The Observation Method for Bridge Scour: Case Histories

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ABSTRACT: *Bridge scour is the number one cause of bridge collapse in the USA yet the existing guidelines are felt to be excessively conservative. These apparently conflicting statements are due to the fact that most bridge foundations designed before 1987 did not consider scour as part of the design. The Observation Method for Scour (OMS) was developed to address the conservatism inherent in the current procedures by relying significantly on past observations at the bridge. The OMS works in four steps. Step 1 consists of collecting the maximum observed scour depth at the bridge, Z_{mo}. Step 2 consists of finding out what is the biggest flood velocity V_{mo} that the bridge has been subjected to since its construction. Step 3 answers, by using an extrapolation function, the question: what will be the scour depth Z_{fut} if the bridge is subjected to a major flood velocity V_{fut}. Step 4 is a comparison between Z_{fut} and the allowable scour depth Z_{all} for the foundation. Eleven bridge scour case histories in Texas and in Massachusetts are presented where the OMS was applied and the results are used to compare predicted and measured values of Z_{fut} for both the OMS and the current FHWA guidelines. The advantages and drawbacks of the OMS are outlined in a final section.*

KEYWORDS: Observation Method, Bridge scour, Z-future charts, Probability of failure

SITE LOCATION: Geo-Database

INTRODUCTION

Bridge scour (Fig. 1) is the formation of holes in the soil due to water flow around bridge supports. These scour holes can form around the pier in the river (pier scour) or around the abutment (abutment scour) or can be due to the narrowing of the river flow (contraction scour). Bridge scour is the number one cause of bridge collapse in the USA as shown by the hydraulic condition bar in Fig. 2. Yet the current FHWA guidelines are considered by many to be very conservative on the average (Fig. 3). These apparently conflicting statements come from the fact that the foundation of most bridges built before 1987 was not designed for scour. Thus the pre-1987 bridges have most of the scour problems while the post-1987 bridges are very conservatively designed against scour. On 5 April 1987, the New York State Thruway Bridge over Schoharie Creek collapsed due to scour and 10 people died. This disaster prompted a national reaction, which through research and design guidelines has made bridges in the USA much more scour safe (Fig. 4). Fig. 3 shows significant conservatism on the average and significant scatter overall. Because of the scatter, the FHWA guidelines are sound since they minimize the number of times where the scour depth is likely to be under-estimated.

A new method is proposed and evaluated against case histories in this article to decrease the scatter in the predictions and decrease the conservatism on the average without increasing the probability of underestimating the scour depth. The method is called the Observation Method for Scour or OMS because it is based primarily on observed measurements at the bridge

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sites. The method consists of measuring the current scour depth at the bridge site, finding out how big of a flood the bridge has experienced, and extrapolating these observations to predict how deep the scour hole would become should the bridge be subjected to a major future flood. The OMS is evaluated against eleven bridge case histories in Texas and Massachusetts.

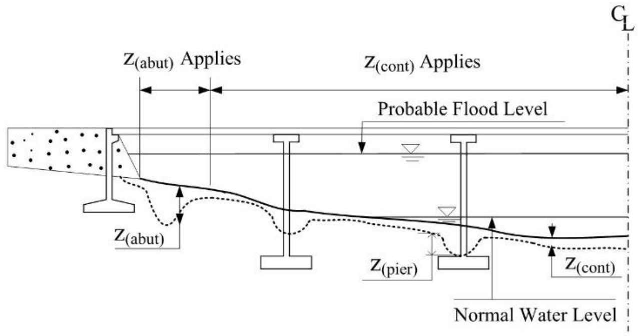


Figure 1. Bridge scour.

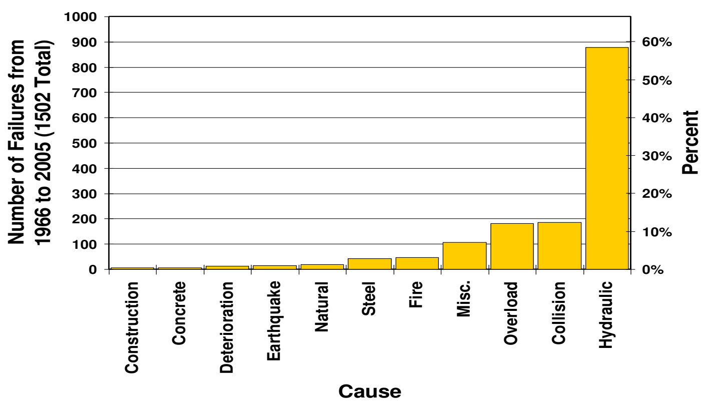


Figure 2. Causes of bridge failures in the USA (Briaud, 2006).

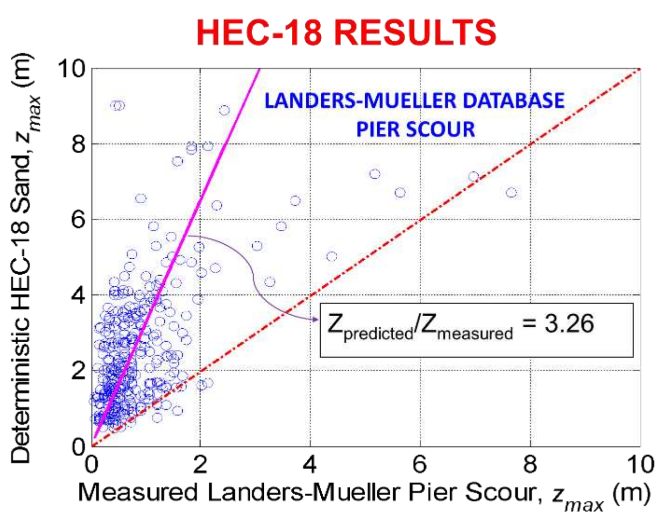


Figure 3. Predicted vs. measured pier scour depth using Landers-Mueller database (Landers, Mueller, 1996, Briaud et al., 2014).

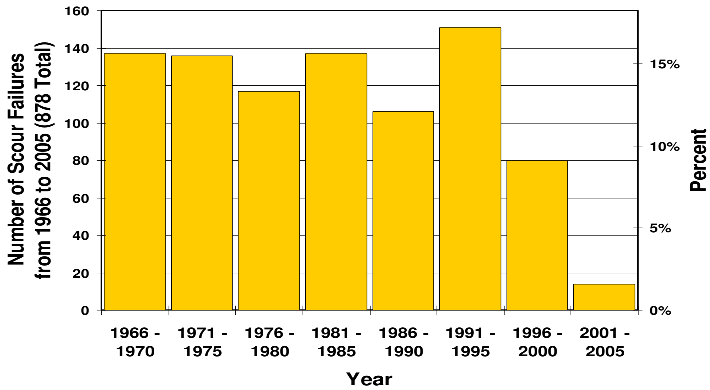


Figure 4. Impact of scour research and associated design guidelines on bridge scour failures in the USA (Briaud, 2006).

THE OBSERVATION METHOD FOR SCOUR – OMS

The observation method for scour (OMS) has been described in the following documents (Briaud et al., 2009, Govindasamy et al., 2013, Briaud et al., 2016). The steps to predict the future scour depth at existing bridges by using the OMS are summarized below.

Step 1: Obtain the maximum observed scour depth Z_{mo} at the bridge

The maximum observed scour depth Z_{mo} is obtained from the bridge inspection records by studying the river bottom profile (Fig. 1). To predict pier scour, Z_{mo} is the maximum observed value of $Z_{(pier)}$ in Fig. 1. To predict abutment scour Z_{mo} is the maximum obsevred value of $Z_{(abut)}$ in Fig. 1. To predict contraction scour, Z_{mo} is the maximum observed value of $Z_{(contraction)}$ in Fig. 1.

Step 2: Obtain the highest flood the bridge has seen

This is done by first collecting the records of all USGS flow gages in a State (Fig. 5). Then for each one of the gages, a detailed flood analysis is conducted to identify the maximum observed recurrence interval RI_{mo} during each year at the gage location on that river.

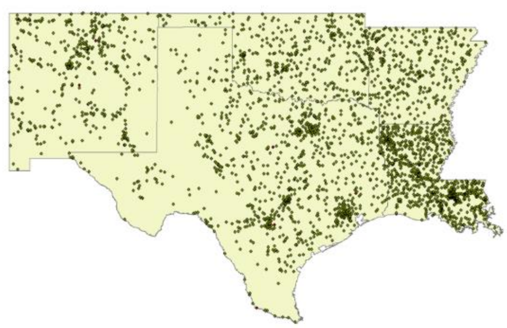


Figure 5. Location of the flow gages used for mapping Texas and neighboring States (Briaud et al., 2009).

Then RI_{mo} contour maps are prepared for the state for any one year and organized in a software called TAMU-OMS. If RI_{mo} is required for a period of several years, the life of the bridge for example, the yearly RI data is combined over the required period and TAMU-OMS outputs a map covering the required period (e.g., Fig. 6). Linear interpolation is used to obtain RI_{mo} at river locations where a gage is not available. The velocity ratio (V_{fut}/V_{mo}) is obtained from the recurrence interval ratio (RI_{fut}/RI_{mo}) by using a combination of correlation using all the flow gage data and open channel hydraulics (Briaud et al. 2009). These relationships depend on the recurrence interval and are embedded in TAMU-OMS, but a reasonable approximation is given below:

$$\left(\frac{V_{mo}}{V_{fut}}\right) = \left(\frac{Q_{mo}}{Q_{fut}}\right)^{0.35} = \left(\left(\frac{RI_{mo}}{RI_{fut}}\right)^{0.261}\right)^{0.35} = \left(\frac{RI_{mo}}{RI_{fut}}\right)^{0.091} \quad (1)$$

Where V_{fut} and V_{mo} are the future flood velocity being considered and the maximum observed velocity, Q_{fut} and Q_{mo} are the future flood flow being considered and the maximum observed flow, and RI_{fut} and RI_{mo} are the future flood recurrence interval being considered and the maximum observed recurrence interval.

