Validating Common Collapse Conjectures in U.S. Bridges

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ABSTRACT

Bridge collapse is a rare event. However, given the 610,000 plus bridges in the United States and existing level of structural reliability, a certain number of bridge collapses are expected. The New York State Department of Transportation maintains a bridge collapse database, which has been combined with the National Bridge Inventory (NBI) into a new database of the NBI ratings and appraisal for the inspection before collapse occurred. The new database contains 428 bridges that have collapsed and are in record between 1992 and 2014. The compiled-collapse database allows for the evaluation of common conjectures among collapsed bridges. Common conjectures that are studied are structural deficiency and bridge collapse, scour critical rating and hydraulic collapse, age and bridge collapse, and design-provision improvements. Structural deficiency and collapse are associated. The scour critical rating and the condition rating of the substructure indicates that the minor scour is a precursor to accelerated deterioration. Minor scour appears to be a greater hazard to the substructure than it is currently assessed. For collision-caused collapse, newer bridges are built with an improved bridge characteristic that have reduced the chances of a random-event strike. For overload-caused collapse, newer bridges are designed with increased loading requirements that have reduced the chances of overload.

INTRODUCTION

Past investigations analyzed trends among collapsed bridges in the United States by associating the New York State Department of Transportation (NYSDOT) database (1 ; 2; 3; 4;5). 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) analyzed collapse-trends for bridges that failed between 1989 and 2000. From their 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 (6) have also determined that hydraulic failure is the number one cause of bridge failure in the United States, and Montalvo and Cook (4) confirmed it through the analysis of the NYSDOT database.

The Center for Disease Control (CDC) maintains a fatality database, which presents the characteristics of those dying in the United States, to determine life expectancy, and to compare mortality trends (7). With the vast-amount of data that the CDC collects, this agency is better equipped with data-driven prevention. These qualities are all desirable in the field of structural engineering and in particular bridges in the transportation systems. Unfortunately, the fatality or collapse of bridges has yet to follow suit on the data collection on such a wide scale. This is in part due to the stigmatism and public perception of reporting bridge collapses. As a result, bridge collapse research and data collection are generally limited to significant catastrophic collapses or events. The majority of the bridge collapse-events are not considered major events. In this study, with a large sample size of collapsed bridges, analysis of bridge-collapse conjectures is possible.

Common collapsed-bridge conjectures are assessed in an effort to advance the knowledge and predictors of bridge collapse based on the condition and state of bridges from inspection information prior to collapse. The information presented can assist bridge owners and managers in understanding the likelihood of bridge collapse based on mathematical evidence and observed trends.

The investigation presents the databases and statistical methods followed by the analysis preformed. The assessment to-date evaluates structural deficiency, scour and scour critical ratings, limited age analysis, and evidence of increased bridge longevity with improved design specifications.

DATABASES

Two databases used to assess common conjectures among collapsed bridges are the National Bridge Inventory (NBI) and the NYSDOT Bridge collapse database. The 2014 NBI database contains inspection data for the 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 inspection 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 bridges 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, 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 (excludes pedestrian, railroad, etc.) that have collapsed and are associated with pre-collapse NBI data between the period of 1992 and 2014. With the data, several assessments on common conjectures are investigated through mathematical processes. The large sample size in this study provides control on the variability of the data.

TABLE 1 NBI Condition Ratings (10)

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.

ANALYTICAL METHODS

The majority of data fields assessed in the compiled data are nonparametric or skewed and are not normally distributed. The control data (8) is also nonparametric, from a normality check, for the same data fields. Nonparametric statistics (i.e. median instead of mean) and statistical methods enable assessment of common conjectures among collapsed bridges.

One statistical test 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 (11). 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 Analysis of Variance (ANOVA), but considered the nonparametric alternative to it.

