular bridge piers at high Froude numbers." *Rep. No. FHWA-RD-79-104*, FHWA, Washington DC.
- Jette, C.D., and Hanes, D.M. 1997. "High resolution sea-bed imaging: an acoustic multiple transducer array." *Measurement Science and Technology*, 8, 787-792.
- Jones, J.S. 2000. In personal communication by e-mail to D.M. Sheppard.
- Jones, J.S., and Sheppard, D.M. 2000. "Scour at Wide Piers," accepted for publication in the *Proceedings* for the 2000 Joint Conference on Water Resources Engineering and Water Resources Planning and Management Conference, Minneapolis, MN, July 30-August 2.
- Krishnamurthy, M. 1970. "Discussion of 'Local scour at bridge crossings' by Shen H.W., Schneider, V.R. and Karaki, S.S." *Trans. of ASCE*, 96(HY7), 1637-1638.
- Laursen, E.M. 1962. "Scour at bridge crossings." *Trans. of ASCE*, 84(HY1), 166-209.
- Laursen, E.M., and Toch, A. 1956. "Scour around bridge piers and abutments." *Bulletin No. 4*, Iowa Highway Research Board, Ames, IA.
- Melville, B.W. 1975. "Local scour at bridge sites." *Report No. 117*, University of Auckland, School of Engineering, Auckland, New Zealand.
- Melville, B.W. 1985. "Live-bed scour at bridge piers." *Journal of Hydraulic Engineering*, 110(9), 1234-1247.
- Melville, B.W. 1997. "Pier and abutment scour-an integrated approach." *Journal of Hydraulic Engineering*, 123(2), 125-136.

- Melville, B.W., and Chiew, Y.M. 1999. "Time scale for local scour at bridge piers." *Journal of Hydraulic Engineering*, 125(1), 59-65.
- Melville, B.W., and Sutherland, A.J. 1988. "Design method for local scour at bridge piers." *Journal of Hydraulic Engineering*, 114(10), 1210-1226.
- Neill, C.R. 1964. "River bed scour, a review for bridge engineers." *Contract No. 281*, Res. Council of Alberta, Calgary, Alberta, Canada.
- Neill, C.R. 1973. *Guide to Bridge Hydraulics*. Roads and Transportation Association of Canada, University of Toronto Press, Canada.
- Nicollet, G., and Ramette, M. 1971. "Affouillement au voisinage de ponts cylindriques circulaires." *Proc. of the 14th IAHR Congress*, Vol. 3, Paris, France, 315-322.
- Pilarczyk, K.W. 1995. "Design tools related to revetments including riprap." *River, Coastal and Shoreline Protection: Erosion Control using Riprap and Armour Stone*, John Wiley & Sons, New York, 17-38.
- Raudkivi, A.J., and Ettema, R. 1977. "Effect of sediment gradation on clear water scour." *Journal of Hydraulic Engineering*, 103(10), 1209-1212.
- Rouse, H. 1946. *Elementary Fluid Mechanics*. John Wiley & Sons, New York.
- Shen, H.W. 1971. "Scour near piers." *River Mechanics*, Vol. II, Chapter 23, Colorado State University, Fort Collins, CO.
- Shen, H.W., Schneider, V.R., and Karaki, S.S. 1967. "Mechanics of local scour." *Pub. No. CER66HWS22*, Civil Engineering Department, Colorado State University, Fort Collins, CO.
- Sheppard, D.M., Odeh, Mufeed and Glasser, Tom 2002. "Clearwater Local Sediment Scour Experiments." *Report No. UFL/COEL-TR/131*, Civil and Coastal Engineering Department, University of Florida, Gainesville, FL.

- Sheppard, D.M. 1997. "Conditions of maximum local scour." *Report No. UFL/COEL-97/006*, Coastal and Oceanographic Engineering Department, University of Florida, Gainesville, FL.
- Sheppard, D.M. 2000. "A Method for Scaling Local Sediment Scour Depths from Model to Prototype," accepted for publication in the *Proceedings* for the 2000 Joint Conference on Water Resources Engineering and Water Resources Planning and Management Conference, Minneapolis, MN, July 30-August 2.
- Sheppard, D.M. 2000. "Physical Model Local Scour Studies of the Woodrow Wilson Bridge Piers," accepted for publication in the *Proceedings* for the 2000 Joint Conference on Water Resources Engineering and Water Resources Planning and Management Conference, Minneapolis, MN, July 30-August 2.
- Sheppard, D.M., and Jones, J.S. 1998. "Scour at complex pier geometries." *Compendium of Scour Papers from ASCE Water Resources Conferences*, Eds. E.V. Richardson and P.F. Lagasse, ASCE, New York.
- Sheppard, D.M., and Jones, S. 2000. "Local Scour at Complex Piers," accepted for publication in the *Proceedings* for the 2000 Joint Conference on Water Resources Engineering and Water Resources Planning and Management Conference, Minneapolis, MN, July 30-August 2.
- Sheppard, D.M., Odeh, M., Glasser, T., and Pritsivelis, A. 2000. "Clearwater Local Scour Experiments with Large Circular Piles," accepted for publication in the *Proceedings* for the 2000 Joint Conference on Water Resources Engineering and Water Resources Planning and Management Conference, Minneapolis, MN, July 30-August 2.

- Sheppard, D.M., and Ontowirjo, B. 1994. "A local sediment scour prediction equation for circular piles." *Report No. UFL/COEL-TR/101*, Coastal and Oceanographic Engineering Department, University of Florida, Gainesville, FL.
- Sheppard, D.M., Sheldon, J., Smith, E., and Odeh, M. 2000. "Hydraulic Modeling and Scour Analysis for the San Francisco-Oakland Bay Bridge," accepted for publication in the *Proceedings* for the 2000 Joint Conference on Water Resources Engineering and Water Resources Planning and Management Conference, Minneapolis, MN, July 30-August 2.
- Sheppard, D.M., Zhao, G., and Ontowirjo, B. 1995. "Local scour near single piles in steady currents." *ASCE Conference Proceedings: The First International Conference on Water Resources Engineering*, San Antonio, TX.
- Shields, A. 1936. "Anwendung der Aehnlichkeitsmechanik und der turbulenz forschung auf die geschiebebewegung." *Mitt. Preuss. Versuchanstalt Wasserbau Schiffbau*, Berlin, Germany.
- Sleath, J.F. 1984. *Sea Bed Mechanics*. John Wiley & Sons, New York.
- Snamenskaya, N.S. 1969. "Morphological principle of modelling of river-bed processes." *Science Council of Japan*, vol. 5-1, Tokyo, Japan.
- Tison, L.J. 1940. "Erosion autour des piles de ponts en riviere." *Annales des Travaux Publics de Belgique*, 41(6), 813-817.
- U.S. Department of Transportation. 1995. "Evaluating scour at bridges." *Hydraulic Engineering Circular No. 18*, Pub. No. FHWA-IP-90-017, FHWA, Washington, DC.
- Venkatadri, C. 1965. "Scour around bridge piers and abutments." *Irrigation Power*, January, 35-42.

White W. R. 1973. "Scour around bridge piers in steep streams." *Proc. 16th IAHR Congress*, Vol. 2, Sao Paulo, Brazil, 279-284.