Journal of Civil Engineering and Architecture 12 (2018) 810-815
doi: 10.17265/1934-7359/2018.11.004

A Concise Analysis of Hydraulic Bridge Collapse

Cristopher Montalvo[1] and Wesley Cook[2]

1. Department of Civil and Environmental Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA 24060, USA

2. Department of Civil and Environmental Engineering, New Mexico Institute of Mining and Technology, Socorro, NM 87801, USA

Abstract: The New York State Department of Transportation maintains a database of over 428 bridges that have collapsed in the United States between 1992 and 2014. These collapsed bridges are associated with inspection data from the NBI (National Bridge Inventory) dated just prior to collapse. Out of 428 bridges in the compiled-collapse database, 237 (55.4%) have collapsed due to a hydraulic-induced failure. A test of independence between the scour critical rating and hydraulic failure indicates that the two variables are associated. Almost half of the bridges (46.4%) that collapsed due to a hydraulic failure are inspected and rated scour stable, which indicates a discrepancy between the scour critical rating and hydraulic collapse. Evidence of accelerated deterioration is found in conjunction with substructure condition ratings. Underwater inspection of in-service bridges shows decreased substructure condition ratings compared to decks and superstructures. The evaluation of the bridge components for hydraulic collapse (median rating of "5") and the in-service population (median rating of "7") yield a lower rating for the substructure. The presence of minor scour at the substructure is a greater hazard than currently described by the inspection system.

Key words: Bridge collapse, hydraulic failure, scour.

1. Introduction

Past investigations analyze trends among collapsed bridges in the United States by using the NYSDOT (New York State Department of Transportation) database [1-4]. Cook et al. [2] assess trends among collapsed bridges for the state of New York; a frequency of bridge collapse is expected to be 1/4700 annually with additional validation from other states. Wardhana and Hadipriono [1] analyze collapse-trends for bridges that failed between 1989 and 2000. From the study, statistics such as the mean lifespan of a collapsed-bridge (52.5 years) is determined. It is also stated, that hydraulic collapse is the number one cause of bridge failure in the United States. Similar investigations with a different database [5] have also determined that hydraulic collapse is the number one cause of bridge failure in the United States, and Montalvo and Cook [6] confirmed it through the analysis of the NYSDOT database, which contains information on the 428 bridges that collapsed between 1992 and 2014.

Corresponding author: Wesley Cook, Ph.D./assistant professor in civil and environmental engineering; research field: bridge risk assessment. E-mail: wes.cook@nmt.edu.

CDC (Center for Disease Control) [7] maintains a fatality database, which presents the characteristics of the mortality rate in the United States, to determine life expectancy, and to compare mortality trends. With the vast-amount of data that the CDC collects, there are data-driven prevention methods updated recurrently. Similar data-driven prevention methods are desired for structural engineering and the infrastructure system.

2. Compiled-collapse Database

Two databases used to assess hydraulic-caused collapse bridges collapse are the United States NBI (National Bridge Inventory) and the NYSDOT bridge collapse database. The NBI 2014 database contains inspection data for more than 610,000 vehicular bridges in the United States [8]. In-service bridge data and statistics obtained from NBI 2014 act as control data. In addition, the NBI contains bridge inspection data over multiple years dating back to 1992. Bridge inspections ratings are on a scale from “0” to “9”, with “0” signifying that the structure is closed or failed, and “9” being the best condition, see Table 1 for a breakdown of the rating system. The NYSDOT bridge collapse database contains United States collapsed bridge data acquired through valid sources. For the purposes of this study, failure or collapse is either partial collapse or total collapse. Partial collapse is “severe deformation to several primary members of a span which allows travel but endangers the lives of those passing on or under the structure.” Total collapse is “severe deformation to several primary members of a span or several spans which leaves the structure unpassable” [9]. The NYSDOT database generally contains the year built of the bridge, the year it collapsed, the cause of collapse of the bridge, feature intersection, material of the bridge, and bridge type as well as comments which can further explain the collapse of the structure.

