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VIBRATIONAL EVALUATION OF TENDONS IN SEGMENTAL SECTIONS OF SUNSHINE SKYWAY BRIDGE MAIN SPANS

Contract No. BD544 RPWO#3
Final Report to Florida Department of Transportation

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16. Abstract

This report presents results of vibration tests of external post-tensioned tendons of Main Spans of the Sunshine Skyway Bridge and amplifies the scope of previous interim communications. The tests were intended to aid in detecting possible corrosion damage or other distress leading to reduced or uneven tendon tension. Included is detailed analysis of data from tendons obstructed by contact against other tendons, using newly available data processing methodology. Vibrational testing was successfully conducted for about 85 % of the tendon segment inventory initially considered for testing. Most tendons not evaluated were found to be not sufficiently accessible or too obstructed for this type of test. Average estimated tension values agreed with those expected from design. Variability of results was comparable with that obtained in previous similar surveys of FDOT bridges. Available results do not show dramatic tension disparities between continuing or directly opposed tendon segments that would be clearly indicative of tendon distress. Relatively low tensions have been obtained for some tendons but the low values appear to affect evenly several tendons in the same grouping, suggesting systematic causes other than punctual distress.

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TABLE OF CONTENTS

NOTICE

EXECUTIVE SUMMARY

The objective of this project was to plan, prepare for, and analyze vibrational data acquired from the external tendons in the segmental sections of the Sunshine Skyway bridge main spans by a separate contractor. Findings of this project were obtained for the majority of tendons in the main spans of this bridge and conveyed to the Florida Department of Transportation (FDOT) in an interim report dated January 8, 2004. Refined analysis methods developed under the ongoing FDOT Project BC353-44 have been used to expand the number of tendons that could be analyzed and to provide more accurate estimates of tension of the other tendons. This report presents those expanded and updated analyses, including evaluation of data from tendons obstructed by contact against other tendons. Vibrational testing was successfully conducted for about 85% of the tendon segment inventory initially considered for testing. Most tendons not evaluated were found to be not sufficiently accessible or too obstructed for this type of test. Average estimated tension values agreed with those expected from design. Variability of results was comparable with that obtained in previous similar surveys if FDOT bridges. Available results do not show dramatic tension disparities between continuing or directly opposed tendon segments that would be clearly indicative of tendon distress. Relatively low tensions have been obtained for some tendons but the low values appear to affect evenly several tendons in the same grouping, suggesting systematic causes other than punctual distress. A table of tendons meriting detailed attention in future inspections is presented.

NOTE ON SCOPE OF THIS REPORT

Findings of this project were obtained for the majority of tendons in the main spans of this bridge and conveyed to the Florida Department of Transportation (FDOT) in an interim report dated January 8, 2004. Preparation of a final report was postponed however, as it was anticipated that a more advanced force calculation method would be developed in an upcoming FDOT project to permit evaluation of tension in tendons that were partially obstructed during vibration. An initial version of such method has now become available from progress in the FDOT Project “Validation and Practical Procedure for Vibrational Evaluation of Tendons”, BC353 RPWO #44 (named BC353-44 in the following) , and has been applied to refine and complete the force estimates of all the tendons suitable for analysis in the segmental sections of the Sunshine Skyway bridge main spans. The updated results confirm much of the preliminary findings, expand the number of tendons that could be analyzed, and are presented in this Final Report which supersedes any previous draft version.

BACKGROUND

The objective of this project was to plan, prepare for, and analyze vibrational data acquired from the external tendons in the segmental sections of the Sunshine Skyway bridge main spans by a separate contractor.

The University of South Florida (USF) prepared in cooperation with FDOT a vibrational test plan for the tendons. USF prepared test equipment based on that used for a previous investigation conducted for FDOT for the Niles Channel Bridge [1]. In addition, USF trained both in campus and at the bridge the separate contract operators on the operation of the test equipment.

The data were acquired in May and June, 2003 and delivered to USF. Data consisted of (i) data forms containing tendon segment lengths, frequencies for the Mode 1 and 2 peaks for each tendon segment tested (used for simplified calculations not reported here) and (ii) electronic files in *.wav* format containing the accelerometer output records of each measurement. Each tendon was tested four times (two each for two different hammer impact directions).

