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Safe Capacity of Suspension Bridge Cables
Sécurité de la capacité portante des câbles de ponts suspendus
Sichere Traglast von Hängebrückenseilen

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SUMMARY

A common type of deterioration and resultant defects in the main cable wires has been observed in recent in-depth inspections of some older suspension bridges. The deterioration and defects are highlighted in the description of a typical case history of a suspension bridge inspection undertaken on the Bear Mountain Bridge. A description of the bridge, its inspection and relevant testing of wires is described. The deterioration of the wires and resultant defects are discussed and compared with similar defects observed on three other comparable suspension bridges also inspected recently. An estimation of remaining cable capacity is described, together with a discussion of the effects of the reduction of safety factors on the design loads.

RÉSUMÉ

Des types communs d'usure et de dommages consécutifs ont été tout dernièrement découverts au cours d'inspections minutieuses effectuées sur un certain nombre d'anciens ponts suspendus. L'auteur en fait la description à l'aide des résultats fournis par le cas d'une inspection typique et des essais de fils de câbles opérés sur le pont Bear-Mountain. Il donne également l'estimation de la capacité portante résiduelle des câbles et cite les effets de la réduction des coefficients de sécurité sur les charges de calcul.

ZUSAMMENFASSUNG

Bei kürzlich durchgeführten gründlichen Inspektionen einiger älterer Hängebrücken, wurde eine ihnen gemeinsame Art der Abnützung und entsprechende Folgeschäden gefunden. Sie werden anhand eines typisches Inspektionsergebnisses der Bear-Mountain-Brücke und zugehörigen Drahttests beschrieben. Die Abnützungs- und Schadensmerkmale der Drähte werden mit denen vergleichen, die kürlich an drei ähnlichen Hängebrücken entdeckt wurden. Die Abschätzung der Resttragfähigkeit der Seile und die Folgen der verminderten Sicherheitsbeiwerte auf die Bemessungseinwirkungen werden erörtert.

1. INTRODUCTION

1.1 In-depth inspections have been undertaken recently on a number of older suspension bridges with the primary purpose of inspecting the condition of the wires of the main suspension cables. This was in order to determine if any deterioration has occurred, if so how much, and to compute the remaining structural capacity of the overall cable.

1.2 Steinman has undertaken such in-depth inspections on the Bear Mountain Bridge across the Hudson River approximately 40 miles north of New York City, the suspension span of the Triboro Bridge across Hell's Gate in New York City, and the Golden Gate Bridge in San Francisco. In addition, Steinman has been involved in a consulting capacity for the in-depth inspection of the Mid-Hudson Bridge across the Hudson River at Poughkeepsie.

1.3 All four of these bridges were completed more than 55 years ago. The Bear Mountain Bridge was completed in 1924, the Triboro Bridge was completed in 1936, the Golden Gate Bridge was opened to traffic in 1937, and the Mid-Hudson Bridge was completed in 1936. As such, they represent a good sample of the type of medium to long span bridges being constructed in the United States between the two World Wars.

1.4 In-depth inspection techniques for viewing and establishing the condition of suspension bridge main cable wires were developed by Steinman in the early 1980's initially for inspecting the main cables of the Brooklyn Bridge, in New York City. These techniques were successfully utilized on the special investigation of the Williamsburg Bridge, also in New York City in 1988/89 when it was demonstrated that the condition and capacity of the cables was fully adequate for the design loads imposed.

1.5 The four bridges which are the subject of this paper represent a more commercial and standardized practice of the construction of suspension bridges than either the Brooklyn Bridge or the Williamsburg Bridge. All four bridges have main cables that were constructed using the aerial spinning techniques for cable wire developed by the John A. Roebling Sons Company. All four bridges have galvanized bridge wire of approximately 4.95mm in diameter with a minimum ultimate tensile strength varying from 1500 N/mm^2 to 1600 N/mm^2. The wire for the Bear Mountain Bridge and the Golden Gate Bridge came from John A. Roebling Sons Company, and the wire for the Triboro Bridge and the Mid-Hudson Bridge was supplied by American Steel & Wire Company.

1.6 The size of the spans and cables, with the exception of the Golden Gate Bridge are all roughly comparable. The make-up, size of cable, and spans are listed in Table 1 and the bridges are illustrated in Figure 1.

2. IN-DEPTH INSPECTION - A CASE STUDY

2.1 A description of the inspection of the Bear Mountain Bridge is provided to illustrate the means of inspecting the cables.

2.2 The Bear Mountain Bridge was constructed in 1923/4 as the first fixed crossing of the Hudson River south of Albany, which is approximately 100 miles north of the bridge. At the time of construction it had the longest clear span in the world, 497.2m.