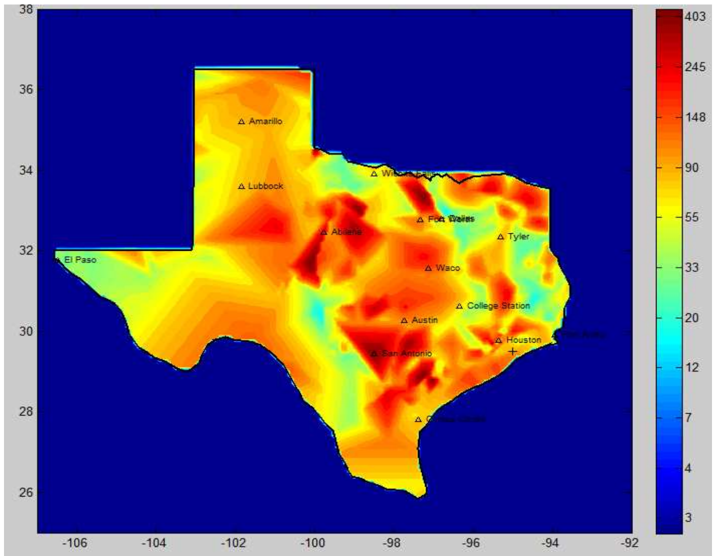


Figure 6. Maximum recurrence interval RI_{mo} map for Texas for 1920 to 2005.

<u>Step 3: Predict the future scour depth for a chosen future flood</u>
Now that the ratio V_{fut}/V_{mo} is known, we must predict the ratio Z_{fut}/Z_{mo}:

$$\left(\frac{Z_{fut}}{Z_{mo}}\right) = F\left(\frac{V_{fut}}{V_{mo}}\right) \quad (2)$$

In this equation V_{fut}/V_{mo} is known from step 2 and Z_{mo} is known from step 1. The problem is to find the function F. This is done by using the TAMU-SCOUR method (Briaud, 2013) which is included in the most recent version of HEC-18 (Arneson et al., 2012). A total of half a million scour cases were considered, calculated, and plotted. Fig. 7 shows an example of the calculations for the given set of variables shown in the legend. Each dot on the figure is one TAMU-SCOUR method calculation for a bridge scour case. These half million cases covered a large variety of scour combinations including scour types (Fig. 1), bridge and river dimensions (e.g.: pier width from 1 to 10 m, contraction ratio from 0.1 to 0.9, water depth 1 to 20 m), length of the future hydrograph t_{hyd} (5 to 25 years), and soil type represented by a soil erosion category. The soil erosion category came from the chart proposed by Briaud (2013) (Fig. 8) which is based on the soil type and associated USCS classification. This erosion category number gives a zone on Fig. 8 within which the erosion function (erosion rate vs. shear stress or vs. water velocity) of the soil is likely to be found.

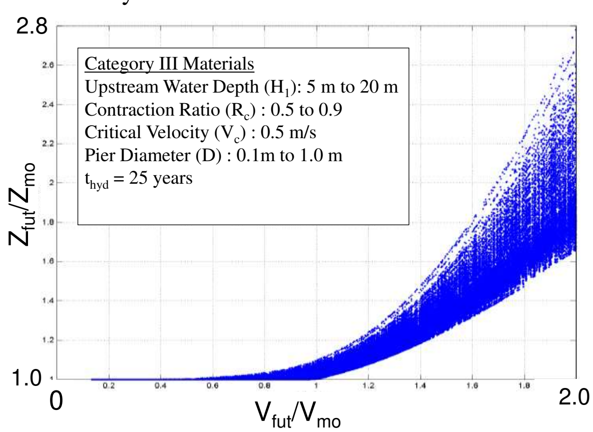


Figure 7. Large number of calculations to select conservative envelope for Z_{fut} chart.

In the end and to be conservative, the upper bound of all dots shown on the example of Fig. 7, was selected as the recommended curve for that Z_{fut} chart. These charts are embedded in the software TAMU-OMS and require the following input: scour type, soil type, time duration of the hydrograph, and the size of the obstacle. At the end of step 3, the future scour depth Z_{fut} that the bridge would experience should it be subjected to the chosen future flood (V_{fut}) is estimated by obtaining the ratio Z_{fut}/Z_{mo} from the Z_{fut} chart and multiplying that ratio by the known value of Z_{mo} from step 1. This is automated with TAMU-OMS.

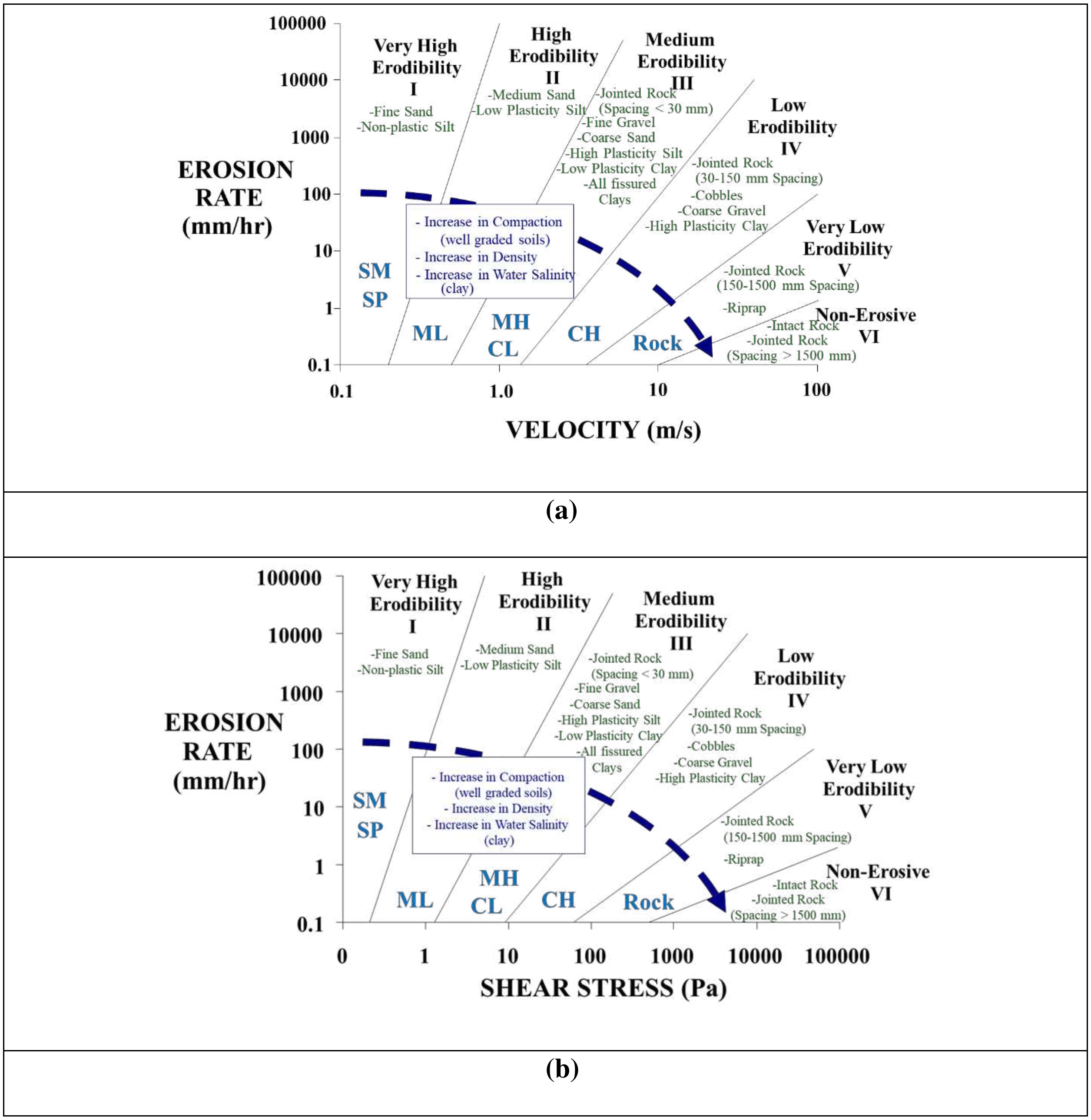


Figure 8. Erosion categories charts (Briaud, 2013): (a) erosion rate vs. velocity; (b) erosion rate vs. shear stress.

<u>Step 4: Compare the future scour depth to the foundation depth</u>

This step consists of comparing Z_{fut} to the allowable scour depth Z_{all}. For example, the Texas DOT considers that the allowable pier scour depth for one event is half the pile length. From the comparison between Z_{fut} and Z_{all} the scour situation for the bridge is appraised and decisions are made.

CASE HISTORIES

A database of 11 full-scale bridge case histories was collected to evaluate the precision of the TAMU-OMS method. Four of those bridges were located in Texas and seven in Massachusetts. The bridge identification number from the DOT inventory, the bridge location, the year built, the soil type and the soil erosion category from Fig. 8 are listed in Table 1.