TENDON POSITION AND NOMENCLATURE

Figure A1 (multiple pages) in Appendix 1 show the placement and naming procedure for the 480 tendon segments that were slated for vibration testing in the Main Spans. The figures are stylized Plan views, oriented so North (N) is to the left. The test equipment was placed in Test Stations covering groups of tendon segments as indicated in Figure A1. Tests were conducted in nearly all of those tendon segments, but in numerous cases there were obstructions to vibration due to contact to other components or between tendons. Whenever feasible, clamps were placed on obstructed tendon segments to facilitate testing as fretted segments. Each tendon segment is named by a 6-digit number and a two-letter cardinal designation. In the following, note that span number is the same as the number of the pier at the South (S) end of the span.

The first 3 digits indicate the number of the span in which the tendon segment is located, except when identical segments of the same tendon are centered on a pier, in which case the 3 digits indicate the pier number. The next 3 digits designate the type of tendon per bridge construction drawings. A two-character cardinal code placed last designates position within a multiple group of otherwise identical tendons, exemplified as follows: 116211NE is a tendon segment on the E (Northbound) side of the bridge span, having an identical continuation segment (116211SE) on the S side of Pier 116, and both segments have identically configured segments on the W (Southbound) side of the span. It is noted that the vibration procedure estimates tension separately for each of the freely vibrating segments of a given continuous tendon.

TENDON PARAMETERS AND SPECIAL CASES

For the tension calculations the linear mass of each type of tendon was estimated using the tendon dimensions, number and type of strands, and materials properties indicated in Table 1. Dimensions and number/type of strands are based on a combination of direct measurements and references to available information at the time of calculation. Materials properties are assumed following plausible estimates. Should updated parameter information become available, reevaluation of mass per unit length is straightforward. As estimated tendon force is directly proportional to linear mass [1,2,3], any adjustment resulting from parameter update would only displace force estimates globally and not change proportional differences between peer tendons.

The length of each tendon segment is documented in Tables A1-1 and A1-2 (Appendix 1). For uniformity with recent vibration test reports from other bridges, the reported length for unobstructed tendon segments is the concrete-to-concrete distance between faces of deviation blocks or between faces of diaphragm and deviation block (idealized as LT in Figure 2a).

Vibration obstructions were encountered in ~ ¼ of the segments tested. The most common obstruction was mutual, Figure 1. Obstruction resulted from tendon types 3XX (oriented generally N-S) sometimes barely touching sloping tendons of type 0XX (on an E-W plane, at about 45^{o} from the horizontal). Tendons type 0XX are placed between sloping concrete struts that permit installing temporary elevating frets as shown to completely remove obstruction of the 0XX tendon. The 3XX tendon is elevated by about 0.25 in (6 mm) by adjusting the fret threaded rods. On first approximation, the frets act as pining supports, for a tendon configuration as shown in Figure 2b. The reported free length in those cases is the distance from the concrete face to the centerpoint of the closest fretting clamp, idealized as L2 in Figure 2b. For these tendon segments Table A1-2 lists the values of L1 as well as LT and L1+L2.

For unobstructed tendon segments tension estimates were calculated assuming configuration (a) in Figure 2 with vibration length LV=LT, following the general approach used in Ref.[1] and refined as outlined in Reference [3,4] per the findings to date from BC353-44. That procedure uses data from vibrations mode 1 up to mode 7. The possible effect of the short portion of steel duct emerging from the deviation block or the diaphragm in this and in the fretted cases was not considered. However, based on findings to date from BC353-44, any later potential correction for this effect is not anticipated to be large.

For tendons obstructed as in Figure 2(b) a provisional modification of the same calculation procedure was used as follows based on findings to date from BC353-44 : (i) an interim tension value was first calculated using the same procedure as for the unobstructed tendons but using LV=L2 and normally limiting the analysis to the frequency data for vibration modes 1 to 3 (27 strand tendons) or 1 to 2 (17 strand tendons); (ii) the interim force value was then multiplied by a flat correction factor of 1.03 (17 strand tendons) or 1.05 (27 strand tendons) and reported as the tension estimate for that tendon segment. The correction factors stem from the pinned (instead of clamped) condition at the fret points, and the added effect of incomplete rigidity of the clamps and support beam. The correction factors were customized to the present configuration and calculated as part of the tasks in BC353-44. It is anticipated that more refined estimations of the correction factors will become available in the future so the present application should be viewed as provisional.