	Bear Mountain	Mid-Hudson	Triborough	Golden
Year Completed	1924	1936	1936	1937
Main Span (m)	497.4	457.2	420.6	1280.2
Cable Diameter	464	425	527	924
Number of Wires per Cable	7292	6080	9176	27572
Minimum Ultimate Tensile Strength (N/mm^2)	1500	1500	1600	1550
Residual Diameter of Wire Curvature	1680	1830	1470	1830

TABLE 1
SUMMARY OF CABLE DATA
(all dimensions in millimeters unless noted)

2.3 The two towers of the bridge are 106.7m high. The clearance from mean high water level to the underside of the stiffening truss at the towers is 42.1m, rising to 46.6m at mid-span. The designed span to sag ratio is 8.16 under dead load. The bridge has straight backstays with truss supported end spans. The main stiffening truss is 9.14m deep, supported by two part 57mm diameter wire rope suspenders connected to cantilever extensions of beams supporting the bottom chord. The cables are at 18.70m centers, outside the face of the stiffening truss, and dip down at mid span below the top chord of the stiffening truss.

2.4 The construction of the bridge incorporated certain advances in technology which have subsequently permitted the adoption of unlimited size of cables on other bridges. Previous to the construction of the Bear Mountain Bridge it had been the practice to spin the strands and serve them with round wire to hold together the parallel wire. When the first seven strands had been completed, they were formed into a circle, the serving wires to the strands removed, the whole formed into a homogeneous group and re-served with round wire. The next set of strands were then spun, and formed to a layer around the central core. Again the serving wire to each strand and the core was removed, and the whole re-served. The process continued until the full cable was completed, and then the whole was compacted. This was an extremely lengthy and time-consuming process.

2.5 With the Bear Mountain Bridge, the use of flat steel wire serving bands was adopted for the strands. This permitted the spinning of each strand and its placement in the overall preliminary hexagon shape, without the tedious forming procedure. When all strands were completed, the flat bands were all cut, the bands to all external strands were removed and the compaction undertaken.

2.6 In-depth inspection of the cable was undertaken at four points along the cable. These were the backstay just outside the anchorage, the tower top at one panel point into the main span from the saddle, at mid span, and at the one-third point of the main span. The backstay and mid span location were selected as those locations most likely to reveal any water that may have entered the cable. The tower top location is that point of maximum cable load, and the one-third point is that location subject to the most flexure under live load. All locations selected were on the north cable except for the one third point location.

2.7 Inspection of the cable is undertaken by removing the protective wrapping wire and driving wedges into the cable in order to provide a visual check of