Table 1. Database of 11 bridge scour case histories in Texas and Massachusetts: physical information.

Bridge#	State	City /Town	Highway	River	Longitude	Latitude	Year Built	Soil Material	Erosion Category
0188-02-023	TX	Houston	SH 36	Big Creek	-95.81305	29.47642	1932	Sand, Silt	I & II
0072-04-020	TX	San Antonio	US 87	Guadalupe	-98.8967	29.96498	1932(1984)	Sand, gravel, clay	I & II
170-0177-05-119	TX	Houston	US 59	Peach Creek	-95.18168	30.20833	1970	Sand	I & II
0382-05-021	TX	Bryan	SH 7	Navasota	-96.33053	31.25425	1956	Sand, Sandy silty clay	I & II
B13001-1EA	MA	Blackstone	Bridge Street	Blackstone River	-71.53869	42.01686	1955	Cobble, boulders, gravel	III
B28032-0JC	MA	Buckland	State Route 2	Deerfield	-72.73625	42.61303	1954	sand, gravel	III
D06002-0U4	MA	Deerfield	US 5	Water Deerfield	-72.59211	42.57028	1932	sand, silty	I & II
B28009-0JD	MA	Buckland	State Route 2	Deerfield	-72.74625	42.61819	1954	sand, gravel, silt. Mud	III
D10005-367	MA	Dover	Chestnut ST	Water Chales	-71.23717	42.26003	1922	Sand, Gravel, Boulders, cobbles	III
D12026-1XX	MA	Dudley	Sttate Route 131	Quinebaug	-71.95919	42.02778	1930(1984)	Rock, Gravel, cobble	IV
E01001-41Q	MA	East Bridgewater	Spring ST	Water Matfield	-70.96717	42.02644	1946	Sand	I & II

For each bridge, the following information was collected.

1. Observed scour depth as a function of time. This came from the inspection records which are required to be collected every two years in the USA.

2. Observed flow as a function of time. This came from the flow gages information.

3. Soil type. This came from the site borings.

4. Bridge support (pier or abutment) geometry. This came from the construction plans.

5. River geometry (contraction). This came from the bridge files.

This information is summarized in Table 2. With this information the following process was followed. Let's say that the bridge was built in 1960 (year built) and that items 1 and 2 above were available from 1960 to 2010 (end year). We would consider the year 1990 (intermediate year) and find Z_{mo} and V_{mo} from 1960 to 1990. Then the year 2000 (year predicted) might be chosen as the year for which the Z_{fut} would be predicted. Then V_{fut} for the period 1990-2000 was found by reading the maximum flow Q_{fut} on the gage record from 1990 to 2000, transforming it into RI_{fut} and then into V_{fut} using equations exemplified by Eq. 1. Then we would use Z_{mo} and V_{mo} from 1960 to 1990 and V_{fut} from 1990-2000 and predict Z_{fut} for the year 2000. This gave us $Z_{fut(predicted)}$. Then the inspection record from 1990 to 2000 would give us $Z_{fut(measured)}$. In this fashion we ended up with a $Z_{fut(predicted)}$ and a $Z_{fut(measured)}$ for that bridge. This procedure was applied several times for each bridge by varying the year predicted. Then the process was repeated for the 4 bridges in Texas and the 7 bridges in Massachusetts. The results are tabulated in Table 2. As an example, the case history for bridge B13001-1EA is described next in more detail.

TAMU-OMS PREDICTIONS VS. MEASUREMENTS

Two examples are presented to illustrate the sequence of calculations for all the bridge case histories:

Case #1 - bridge B13001-1EA from 2002 to 2005 ($RI_{fut}/RI_{mo}>1$)

- Bridge B13001-1EA was built in 1955. The observed scour depth and the observed flow were available from 1955 to 2010. The year 2002 was considered as the intermediate year. As such the record from 1955 to 2002 would be used to predict the future scour depth Z_{fut} between 2002 and 2005 (year predicted).
- The maximum observed scour depth Z_{mo} between 1955 and 2002 was found to be 2.01 m and the maximum observed recurrence interval RI_{mo} during the same period was 28 year. The maximum recurrence interval from 2002 and 2005, RI_{fut}, was 146 year.
- The soil erosion category based on the borings available was category 3, the pier diameter was 1.22 m and the scour type was pier scour.
- Using the relationships established during the research work, embedded in TAMU-OMS and approximated by Eq. 1, the ratio V_{fut}/V_{mo} was obtained from the recurrence interval ratio (RI_{fut}/RI_{mo} = 146/28 = 5.214) and was found to be 1.145.
- Then given the soil erosion category (3), the scour type (pier), the length of the future hydrograph considered (t_{hyd} = 5 years) and the value of V_{fut}/V_{mo} (1.145), the value of Z_{fut}/Z_{mo} was found from the Z_{fut} chart embedded in TAMU-OMS (Fig. 7 is an example) to be 1.17.
- Since Z_{mo} was 2.01m and since Z_{fut}/Z_{mo} was 1.17, the predicted $Z_{fut(predicted)}$ was 2.34 m.
- The measured maximum depth of scour $Z_{fut(measured)}$ during the period of 2002 to 2005 was found from the bridge inspection record to be 2.07 m.

Case #2 - bridge B13001-1EA from 2007 to 2010 ($RI_{fut}/RI_{mo}<1$)

- In this case, the year 2007 was considered as the intermediate year. As such the record from 1955 to 2007 would be used to predict the future scour depth Z_{fut} between 2007 and 2010.
- The maximum observed scour depth Z_{mo} between 1955 and 2007 was found to be 2.07 m and the maximum observed recurrence interval RI_{mo} during the same period was 146 year. The maximum recurrence interval from 2007 and 2010, RI_{fut}, was 68 year.
- The soil erosion category based on the borings available was category 3, the pier diameter was 1.22 m and the scour type was pier scour.
- Using the relationships established during the research work, embedded in TAMU-OMS and approximated by Eq. 1, the ratio V_{fut}/V_{mo} was obtained from the recurrence interval ratio (RI_{fut}/RI_{mo} = 68/146 = 0.466) and was found to be 0.95.
- Then given the soil erosion category (3), the scour type (pier), the length of the future hydrograph considered (T_{hyd} = 5 years) and the value of V_{fut}/V_{mo} (0.95), the value of Z_{fut}/Z_{mo} was found from the Z_{fut} chart embedded in TAMU-OMS (Fig. 7 is an example) to be 1.07.
- Since Z_{mo} was 2.07 m and since Z_{fut}/Z_{mo} was 1.07, the predicted $Z_{fut(predicted)}$ was 2.22 m.

The measured maximum depth of scour $Z_{fut(measured)}$ during the period of 2007 to 2010 was found from the bridge inspection record to be 2.01 m

Table 2. Database of 11 bridge scour case histories in Texas and Massachusetts: engineering information.

Bridge#	Erosion Category	Year Built	End year	Intermediate year	Year predicted	Pier diameter (m)	TAMU-OMS			Z_{mo} (m)	T_{hyd} (year)	Z_{fut}/Z_{mo} by Z-future Chart	Z-future Scour Depth (m)	Z-future Scour Depth (m)	Z-future Scour Depth (m)
							RI_{mo}	RI_{fut}	V_{fut}/V_{mo}	Pier &Cont		Pier&Cont	OMS (Pier & Cont)	HEC-18 (Pier)	Measured
0188-02-023	I/II	1932	2005	1994	1995	0.37	240	15	0.75	1.16	5	1.000	1.10	1.62	1.16
		1932	2005	1995	1997	0.37	240	2	0.68	1.16	5	1.000	1.16	1.62	1.16
		1932	2005	1997	1998	0.37	240	2	0.68	1.16	5	1.000	1.16	1.62	1.13
		1932	2005	1998	2001	0.37	240	3	0.68	1.16	5	1.000	1.16	1.62	1.07
		1932	2005	2001	2005	0.37	240	5	0.68	1.16	5	1.000	1.16	1.62	0.79
0072-04-020	I&II	1932	2000	1998	2000	1.83	68	8	0.73	1.92	5	1.000	1.92	7.15	1.92
170-0177-05-119	I&II	1970	2006	1999	2001	0.41	129	8	0.7	2.50	5	1.000	2.50	1.15	1.55
		1970	2006	2001	2003	0.41	129	7	0.7	2.50	5	1.000	2.50	1.15	2.41
		1970	2006	2003	2005	0.41	129	4	0.7	2.59	5	1.000	2.50	1.15	2.59
		1970	2006	2005	2006	0.41	129	1	0.7	2.59	5	1.000	2.59	1.15	2.44
0382-05-021	I&II	1956	2005	1994	1996	0.37	22	7	0.795	1.22	5	1.000	1.22	1.60	1.68
		1956	2005	1996	1998	0.37	22	3	0.795	1.68	5	1.000	1.68	1.60	1.89
		1956	2005	1998	2001	0.37	22	6	0.795	1.89	5	1.000	1.89	1.60	1.89
		1956	2005	2001	2003	0.37	22	8	0.795	1.89	5	1.000	1.89	1.60	2.32
		1956	2005	2003	2005	0.37	22	3	0.795	2.32	5	1.000	2.32	1.60	2.47
B13001-1EA	III	1955	2010	1989	1996	1.22	28	11	0.995	1.55	7	1.080	1.68	2.59	1.98
		1955	2010	1999	2002	1.22	28	6	0.96	1.98	5	1.075	2.13	2.59	2.01
		1955	2010	2002	2005	1.22	28	146	1.145	2.01	5	1.165	2.34	2.59	2.07
		1955	2010	2005	2007	1.22	146	20	0.835	2.07	5	1.040	2.16	2.85	2.07
		1955	2010	2007	2010	1.22	146	68	0.95	2.07	5	1.070	2.22	2.85	2.01
B28032-0JC	III	1954	2010	2004	2007	3.22	10	29	1.24	1.49	5	1.240	1.85	4.45	1.34
		1954	2010	2007	2010	3.22	29	8	0.95	1.49	5	1.070	1.60	4.74	1.46
D06002-0U4	I&II	1932	2012	1996	2002	4.88	68	8	0.85	2.77	6	1.000	2.77	5.95	3.20
		1932	2012	2002	2003	4.88	68	1	0.85	3.20	5	1.000	3.20	5.95	2.59
		1932	2012	2003	2004	4.88	68	4	0.85	3.20	5	1.000	3.20	5.95	2.93
		1932	2012	2004	2005	4.88	68	22	0.94	3.20	5	1.000	3.20	5.95	2.87
		1932	2012	2005	2006	4.88	68	4	0.85	3.20	5	1.000	3.20	5.95	2.74
		1932	2012	2006	2007	4.88	68	3	0.85	3.20	5	1.000	3.20	5.95	2.65
		1932	2012	2007	2008	4.88	68	2	0.85	3.20	5	1.000	3.20	5.95	2.99