Tendons suffering other forms of vibration obstruction were noted as such (see Results and Comments section) for future reference. About 85% of the tendon segments indicated in Figure 1 yielded data suitable for evaluation.

Table 1 - Tendon parameters used for linear mass estimates

Tendon Types	Number of Strands	Strand Size in (mm)	Strand Linear Mass lb/ft (Kg/m)	Duct Outer Diameter in (mm)	Duct Wall Thickness in (mm)	Resulting Tendon Linear Mass lb/ft (Kg/m)
307-313 315-325	27	.5 (12.7)	13.96 (20.79)	4.51 (114.55)	.187 (4.76)	22.53 (33.53)
All Others	17	.5 (12.7)	8.79 (13.09)	3.51 (89.15)	.17 (4.32)	13.82 (20.56)

Material	Density lb/ft^3 (Kg/m^3)
Duct HDPE	62.4 (1000)
Grout	115.5 (1850)
Steel	486.9 (7800)

Figure 1. Example of Type 306 tendon (left to right) obstructed by touching a Type 014 tendon. Elevating frets are placed on each strut lifting the Type 306 tendon slightly so it clears the other tendon. The Type 014 tendon is then completely unobstructed and tested normally. Vibration testing of the Type 306 tendon is conducted on the side to the right of the right fret, with tension calculated using a specialized procedure. S is to the left.

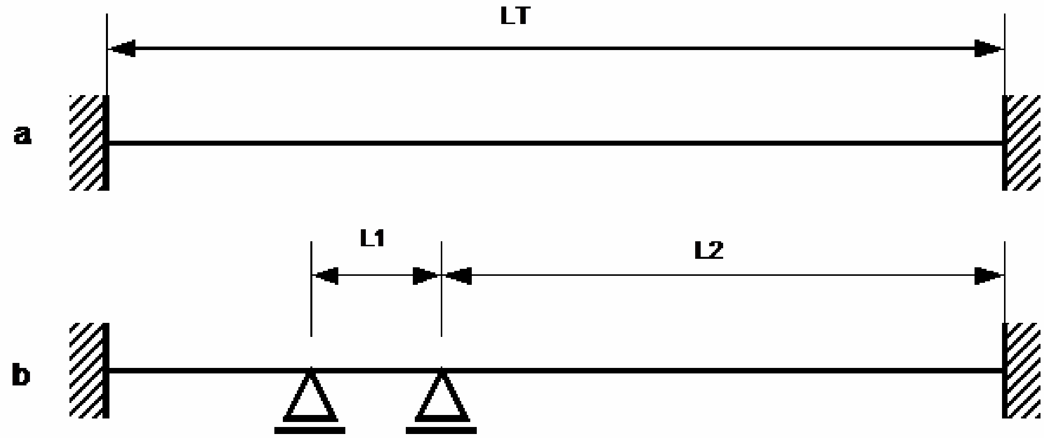

Figure 2. Tendon configurations assumed for force calculations. (a) normal unobstructed tendon, clamped at both ends, vibration length LV=L1; (b) Obstruction as in Figure 1, LV=L2 . Pinned condition involves some compliance.

RESULTS AND COMMENTS

Listing of results and comparisons

The estimated tensions for the tendon segments for which calculations were feasible are reported in Table A2. Appendix 1. Tensions are reported as Force per Strand both in English (kips/Strand; kips=1,000 pound-force) and SI (kN/Strand) units. Note that 1 kN = 0.225 kips. Results are arranged generally per the tendon segment layout in Figure A1, but the order for the part of the main span South of the midpoint has been reversed so in both cases the listing proceeds from the bridge approach toward the centerline. For each test station the tendons are listed by the 6-digit number on one column, and the result for each individual tendon segment given under the column corresponding to its cardinal designator (NE, etc). The listing order of N and S designators is reversed south of the midpoint so the table follows a plan comparable to that in Figure A1.