Using the NBI and NYSDOT bridge collapse databases, a new database compilation associates the NBI data of bridges for the inspection ratings prior to collapse and collapse data. There are 428 vehicular bridges that have collapsed and are associated with pre-collapse NBI data between the period of 1992 and 2014. The compiled-collapse database allows for the analyses of conjectures among hydraulic-caused collapse bridges.

3. Analytical Methods

The majority of data fields assessed in the compiled data are nonparametric or skewed and do not have a normal distribution. The skewed nature of data is self-evident in comparison of the means and medians discussed below (e.g. age, condition ratings, etc.). In addition, the control data (NBI 2014) is also nonparametric, from a normality check, for the same data fields. Nonparametric statistics (i.e. median instead of mean) and statistical methods allow for the assessment of common conjectures among hydraulic-caused collapse bridges.

One statistical test commonly used in this investigation is the Kruskal-Wallis H Test. The Kruskal-Wallis H Test is a rank-based nonparametric that can be used to determine if there are statistically significant differences between two or more groups of an independent variable on a continuous or ordinal dependent variable [10]. The Kruskal-Wallis H Test is a nonparametric test which does not require or assume normality in the data. A Kruskal-Wallis H Test is similar to a one-way ANOVA (analysis of variance), but is considered the nonparametric alternative to it.

Table 1 Bridge components condition ratings [11].

Code description
N NOT APPLICABLE
9 EXCELLENT CONDITION
8 VERY GOOD CONDITION—no problems noted.
7 GOOD CONDITION—some minor problems.
6 SATISFACTORY CONDITION—structural elements show some minor deterioration.
5 FAIR CONDITION—all primary structural elements are sound but may have minor section loss, cracking, spalling or scour.
4 POOR CONDITION—advanced section loss, deterioration, spalling or scour.
3 SERIOUS CONDITION—loss of section, deterioration, spalling or scour have seriously affected primary structural components. Local failures are possible. Fatigue cracks in steel or shear cracks in concrete may be present.
2 CRITICAL CONDITION—advanced deterioration of primary structural elements. Fatigue cracks in steel or shear cracks in concrete may be present or scour may have removed substructure support. Unless closely monitored it may be necessary to close the bridge until corrective action is taken.
1 “IMMINENT” FAILURE CONDITION—major deterioration or section loss present in critical structural components or obvious vertical or horizontal movement affecting structure stability. Bridge is closed to traffic but corrective action may put back in light service.
0 FAILED CONDITION—out of service—beyond corrective action.

Table 2 Scour critical rating [11].

Code description
N Bridge not over waterway.
U Bridge with "unknown" foundation that has not been evaluated for scour. Since risk cannot be determined, flag for monitoring during flood events and, if appropriate, closure.
T Bridge over "tidal" waters that has not been evaluated for scour, but considered low risk. Bridge will be monitored with regular inspection cycle and with appropriate underwater inspections.
9 Bridge foundations (including piles) on dry land well above flood water elevations.
8 Bridge foundations determined to be stable for assessed or calculated scour conditions; calculated scour is above top of footing.
7 Countermeasures have been installed to correct a previously existing problem with scour. Bridge is no longer scour critical.
6 Scour calculation/evaluation has not been made. (Use only to describe case where bridge has not yet been evaluated for scour potential.)
5 Bridge foundations determined to be stable for calculated scour conditions; scour within limits of footing or piles.
4 Bridge foundations determined to be stable for calculated scour conditions; field review indicates action is required to protect exposed foundations from effects of additional erosion and corrosion.
3 Bridge is scour critical; bridge foundations determined to be unstable for calculated scour conditions:
2 Bridge is scour critical; field review indicates that extensive scour has occurred at bridge foundations. Immediate action is required to provide scour countermeasures.
1 Bridge is scour critical; field review indicates that failure of piers/abutments is imminent. Bridge is closed to traffic.
0 Bridge is scour critical. Bridge has failed and is closed to traffic.