		1932	2012	2008	2009	4.88	68	8	0.85	3.20	5	1.000	3.20	5.95	2.71
		1932	2012	2009	2010	4.88	68	2	0.85	3.20	5	1.000	3.20	5.95	2.83
		1932	2012	2010	2011	4.88	68	2	0.85	3.20	5	1.000	3.20	5.95	2.90
		1932	2012	2011	2012	4.88	68	2	0.85	3.20	5	1.000	3.20	5.95	2.93
B2800 9-0JD	III	1954	2009	1992	2001	3.66	10	7	1.185	2.05	9	1.180	2.42	7.11	2.26
		1954	2009	2001	2006	3.66	10	29	1.24	2.26	5	1.240	2.81	7.11	2.23
		1954	2009	2006	2009	3.66	29	8	0.95	2.26	5	1.070	2.42	7.56	1.75
D1000 5-367	III	1922	2014	2009	2014	1.22	34	30	1.015	0.16	5	1.095	0.18	2.68	0.13
D1202 6-1XX	IV	1930 (1984)	2013	1992	1995	1.22	29	2	0.95	1.40	5	1.010	1.42	2.22	0.91
		1930 (1984)	2013	1995	1998	1.22	29	5	0.95	1.40	5	1.010	1.42	2.22	1.28
		1930 (1984)	2013	1998	2001	1.22	29	4	0.95	1.40	5	1.010	1.42	2.22	1.10
		1930 (1984)	2013	2001	2004	1.22	29	5	0.95	1.40	5	1.010	1.42	2.22	1.13
		1930 (1984)	2013	2004	2007	1.22	29	247	1.17	1.40	5	1.015	1.42	2.22	1.74
		1930 (1984)	2013	2007	2010	1.22	247	30	0.845	1.74	5	1.005	1.75	2.51	1.83
		1930 (1984)	2013	2010	2013	1.22	247	2	0.76	1.83	5	1.000	1.83	2.51	2.29
E0100 1-41Q	I& II	1946	2004	1992	1998	0.30	47	14	0.93	0.57	6	1.005	0.57	1.49	0.45
		1946	2004	1998	2001	0.30	47	8	0.89	0.57	5	1.000	0.57	1.49	0.60
		1946	2004	2001	2004	0.30	47	2	0.89	0.60	5	1.000	0.60	1.49	0.54

TAMU-OMS prediction vs. measurement for all case histories

The comparisons between the measured scour depth and the TAMU-OMS predicted scour depth for the 11 bridges are tabulated in Table 2 and presented in Fig. 9. It indicates a very reasonable match.

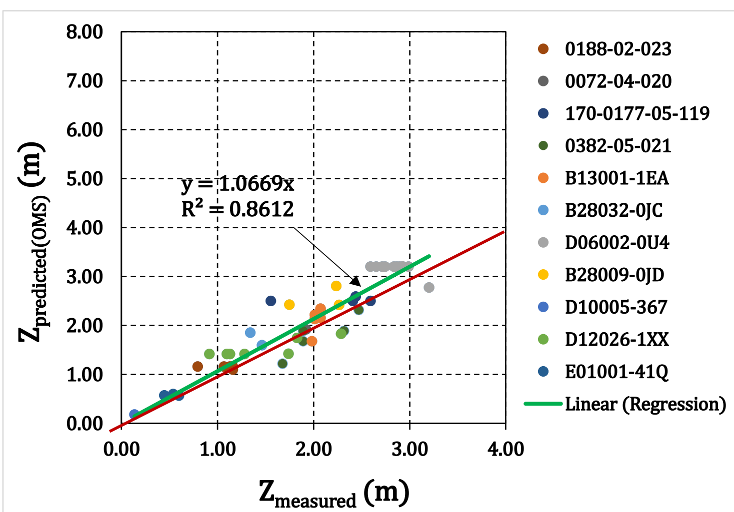


Figure 9. Comparison between measured and OMS predicted Z_{fut} for 11 bridges in Texas and Massachusetts.

HEC-18 PREDICTIONS VS. MEASUREMENTS

Predictions were also performed using the HEC-18 current method (Table 2, Arneson et al., 2012). In addition to the input required for the TAMU-OMS method, the water depth y and the flow velocity v are needed for the HEC-18 calculations. These quantities were obtained from the following Eq. 3 and Eq. 1 (Briaud et al., 2016).

$$\left(\frac{y_{mo}}{y_{fut}}\right)=\left(\frac{Q_{mo}}{Q_{fut}}\right)^{0.525}=\left(\left(\frac{RI_{mo}}{RI_{fut}}\right)^{0.261}\right)^{0.525}=\left(\frac{RI_{mo}}{RI_{fut}}\right)^{0.137} \tag{3}$$

Based on the calculated water depth and the calculated flow velocity as well as the other input quantities, the HEC-18 calculations were performed. All the parameters used to caculate the scour depth according to HEC-18 are listed in Table 3; the parameters are defined in HEC-18 (Arneson et al., 2012). The results are tabulated in Table 3 and the comparison between the HEC-18 predicted scour depths and the measured scour depths is presented on Fig. 10. As an example, the case history of bridge B28009-0JD is described next for two scenarios.

Case #1 - Bridge B28009-0JD from 2001 to 2006 ($RI_{fut}/RI_{mo}>1$)

- Bridge B28009-0JD was built in 1954 (year built). The observed flow hydrograph was available from 1954 to 2009 (end year). The year 2001 (intermediate year) was considered as the intermediate year. As such the record from 1954 to 2001 would be used to predict the future scour depth Z_{fut} between 2001 and 2006 (year precicted).
- The maximum observed recurrence interval RI_{mo} between 1954 and 2001 was 10 year and the maximum recurrence interval from 2001 and 2006, RI_{fut}, was 29 year.
- The water depth and the water velocity for the 100-year flood were found in the bridge design/monitoring report to be 8.38 m and 1.98 m/s respectively.
- Using the Eq. 3 and 4 as well as the water depth and velocity for RI equal 100 year, the water depth and the water velocity for RI equal 10 year were calculated to be 6.11 m and 1.61 m/s.
- The scour type was pier scour, the pier diameter was 3.66 m, and the other variables such as pier length, and attack angle were obtained from the bridge design/monitoring report and are listed in Table 3.
- Based on the information above, the HEC-18 predicted $Z_{fut(predicted)}$ value was calculated to be 7.11 m.
- The measured maximum depth of scour $Z_{fut(measured)}$ during the period of 2001 to 2006 was found from the bridge inspection record to be 2.23 m.

The case #2 - Bridge B28009-0JD from 2006 to 2009 ($RI_{fut}/RI_{mo}<1$)

- In this case, the year 2006 was considered as the intermediate year. As such the record from 1955 to 2006 would be used to predict the future scour depth Z_{fut} between 2006 and 2009.
- The maximum observed recurrence interval RI_{mo} between 1955 and 2006 was 29 year and the maximum recurrence interval from 2006 and 2009, RI_{fut}, was 8 year.
- The water depth and the water velocity for the 100-year flood were found in the bridge design/monitoring report to be 8.38 m and 1.98 m/s respectively.
- Using the Eq. 3 and 4 as well as the water depth and velocity for RI equal 100 year, the water depth and the water velocity for RI equal 29 year were calculated to be 7.07 m and 1.77 m/s.
- The scour type was pier scour, the pier diameter was 3.66 m, and the other variables such as pier length, attack angle were obtained from the bridge design/monitoring report and are listed in Table 3.
- Based on the information above, the HEC-18 predicted $Z_{fut(predicted)}$ value was calculated to be 7.56 m
- The measured maximum depth of scour $Z_{fut(measured)}$ during the period of 2006 to 2009 was found from the bridge inspection record to be 1.75 m.

Inspection of Figs. 9 and 10 shows that the scatter in TAMU-OMS is significantly reduced compared to the scatter in the current HEC-18 method. Indeed the R^2 value for the predicted vs. measured regression is increased from 0.3061 for HEC-18 to 0.8612 for TAMU-OMS. Also the degree of conservatism is practically eliminated since the mean ratio between the predicted scour depth over the measured scour depth (slope of the regression line) decreases from 1.7687 for HEC-18 to 1.0669 from TAMU-OMS.

