Ice-Crushing Strength

Ice-crushing strength was measured at the six sites shown in figure 1. Ice-crushing-strength measurements didn't begin until early February 1999 because of the mild winter of 1999, and continued until April 2001. As previously discussed in the ice-thickness section of this report, the 1999-2001 data-collection winters included both one of the warmest and one of the coldest winters on record. The 2000 winter was the 8th warmest winter, and the 2001 winter was the 11th coldest winter in a period of 111 years of record. This winter temperature variation allowed a wide range of measured ice-crushing strengths, as ice strength is very dependent on the temperature of the ice during testing.

Ice-crushing strength was measured both in the winter and in the spring as close to ice breakup as feasible. The maximum ice-crushing strengths were measured in mid- to late winter when the ice was the coldest. Ice-crushing strengths measured at and near breakup during the spring thaw were much less. The magnitude of ice-crushing strength when the ice breaks up and sometimes flows down a river or moves by wind across a lake or reservoir is important because this ice-crushing strength may be more applicable to use in bridge-design equations.

Ice breakup transforms an ice-covered river or lake or reservoir into an open river or lake or reservoir. The breakup may involve two possible extremes, thermal meltout and mechanical breakup. Thermal melt out occurs when the ice mass deteriorates through warming and absorption of solar radiation and melts in place with no increase in flow and little or no ice movement. Mechanical breakup occurs when the ice mass breaks up due to an increase in flow entering the river. This breakup can be rapid because no deterioration of the ice mass is necessary. The introduced water creates stresses in the ice mass that cause cracks to form, leading to the breakup of the ice into chunks. Ice moves much like sediment, which moves through high energy reaches and deposits in lower energy locations. Bridges generally do not slow or stop ice flow unless pier spacing is narrow in relation to ice flow size or unless the bridge holds the winter sheet ice in place. Ice jams occur at locations where the ice is obstructed as the ice chunks flow downstream or where the energy slope of the river decreases. These ice jams impede the flow causing upstream flooding and subsequent downstream flooding when the jams suddenly release.

Many rivers in South Dakota undergo a combination of thermal meltout and mechanical breakup. The ice mass deteriorates during a warm-up period, while at the same time the warm up causes increased flow into the river. Lakes or reservoirs also can undergo a combination of thermal meltout and mechanical breakup as the lake or reservoir ice typically melts in place, but before complete melting, ice chunks can be moved by high winds against bridge structures. At the two James River and two Missouri River reservoir sites, observed breakup was closer to thermal meltout than mechanical breakup. A combination of the two breakup extremes occurred at the White River and Grand River sites.

Ice-crushing strengths used in bridge design in South Dakota were evaluated in a limited way by comparing ice-crushing strengths used in bridge design to ice-crushing strengths measured at the data-collection sites. A more extensive study, involving direct measurement of ice forces at bridge structures, would be useful. This would allow a measurement of the magnitude of the force applied by ice on bridge structures at both the time of maximum ice-crushing strength in mid- to late winter and of the ice force applied during spring breakup. Literature applicable to the ice-crushing strength was researched to gain an understanding of how ice-crushing strength develops. This was done in conjunction with the literature search on ice-thickness estimation.

Data Summary

Ice-crushing strength measured at the six sites from February 1999 to April 2001 ranged from 58 lb/in^2 to greater than 1,046 lb/in^2 (table 4). The samples collected for measurements of ice-crushing strength varied from very-clear columnar ice collected near the bottom of the ice mass (fig. 15A) to milky-colored snow ice (fig. 15B) to sediment-layered ice (fig. 15C). Columnar ice is ice that consists of column-shaped grains (U.S. Army Corps of Engineers, 1996). Snow ice is ice that forms when snow slush freezes on an ice cover. The presence of air bubbles makes it appear white (U.S. Army Corps of Engineers, 1996). Boxplots summarizing the collected ice-crushing-strength data are shown in figure 16. Crushing-strength data used that were greater than specific values were set equal to those values for purpose of the boxplots. The largest ice-crushing strengths were measured from samples collected from

A Clear ice sample taken from the bottom section of the ice mass at site 5 (Oahe Reservoir near Mobridge) on January 11, 2001

B Milky-colored ice sample after removed from ice-crushing machine at site 1 (James River at Huron) on April 2, 2001

C Ice sample with alternating clear and sediment-mixed layers at site 3 (White River near Oacoma) on January 10, 2001