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

STRUCTURAL DEFICIENCY

Structurally deficient (SD) are bridges generally in poor condition and have a rating of 4 or less for the deck, superstructure, substructure or a 2 for waterway adequacy (12). Out of the 428 bridges that collapsed, 197 (46.0 %) are structurally deficient (see Table 2). For all the bridges currently in-service in the United States, 53,354 (9.0 %) out of more than 610, 000 are structurally deficient. The significant amount of bridges that are structurally deficient and failed suggest that there is a possible association between structural deficiency and bridge failure. A chi-squared test of independence (see Table 2) assesses the association between structural deficiency and collapse and indicates that the two variables are associated. The result concludes that structural deficiency or poor condition in inspection element condition rating in the United States is a possible indicator of bridge failure. An analysis of structural deficiency per collapse-cause yields different conjectures. As per Table 3, overload–caused collapse bridges are 53.3% structurally deficient in the superstructure. Hydraulic-caused collapse bridges are 32.5% structurally deficient in the substructure. Deterioration-caused collapse has similar quantities of structural deficiency in each bridge component, and they all have equal median condition ratings. Collision-caused collapse is lower all around in structural deficiency but, remains higher than the in-service population. From the comparison the component leading structural deficiency also appears to relate to the cause of collapse, more discussion on this topic is located in the Age and Bridge Collapse section.

TABLE 2 Contingency Table for Structural Deficiency (SD) vs Collapse

	Failed Bridges	In-service Population
SD Bridges	197 (46.0%)	53,354 (8.7%)
NON-SD Bridges	231 (54.0%)	557, 073 (91.3%)
$\sum$	428	610,427

TABLE 3 Structural Deficiencies (SD) per Type of Collapse

Type of Collapse	SD Deck	SD Superstructure	SD Substructure	Median Age
Overload	14 (23.3%)	32 (53.3%)	25 (41.7%)	68
Hydraulic	38 (16.0%)	48 (20.2%)	77 (32.5%)	54
Deterioration	12 (33.3%)	14 (38.9%)	14 (38.9%)	48
Collision	6 (7.3%)	14 (17.1%)	13 (15.9%)	43
In-service Population	4,968 (0.8%)	22,264 (3.6%)	29,189 (4.8%)	41

SCOUR CRITICAL RATING

There are 237 (55.4%) bridges that have collapsed due to a 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 (13) the scour critical rating (NBI Item 113) is assessed. Scour is erosion of streambed or bank material due to flowing water; often considered as being localized (13). A chi-squared test of independence (see Table 4 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 Figure 1 for the distribution of the scour critical ratings ('6', 'U', 'T', and 'N' are omitted for simplicity) and see Table 5 for a breakdown of the ratings. For the scour critical rating, an elemental rating given with '9' through '4' excluding a '6', signifies that the substructure is rated scour stable, a '6' indicates that the scour evaluations have not been made, and '3' through '0' indicate that the substructure is rated scour critical. Upon the inspection of Figure 1, the majority of the bridges in the in-service population and hydraulic-caused collapse bridge are given a scour critical rating between '8 and 4'. A rating between an '8' and a '4' indicates that bridges have been evaluated as scour stable. Bridges are rated scour stable, even though scour causes the majority of bridge failures in the United States. It is evident that there is a discrepancy between the scour critical rating given and the cause of collapse.

As per Table 6, 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 or scour. Hydraulic-caused collapse bridges experience an age-induced deterioration for the deck and the superstructure. For the substructure, there is an accelerated deterioration compared to the deck and the superstructure. 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 rational. With the accelerated deterioration of the substructure, a better 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 more critical than it is currently assessed to be.

With the discrepancy between the scour critical rating and hydraulic collapse, underwater inspections are evaluated for hydraulic-caused collapse bridges. Only 16 (6.8%) of the hydraulic-caused collapse bridges require an underwater inspection; while the in-service population only requires underwater inspections for 19,267 (3.2%) of the bridges in the United States. In addition, 520,000 plus (85.2%) bridges in the United States are over a waterway. 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 and scour critical rating.

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 should account for the hazard that minor scour represents in case a flood occurs. Modifying the scour critical rating to account for the probability of failure due to flood events can help preserve bridges in the United States.