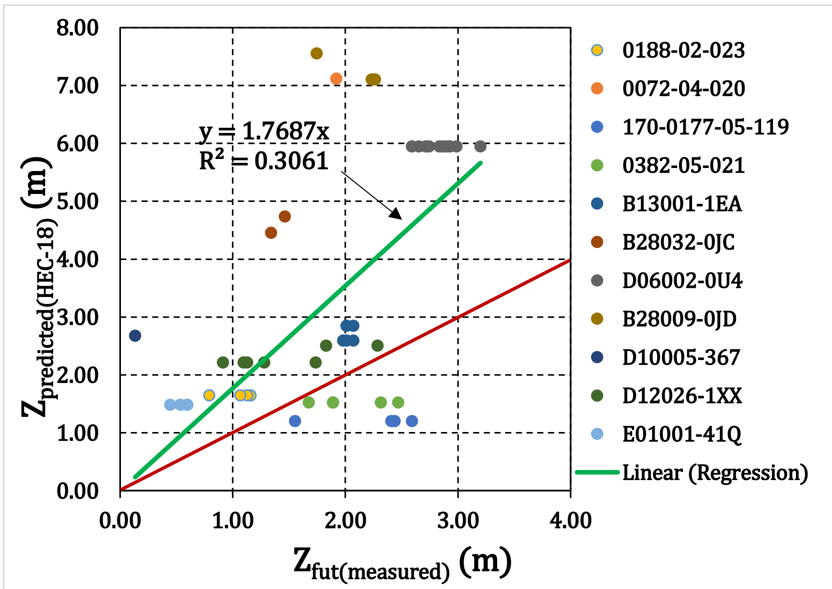


Figure 10. Comparison between measured and HEC-18 predicted scour depth for 11 bridges in Texas and Massachusetts.

Table 3. Database of 11 bridge scour case histories in Texas and Massachusetts: engineering information for HEC-18.

Bridge#	Year built	End year	Intermediate year	Year predicted	RI_{mo}	RI_{fut}	y_1 (m)	a (m)	L (m)	θ (o)	a' (m)	L/a	V_1 (m/s)	F_r	K_1	K_2	K_3	$y_{s(total)}$_measured (m)	$y_{s(pier)}$_calculated_HEC-18 (m)
0188-02-023	1932	2005	1994	1995	240	15	5.59	0.37	0.37	20	0.47	1.00	2.92	0.39	1.00	1.18	1.10	1.16	1.65
	1932	2005	1995	1997	240	2	5.59	0.37	0.37	20	0.47	1.00	2.92	0.39	1.00	1.18	1.10	1.16	1.65
	1932	2005	1997	1998	240	2	5.59	0.37	0.37	20	0.47	1.00	2.92	0.39	1.00	1.18	1.10	1.13	1.65
	1932	2005	1998	2001	240	3	5.59	0.37	0.37	20	0.47	1.00	2.92	0.39	1.00	1.18	1.10	1.07	1.65
	1932	2005	2001	2005	240	5	5.59	0.37	0.37	20	0.47	1.00	2.92	0.39	1.00	1.18	1.10	0.79	1.65
0072-04-020	1932	2000	1998	2000	68	8	8.91	1.83	14.02	10	4.24	7.67	2.73	0.29	1.00	1.73	1.10	1.92	7.12
170-0177-05-119	1970	2006	1999	2001	129	8	5.21	0.41	0.41	0	0.41	1.00	1.43	0.20	1.10	1.00	1.10	1.55	1.20
	1970	2006	2001	2003	129	7	5.21	0.41	0.41	0	0.41	1.00	1.43	0.20	1.10	1.00	1.10	2.41	1.20
	1970	2006	2003	2005	129	4	5.21	0.41	0.41	0	0.41	1.00	1.43	0.20	1.10	1.00	1.10	2.59	1.20
	1970	2006	2005	2006	129	1	5.21	0.41	0.41	0	0.41	1.00	1.43	0.20	1.10	1.00	1.10	2.44	1.20
0382-05-021	1956	2005	1994	1996	22	7	5.00	0.37	0.37	0	0.37	1.00	2.95	0.42	1.10	1.00	1.10	1.68	1.52
	1956	2005	1996	1998	22	3	5.00	0.37	0.37	0	0.37	1.00	2.95	0.42	1.10	1.00	1.10	1.89	1.52
	1956	2005	1998	2001	22	6	5.00	0.37	0.37	0	0.37	1.00	2.95	0.42	1.10	1.00	1.10	1.89	1.52

	1956	2005	2001	2003	22	8	5.00	0.37	0.37	0	0.37	1.00	2.95	0.42	1.10	1.00	1.10	2.32	1.52
	1956	2005	2003	2005	22	3	5.00	0.37	0.37	0	0.37	1.00	2.95	0.42	1.10	1.00	1.10	2.47	1.52
B13001-1EA	1955	2010	1989	1996	28	11	5.83	1.22	11.89	0	1.22	9.75	2.50	0.33	0.90	1.00	1.10	1.98	2.59
	1955	2010	1996	2002	28	6	5.83	1.22	11.89	0	1.22	9.75	2.50	0.33	0.90	1.00	1.10	2.01	2.59
	1955	2010	2002	2005	28	146	5.83	1.22	11.89	0	1.22	9.75	2.50	0.33	0.90	1.00	1.10	2.07	2.59
	1955	2010	2005	2007	146	20	7.31	1.22	11.89	0	1.22	9.75	2.90	0.34	0.90	1.00	1.10	2.07	2.85
	1955	2010	2007	2010	146	68	7.31	1.22	11.89	0	1.22	9.75	2.90	0.34	0.90	1.00	1.10	2.01	2.85
B28032-0JC	1954	2010	2004	2007	10	29	5.56	3.22	15.24	0	3.22	4.73	2.05	0.28	0.90	1.00	1.10	1.34	4.45
	1954	2010	2007	2010	29	8	6.43	3.22	15.24	0	3.22	4.73	2.26	0.28	0.90	1.00	1.10	1.46	4.74
D06002-0U4	1932	2012	1996	2002	68	8	9.40	4.88	24.38	0	4.88	5.00	1.82	0.19	0.90	1.00	1.10	3.20	5.95
	1932	2012	2002	2003	68	1	9.40	4.88	24.38	0	4.88	5.00	1.82	0.19	0.90	1.00	1.10	2.59	5.95
	1932	2012	2003	2004	68	4	9.40	4.88	24.38	0	4.88	5.00	1.82	0.19	0.90	1.00	1.10	2.93	5.95
	1932	2012	2004	2005	68	22	9.40	4.88	24.38	0	4.88	5.00	1.82	0.19	0.90	1.00	1.10	2.87	5.95
	1932	2012	2005	2006	68	4	9.40	4.88	24.38	0	4.88	5.00	1.82	0.19	0.90	1.00	1.10	2.74	5.95
	1932	2012	2006	2007	68	3	9.40	4.88	24.38	0	4.88	5.00	1.82	0.19	0.90	1.00	1.10	2.65	5.95
	1932	2012	2007	2008	68	2	9.40	4.88	24.38	0	4.88	5.00	1.82	0.19	0.90	1.00	1.10	2.99	5.95
	1932	2012	2008	2009	68	8	9.40	4.88	24.38	0	4.88	5.00	1.82	0.19	0.90	1.00	1.10	2.71	5.95
	1932	2012	2009	2010	68	2	9.40	4.88	24.38	0	4.88	5.00	1.82	0.19	0.90	1.00	1.10	2.83	5.95
	1932	2012	2010	2011	68	2	9.40	4.88	24.38	0	4.88	5.00	1.82	0.19	0.90	1.00	1.10	2.90	5.95
	1932	2012	2011	2012	68	2	9.40	4.88	24.38	0	4.88	5.00	1.82	0.19	0.90	1.00	1.10	2.93	5.95
B28009-0JD	1954	2009	1992	2001	10	7	6.11	3.66	23.16	10	7.62	6.33	1.61	0.21	0.90	1.61	1.10	2.26	7.11
	1954	2009	2001	2006	10	29	6.11	3.66	23.16	10	7.62	6.33	1.61	0.21	0.90	1.61	1.10	2.23	7.11
	1954	2009	2006	2009	29	8	7.07	3.66	23.16	10	7.62	6.33	1.77	0.21	0.90	1.61	1.10	1.75	7.56
D10005-367	1922	2014	2009	2014	34	30	3.21	1.22	11.28	0	1.22	9.25	2.54	0.45	1.00	1.00	1.10	0.13	2.68
D12026-1XX	1930 (1984)	2013	1992	1995	29	2	4.50	1.22	18.29	0	1.22	12.00	1.88	0.28	0.90	1.00	1.10	0.91	2.22
	1930 (1984)	2013	1995	1998	29	5	4.50	1.22	18.29	0	1.22	12.00	1.88	0.28	0.90	1.00	1.10	1.28	2.22
	1930 (1984)	2013	1998	2001	29	4	4.50	1.22	18.29	0	1.22	12.00	1.88	0.28	0.90	1.00	1.10	1.10	2.22
	1930 (1984)	2013	2001	2004	29	5	4.50	1.22	18.29	0	1.22	12.00	1.88	0.28	0.90	1.00	1.10	1.13	2.22
	1930 (1984)	2013	2004	2007	29	247	4.50	1.22	18.29	0	1.22	12.00	1.88	0.28	0.90	1.00	1.10	1.74	2.22
	1930 (1984)	2013	2007	2010	247	30	6.04	1.22	18.29	0	1.22	12.00	2.28	0.30	0.90	1.00	1.10	1.83	2.51
	1930 (1984)	2013	2010	2013	247	2	6.04	1.22	18.29	0	1.22	12.00	2.28	0.30	0.90	1.00	1.10	2.29	2.51
E01001-41Q	1946	2004	1992	1998	47	14	2.61	0.30	13.72	12	1.06	12.00	0.85	0.17	1.00	2.25	1.10	0.45	1.49
	1946	2004	1998	2001	47	8	2.61	0.30	13.72	12	1.06	12.00	0.85	0.17	1.00	2.25	1.10	0.60	1.49
	1946	2004	2001	2004	47	2	2.61	0.30	13.72	12	1.06	12	0.85	0.17	1.00	2.25	1.10	0.54	1.49

Note: all parameters are defined in HEC-18 (Arneson et al., 2012).