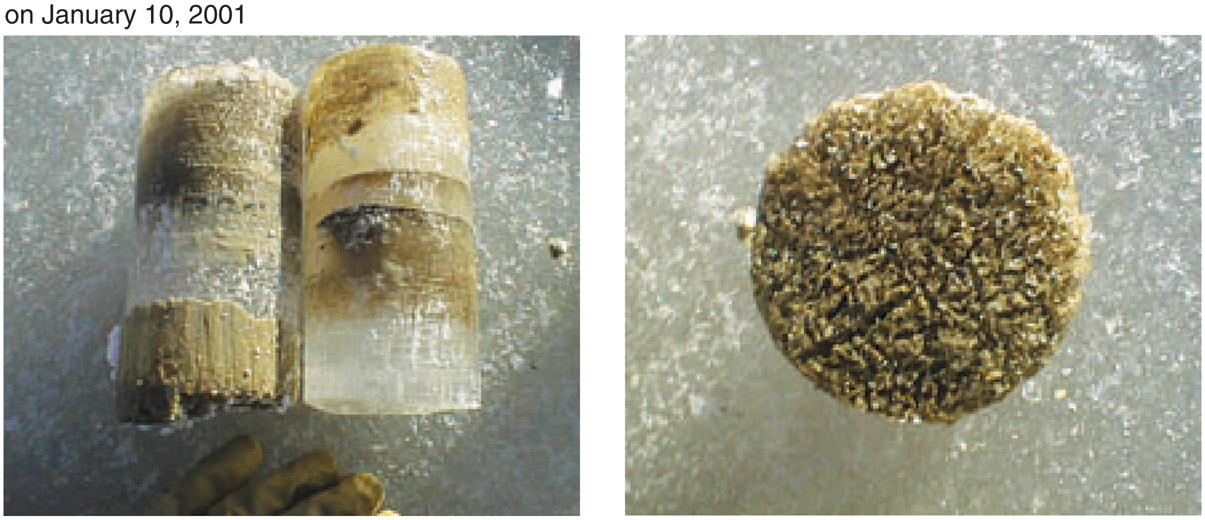


Figure 15. Photographs of samples collected for measuring ice-crushing strength at ice-data collection sites in South Dakota.

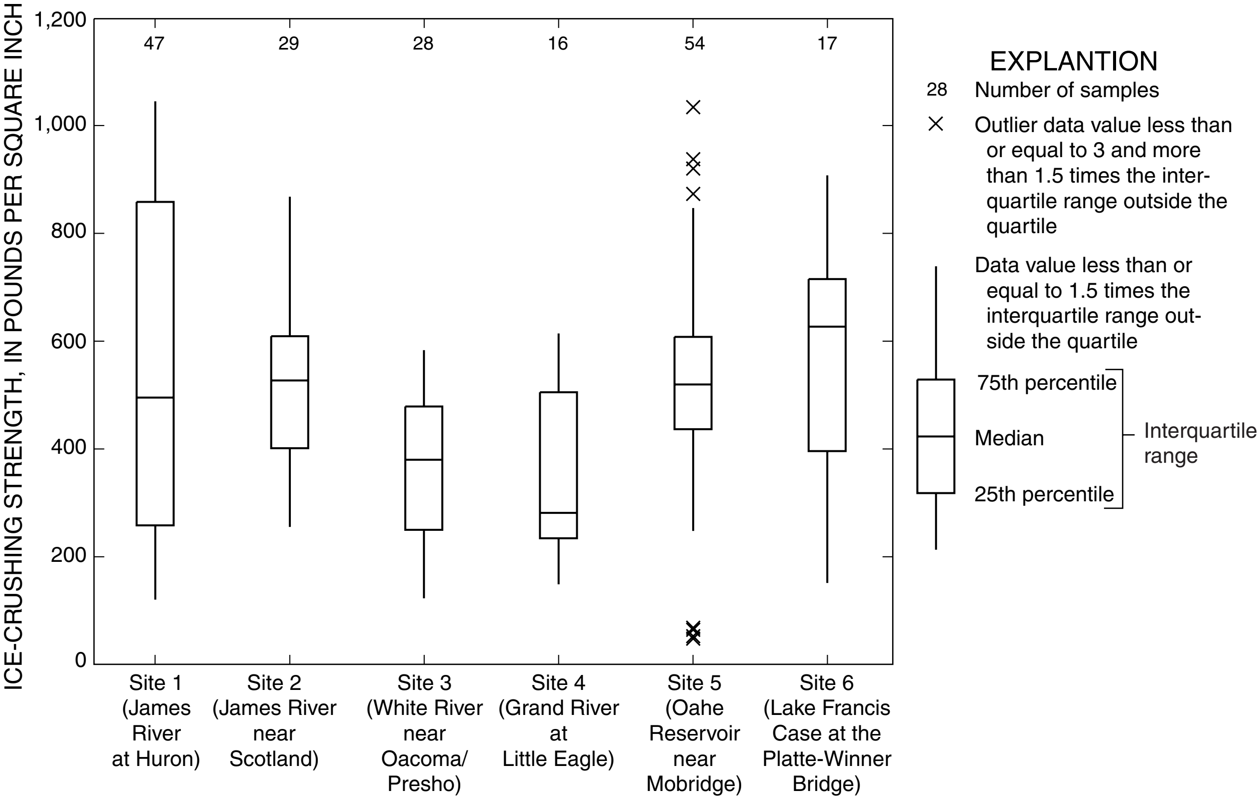


Figure 16. Boxplots of measured ice-crushing strength at ice-data collection sites for the study, 1999-2001.

site 5 (Oahe Reservoir near Mobridge) and site 1 (James River at Huron). The smallest ice-crushing-strength measurement was 58 lb/in^2 from a sample collected from site 5. The initial plan for data collection was to collect data at all six sites each year of the study in early January, February, and March. This initial plan was modified depending on ice conditions encountered at each site. The colder climate in northern South Dakota provided more opportunities to measure ice; thus, more data were collected at sites 1 (James River at Huron) and 5 (Oahe Reservoir near Mobridge) than the other sites.

Ice-crushing strength was measured once at site 1 (James River at Huron) in 1999, twice in 2000, and four times in 2001. Ice-crushing strength measured at site 1 was highly variable and ranged from 228 to 522 lb/in^2 in 1999, 180 lb/in^2 to greater than 1,042 lb/in^2 in 2000, and 207 lb/in^2 to greater than 1,046 lb/in^2 in 2001. The maximum ice-crushing strength of greater than 1,046 lb/in^2 was measured in the winter of 2001, which was the 11th coldest winter of record (table 2). Surprisingly, a similar large maximum ice-crushing strength of greater than 1,042 lb/in^2 was measured in the 2000 winter, which was a much milder winter than the 2001 winter. The largest ice-crushing strengths were measured in the middle of the winter in January and early February. In January 2000, the average ice-crushing strength was about 950 lb/in^2, and in January and February 2001, the average ice-crushing strength was about 800 and 850 lb/in^2, respectively. As expected, the smallest ice-crushing strengths were measured during the spring near breakup. In 2001, the average ice-crushing strength measured near breakup was about 200 lb/in^2.

