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By

Tatsuaki Nakato[1]

Abstract

In 1991 the Iowa Department of Transportation (IADOT) was constructing a new bridge across the Mississippi River (approximately River Mile 404) on U.S. 34 at Burlington, Iowa, when some hazardous material (old coal tar) was found along the right river bank (Iowa side) within a thin sand layer, approximately 2.4 m thick, of the river bottom which overlaid the shale rock. The original design of the bridge-pier scour protection called for placement of riprap materials around the bridge pier. However, the discovery of the coal tar forced a design change of the pier footings to allow for the future clean-up operation of the hazardous material. A re-designed scheme involved possible elimination of proposed riprap. In order to evaluate the entire system's safety against potential scour problems, IADOT decided to extract undisturbed shale samples and test them using prototype velocity scales under a realistic prototype time scale under laboratory conditions. This practical approach was needed because of the uncertainties involved in estimating prototype velocities around bridge piers during extreme flood events, and a scarcity of literature available on the subject. Laboratory scour tests were conducted at IIHR-Hydroscience & Engineering, formerly Iowa Institute of Hydraulic Research (IIHR), The University of Iowa, for two shale specimens which were sampled directly from the bridge construction site. Although the samples were not under the desired undisturbed conditions, the laboratory test results using round jets indicated some potential for scour under high flow velocities. However, because there are so many unknown factors involved, such as true magnitudes of velocities in the scour hole, impact of large-scale eddies within the scour hole on shale-rock stability, surface conditions of shale rock when exposed in the prototype, changes in homogeneity of the shale-rock formation during construction activities, etc., the laboratory erodibility tests could by no means simulate the exact physical phenomena which would occur in the prototype. Instead, the test results reported should be viewed as an indication of probable events that would take place in the prototype.

Introduction

The primary objectives were to investigate through laboratory tests: (1) whether or not the shale would deteriorate and erode under high flow velocities (erodibility); (2)

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if so, at what velocities the shale would deteriorate and erode (critical erodible velocity); and (3) if so, how fast the shale would be eroded (erosion rate).

Samples

Three samples were extracted on 20 August 1991 from Shaft 6 of Pier S-2 that supports Spans S1 and S2 of the new bridge. As shown in Figure 1, the three samples were collected by means of a 61-cm diameter core barrel. According to IADOT (Rost, Field Report dated 29 August 1991), it was noticed that the upper zone of the first extraction was fractured presumably due to seating of the casing and the effect of the screwing process of the core barrel. The second and the third extractions also yielded samples similar to the first one. Large sample specimens were placed on a plastic bag in two separate plywood boxes, and hot wax was poured at a temperature of 49°C between the plastic bags and the samples such that the samples were completely encased at the bridge construction site.