EVALUATING PROBABILITY OF FAILURE AND PRIORITIZING REPAIRS

TAMU-OMS can also be used to evaluate the probability of failure due to scour for a bridge over water. The risk defined as the product of the probability of failure times the value of the consequence can then be evaluated separately by using allowable risk targets of 0.001 fatalities per year and $1000 per year as proposed by Briaud (2013). The probability of failure presented in Figure 11 and Table 4 is based on a comparison between the future scour depth predicted by TAMU-OMS, Z_{fut}, and the allowable scour depth Z_{all}. In this case the scour depth Z_{fut} is calculated based on the design flood, say the 100 year flood and the allowable scour depth Z_{all} is established on the basis of safe local practice. For example in Texas and for a one time flood, the allowable pier scour depth is taken as one half the original embedded pile length. Actually, two allowable scour depth are identified, Z_{af} and Z_{bf}. The scour depth Z_{af} is the allowable scour depth after the flood and is the same as Z_{all}, but Z_{bf} is the scour depth which would lead to a scour depth equal to Z_{all} should the bridge be subjected to the design flood. The relationship between Z_{bf} and Z_{af} is obtained from the charts in TAMU-OMS with the following input. The RI_{mo} is the one for the bridge until the present, RI_{fut} is the design RI value, and all other parameters (soil, scour type, and so on) are the ones for the specific bridge site. Fig. 11 and Table 4 give a proposed probability of failure rating for bridges. It also indicates what action might be needed for each probability level.

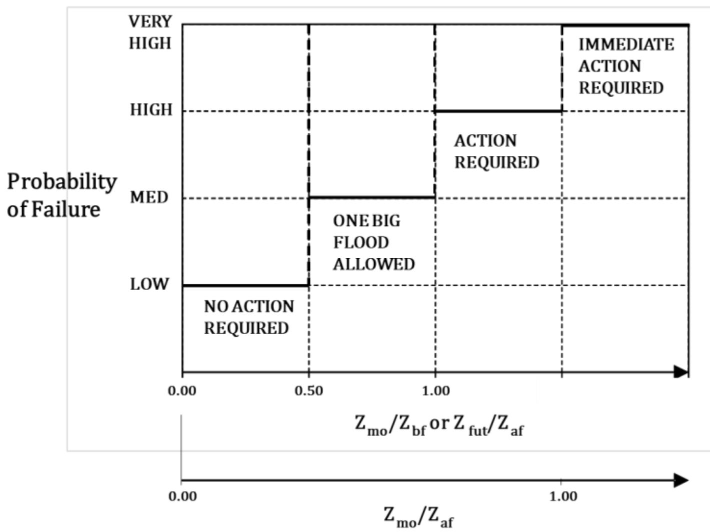


Figure 11. Probability of failure evaluation chart for scour at bridges based on TAMU-OMS.

The recommendations of Table 4 summarize the following opinions. If the future scour depth calculated by TAMU-OMS for the chosen future flood is less than half the allowable scour depth, the bridge is considered to have a "low probability of failure" and no repair is required. If the future scour depth calculated by TAMU-OMS for the chosen future flood is between half the allowable scour depth and the allowable scour depth, the bridge is considered to have a "moderate probability of failure", the bridge should be on a scour watch list, and close monitoring is required especially after the next big flood. If the future scour depth calculated by TAMU-OMS for the chosen future flood is higher than the allowable scour depth, but the maximum observed scour depth is less than the allowable scour depth, the probability of failure is high and action to repair the scour hole is a high priority. If the future scour depth calculated by TAMU-OMS for the chosen future flood is higher than the allowable scour depth and the maximum observed scour depth is also higher than the allowable scour depth, the probability of failure is very high and immediate action to repair the scour hole is required.

Table 4. Probability of failure evaluation for scour at bridges based on TAMU-OMS.

SCOUR DEPTH COMPARISON	PROBABILITY OF FAILURE	ACTION
$Z_{fut} < 0.5 Z_{all}$	Low	Continue regular inspections
$0.5 Z_{all} < Z_{fut} < Z_{all}$	Moderate	Increase inspection frequency. Consider repair
$Z_{fut} > Z_{all}$ but $Z_{mo} < Z_{all}$	High	Repair is high priority
$Z_{fut} > Z_{all}$ and $Z_{mo} > Z_{all}$	Very High	Repair immediately

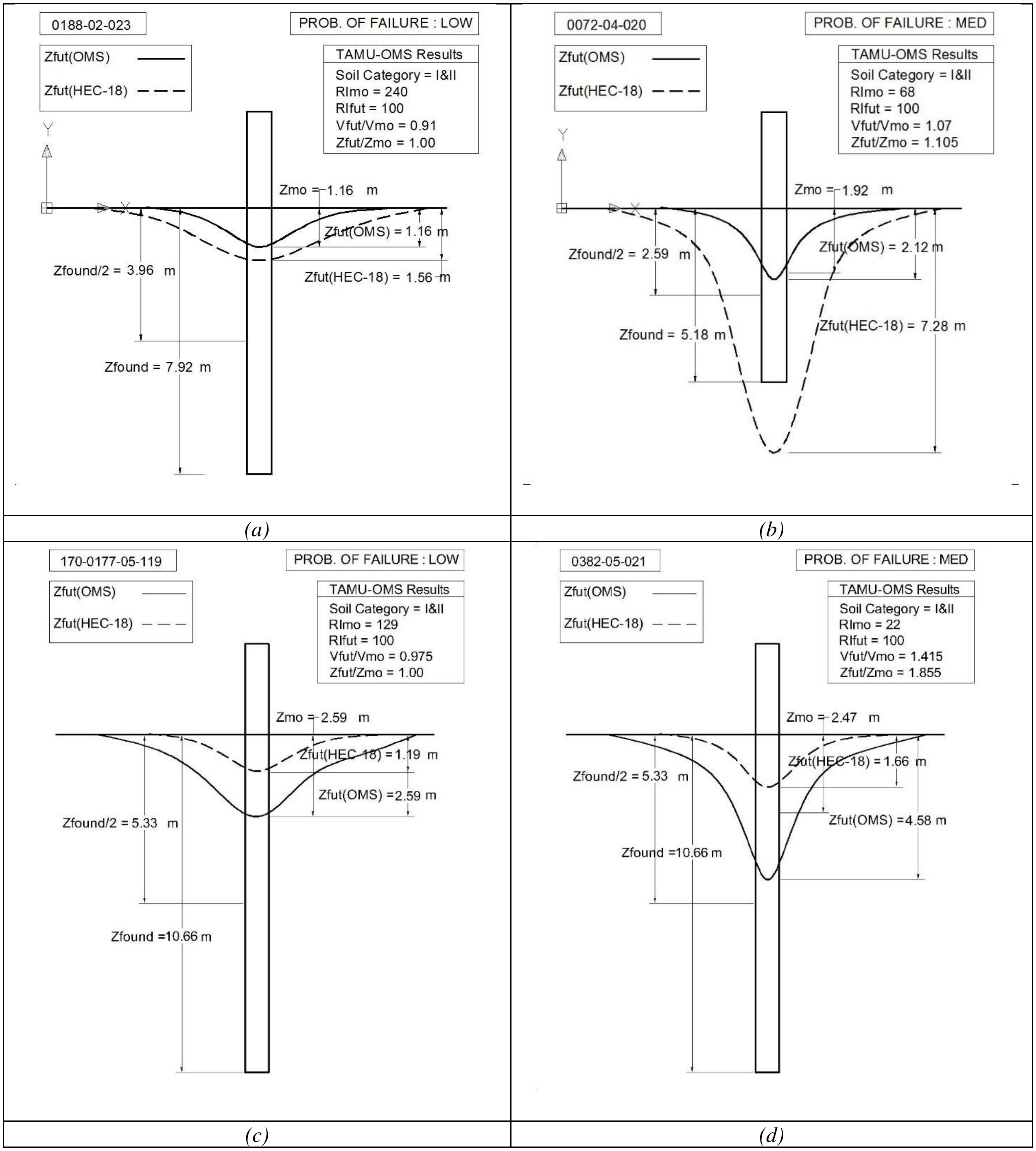
The evaluation of the 11 bridges in the database according to the probability of failure if these bridges were subjected to a 100 year design flood is presented in Table 5. Out of 11 bridges, 4 bridges are found to have a low probability of failure according to TAMU-OMS, 3 bridges are found to have a moderate probability of failure, 3 bridges are found to have a very high probability of failure with immediate repair needed and the last one cannot be evaluated because the foundation depth is unknown. Drawings for all bridge scour situations are presented in Fig. 12. An example of the evaluation procedure for bridge B13001-1EA is presented next.