For all samples collected at site 1, the ice was crushed at rates between 0.0006 and 0.0013 in/sec, and sample sizes (diameter by length) varied from 3.5 by 6 inches to 3.5 by 8.25 inches and from 4 by 4.5 inches to 4 by 8.5 inches. The ice-crushing strengths measured using samples that are not close to the ideal length-to-diameter ratio of 2 to 1 should be used with caution. For quality-assurance purposes, ice-crushing strength usually was measured at this same location using other samples that were at or near this ratio.

During the study, breakup at site 1 was more of a thermal meltout than a mechanical breakup. A series of photographs in figure 17 illustrates spring breakup at this site in April 2001. Due to warmer temperatures and input of "warm" upstream tributary water, the measured maximum ice thickness decreased from about 2 ft on April 2 to less than 1 ft by April 4. A 2-inch rain on April 6 further deteriorated the ice mass. Based on shore observation on April 6 (ice was unsafe for a direct measurement), the thickness of the ice mass at the site decreased to only a few inches. By April 9, the ice mass was completely gone.

Ice-crushing strength was measured at site 2 (James River near Scotland) once in 1999 and 2000 and three times in 2001. Ice-crushing strength measured at site 2 ranged from 417 to 603 lb/in^2 in 1999, 565 to 694 lb/in^2 in 2000, and 255 to 869 lb/in^2 in 2001. The maximum ice-crushing strength of 869 lb/in^2 was measured during the winter of 2001 (the 11th coldest winter of record). The largest ice-crushing strengths were measured in the middle of the winter in January and early February. The largest ice-crushing strengths at site 2 didn't vary nearly as much as ice-crushing strengths measured at site 1 (James River at Huron). For January and February measurements, average ice-crushing strength ranged from about 475 to 625 lb/in^2 at site 2, as compared to the range of about 300 to 950 lb/in^2 at site 1. The smallest ice-crushing strengths at site 2 were measured in the spring near breakup. In 2001, average ice-crushing strength measured near breakup was about 275 lb/in^2. For all samples, the ice was crushed at rates between 0.0005 and 0.0011 in/sec, and sample sizes (diameter by length) varied from 3.5 by 6.25 inches to 3.5 by 8 inches and from 4 by 5 inches to 4 by 8 inches.

Like site 1, breakup at site 2 was more of a thermal meltout than a mechanical breakup. During the spring breakup in March 2001, the ice mass first deteriorated at the shoreline (fig. 18A). By March 20, there was about 10 ft of open water on both sides of the James River at the site. A ladder was used to get on the ice to collect samples over the open water as shown in figure 18B. The ice-mass top was very slushy with some open water in areas on top of the ice. The maximum ice thickness ranged from about 1 to 1.5 ft for the western one-half of the James River at this site. Ice on the eastern one-half was less than 1 ft thick and deemed unsafe for data collection.

Ice-crushing strength was measured at site 3 (White River near Oacoma/Presho) once in 2000 at the Presho and Oacoma locations and twice in 2001 at the Oacoma location. Ice-crushing strength measured during the winter months at site 3 ranged from 180 to 579 lb/in^2 in 2000 and from 214 to 585 lb/in^2 in 2001. On February 13, 2001, the White River at the site had limited water and corresponding little ice (0.1 ft). Consequently, no ice-crushing-strength data were collected. The maximum ice-crushing strength of 585 lb/in^2 was measured in the 2001 winter, the 11th coldest winter of record; however, a similar large ice-crushing strength of 579 lb/in^2 was measured in the 2000 winter, which was a much milder winter than the 2001 winter. The largest ice-crushing strengths were measured in the middle of the winter in January and early February. The average ice-crushing strengths measured during the middle of winter (450 to 475 lb/in^2) varied similarly to the ice-crushing strengths measured at site 2 (James River near Scotland). The smallest ice-crushing strengths were measured during the spring near breakup. In 2000 and 2001, the average ice-crushing strength was measured at 225 lb/in^2 near breakup. For all samples, the ice was crushed at rates between 0.0008 and 0.0010 in/sec, and sample sizes (diameter by length) varied from 3.5 by 5 inches to 3.5 by 8 inches and from 4 by 4.5 inches to 4 by 6 inches.

Breakup at site 3 usually was more of a mechanical breakup than a thermal meltout. Breakup in 2001 occurred near March 13 when the ice broke into chunks and flowed down the White River. The ice chunks intermittently were jammed at site 3 as shown in figures 19A and 19B. The samples needed for ice-crushing-strength measurement were collected by walking on this ice jam (when it wasn't moving) and manually collecting ice chunks that were large enough for use in the ice-coring machine (figs. 19C and 19D). The samples collected on March 13 were obtained very near the start of the breakup, before the samples were changed by spring temperature variations.

Figure 17. Sequence of photographs showing breakup at ice-data collection site 1 (James River at Huron), April 2001.

A Open water looking downstream at site 2 (James River near Scotland) on March 20, 2001

B Open water was crossed to collect samples on upstream side of bridge at site 2 (James River near Scotland) on March 20, 2001

Photograph by Franklin D. Amundson

Figure 18. Photographs showing the breakup at ice-data collection site 2 (James River near Scotland), site 4 (Grand River at Little Eagle), and site 5 (Oahe Reservoir near Mobridge).

C Remnants of ice jam near shore at site 4 (Grand River at Little Eagle) on February 12, 1999

D Open water near shore at site 5 (Oahe Reservoir near Mobridge) on March 21, 2001. Ice chunks were collected by wading out to the ice mass. Samples were collected using the core drill on collected ice chunks.