Another statistical used in this investigation is the Chi-squared test. The Chi-squared test examines independence of binary variables at 1 degree of freedom.

4. Scour Critical Rating

There are 237 or 55.4% of the total bridges that have collapsed as a result of hydraulic-induced failure. Given that hydraulic-caused collapse is the number one cause of bridge failure, it is critical to gain a deeper understanding of trends for this cause of collapse. Since the majority of hydraulic collapses are a result of a scour-induced failure [12] the scour critical rating (NBI Item 113) is assessed. Scour is erosion of streamed or bank material due to flowing water; often considered as being localized [13]. For the scour critical ratings (Table 2), hydraulic-caused collapse bridges are given an elemental rating with "9-4" (46.4%) signifying that the substructure is rated scour stable, a "6" (34.6%) indicates that the scour evaluations have not been made, and "3-0" (9.3%) indicate that the substructure is rated scour critical. Upon the inspection of Fig. 1, the majority of the bridges, collapsed or in-service, have a stable scour critical rating between "9 and 4". However, the collapsed bridges have lower ratings comparatively. It is evident that there is a discrepancy between the scour critical rating given and the cause of collapse. A test of independence (see Table 3 for the contingency table) performed between hydraulic failure and the scour critical rating yields a p-value of less than "0.001", which indicates that the two variables are associated. See Fig. 1 for the distribution of the scour critical rating ("6", "U", "T", and "N" are omitted for simplicity). The majority of the failed bridges have a scour critical rating that reflects a stable condition of the substructure even though scour causes the majority of bridge failures in the United States.

5. Bridge Component Conditions

To gain a greater understanding of the discrepancy between the scour critical rating and hydraulic collapse, the condition of the substructure is analyzed. A Kruskal Wallis H test evaluates any differences between the conditions of the substructure (NBI Item 60) for hydraulic collapse and the in-service population.

As per Table 4, hydraulic-caused collapse has a median condition rating of a "5", and the in-service population has a median condition rating of a "7" (see Table 1 for the condition rating descriptions). A rating of a "5" represents minor section loss, cracking, spalling