TABLE 4 Scour Critical Rating Contingency Table

	Hydraulic Failure	In-service Population
Scour Critical	22	22,387
Non-Scour Critical	109	448,572
∑	131	470,959

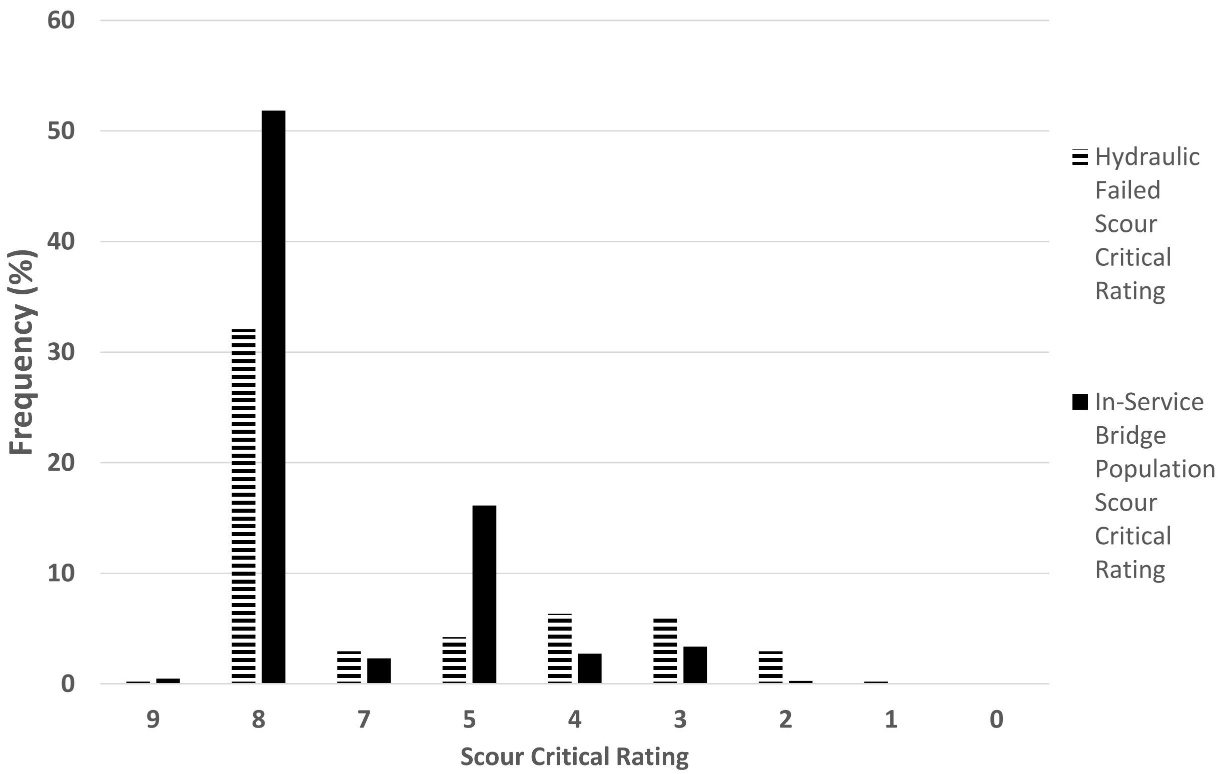

FIGURE 1 Histogram of the Scour Critical Rating for Hydraulic Failure

TABLE 5 NBI Scour Critical Bridge Ratings (*9*)

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.

AGE AND BRIDGE COLLAPSE

An analysis of age and collapse indicates that the mean age of bridges in the collapse-database is 55 years with a standard deviation of 27 years, and median of 51 years. Age is assessed per type of collapse. As per Table 6, there is an age-induced deterioration for all collapse-types (4). However, the age deterioration is not sufficiently rapid to be a serious hazard to the condition of the structure. In general, for each cause of collapse there is an alternate-cause induced accelerated deterioration. For overload-caused collapse, the superstructure has a lower condition rating than the deck and the superstructure. The accelerated deterioration of the superstructure in overload-caused collapse bridges requires further investigation. Hydraulic-caused collapse bridges have a lower condition rating for the substructure. The lower condition rating is attributed to the accelerated deterioration caused by the presence of minor scour. Deterioration-caused collapse differs from the other causes of collapse as it experiences an even deterioration between components; the median age is lower than hydraulic-caused collapse and overload-caused collapse bridges. Collision-caused collapse bridges fail due to a random-event induced strike. For all causes of collapse, there are apparent variables besides age that deteriorates bridges at a faster rate than age does.