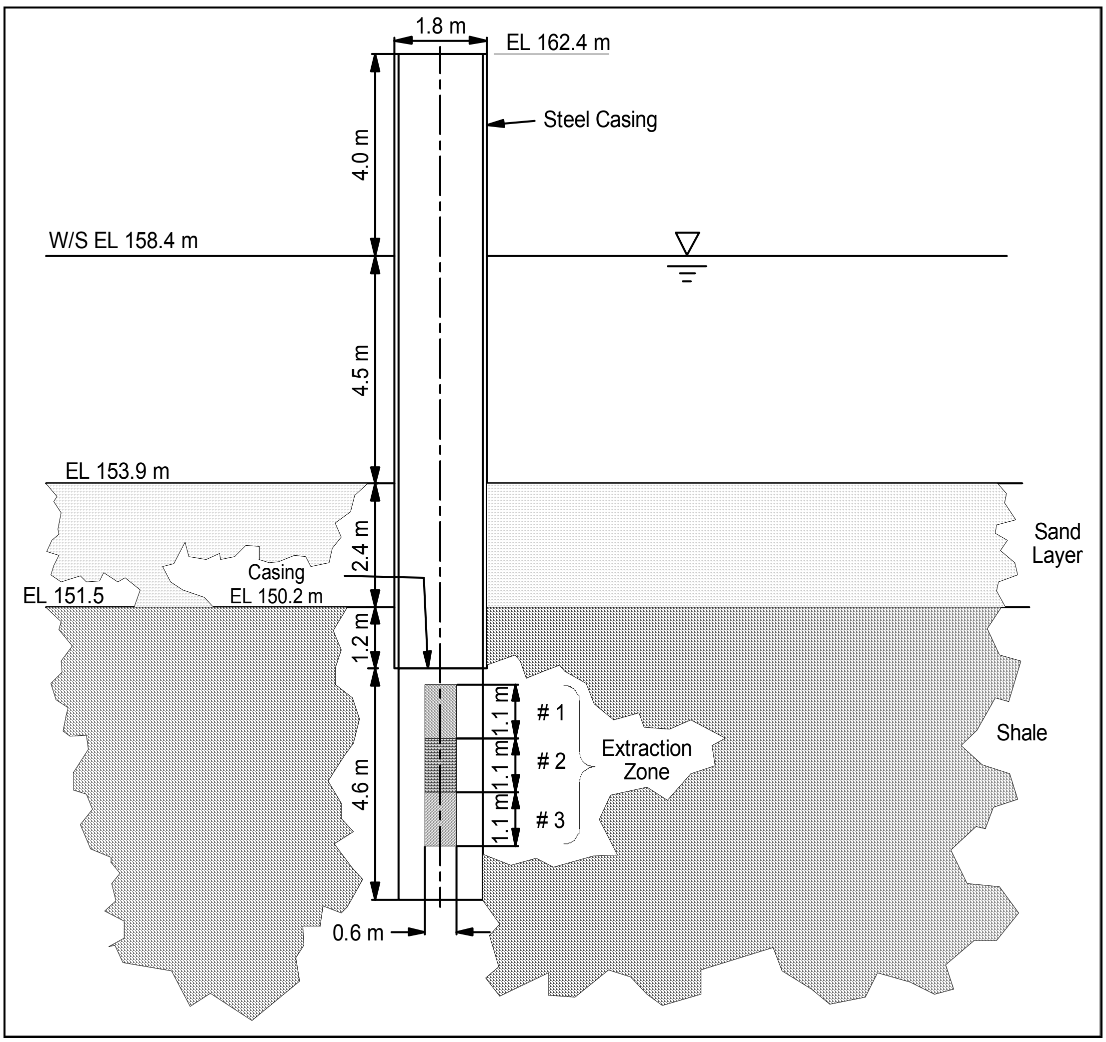

Figure 1. Prototype vertical sample location

Testing Facility

A re-circulating testing facility, as depicted in Figure 2, was constructed and installed on the first floor of the IIHR main building. The flow was re-circulated through a 5.1-cm diameter copper pipe by means of a 2.24-kw centrifugal pump, manufactured by Dunham-Bush Inc. The 5.1-cm piping system was fitted with a calibrated orifice meter for the flow-rate measurement and the discharge was regulated by means of a standard gate valve. Each shale sample container was placed inside the model basin box, which was 1.47-m long, 0.76-m wide, and 0.96-m deep. As shown in Figure 2, the testing box was partitioned by a vertical wall in order to maintain a stable water level within the test compartment. High-velocity jet flow was directed toward the shale surface at a known angle.