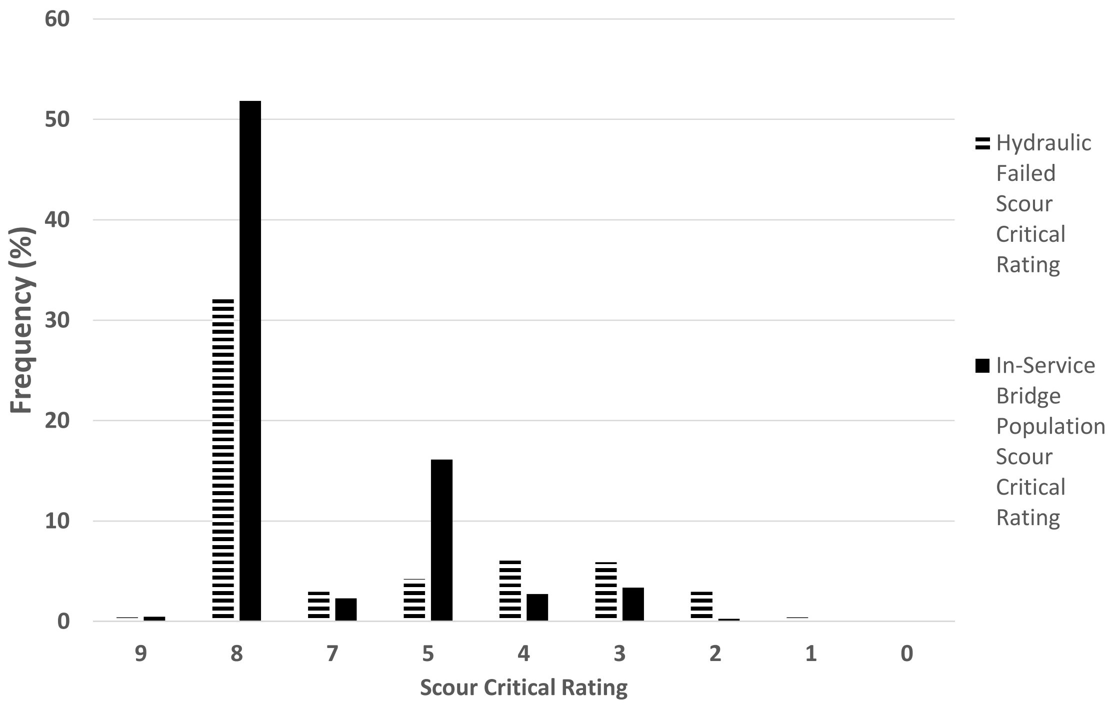

Fig. 1 Histogram of the scour critical rating for hydraulic failure vs. NBI.

Table 3 Scour critical rating contingency table.

	Hydraulic failure	In-service population
Scour critical	22	22,387
Non-scour critical	109	448,572

Table 4 Age vs. median condition ratings.

Cause of collapse	Age (years)	Deck	Superstructure	Substructure
In-service population	41.0	7	7	7
Hydraulic	53.5	6	6	5

Table 5 In-service population median condition ratings.

Cause of collapse	Age (years)	Deck	Superstructure	Substructure
Underwater inspected	46.0	7	7	6
Non-underwater inspected	41.0	7	7	7

Table 6 In-service population scour critical rating.

Cause of collapse	Age (years)	Scour critical rating
Underwater inspected	46.0	8
Non-underwater inspected	41.0	8

or scour. Hydraulic-caused collapse bridges experience an age-induced deterioration for the deck and the superstructure. For the substructure, compared to the deck and superstructure, there is an accelerated deterioration caused by additional variables. Since hydraulic-caused collapse is the number one cause of bridge failure, assuming that a rating of a “5” has been given due to minor section loss, cracking or spalling is not logical. With the accelerated deterioration of the substructure, a rational approach for hydraulic collapse is to assume that the substructure has a median rating of a “5” because of the presence of minor scour. The hazard that minor scour represents for the substructure is therefore, more critical than currently assessed.

6. Possible Solutions

With the discrepancy between the scour critical rating and hydraulic collapse, underwater inspections are evaluated for the in-service population. In the in-service population, only 19,267 of the bridges (3.2%) require underwater inspections in the United States. A Kruskal-Wallis H Test is performed for in-service bridges requiring underwater inspection, and bridges do not require underwater inspections. As per Table 5, there is an even age-induced deterioration for the deck and superstructure of the in-service population. Again, lower median ratings for the substructure are obtained, but as a result of more in-depth inspections for the in-service population. Given the large sample size (19,267) of in-service underwater inspected bridge population, the hazard that minor scour represents to the substructure is being identified. Increasing the number of bridges that require an underwater inspection has the potential to provide a better assessment for the condition rating of the substructure.

A Kruskal-Wallis H test is performed for the scour critical rating of bridges in the in-service population that require underwater inspections, and bridges that do not (see Table 6). The result of the test yields a p-value of less than "0.001" at 1 degree of freedom. Underwater inspected bridges have a median condition of an "8", and non-underwater inspected bridges have the same median condition rating. With the large sample size, the results have a high statistical power. Underwater inspections do not detect any decrease in the scour critical rating. The discrepancy between the scour critical rating and hydraulic collapse does not improve with underwater inspections. As a result, the efficiency of the scour critical rating is in question.

The current rating system holds minor scour on-par with minor section loss, cracking or spalling. Given that hydraulic collapse is the number one cause of bridge failure in the United States, the presence of minor scour presents as a greater concern than minor section loss, cracking, or spalling. The description of scour in the condition rating system (Table 1), is unequal to the description of section loss, spalling, deterioration and cracking. A plausible solution to the discrepancy of scour throughout the condition rating system is to escalate the hazard that scour represents to the substructure (minor scour is equivalent to the hazard of advanced section, deterioration, or spalling).