Photograph by Franklin D. Amundson

Figure 18. Photographs showing the breakup at ice-data collection site 2 (James River near Scotland), site 4 (Grand River at Little Eagle), and site 5 (Oahe Reservoir near Mobridge).—Continued

A Ice jam (no movement of ice) looking upstream of bridge

B Ice breakup dowstream of bridge with flowing ice

Figure 19. Photographs showing the mechanical breakup on March 13, 2001, at ice-data collection site 3 (White River near Oacoma).

C Ice chunks collected from the ice jam

D Ice chunks with samples already drilled out

Figure 19. Photographs showing the mechanical breakup on March 13, 2001, at ice-data collection site 3 (White River near Oacoma).—Continued

Ice-crushing strength was measured at site 4 (Grand River at Little Eagle) once in 1999, twice in 2000, and once in 2001. Ice-crushing strength measured at site 4 ranged from 229 to 577 lb/in^2 in 1999, 148 to 615 lb/in^2 in 2000, and 236 to 411 lb/in^2 in 2001. Little water in the Grand River was available for freezing during January and February 2001, and thus little ice was formed and no samples collected for measurement of ice-crushing strength. The maximum ice-crushing strength of 615 lb/in^2 was measured in the winter of 2000. The smallest ice-crushing strengths were measured in the spring near breakup. In 1999, 2000, and 2001, average ice-crushing strength measured near breakup was about 400, 300, and 300 lb/in^2, respectively. The samples measured for ice-crushing strength in both 1999 and 2001 were taken from ice chunks near the shore. The 400-lb/in^2 ice-crushing strength measured in 1999 probably was an overestimation because the ice chunks that were sampled from probably had been refrozen after deposition. For all samples, the ice was crushed at rates between 0.0007and 0.0011 in/sec, and sample sizes (diameter by length) varied from 3.5 by 7 inches to 3.5 by 8 inches and from 4 by 5 inches to 4 by 7.5 inches.

Breakup at site 4 usually was a combination of a thermal meltout and mechanical breakup. Breakup in 1999 occurred in February when ice broke up into chunks and flowed down the river. On February 12, 1999, ice samples were collected from the remnants of this ice breakup (fig. 18C) by using the core machine to drill samples from ice chunks near the shoreline. Some of the ice chunks were almost 2 ft thick.

Ice-crushing strength was measured at site 5 (Oahe Reservoir near Mobridge) once in 1999, twice in 2000, and three times in 2001. Ice-crushing strength measured at site 5 was highly variable and ranged from 387 to 685 lb/in^2 in 1999, 247 to 883 lb/in^2 in 2000, and 58 to greater than 1,046 lb/in^2 in 2001. The maximum ice-crushing strength of greater than 1,046 lb/in^2 was measured in the winter of 2001 (11th coldest winter of record). As at the other sites, the largest ice-crushing strengths were measured in the middle of the winter in January and early February. Average ice-crushing-strength measurements in January and February ranged from about 500 to 650 lb/in^2 as compared to an average ice-crushing strength of 75 lb/in^2 near the 2001 spring breakup. For all samples, the ice was crushed at rates between 0.0008 and 0.0010 in/sec, and sample sizes (diameter by length) varied from 3.5 by 5.5 inches to 3.5 by 8.25 inches and from 4 by 5 inches to 4 by 8 inches. Because of the large area to obtain ice samples (greater that 1 mile) and northern location in South Dakota, more samples were collected at this site than any other site. This large number of samples was used to assess the quality of the ice-crushing-strength data and to measure any variation between top and bottom samples. The results of the assessment are discussed in the next section.

Breakup at site 5 was more of a thermal meltout than a mechanical breakup. The ice mass broke up near shore where the depths were shallower and water was warmer from runoff. This resulted in an increasingly larger area of open water near shore. For the 2001 breakup, ice samples were collected by wading through 20 ft of open water to the ice mass and chipping off ice blocks using an ice chisel as shown in figure 18D. These ice blocks were then transferred to shore, and samples were collected for crushing using the ice-coring machine.

Ice-crushing strength was measured at site 6 (Lake Francis Case at the Platte-Winner Bridge) only in 2001. Because of large variations in water levels and the mild winters of 1999 and 2000 and corresponding unsafe ice, no ice data were collected at the site in 1999 and 2000. Ice-crushing strength measured at site 6 in 2001 ranged from 151 to 907 lb/in^2. Average ice-crushing strength was estimated as 725 lb/in^2 on February 13, 2001. No data were collected during spring breakup because it was not possible to collect samples from the ice mass in March, as an open shoreline rapidly formed in early March. This open water was too extensive and too deep to wade out to the ice mass to collect samples. The best estimates of ice-crushing strength for this site during breakup probably are the ice-crushing strengths ranging from 151 to 428 lb/in^2 with an average of about 250 lb/in^2 measured in January 2001. These samples were collected by wading through open water to the ice mass. For all samples, the ice was crushed at rates between 0.0010 and 0.0013 in/sec, and sample sizes (diameter by length) varied from 3.5 by 6 inches to 3.5 by 8 inches.