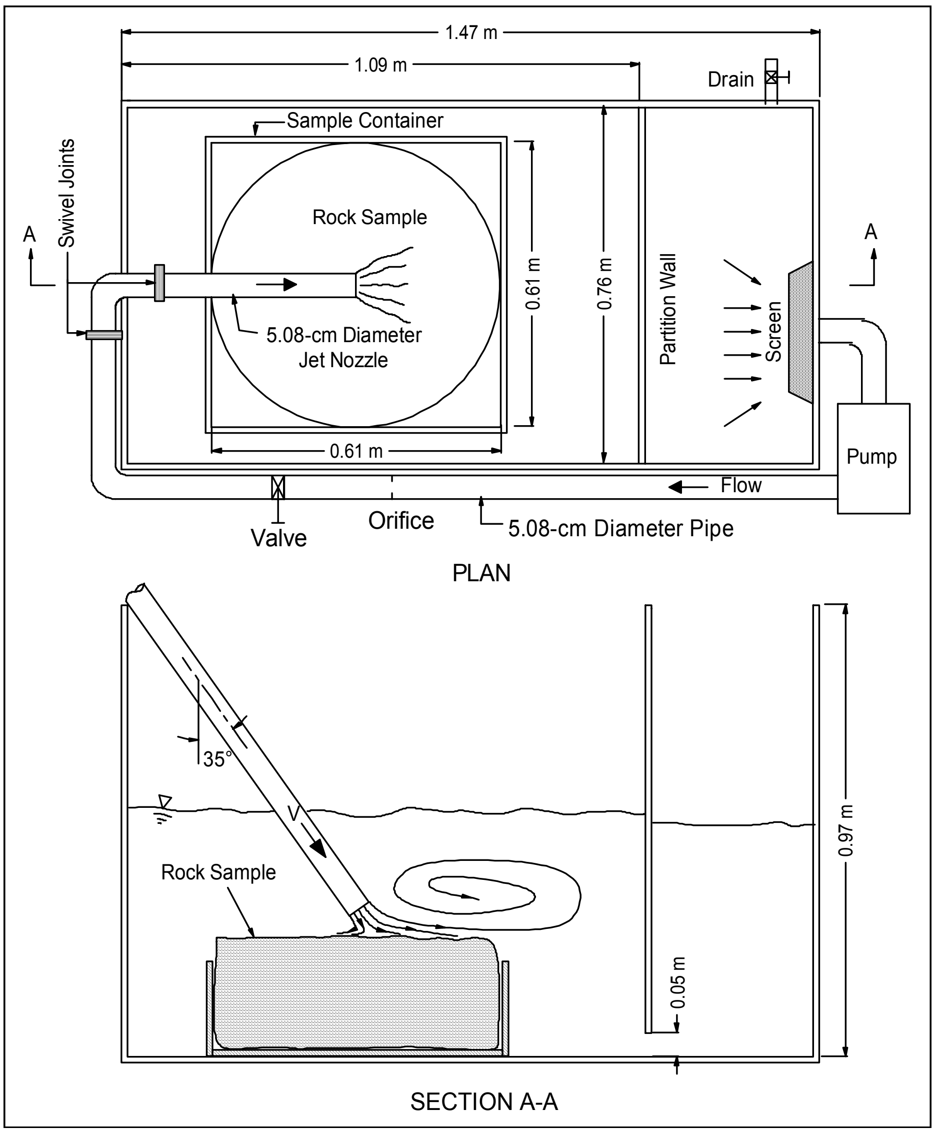

Figure 2. Test set up used to investigate shale-rock erosion

Test Procedure

The portion of wax that covered the top was first removed carefully from each shale sample, and the container holding the shale sample was placed immediately in the testing facility. The testing box was then filled with water, immersing the sample.

In each test, a low velocity jet, for example, 1.5m/s, was first applied, and close visual observations were made at short time intervals to identify any sign of deterioration or erosion of the sample surface. If any erosion was detected, erosion depth, its extent, and time span of exposure to high velocities were recorded, and some still photographs were taken to document the erosion process. In each test case, at least the initial and the final conditions of the sample surface were photographed. Water was drained from the testing facility for several minutes during photographing, but was re-filled promptly.

Test of Extraction 3 Sample (EXT3)

Two boxes containing the Extraction 1 sample and the Extraction 3 sample were delivered to IIHR by IADOT on 12 December 1991. The sample condition was not good, as can be seen in Figure 3 for the Extraction 3 sample. Apparently, the samples were kept outdoors and were exposed to severe cold weather conditions. The wax was cracked due to expansion of the shale. When the wax was removed, the surface of the Extraction 3 sample (EXT3) was found to be wet and soft like clay. In order to obtain a hard surface sample, the soft material was scraped and washed off.