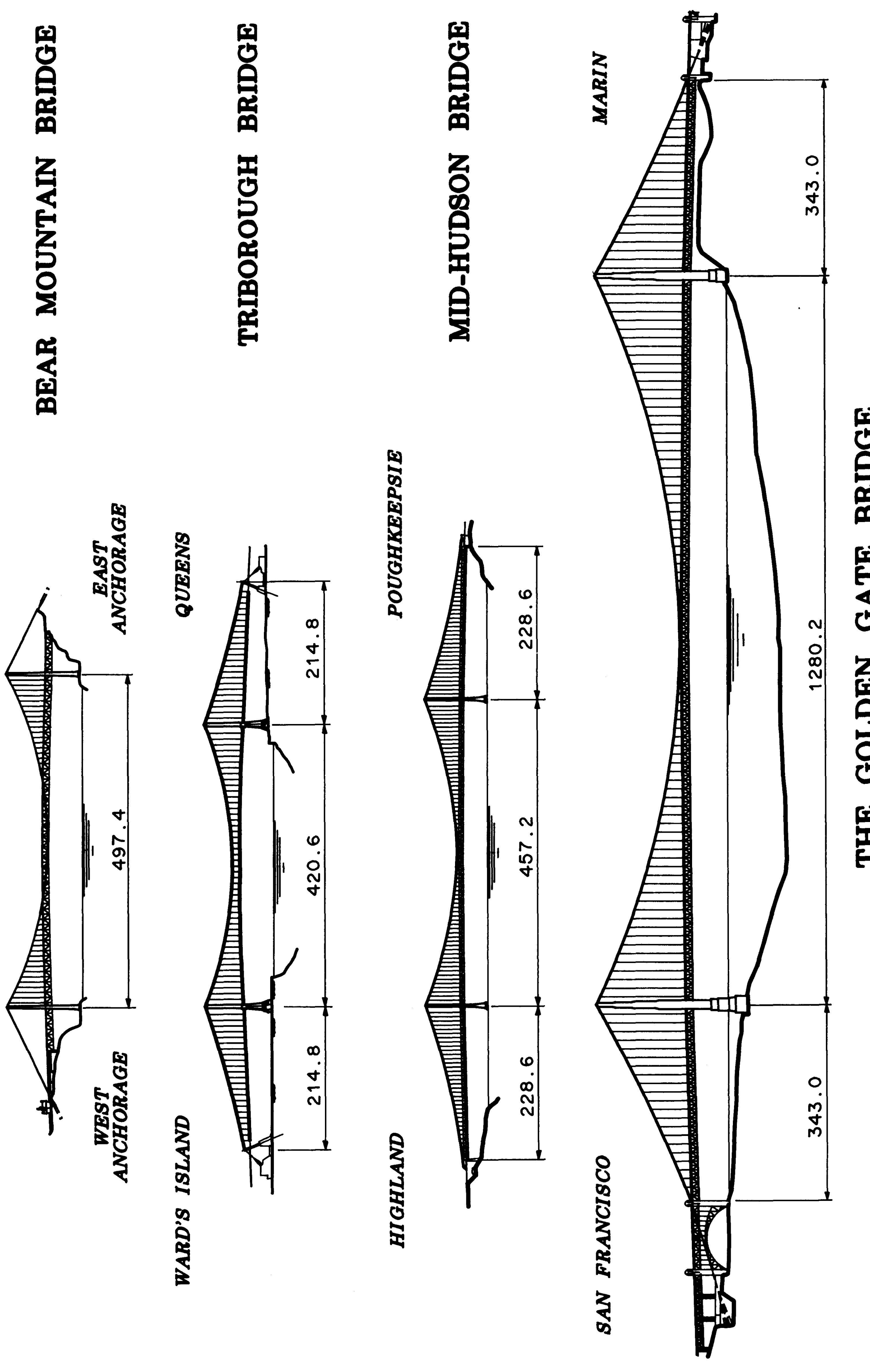
BEAR MOUNTAIN BRIDGE
WEST ANCHORAGE
EAST ANCHORAGE
497.4
TRIBOROUGH BRIDGE
WARD'S ISLAND
QUEENS
214.8
420.6
214.8
MID-HUDSON BRIDGE
HIGHLAND
POUGHKEEPSIE
228.6
457.2
228.6
THE GOLDEN GATE BRIDGE
SAN FRANCISCO
MARIN
343.0
1280.2
343.0

Figure 1

interior wire conditions. Wedges were driven into the cable at four radial positions around the cable, except at the mid span location where four additional grooves were opened.

2.8 At the three main span locations, suspender ropes and associated cables were removed in order to provide observation of conditions under the cable bands. Purpose made jacking equipment was designed and supplied in order to free the suspender rope, and subsequently re-tension the new ropes after installation.

2.9 After full inspection of the cable surfaces and wedged grooves, the wedges were withdrawn and the cable recompacted using a specially designed and supplied compactor. After completion of compaction, the cable bands were replaced on a new layer of red lead paste applied over the cable wires, and the new suspender ropes installed and tensioned.

2.10 The cable was then wrapped with soft galvanized wire by means of a purpose built two ply wrapping machine, also laid over a fresh layer of red lead paste applied to the main cable. A minimum tension in the wire of 665N was specified.

2.11 Full visual inspection of the exposed wires was undertaken using photographs and a standardized form of recording corrosion levels. All broken wires were located on position charts showing both the cross section, and longitudinal locations. Broken wires were labelled and sampled and the samples sent to Carleton Laboratory at Columbia University for detailed visual and microscopic inspection, and physical testing.

2.12 Wherever possible broken wires were respliced using a technique developed for Brooklyn Bridge, incorporating the use of repair wires joined to bridge wire with hydraulically crimped ferrules and the repair wires themselves joined and tensioned with threaded ferrules.

3. TESTING OF SAMPLES

3.1 Visual inspection of all wire samples was undertaken, with special effort being given to the broken ends of the wires. Microscopic examination of all broken ends was undertaken and two specimens were viewed under the Scanning Electron Microscope. Five wires were tested for hydrogen embrittlement with two samples showing elevated hydrogen levels.

3.2 Longitudinal sections of two wire samples were prepared and viewed under the microscope in order to provide further information on the failure patterns.

3.3 Standard tensile tests were made on a number of wire samples, with specimens approximately 450mm long. Additional tensile tests were performed on long sections of wire up to 5.2m in length in order to compare the possible effect of the straightening of the wire from the coil set. Four fatigue tests were undertaken on short wire samples and finally additional tensile tests were performed on the broken ends of certain of the long samples which had failed at low ultimate tensile stresses.