Evaluation of Ice-Crushing Strength

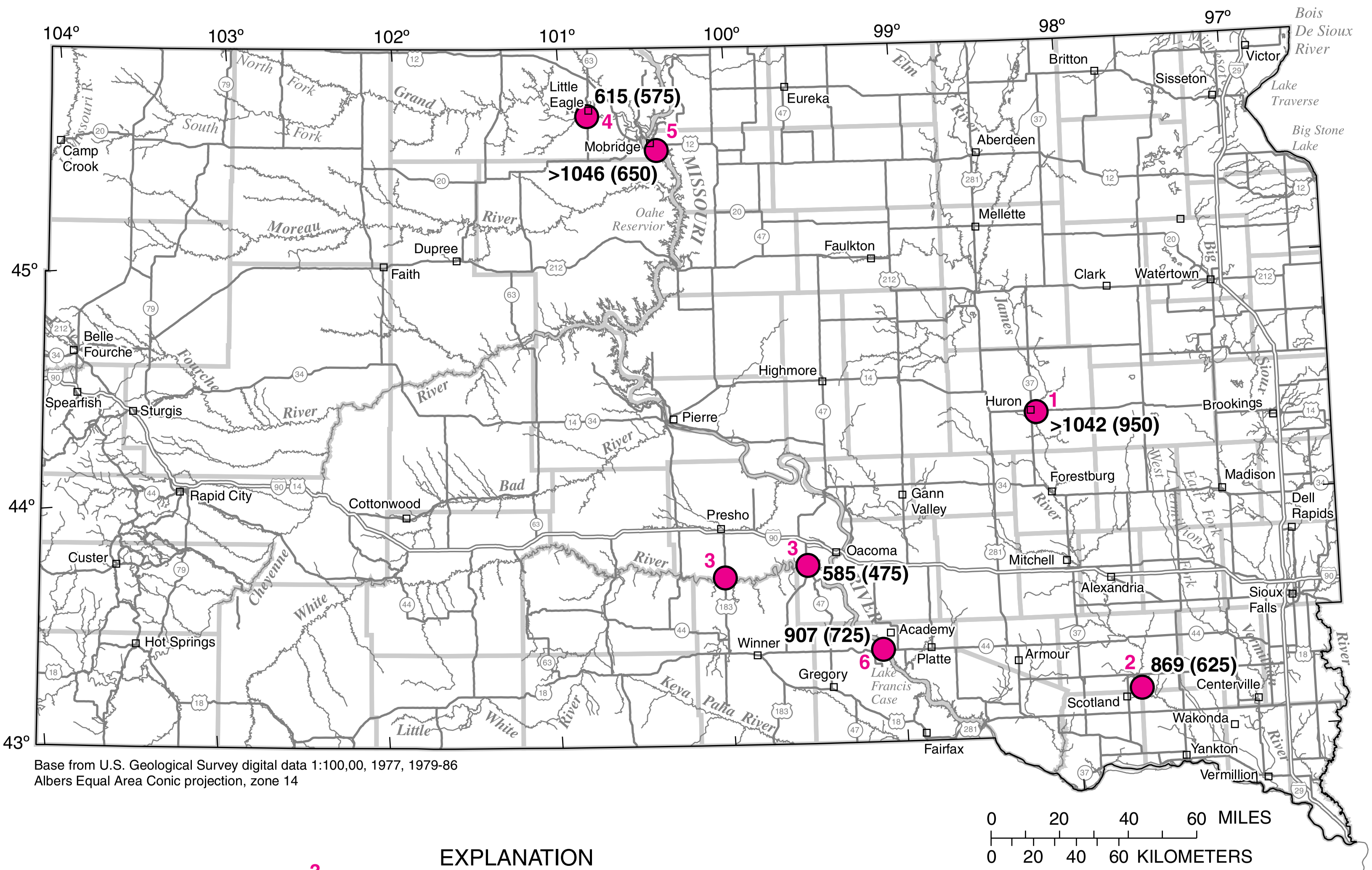
Ice-crushing-strength data collected in the field were evaluated to a limited degree to see how they compared to ice-crushing strengths used in bridge design in South Dakota. There are ice-crushing-strength estimation equations available to use for comparisons with measured strength; however, these equations require extensive data that are hard to collect or not readily available. The ice-crushing strengths measured during spring breakups probably are the most applicable values for bridge design.

A summary of the maximum ice-crushing strengths is presented in figure 20, which shows both the individual maximum ice-crushing strength and the maximum average ice-crushing strength measured at each site during the data-collection period. For example, the maximum ice-crushing strength measured at site 2 (James River near Scotland) from 1999 to 2001 was 869 lb/in^2 on February 12, 2001, from a sample collected 100 ft from the shoreline. The maximum average ice-crushing strength at this site was 625 lb/in^2 on January 24, 2000. The average ice-crushing strengths at this site ranged from 275 to 625 lb/in^2 during the data-collection period.

Potential maximum ice-crushing strengths across South Dakota were not estimated because no ice-crushing-strength estimation equations were evaluated. However, based on data collected, maximum ice-crushing strengths averaged from about 475 lb/in^2 at site 3 (White River near Oacoma/Presho) to about 950 lb/in^2 at site 1 (James River at Huron). Individual maximum ice-crushing-strength measurements were the lowest at site 3 (White River near Oacoma/Presho) and site 4 (Grand River at Little Eagle) (585 and 615 lb/in^2, respectively). The individual maximum ice-crushing strengths were 869 and 907 lb/in^2 at site 2 (James River near Scotland) and site 6 (Lake Francis Case at the Platte-Winner Bridge), respectively, and greater than 1,046 lb/in^2 at both site 1 (James River at Huron) and site 5 (Oahe Reservoir near Mobridge). Based on an analysis of this limited ice-crushing-strength data, ice-crushing strengths of about 1,000 lb/in^2 could be expected at any site in South Dakota if enough water is available for freezing and if the winter is as cold as the 2001 winter.