Figure 3. Snow-covered rock sample when delivered

The EXT3 sample was then placed in the testing facility, and the 5.1-cm diameter pipe was installed 7.6 cm above the center of the surface at a jet-impinging angle of 55° from the horizontal plane, as shown in Figure 1. The water depth in the tank was maintained at 53.3 cm. The first test was to run the model at a mean jet velocity of 1.52 m/s. After 21 hrs. of testing, no erosion was detected.

The mean jet-nozzle velocity was then increased to 3.05 m/s in the second run. Small loose shale fragments were peeled off from the sample surface immediately after starting the test. Sometime between 8 hrs. and 27 hrs., several large rock pieces, about 2.5 cm thick, were dislodged from the sample surface. After 64 hrs. of testing, there were some significant erosion patterns that developed over the shale surface. The deepest scour was found around the sample edge, and it was about 5.1 cm deep. Many complex cracks developed in a cascading manner (scour depth increasing in steps) extending outward from the jet nozzle.

The final phase was run for 13.5 hrs. at a jet velocity of 4.57 m/s. Immediately after starting the pump, numerous small shale fragments, 2.5 - 3.8 cm in diameter, were observed peeling off. After 7 hrs. of testing, the tank was dewatered and several photographs were taken. It was clear that significant scour and deterioration of the shale surface occurred with this high jet velocity. This series was stopped after running for 13.5 hrs., at which time the largest scour depth measured was 15.2 cm. The centerline scour profile is depicted in Figure 4, and a plan view of the specimen is shown in Figure 5. Shale flakes which were peeled off the sample were smaller than about 5.1 cm (examine Figure 5 with the fact that the jet pipe diameter was 5.1 cm).

In summary, there was a strong indication that the shale sample tested (EXT3) as provided had scour potential at a jet velocity of 3.05 m/s. However, it must be noted that the sample was apparently frozen and the shale texture had deteriorated somewhat prior to testing.

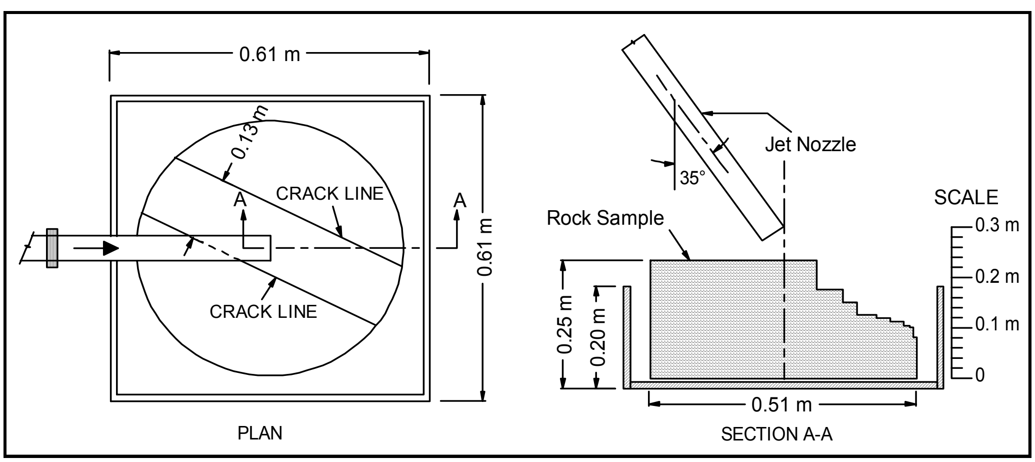

Figure 4. Final scour profile with EXT3 sample (V = 4.57 m/s and t = 13.5 hrs)