Evaluation for Bridge B13001-1EA

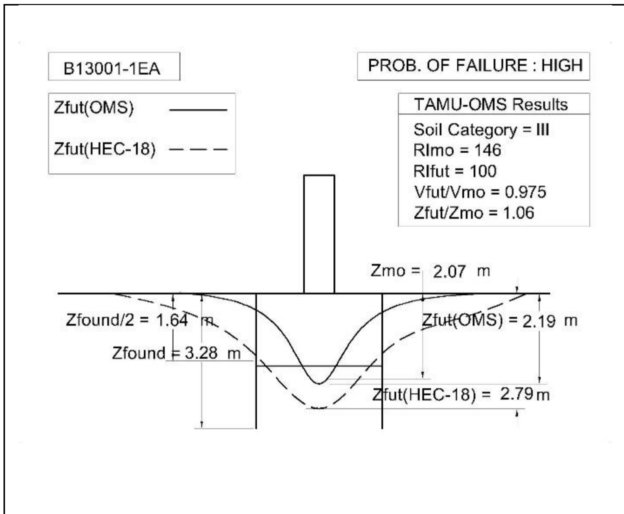
- Bridge B13001-1EA was built in 1955. The observed scour depth and the observed flow were available from 1955 to 2016. The records indicated that the value of Z_{mo} from 1955 to 2016 was 2.07 m.
- During that period, the maximum observed recurrence interval RI_{mo} was 146 year and the RI_{fut} would be 100 since the evaluation consisted of finding out what would happen should the bridge be subjected to the 100 year design flood. The corresponding ratio of V_{fut}/V_{mo} was calculated to be 0.975.
- The borings indicated that the soil erosion category was 3, the scour type was pier scour, and the pier diameter was 1.22 m.
- For the 100 year design flood as the future flood, the Z_{fut}/Z_{mo} was calculated to be 1.06 based on the soil erosion category, the value of V_{fut}/V_{mo} and the scour type.
- Since the value of Z_{mo} was 2.07 m and since the ratio of Z_{fut}/Z_{mo} was 1.06, the predicted value of the scour depth $Z_{fut(predicted)}$ was 2.19 m.
- The allowable pier scour depth, Z_{all} or Z_{af} in this case was taken as one half the embedded foundation depth. The foundation was a spread footing embedded 3.28 m into the soil; therefore Z_{all} was 1.64 m.
- The comparison between Z_{all} and Z_{fut} shows that this bridge is in the "high probability of failure" category based on Fig. 11 and Table 4. Indeed $Z_{fut} > Z_{all}$.

Table 5. Probability of failure for the database of 11 bridge scour case histories in Texas and Massachusetts.

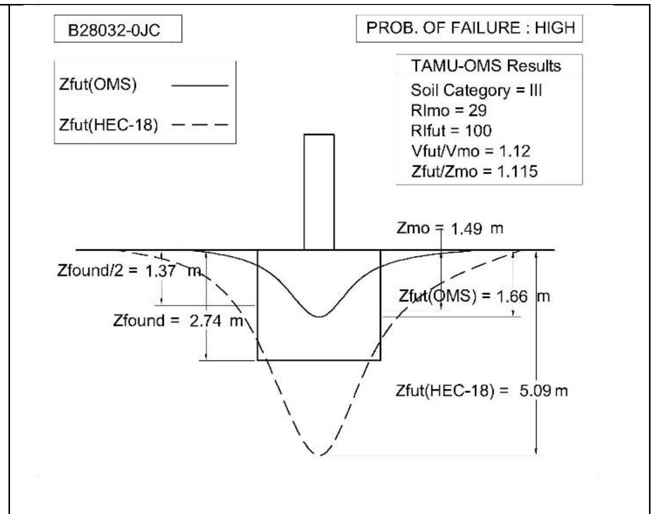
Bridge#	Erosion Category	RI_{mo} (year)	V_{fut}/V_{mo}	Z_{mo} (m)	Z_{fut}/Z_{mo}	$Z_{fut(OMS)}$ (m)	Z_{af} (m)	Z_{bf} (m)	Scour Probability of Failure	Action required
0188-02-023	I & II	240	0.91	1.16	1.000	1.16	3.96	3.96	Low	No
0072-04-020	I & II	68	1.07	1.92	1.105	2.12	2.59	2.34	Med	No
170-0177-05-119	I & II	129	0.98	2.59	1.000	2.59	5.33	5.33	Low	No
0382-05-021	I & II	22	1.42	2.47	1.855	4.58	5.33	2.88	Med	No
B13001-1EA	III	146	0.98	2.07	1.060	2.19	1.64	1.55	Very High	Yes
B28032-0JC	III	29	1.12	1.49	1.115	1.66	1.37	1.23	Very High	Yes
D06002-0U4	I & II	68	1.04	3.20	1.055	3.38	2.99	2.83	Very High	Yes
B28009-0JD	III	29	1.12	2.26	1.115	2.52	3.11	2.79	Med	No
D10005-367	III	34	1.11	0.16	1.110	0.18	0.53	0.48	Low	No
D12026-1XX	IV	247	0.95	2.29	1.005	2.30	Unknown sheet pile depth	Unknown sheet pile depth	N/A	N/A
E01001-41Q	I & II	74	1.03	0.60	1.080	0.65	5.37	4.97	Low	No


0188-02-023
PROB. OF FAILURE : LOW
Zfut(OMS)
Zfut(HEC-18)
TAMU-OMS Results
Soil Category = I&II
RImo = 240
RIfut = 100
Vfut/Vmo = 0.91
Zfut/Zmo = 1.00
Zmo = 1.16 m
Zfut(OMS) = 1.16 m
Zfut(HEC-18) = 1.56 m
Zfound/2 = 3.96 m
Zfound = 7.92 m
0072-04-020
PROB. OF FAILURE : MED
Zfut(OMS)
Zfut(HEC-18)
TAMU-OMS Results
Soil Category = I&II
RImo = 68
RIfut = 100
Vfut/Vmo = 1.07
Zfut/Zmo = 1.105
Zmo = 1.92 m
Zfound/2 = 2.59 m
Zfut(OMS) = 2.12 m
Zfound = 5.18 m
Zfut(HEC-18) = 7.28 m
170-0177-05-119
PROB. OF FAILURE : LOW
Zfut(OMS)
Zfut(HEC-18)
TAMU-OMS Results
Soil Category = I&II
RImo = 129
RIfut = 100
Vfut/Vmo = 0.975
Zfut/Zmo = 1.00
Zmo = 2.59 m
Zfut(HEC-18) = 1.19 m
Zfut(OMS) = 2.59 m
Zfound/2 = 5.33 m
Zfound =10.66 m
0382-05-021
PROB. OF FAILURE : MED
Zfut(OMS)
Zfut(HEC-18)
TAMU-OMS Results
Soil Category = I&II
RImo = 22
RIfut = 100
Vfut/Vmo = 1.415
Zfut/Zmo = 1.855
Zmo = 2.47 m
Zfut(HEC-18) = 1.66 m
Zfound/2 = 5.33 m
Zfut(OMS) = 4.58 m
Zfound =10.66 m

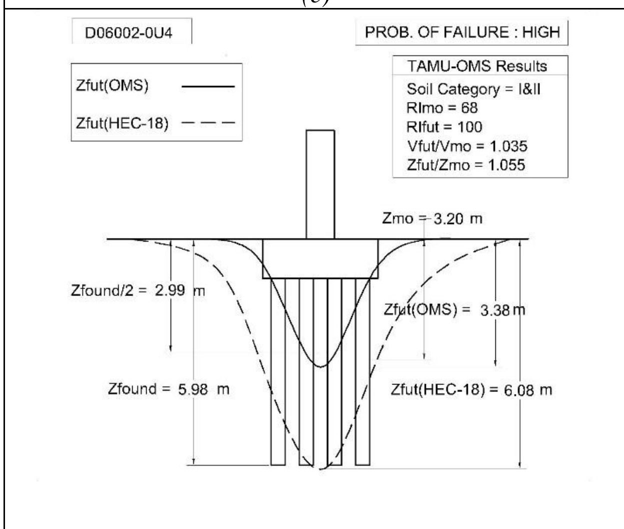
(a) *(b)* *(c)* *(d)*


B13001-1EA
PROB. OF FAILURE : HIGH
Zfut(OMS)
Zfut(HEC-18)
TAMU-OMS Results
Soil Category = III
RImo = 146
RIfut = 100
Vfut/Vmo = 0.975
Zfut/Zmo = 1.06
Zmo = 2.07 m
Zfound/2 = 1.64 m
Zfut(OMS) = 2.19 m
Zfound = 3.28 m
Zfut(HEC-18) = 2.79 m

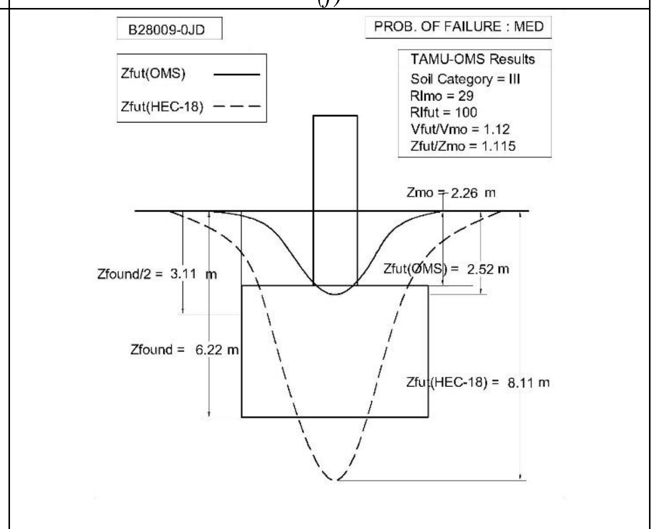
(e)