Shaded cells in Table A2 indicate tendon segments for which a vibration obstruction was encountered that still permitted testing. Shading only on the borders indicate obstruction was as in Figure 1. Full shading indicate obstructions from other sources (e.g. contact to the web wall). Data in shaded cells are expected to be affected by greater uncertainty than usual. Tendon segments not tested or tested but with data unsuitable for analysis are so noted.

To facilitate identifying tendon segments that may be giving indications of distress, Table A2 shows also a comparison of the results of symmetrically placed components (whenever both results are available). The listings show how much the estimated tension of the segment of each tendon S of a deviation block differed from that of the segment of that tendon on the N side of the block. Designating tension of S and N sides by T_S and T_N respectively, the S-N disparity is defined (in percents) by

$$\text{S-N Disparity\%} = 100\, [T_S - T_N] / [(T_S + T_N) / 2]$$

The E or W designation before (S-N) indicates that the disparity corresponds to pairs of tendon that segments are on the E (Northbound) or W (Southbound) side of the Main Span. Under normal conditions the disparity would be small. However, if one of the sides of the tendon had experienced significant tension loss due to distress such as corrosion, an appreciable tension difference may be manifested because of bond at the block. Note that for tendon segments south of the midpoint an N-S disparity is given instead, for uniformity with the reversed listing order used there.

Table A2 shows a also similarly evaluated E-W disparity, this time comparing the tension of identical elements on both sides of the bridge. Although those elements are physically independent, they are symmetric and should have nearly the same tension. Large differences between both tensions may be revealing (although not as much as the N-S comparison indicated above) of distress at the tendon showing the lower force. For some tendon classes (e.g. many in the 3XX series and all in the 001 to 021 series) this was the only possible comparison with a symmetric element, as a N-S continuation component was not suitable accessible for testing or simply did not exist.

Comparison is also possible with symmetrically placed tendons on the other side of the bridge centerline (i.e. tensions results from Test Station 1 vs. those from Test Station 30 and so on). Because of relative remoteness between elements and of their different placement times this comparison is less valuable as those described above. Nevertheless, the resulting percentage disparity values (not listed in Table A1) were taken into consideration as an additional check when examining for possibly distressed tendons.

The estimated tension results are presented using 0.1 kN/Strand and 0.1 kips/Strand precision to minimize the effect of roundoff errors in any later numeric manipulation by users of the results. Experience to date shows that typical reproducibility of results (keeping input parameters the same) using the present data acquisition and calculation procedures is in the order of 1% to 2%, or about one significant digit less than the tabulation precision. Test uncertainty (e.g. mechanical complications in vibrational response, spectrum peak identification problems) could occasionally result in larger variability. If improved calculation models become available in the future, tensions may be recalculated accordingly. To that end, the original electronic data files from these field tests are archived permanently at USF. Discrepancies are presented only with 1 percent unit resolution.

It is emphasized that regardless of the reproducibility of the measurement results, the force estimates are also subject to global or individual inaccuracy from uncertainty in the input parameters used. Important among those are the mass per unit length (which depends on grout condition and voidage), and the effective vibrating length (affected by hidden vibration obstructions not considered above). Background information (e.g number of strands and gage) is also subject to some uncertainty, since the tendon interior is normally not subject to direct examination, and available documentation may not reflect all design revisions.

General trends

Table 2 shows the average and standard deviation of the estimated tensions for each tendon type group. The average estimated tension is also compared with the tension of a strand with the same nominal cross sectional area tensioned to the Guaranteed Ultimate Tensile Strength (GUTS) (1.86 GPa (270 ksi)). The range of percentages is shown as well.

The tendons analyzed had typical estimated tension in the order of 60% of ultimate strength, consistent with findings of tendons in other bridges under comparable conditions, keeping in mind the uncertainty issues indicated above. No estimated tension was below 44% of ultimate strength. As shown in Table 2, with the exception of the 200 and 00A-C series of tendons the estimated tensions were relatively narrowly distributed (standard deviation in the order of 4% of the mean) and with mean exceeding 61% of GUTS. The range of percentages observed is within reasonable expectation for a structure of this type.