American Association of State Highway and Transportation Officials (AASHTO) design values for the ice-crushing strength of ice range from 100 to 400 lb/in^2 (Daris Ormesher, South Dakota Department of Transportation, written commun., 1999), which could result in large variations in bridge design. The design criteria (AASHTO Design Method) used by the SDDOT Bridge Section sets ice-crushing strength at 100 lb/in^2 for purposes of bridge design. Even if the assumption is made that ice does not put extensive force on bridge structures except when it breaks up in the spring and is driven by flow or wind against the structures, measured ice-crushing strength near spring breakup usually was much greater than 100 lb/in^2. The average ice-crushing strength measured near breakup at the six ice-data collection sites in South Dakota ranged from 75 to 300 lb/in^2 (fig. 21). An ice-crushing strength of 250 lb/in^2 would not be anomalous for expected ice-crushing strengths during spring breakup in South Dakota. Site 3 (White River near Oacoma/Presho) provided the most applicable data for an analysis of mechanical breakup because the samples for ice-crushing on March 13, 2001, were taken from ice that had broken up and started to flow downstream into the bridge piers. The average ice-crushing strength for samples collected on this date was about 225 lb/in^2 and ranged from 214 to 271 lb/in^2. Site 1 (James River at Huron) provided the most applicable data for an analysis of ice-crushing strength for a breakup representative of a thermal meltout and with extensive available data. This site was monitored extensively near the breakup during 2001. Ice-crushing strength was about 200 lb/in^2 just before the final breakup in April 2001.

As previously stated, the samples collected for ice-crushing-strength measurement varied from very-clear columnar ice collected near the bottom of the ice to milky-colored snow ice to sediment-layered ice. A description of the ice samples is included in table 4 along with the measured ice-crushing strengths. No conclusions could be reached from an analysis of the ice-crushing strength data as related to the different types of ice because data collection was not tailored to ice type. Limited specific conductance data, which was measured only in 2001, also are included in this table. The location in the vertical column of the ice mass from which the sample was taken also is presented in table 4. If there was sufficient ice thickness, samples were taken in the upper, middle, and lower part of the ice columns. An analysis was done to see if the magnitude of the ice-crushing strength depended on the location the sample was taken in the vertical column. There were 22 instances where ice-crushing strength was measured at the same time and location for both an upper or middle and lower sample. The ice-crushing strength of the sample from the upper or middle column was equal to or greater than that from the lower column in about 45 percent of the sample pairs and was lower in about 55 percent of the sample pairs, so the results were inconclusive. The magnitude of the difference between the lower sample ice-crushing-strength values as compared to the upper or middle sample ice-crushing-strength values averaged about 22 percent. Variation in strength near the top or middle of the ice cover versus the bottom could depend on air temperature or ice type. If the air temperature is well below freezing, the upper or middle portion of the ice would be colder and therefore stronger than the bottom, which would be at about 32°F where in contact with the underlying water. Ice type also results in strength variation as columnar ice is stronger than the snow ice.



Base from U.S. Geological Survey digital data 1:100,00, 1977, 1979-86
Albers Equal Area Conic projection, zone 14

EXPLANATION

3 >1042 (950) ICE DATA-COLLECTION SITE—Pink number is site number in table 1. Black number is individual maximum ice-crushing strength (> is greater than) and number in parentheses is the maximum average ice-crushing strength, both in pounds per square inch

Figure 20. Maximum ice-crushing strength measured at ice-data collection sites in South Dakota.