Figure 5. Surface condition of EXT3 sample after 13.5 hrs

Before presenting other test results, it is important to recognize that the terminology "mean jet velocity (V)" used in this report is defined as flow discharge (Q) divided by pipe cross-section area (A). According to Daily and Harleman (1966), a turbulent circular jet may have the following approximate relationships:

$$\frac{V}{V_m} = \frac{1}{\left(1 + \frac{r^2}{0.016z^2}\right)^2} \tag{1}$$

$$\frac{V_m}{V_0} = 6.4\left(\frac{D}{z}\right) \tag{2}$$

and

$$L_0 = 6.4D + 0.6D = 7D \tag{3}$$

where V = jet velocity at point (z,r); z = longitudinal distance from the actual origin of jet defined in Figure 6; r = radial coordinate normal to z axis; V_m = maximum jet velocity along the z axis; V_o = jet core velocity at nozzle; D = pipe diameter; and L_o = distance required for jet to fully develop. Because D = 5.1 cm in this case, the jet core velocity would be expected to extend about 35.6 cm. Although the test condition was such that there was a rigid shale surface on which jet flow impinged and deflected in a complex three-dimensional manner, it can be assumed that the jet core velocity was maintained at least locally over the sample surface along the jet centerline.

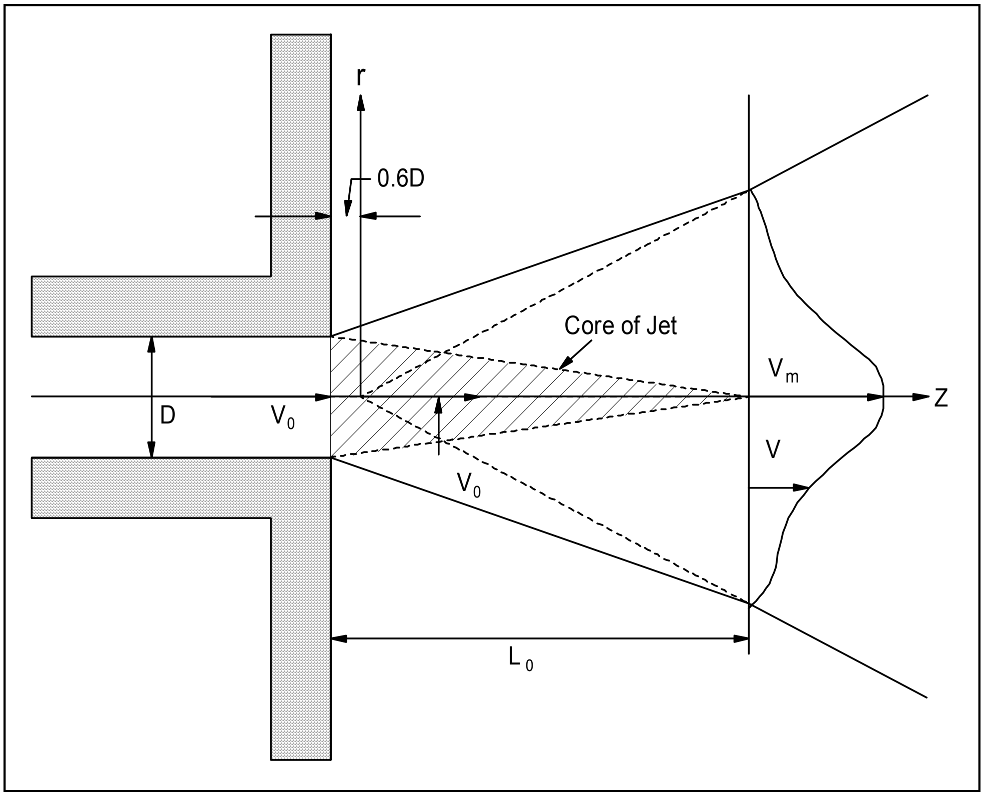

Figure 6. Definition sketch of circular jet

Test of Extraction 1 Sample (EXT1)

Because it was recognized during the test with the EXT3 sample that a minor flaking process occurred with a jet velocity of 3.05 m/s, and severe flaking took place when the jet velocity was increased to 4.57 m/s, it was decided to test the second sample (EXT1) with a starting velocity of 1.83 m/s and to increase jet velocities at a smaller increment.