TABLE 6 Age vs Median Condition Ratings

Cause of Collapse	Age (Years)	Deck	Superstructure	Substructure
Collision	43.0	6	6	6
Deterioration	47.5	5	5	5
Hydraulic	53.5	6	6	5
Overload	68.0	6	4	5
In-service Population	41.0	7	7	7

EVIDENCE OF IMPROVED DESIGN SPECIFICATIONS

Improvements to the bridge design specifications are continuous and evidence of increased bridge longevity; however, post implementation can be difficult to measure. Through this retrospective analysis, two improvements to the design specifications that show association with bridge collapse are decreased minimum vertical clearance and decreased operating rating. These two areas are compared with collision-caused and overload-caused collapse, respectively.

Minimum Vertical Under-Clearance

As per Table 7, collision-caused collapse has the highest frequency usage (ADT and ADTT) from all of the causes of collapse indicating bridges with higher usage are more likely to experience high impact loads.

The geometric characteristic of the collision-caused collapse bridges is analyzed to understand the impact that the improvement to the design provisions have on collision-caused collapse. The bridge characteristic analyzed is the minimum vertical under-clearance. A Kruskal-Wallis H test compares the median minimum vertical under-clearance bridge characteristic for the compiled database and the in-service population. The Kruskal-Wallis H test's result for the minimum vertical clearance (NBI Item 54) yields a p-value of 0.016 at 1 degree of freedom. See Table 8 for the median minimum vertical clearance for collision-caused collapse and the in-service population. The test indicates that a lower vertical under-clearance increases the chances of a random over-height induced collision. The test also indicates that older bridges tend to have lower minimum vertical clearances. An additional correlation test known as the Spearmen's rank coefficient evaluated the NBI 2014 data to verify older bridges have lower minimum vertical clearances. The results yield a correlation of -0.28, the negative indicates an inverse relationship and the closer the coefficient is to negative one the stronger the inverse correlation. With the result being $-0.28$the correlation appears poor; however, the statistical power due to a sample size of over 100,000 bridges over roadways the value is statistically significant. The result does verify that as age increases minimum vertical clearance decreases. The change in minimum vertical clearance (14) changed from 4.3 m (14 ft) to 4.9 m (16 ft) in 1960. Although collision-caused collapse can be thought of as random events, a statistically significant difference is found in the bridge height and age. The results indicate that the improvements done to the design provisions, such as the increase in minimum vertical clearance, have decreased the chances of collapse in newer bridges.

TABLE 7 ADT and ADTT per Cause of Collapse

Cause of Collapse	Median ADT (NBI Item 29)	Median ADTT (NBI Item 109)
Collision	3500	9
Deterioration	1104	8
Hydraulic	150	6
Overload	123	6
In-service Population	840	6

TABLE 8 Bridge Geometric Characteristic

Category	Median Minimum Vertical Clearance (NBI Item 54)
Collision-caused Collapse	4.9 m (16.1 ft)
In-service Population	5.1 m (16.9 ft)

Design Load and Operating Rating

Inspection of age and the type of collapse (Table 6) show overload-caused collapse bridges tend to be older. An analysis of the Design Load (NBI Item 31) and age is of interest; however, the median design load for overload-caused collapse is ‘0’ meaning “other or unknown.” Where the median age is high, and the design load interpreted as unknown, the lack of information on design loading is compensated by using the Operating Rating (NBI Item 64). Two Kruskal-Wallis H tests compare age and the type of collapse and the Operating Rating, an evaluated condition, and the type of collapse. The result of each Kruskal-Wallis H test yields a p-value of less than 0.001 at 1 degree of freedom. There is a statistical significant difference between the median ages and their respective cause of collapse, and the median operating rating and their respective cause of collapse (shown in Figure 2). The results indicate that overload-caused collapse has the highest median age, even above deterioration-caused collapse, and the lowest operating rating. While the in-service bridge population has the lowest median age and the highest operating rating; newer bridges have a higher operating rating than older bridges do, which can be attributed to the increase of the minimum design load and a lower median age (less deterioration). Lower operating ratings can be attributed to lower minimum design loads, a higher median age and greater deterioration.