4. DISCUSSION OF RESULTS FROM BEAR MOUNTAIN BRIDGE

4.1 The primary cause of the observed wire breakages appears to be stress corrosion, with all fracture surfaces observed exhibiting the characteristic fracture profiles. Representative longitudinal sections of wires also revealed the typical secondary cracks running into the wire.

4.2 A significant number (approximately 40%) of the wire breaks were observed to be immediately adjacent to the strand straps that had been left inside the cable. In addition, the large majority (approximately 90%) of all wire breaks are located in the 300 mm diameter central zone of the cable, thus being topographically situated in the zone where the flat wire serving bands were cut but not removed.

4.3 These banding straps have almost certainly initiated zinc depletion of the galvanized wires as the straps were made of low carbon steel, with no protection. The indication of a possibility of hydrogen embrittlement of the wire breaks tends to support the above-described zinc-depletion effect, and in addition would render the wire itself susceptible to corrosion.

4.4 The definitive reasons for the occurrence of the stress corrosion cannot be readily defined. However, the initial crack planes on all fracture surfaces were located on the inside of the residual curvature of the wire. This seems to indicate that initial occurrence, and subsequent propagation of the crack could be related to the initial manufacture of the wire and its subsequent decoiling.

4.5 The strength testing of the wires showed that the wire generally had the same capacity as when it was originally manufactured, except where stress corrosion has commenced. All tensile tests undertaken showed an average ultimate tensile stress of 1400N/mm^2 except where stress corrosion crack planes were located. Retests of four (4) wires taken from the broken ends of two (2) tensile tests where the failure stresses were low, exhibited revised failure stresses averaging 1375N/mm^2 indicating that the balance of the wire did not have pre-existing cracks comparable to those at which the initial breaks occurred.

4.6 It was noted that in all cases the in-place wire breaks showed corrosion across the entire faces of the fractures. This indicated that the majority if not all of the breaks occurred a significant time past, and that the stress corrosion attack has been retarded in the recent past. This is in agreement with reported maintenance operations where an increased attention to maintenance and painting of the cables has been in effect for approximately the last 10 years.

5. SUMMARY OF RESULTS FROM OTHER BRIDGES

5.1 The inspection of the Golden Gate Bridge showed that the wires generally were in excellent condition. One location was unwrapped and wedged open at six (6) radial positions for inspection, and other than the exterior wires at the low points of the cable where some medium surface corrosion was observed, the interior wires of the cable only exhibit light zinc oxidation with spots of minor ferrous corrosion. Observation of the samples removed for testing showed that these minor corrosion locations were generally on the inside of the residual curvature of the wire. It is to be noted that the wire wrapping system of the cables was very well applied during original construction, and has been maintained during the life of the bridge. The cable was dry when inspected, but this may have been related to the lengthy drought that California has just experienced.

5.2 The inspection of the Triborough Bridge showed that the wires are suffering from some significant corrosion to the surface layers of wires. Four (4) locations were unwrapped for inspection, with one location being wedged open to a depth of 250mm and the other three only to a depth of 50mm. Fractures have occurred in wires at the surface layers, apparently due to hydrogen assisted stress corrosion cracking. These wires were invariably heavily corroded with visible section loss. Interior wires observed exhibit corrosion of the zinc coating with localized areas of ferric corrosion similar to those observed at

Bear Mountain. Observation of the samples removed for testing showed that these corrosion locations, again, were generally located on the inside of the residual curvature of the wire. The wire wrapping system of these cables was not well applied with gaps between the wires evident, and red lead paint was used as a seal layer between the wrapping and main cable wires, instead of red lead paste used on Bear Mountain and Golden Gate. The combination of these two last factors has permitted water to enter the cable and initiate corrosion of the wires.

5.3 The inspection of the Mid Hudson Bridge showed that the wires are suffering from active stress corrosion attack. Forty eight (48) locations have been unwrapped and wedged open full depth for inspection, and a large number of fractured wires have been discovered. In addition there is a wide distribution of local corrosion locations showing pitting and craters, with severe local loss of zinc and local corrosion attack of the steel wire. All fracture surfaces observed were typical of stress corrosion, and all fractures had the initial normal fracture surface on the inside of the residual curvature of the wire. In addition, in a number of samples, when the zinc had been removed from the wire, transverse cracks were observed on the surface of the steel wire at approximately 3mm intervals, and all were located on the inside of the residual wire curvature. Cracking occurred at local areas exhibiting a hard, black corrosion product, even where little loss of section had occurred.