According to IADOT (Rost, Field Report dated 29 August 1991), the second box contained three shale pieces of varying sizes and shapes. The bottom piece was from Extraction 2, and the other two upper pieces were from Extraction 1. When wax was removed for the first time, no visible sample boundaries were detected. Therefore, this shale sample was called EXT1 for convenience. As done for the EXT3 sample previously, the soft deteriorated top surface was removed first. The sample surface was then washed with a garden hose and fractured surface materials were removed prior to testing. Fortunately, a smooth solid surface layer appeared in this sample, as shown in Figure 7. A smooth initial centerline surface profile was able to be measured this time.

Figure 7. Undisturbed shale surface after removing deteriorated material (EXT1)

Figure 8. Surface condition after 41 hrs. of testing with a jet velocity of 2.44 m/s (EXT1)

The first test was conducted with a jet velocity of 1.83 m/s. Even after 19 hrs. of testing, practically no flaking took place. When the jet velocity was increased to 2.44 m/s, some minor flaking took place, as seen in Figure 8. Although the central part of the sample surface remained unchanged except for one minor flaking near the jet nozzle, side areas surrounding the central piece deteriorated considerably.

Figure 9. Surface condition after 38.5 hrs. of testing with a jet velocity of 3.05 m/s (EXT1)

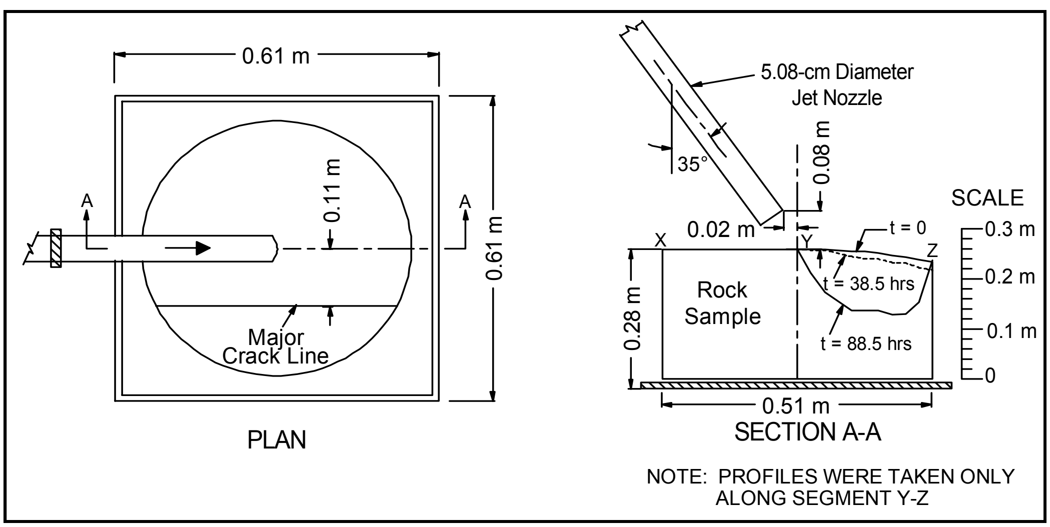

Figure 10. Scour profiles obtained with EXT1 sample with a jet velocity of 3.05 m/s