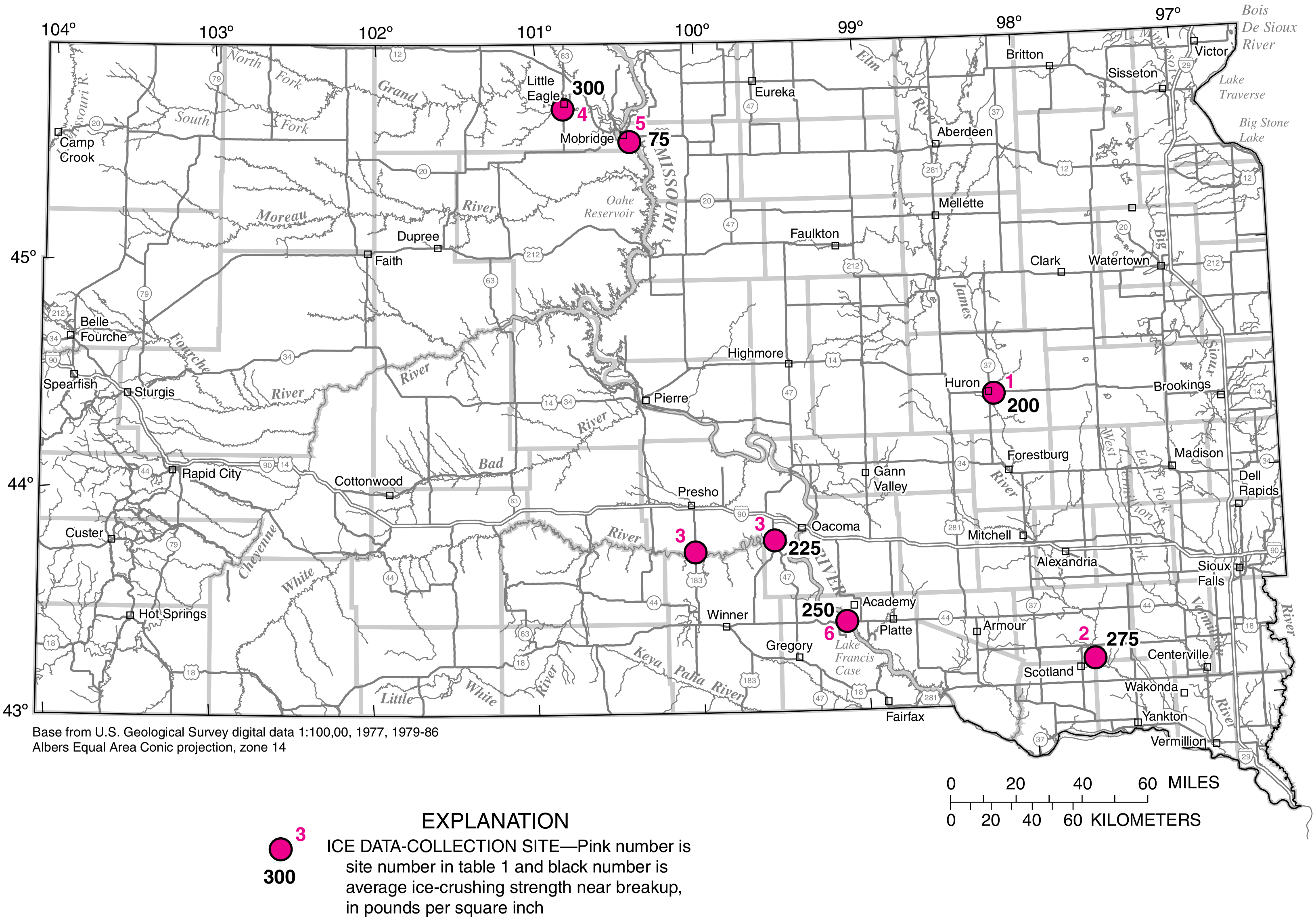


Figure 21. Average ice-crushing strength measured near breakup at the ice-data collection sites in South Dakota.

The evaluation of ice-crushing strength presented in this report is limited by the data collected for the study. The collection of additional data at the six sites used in this study could provide better estimates of ice-crushing strengths. For practical application, the collection of data from more sites, especially in the northeast, northwest, and southwest parts of South Dakota, would be beneficial.

SUMMARY

Estimating the magnitude of ice forces that act on bridge piers and abutments in northern climates is a major concern in the design of new bridges and in the evaluation of the structural stability of existing bridges. Although ice-force estimation equations typically are used for bridge design that address ice thickness and ice-crushing strength, which are the most important variables in the bridge design equations, the estimated ice forces may not be conservative because the ice-thickness and ice-crushing-strength values used in these equations may not be the maximum values that could occur in South Dakota. In response to these concerns, the U.S. Geological Survey (USGS), in cooperation with the South Dakota Department of Transportation, conducted a study to evaluate factors affecting ice forces at selected bridges in South Dakota from June 1998 to September 2002.

Six sites in South Dakota were selected for ice-data collection, which included ice-thickness and ice-crushing-strength data. Ice thickness generally was measured at each site at three to five locations along a transect perpendicular to the direction of flow. Ice-crushing strength was measured at the same six sites where ice-thickness data were collected. Samples with 6- to 12-inch lengths were collected for ice-crushing-strength analyses. Multiple ice samples were collected at each location along the transect to obtain representative samples from the entire vertical section. The samples were crushed at each site using a portable ice-crushing machine until failure was achieved.

Ice thickness measured at the James River at Huron site ranged from 1.1 to 1.3 feet in 1999, 0.7 to 1.2 feet in 2000, and 1.4 to 2.3 feet in 2001. Because the 2001 winter was the 11th coldest winter of record at Sioux Falls, ice-thickness measurements collected during this winter probably are near the maximum ice thicknesses that could occur at this site in the future. Ice thickness measured at the James River near Scotland site ranged from near 0 to 0.9 ft in 1999, 0.5 to 1.0 ft in 2000, and 0 to 1.7 ft in 2001. Ice thickness measured at the White River near Oacoma/Presho site ranged from 0.5 to 1.0 ft in 2000 and from 0.1 to 1.5 ft in 2001. This site had limited water and corresponding little ice (0.1 ft) when data were collected in February 2001. Ice thickness measured at the Grand River at Little Eagle site was 1.2 ft in 1999, ranged from 0.5 to 1.2 ft in 2000, and ranged from 0.2 to 1.4 ft in 2001. Little water was available at the site for freezing in January and February 2001, resulting in little ice formation. Ice thickness measured at the Oahe Reservoir near Mobridge site ranged from 1.7 to 1.8 ft in 1999, 0.9 to 1.2 ft in 2000, and 0 to 2.2 ft in 2001. Ice thickness measured at the Lake Francis Case at the Platte-Winner Bridge site ranged from 1.2 to 1.8 ft in 2001. Because of the large variation in water levels at this site and the mild winters of 1999 and 2000, no ice data were collected in 1999 and 2000.

Historical ice-thickness data measured by the USGS at eight selected streamflow-gaging stations for 1970-97 were compiled. The maximum measured ice thickness at the Grand River at Little Eagle station was 2.9 ft from November 1975 to February 1997, and the maximum measured ice thickness at the White River at Oacoma station was 2.2 ft from December 1975 to January 1995. The maximum ice thickness measured at the two James River stations was 2.0 ft from December 1970 to March 1997 near Scotland and 1.5 ft from February 1982 to January 1995 near Yankton. Maximum ice thickness measured at the two Vermillion River stations was 2.0 ft from December 1970 to February 1983 near Wakonda and 1.5 ft from December 1983 to February 1996 near Vermillion. The maximum ice thickness measured at the two Big Sioux River stations was 2.0 ft from November 1970 to December 1994 near Brookings and 2.2 ft from December 1970 to March 1997 near Dell Rapids.