B28032-0JC
PROB. OF FAILURE : HIGH
Zfut(OMS)
Zfut(HEC-18)
TAMU-OMS Results
Soil Category = III
RImo = 29
RIfut = 100
Vfut/Vmo = 1.12
Zfut/Zmo = 1.115
Zmo = 1.49 m
Zfound/2 = 1.37 m
Zfut(OMS) = 1.66 m
Zfound = 2.74 m
Zfut(HEC-18) = 5.09 m

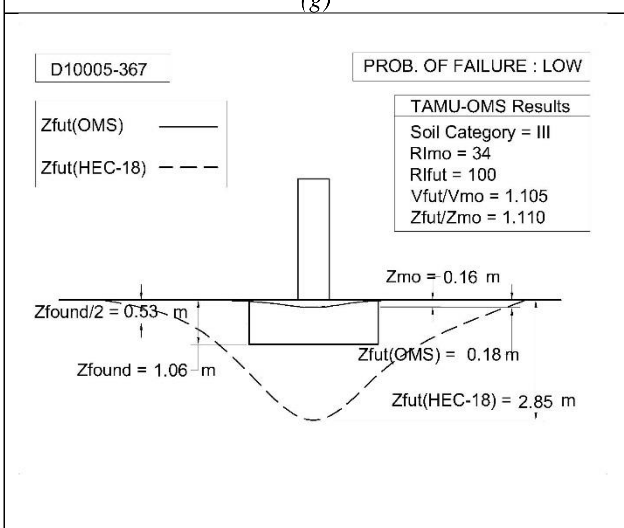
(f)


D06002-0U4
PROB. OF FAILURE : HIGH
Zfut(OMS)
Zfut(HEC-18)
TAMU-OMS Results
Soil Category = I&II
RImo = 68
RIfut = 100
Vfut/Vmo = 1.035
Zfut/Zmo = 1.055
Zmo = 3.20 m
Zfound/2 = 2.99 m
Zfut(OMS) = 3.38 m
Zfound = 5.98 m
Zfut(HEC-18) = 6.08 m

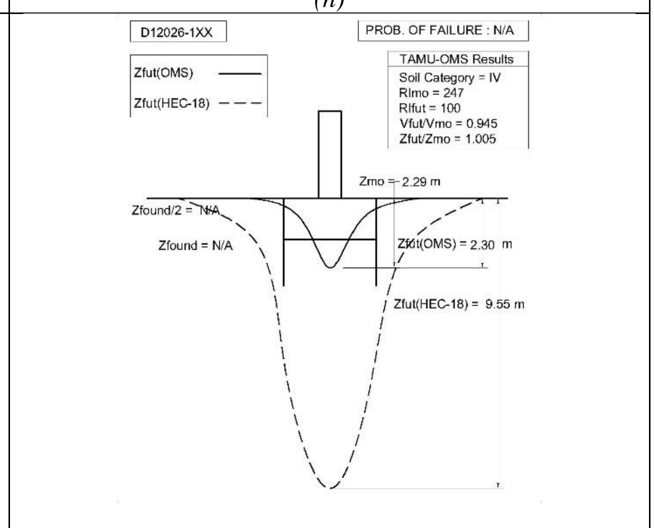
(g)


B28009-0JD
PROB. OF FAILURE : MED
Zfut(OMS)
Zfut(HEC-18)
TAMU-OMS Results
Soil Category = III
RImo = 29
RIfut = 100
Vfut/Vmo = 1.12
Zfut/Zmo = 1.115
Zmo = 2.26 m
Zfound/2 = 3.11 m
Zfut(OMS) = 2.52 m
Zfound = 6.22 m
Zfut(HEC-18) = 8.11 m

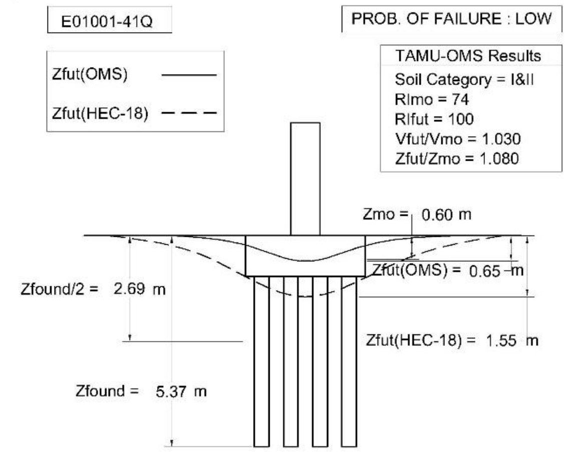
(h)


D10005-367
PROB. OF FAILURE : LOW
Zfut(OMS)
Zfut(HEC-18)
TAMU-OMS Results
Soil Category = III
RImo = 34
RIfut = 100
Vfut/Vmo = 1.105
Zfut/Zmo = 1.110
Zmo = 0.16 m
Zfound/2 = 0.53 m
Zfound = 1.06 m
Zfut(OMS) = 0.18 m
Zfut(HEC-18) = 2.85 m

(i)


D12026-1XX
PROB. OF FAILURE : N/A
Zfut(OMS)
Zfut(HEC-18)
TAMU-OMS Results
Soil Category = IV
RImo = 247
RIfut = 100
Vfut/Vmo = 0.945
Zfut/Zmo = 1.005
Zmo = 2.29 m
Zfound/2 = N/A
Zfound = N/A
Zfut(OMS) = 2.30 m
Zfut(HEC-18) = 9.55 m

(j)



(k)

Figure 12. Scour situation for 11 bridges in Texas and Massachusetts. (a) bridge 0188-02-023, (b) bridge 0072-04-020, (c) bridge 170-0177-05-119, (d) bridge 0382-05-021, (e) bridge B13001-1EA, (f) bridge B28032-0JC, (g) bridge D06002-0U4, (h) bridge B28009-0JD, (i) bridge D10005-367, (j) bridge D12026-1XX, (k) bridge E01001-41Q.

ADVANTAGES AND LIMITATIONS OF TAMU-OMS

The limitations of TAMU-OMS include:

1. TAMU-OMS cannot be used for new bridges because it is based on observations made at the bridge. However, the lessons learned and the observations gathered by using TAMU-OMS on existing bridges can be useful for the scour design of new bridges, particularly if the new bridge is close to the existing bridge as in a replacement project.
2. TAMU-OMS requires a good network of flow gages in the State.
3. The maximum observed scour depth Z_{mo} may include infilling of the scour hole thereby representing a scour depth which is smaller than the scour depth at the peak of the flood. The estimated infilling thickness should be added to Z_{fut}. Briaud et al. (2016) suggest the largest of 1.2 m or 40% of the maximum observed scour depth.
4. The TAMU-OMS has not been developed yet for layered systems and one should be very cautious when using that method in the case of an erosion resistant layer over a more erodible layer.
5. The TAMU-OMS prediction of Z_{fut} is only valid for the next future flood. If this flood occurs, TAMU-OMS must be used again for any future prediction.

The advantages of TAMU-OMS include:

1. There is no need to conduct erosion tests such as the EFA test on samples retrieved from the bridge site. There is a need however to know what soil type is involved within the zone of influence of the potential scour depth.
2. The soil that is being eroded is the actual soil at the site with its own critical velocity. It is not a man-made soil created in a flume and tested to develop prediction equations.
3. The flow history is the actual flow history at the site including all the series of floods which take into account the proper scour rate effect. It is not an assumed constant velocity in a flume lasting long enough to create the maximum scour depth.
4. The geometry of the obstacle provided by the bridge is the actual geometry with all its complexities. It is not a simplified cylinder placed in the middle of a flume with a limited width and associated scaling issues.
5. The method is based on actual observations at the site.
6. TAMU-OMS can be used as a risk management tool. It represents another tool in the scour engineer toolbox. It gives information which is helpful for scour critical bridges as well as for unknown foundation bridges.
7. TAMU-OMS can be used as a bridge scour management tool and a tool to prioritize repairs.

Table 6 summarizes the advantages and drawbacks of TAMU-OMS and the current practice.

Table 6. Advantages and drawbacks of HEC 18 and TAMU-OMS.

HEC 18 ADVANTAGES	DRAWBACKS	TAMU-OMS ADVANTAGES	DRAWBACKS
Used for 30 years	Very conservative on the average	Eliminates over conservatism as predictions are close to measurements	Requires a good network of gages
Well documented in guidelines	Very large scatter	Low scatter	Limited use for new bridges
Based on many years of research	Based on flume tests	Based on full scale bridge behavior	Need to estimate infilling
	Based on fine sand behavior	Based on the in situ soil	Not yet developed for layered soils
	Based on simplified geometry	Based on exact geometry	
	Based on simplified constant velocity	Based on exact hydrograph	
		Can be used as management tool, to evaluate risk, and prioritize repairs	

CONCLUSION

A new method for predicting the future scour depth at existing bridges called the Observation Method for Scour or TAMU-OMS is evaluated by comparing predicted and measured scour depth at 11 bridges in Texas and Massachusetts. The results show that, on average, the OMS eliminates the overconservatism associated with the current practice and significantly decreases the scatter in the predictions. The main limitation of the OMS is that it requires that the user estimates the possibility and magnitude of infilling. More detailed advantages and drawbacks are listed in Table 6. Research on the OMS is continuing.

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