6. <u>DEFECTS EVIDENT IN BRIDGE WIRE</u>

6.1 Three of these bridges are exhibiting common defects and deterioration of the bridge wire making up their main cables. These defects originate with the failure of the overall protective wrapping wire system to the outside of the main cable wires, resulting from a combination of failure of the external paint system, inadequately installed or maintained wrapping wire, and incorrect material specification of the protective paste system to the outside of the main cable wires.

6.2 After water has entered the main cable system, depletion of the zinc galvanizing to the main bridge wires can occur, with the water acting as the electrolyte. In the case of the Bear Mountain Bridge this has been aggravated by the flat wire serving bands remaining in the cable.

6.3 The bridge wire appears to be susceptible to stress corrosion of the main steel wire itself. This can only occur after depletion of the zinc, but after the zinc is lost, local corrosion of the steel wire seems to occur in concentrated local positions, with resultant pitting and cratering.

6.4 The stress corrosion cracking appears to be induced to initiate its action on the inside of the residual curvature of the wire. All three of the Bear Mountain, Triborough and Mid Hudson Bridges have the initial crack planes of the wire fractures originating on the inside of this curve. The wire from the Golden Gate Bridge, exhibited relatively little ferrous corrosion, moderate zinc oxidation, but no cracking.

6.5 It is considered possible that the stress corrosion may be directly related to the initial curvature of the wire. The approximate measured diameters of the curvature are recorded in Table 1. The simple calculation of the equivalent decoiling stress from the minimum radius of 1830mm on the Mid- Hudson Bridge gives an indicative extreme fiber stress of 345N/mm^2. Early research into stress corrosion cracking indicated that the threshold for crack initiation is around 270N/mm^2. Typically, dead load cable stress is somewhat below this on these older bridges. However, the secondary "decoiling stress" appears to be sufficient to exceed this threshold.

7. PROTECTION OF CABLES AND REMAINING CAPACITY

7.1 It is evident from the condition of the wires in the four bridges inspected that the corrosion pattern is only initiated after failure of the protective wrapping system to the main cables and the entrance of water into the cables. It is also evident that even if the corrosion attack has commenced, it is possible to slow, or even halt the attack by increased maintenance of the protective wrapping system, thereby stopping the entry of water into the cable.

7.2 The primary recommendation therefore, is to undertake some means of wrapping to the cables which will totally seal the cables from any entry of water. This can be achieved by means of wrapping the cables with a neoprene sheet wrap, comprising 150mm wide uncured neoprene tape wrapped around the cable with a 50% overlap. The curing of the tape is effected by its exposure to air, and the ends are sealed to the cable bands. The whole is coated with a three-coat liquid chlorosulfonated polyethylene paint system. Overall, this results in a totally impervious flexible sheath to the cable.

7.3 This system can be applied either directly to the surface of the main bridge wires or over the original wire wrapping system. It is considered preferable to leave the original wire wrapping system in place if possible, as this will maintain the compaction of the cable wires. Removal of the wrapping wire can result in loss of compaction up to 5% on the diameter of the cable, thus providing an increased voids ratio of the whole cable. The cable should therefore be at least strapped at sufficient intervals to maintain sufficient compaction. Under no circumstance is it recommended to use neoprene wrap alone, without a positive compacting provision.

7.4 Calculation of remaining cable capacity can be considered as a reduction in the Factor of Safety to failure under load. Such reduced factors of safety have been calculated for the Bear Mountain Bridge and Mid Hudson Bridge. Insufficient data was available for this to be undertaken for the Triborough Bridge, but the Factor of Safety is not considered to be at or near any level to cause concern. It was not considered necessary to make any estimate of reduction of Factor of Safety for the Golden Gate Bridge, due to the good condition of the wires.

7.5 Conservative assumptions were made in projecting the available figures into calculations for remaining cable capacity for both the Bear Mountain and Mid Hudson Bridges. These were:
7.5.1 The percentage of broken wires as a proportion of all wires actually observed at any location is considered to extend through the complete cable cross section.

7.5.2 The strength of unbroken wires is taken as an average strength of the laboratory test values for that location. It is to be noted that all such test values were measured on previously fractured wire samples.

7.5.3 All breaks observed at any one location are effective in conjunction, ignoring any transfer of load by friction and clamping.

7.6 The Factor of Safety on the Bear Mountain Bridge was calculated as having been reduced from 3.74 to 3.25, and on Mid Hudson Bridge from 3.90 to 3.20. In both cases, this still represents an ample reserve of capacity, and presents no cause for alarm. However, the recommended measures referred to above for sealing the cables have been put into effect and the cable wires will continue to be monitored on a regular basis to ensure that the corrosion attack is halted.