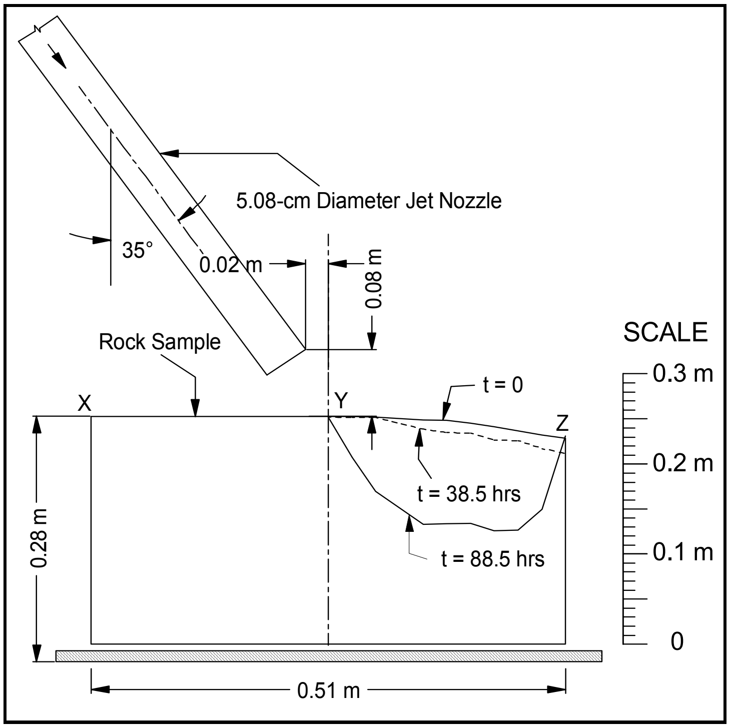

Figure 11. Close-up view of scour profile with EXT1 sample

When the jet velocity was increased to 3.05 m/s, some loose materials peeled off immediately. However, the surface profile of the solid central part remained unchanged even after 31.5 hrs. of continuous testing. At run time of 38.5 hrs., a distinguishable scour was observed, as shown in Figure 9. The measured surface profile is also plotted in Figures 10 and 11. It was determined that approximately, 1.3 cm of the shale material was scoured between 31.5 hrs. and 38.5 hrs. This series of testing was finally stopped after 88.5 hrs. of testing. A large scour hole was discovered, as shown in Figures 10, 11, and 12. The deepest part of the scour hole was approximately 12.7 cm below the original surface elevation.

As stated above, the shale surface did not show any noticeable sign of the scour process during the run time 0 hr. and 31.5 hrs.; and about 1.3 cm deep surface scour was suddenly observed during 31.5 hrs and 38.5 hrs. (overall scouring rate being about 0.033 cm/hr. = 1.3 cm/38.5 hrs.); and a scour hole about 12.7-cm deep was created during 38.5 hrs. and 88.5 hrs. (overall scouring rate being about 0.14 cm/hr = 12.7 cm/88.5 hrs.). This indicates that the shale can withstand for a certain time period high flow velocities as high as 3.05 m/s. However, after a certain time span of exposure, it starts deteriorating, and the scouring action seems to start taking place, the scouring rate appearing to increase in time.

Figure 12. Scour profiles obtained with EXT1 sample with a jet velocity of 3.05 m/s

Conclusions

On the basis of the laboratory tests conducted with the two shale samples, the following conclusions may be drawn:

1. Obviously, the site-specific shale samples, taken from the Mississippi River in Burlington, Iowa, had experienced freezing and thawing processes while kept in the field, and near-surface sample zones, at least the top 5 cm layer from the surface, were severely deteriorated. Although the deteriorated portion was removed as much as possible prior to testing, the exact extent of cracks and internal damage to the sample was not able to be determined. Therefore, the test results presented in this paper should be viewed as a preliminary indication of the deteriorating process of the shale when exposed to a high velocity field.

2. The disturbed shale appeared to deteriorate somewhat when velocities were larger than 2.44 m/s. The shale in good conditions appeared to withstand flow velocities as high as 3.05 m/s for a while (about 30 hrs. in the case of EXT1 sample), but to deteriorate slowly in time. The scouring rate was found to increase in time, and extremely complex fracture patterns seemed to appear.

3. The investigation was the first attempt known to the author to test the physical resistance against scour potential of the shale in a controlled manner. However, there were a number of uncertainties involved in the present study. Therefore, it is strongly recommended that further laboratory investigations similar to this

study be conducted using undisturbed field samples in order to gain more knowledge on general characteristics of the shale or similar erodible rocks.

4. It is recommended that such shale rock samples be kept submersed in river water where samples are taken instead of waxing and that laboratory tests be conducted as soon as samples are extracted to avoid sample deterioration.

Closing Remark

Based on the test results, IADOT decided to protect bridge piers with riprap materials in 1992, which was a truly wise decision because the "Great Flood of '93" hit the Burlington area of the Upper Mississippi River. The average discharge at Burlington, Iowa is about 1,730 m^3/s, and the peak discharge during the '93 flood was estimated to be about 13,600 m^3/s. No damage to the bridge piers was reported during the flood.

References

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