Three ice-thickness-estimation equations that potentially could be used for bridge design in South Dakota were selected. The three equations included the Accumulative Freezing Degree Day (AFDD), Incremental Accumulative Freezing Degree Day (IAFDD), and Simplified Energy Budget (SEB) equations. The AFDD equation is a simple equation that assumes that ice thickness is a function of air temperature. The IAFDD equation, while similar to the AFDD equation, calculates the change in ice thickness from an initial ice thickness rather than the total ice thickness since ice formation began. The SEB equation incorporates more

directly the effects of the temperature difference between the top surface of the ice and the air and the insulating effects of snow cover on the solid ice cover.

The three equations were evaluated by comparing study-collected and historical ice-thickness measurements to equation-estimated ice thicknesses. Additional information needed for the evaluation of the ice-thickness equations was obtained from the National Weather Service (NWS).

Of the three selected equations, the AFDD equation best estimated maximum ice thickness in South Dakota using available data sources with an average variation about the measured value of about 0.4 ft. The IAFDD equation, a similar equation to the AFDD equation, estimated ice thickness nearly as well with an average variation about the measured value of about 0.5 ft. The SEB equation estimated ice thickness slightly more in error with an average variation about the measured value of about 0.6 ft. To avoid a possible bias from using the historical ice-thickness data that may not be as accurate as study-collected ice-thickness data, a comparison was done using only study-collected data. The AFDD equation again best estimated the measured ice thickness with an average variation about the measured value of about 0.2 ft. Additional comparisons were done using both existing historical and study-collected ice-thickness data, but excluding measured ice thickness of less than 1.0 and 1.5 ft. For measured ice thickness greater than 1.0 ft, the AFDD and IAFDD equations again best estimated the measured ice thickness with average variations about the measured values of 0.4 ft for both.

Maximum potential ice thickness was estimated at 19 NWS stations located throughout South Dakota using the AFDD equation. The 1979 winter, which is the coldest winter on record at Sioux Falls, was the winter used to estimate maximum potential ice thickness. To estimate maximum potential ice thickness at rivers and lakes or reservoirs throughout South Dakota, the maximum ice-thickness estimates at the 19 NWS stations were contoured. The maximum potential estimated ice thicknesses generally are the largest in northeastern South Dakota at about 3 ft and are smallest in southwestern and south-central South Dakota at about 2 ft.

Ice-crushing strength was measured from February 1999 to April 2001 at the same six sites where ice-thickness data were collected. Ice-crushing strength was measured both in the winter and spring near ice breakup. The maximum ice-crushing strengths were measured in mid- to late winter, while ice-crushing strengths measured during the spring at and near ice breakup were much less. These lesser strengths that were measured at or near breakup in the spring may be more applicable to use in bridge design equations.

Ice-crushing-strength data measured at the six sites ranged from 58 to greater than 1,046 lb/in^2. The largest ice-crushing strengths measured were from samples collected at the Oahe Reservoir near Mobridge and the James River at Huron sites. The smallest ice-crushing-strength measurement was 58 lb/in^2 from samples collected at the Oahe Reservoir near Mobridge site during spring breakup.

Ice-crushing strength measured at the James River at Huron site was highly variable and ranged from 228 to 522 lb/in^2 in 1999, 180 lb/in^2 to greater than 1,042 lb/in^2 in 2000, and 207 lb/in^2 to greater than 1,046 lb/in^2 in 2001. The maximum ice-crushing strength of greater than 1,046 lb/in^2 was measured in the winter of 2001, the 11th coldest winter of record. Ice-crushing strength measured at the James River near Scotland site ranged from 417 to 603 lb/in^2 in 1999, 565 to 694 lb/in^2 in 2000, and 255 to 869 lb/in^2 in 2001. Ice-crushing strength measured at the White River near Oacoma/Presho site ranged from 180 to 579 lb/in^2 in 2000 and 214 to 585 lb/in^2 in 2001, and ice-crushing strength measured at the Grand River at Little Eagle site ranged from 229 to 577 lb/in^2 in 1999, 148 to 615 lb/in^2 in 2000, and 236 to 411 lb/in^2 in 2001. Ice-crushing strength measured at the Oahe Reservoir near Mobridge site was highly variable and ranged from 387 to 685 lb/in^2 in 1999, 247 to 883 lb/in^2 in 2000, and 58 to greater than 1,046 lb/in^2 in 2001. Ice-crushing strength measured at the Lake Francis Case at the Platte-Winner Bridge also was highly variable and ranged from 151 to 907 lb/in^2 in 2001.

Measured ice-crushing strengths were evaluated to see how they compared to ice-crushing strengths used in bridge design in South Dakota. The ice-crushing strengths measured during spring breakup probably are the most applicable values for bridge design.

Maximum ice-crushing strengths averaged from about 475 lb/in^2 at the White River near Oacoma/Presho site to about 950 lb/in^2 at the James River at Huron site. Individual maximum ice-crushing-strength measurements were the lowest at the White River near Oacoma/Presho and Grand River at Little Eagle sites (585 and 615 lb/in^2, respectively). The individual maximum ice-crushing strengths measured at the James River near Scotland and Lake

Francis Case near the Platte-Winner Bridge sites were 869 and 907 lb/in^2, respectively, and at both the James River at Huron and Oahe Reservoir near Mobridge sites the strengths were greater than 1,046 lb/in^2. From an analysis of this limited ice-crushing-strength data, ice-crushing strengths of about 1,000 lb/in^2 could be expected at any site in South Dakota if enough water is available for freezing and if the winter is as cold as the 2001 winter.

Measured ice-crushing strength during spring breakup usually was greater than 100 lb/in^2, and the average ice-crushing strength measured near breakup at the six ice-data collection sites in South Dakota ranged from 75 to 300 lb/in^2. An ice-crushing strength of 250 lb/in^2 would not be anomalous for expected ice-crushing strengths during the spring breakup in South Dakota.

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