Another method that can address the discrepancy between the scour critical rating and hydraulic collapse is to revise the current rating system. As per the compiled-collapse database, 112 (47.3%) of the hydraulic collapses are classified as a hydraulic-flood collapse. Even though a flood is considered a random event, the scour critical rating inspection system could account for the hazard the existing scour condition represents in case of a flood event. Under this rationale, minor scour can be comparable with the scour critical rating "4" rather than "8" (Table 2). Modifying the scour critical rating to better account for the probability of failure due to flood can help preserve bridges in the United States.

7. Conclusions

There are 237 (55.4%) bridges that have collapsed due to a hydraulic-induced failure. Hydraulic-caused collapse bridges have a median age of 53.5 years. A test of independence confirms that hydraulic collapse and the scour critical rating are associated. However, there is a discrepancy between the scour critical rating given and hydraulic collapse. The majority of the bridges are rated scour stable, yet hydraulic collapse is the number one cause of bridge failure in the United States. The evaluation of the condition of bridge components yields a lower rating for the substructure in hydraulic-caused collapse bridges; the minor scour present at the substructure represents a greater hazard than it is currently perceived as. Requiring more underwater inspection has the potential to provide a better assessment for the condition rating of the substructure. The hazard that minor scour represents to the substructure should be escalated. Adjusting the scour critical rating to better account for the probability of a flood event is a solution to the discrepancy between the scour critical rating and hydraulic failure.

References

[1] Wardhana, K., and Hadipriono, F. C. 2003. "Analysis of Recent Bridge Failures in the United States." *Journal of Performance of Constructed Facilities* 17 (3): 144-50. doi:10.1061/(asce)0887-3828(2003)17:3(144).

[2] Cook, W., Barr, P., and Halling, W. 2015. "Bridge Failure Rate." *ASCE Journal of Performance of Constructed Facilities* 29 (3): 1-8.

[3] Cook, W., and P. Barr. 2017. "Trends among Collapsed Bridges in New York State." *ASCE Journal of Performance of Constructed Facilities* 31 (4): doi:10.1061/(acse)1943-5509.0000996.

[4] Flint, M. M., Fringer, O., Billington, S. L., Freyberg, D. and Diffenbaugh, N. S. 2017. "Historical Analysis of Hydraulic Bridge Collapses in the Continental United States." *Journal of Infrastructure Systems* 23 (3): p.04017005.

[5] Chang, F. E. M. 1973. "A Statistical Summary of the Cause and Cost of Bridge Failures." Publication No. FHWA-RD-75-87. US DOT, Washington, DC.

[6] Montalvo, C., and Cook, W. 2016. "Trends among Collapsed Bridges in the United States." Transportation Research Board.

[7] CDC. 2016. "NVSS—Mortality Data." Retrieved from https://www.cdc.gov/nchs/nvss/deaths.htm. (February 16, 2016).

[8] Federal Highway Administration. 2014. "Federal Highway Administration NBI ASCII Files." Retrieved from https://www.fhwa.dot.gov/bridge/nbi/ascii.cfm. (March 4, 2016).

[9] Auyeung, W. 2014. "NYSDOT National Bridge Failure Database." Structures Division of the New York State DOT, New York.

[10] Laerd Statistics. 2013. "Kruskal-Wallis H Test Using SPSS Statistics." Retrieved from https://statistics.laerd.com/spss-tutorials/kruskal-wallis-h-test-using-spss-statistics.php. (May 4, 2016).

[11] Federal Highway Administration. 1995. "Recording and Coding for the Structure Inventory and Appraisal of the Nation's Bridge." Retrieved from https://www.fhwa.dot.gov/bridge/mtguide.pdf.

[12] AASHTO. 2016. *American Association of State Highway and Transportation Officials (LRFD) Bridge Design Specifications* (interim 7th ed.) Washington, DC: AASHTO Publications.

[13] Federal Highway Administration. 2012. "Evaluating Scour at Bridges." Retrieved from https://www.fhwa.dot.gov/engineering/hydraulics/pubs/hif12003.pdf. (March 16, 2016).