The Design Load and age is also evaluated through correlation Spearmen’s rank coefficient with the NBI 2014 data. The results yield a correlation of -0.34, the negative indicate an inverse relationship. The correlation appears poor; however, the statistical power due to a sample size of over 400,000 bridges with non-zero design load values; the correlation is statistically significant. The result does verify that as age increases design loading decreases or older bridges are designed with lower vehicle loads.

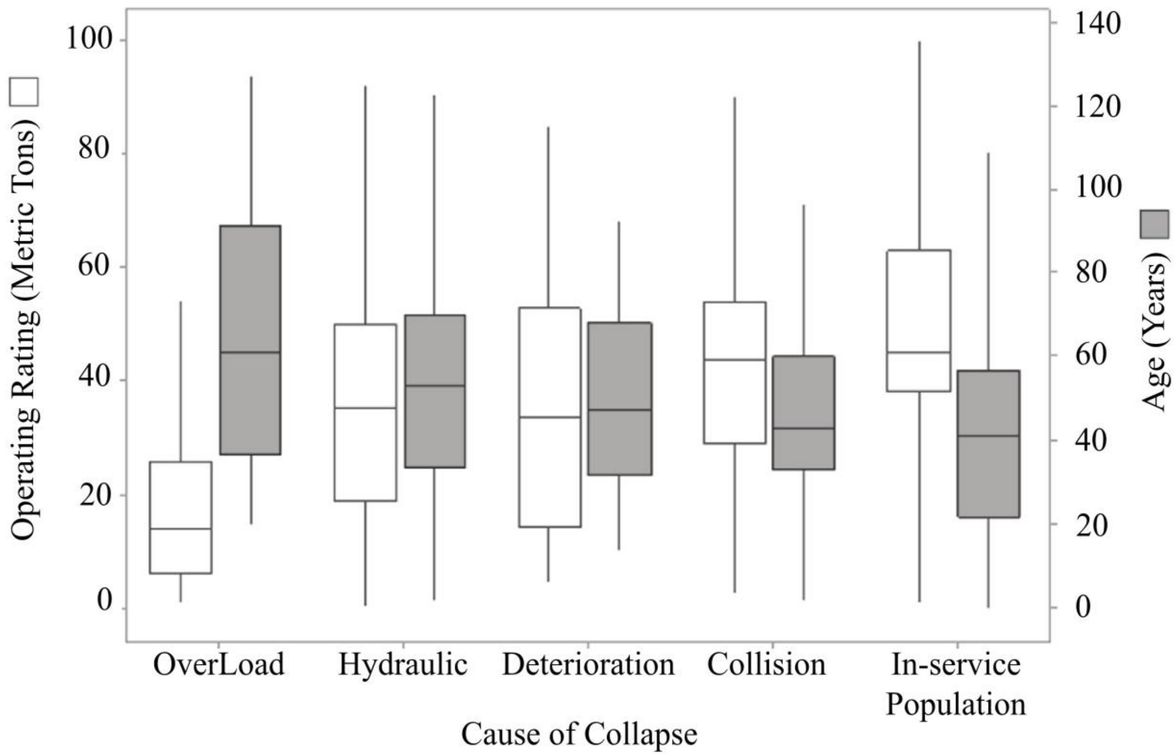

Figure 2 Boxplot of Median Age, and Median Operating Rating per Cause of Collapse

CONCLUSION

There are 428 bridges that have collapsed and are in-record between 1992 and 2014. The mean age of collapse bridges is 55 years with a standard deviation of 27 years, and a median of 51 years. The assessment of common conjectures yields that structural deficiency and collapse are associated. Another test of association indicates that the scour critical rating and hydraulic collapse are associated. The majority of hydraulic-caused collapse bridges are rated as scour stable at the time of inspection. It is evident that there is discrepancy between the scour critical rating and hydraulic collapse. There is potential for accelerated deterioration due to the presence of minor scour at the substructure that the current inspection system is not accounting for. Possible solutions for the discrepancy in the current inspection system for the scour critical rating are to require more underwater inspections, which have the potential to provide a better assessment for the condition rating of the substructure and scour critical rating. Adjusting the scour critical rating to account for the probability of a flood event is a probable solution to the discrepancy between the scour critical rating and hydraulic failure. For collision-caused, newer bridges are being built with higher vertical under-clearance that have reduced the chances of a random-event strike. In addition, new bridges have higher design loadings.

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