Tendons in the 200 and 00A-00C series had a broader distribution of tensions, with extremes favoring the low tension end. Examination of Table A2 shows that most of the low-end tension values are for 00A, 00C and 208 tendon types, sometimes involving continuation tendon segments and peer segments on the other side (e.g. E vs W) of the bridge. The low calculated tensions in those cases appear thus to reflect systematic causes other than punctual incidents of tendon distress. Possible structural systematic factors may include special features in the tensioning procedures of those tendons at the time of construction, normal reduced tension due to deviator block friction at other points of tendons with multiple consecutive unbonded segments, or variances in the density of grout or size of duct used (with consequent local changes in linear mass). Local design revisions or differences not noted in the available documentation could also result in shifts in estimated tensions of a particular tendon group.

Table 2 - Estimated tension results (using linear mass values per Table 1) for each tendon class.

Tendon Type	Average kips/Strand (kN/Strand)	Standard Deviation kips/Strand (kN/Strand)	Average Tension as Equivalent % of GUTS	Range of % of GUTS
200-211 and 00A-00C	23.3 (103.7)	2.2 (10.0)	56	44-69
001-021	26.6 (118.3)	0.9 (4.0)	64	55-71
300-306	25.4 (112.9)	0.5 (2.3)	61	59-64
307-325	25.4 (112.8)	1.4 (6.0)	61	54-72

Identification of possibly deficient tendons

The external tendon arrangements in the main spans is quite complex and involves many different configurations. Therefore, unusual tendon performance is more difficult to identify than in the case of structures were large populations of simple repetitive elements exist, for example in the case of the approach spans of the same bridge or in the regular spans of the Mid Bay Bridge [5]. Moreover, many tendons tended to contact the web wall or had obstructing debris (easily undetected) between tendon and wall, and others required elevation as shown in Figure 1. Consequently, both measurement and modeling uncertainty was greater compared with simpler, less obstructed situations [1,5,6]. While recognizing these limitations, it was sought to identify possibly deficient tendons by noting in Table 3 cases that met either or both of the following criteria:

(a) S-N disparity indicative of unusually lower tension compared to that of a continuing segment of the same tendon on the other side of a web deviation block. On account of the uncertainty issues indicated above, only disparities of 10% or worse were included under this criterion.[1] For tendon segments with no N-S counterpart in Fig. A1 (e.g. the 001-021 Type), this criterion was guided by the E-W disparity value instead.

(b) Unusually low absolute value of estimated tension. Based on the summary on Table 2, the threshold for this criterion was set to 50% of GUTS for tendons in the 200-211 and 00A-00C group and to 55% for all others.

[1] In bridge span configurations less prone to vibration test uncertainty a lower threshold (e.g. 6% [5]) was used for this criterion.

It is noted that indicator (a) merits the most attention since it points to possible marked differences within the same tendon or an immediate direct opposite.

The vast majority of the tendons did not show behavior meeting either criterion. Despite the sources of uncertainty noted above, disparities of continuing or directly comparable tendon segments were usually very small. For the relatively few tendons flagged by indicator (a) (all 2XX or 00A Types), the greatest E(S-N) or W(S-N) disparity was only 14% (11100A NE) and the next-to-worst were only 11%.

Flagging per indicator (b) may be the result of causes other than distress noted earlier, such as inaccuracy in global input parameters, or normal reduced tension due to deviator block friction or other systematic construction issues not associated with a deficiency. These factors may especially relate to the several “C” and “A” tendon segments (short and with high angle of deviation) flagged by this indicator. The same circumstances may have been responsible for triggering the (a) flag in the 00A cases.

Table 3. Tendons flagged for possible deficiency indications

Spans North of Centerline		
Test Station	Tendon Segment	Flagging Criterion
1	116208 SE	b
7	112015 NE	b
10/11	11200A NE	a,b
	11200A SW	b
15	111312 NE	b
	111313 NW	b
Spans South of Centerline		
Test Station	Tendon Segment	Flagging Criterion
30	10700C SE	b
	10700C NW	a,b
28	10800C SE,NE,SW,NW	b
26	109210 NW	a
	109208 SE,NE,SW,NW	b
	10900C SE,NE,SW,NW	b
20/21	111201 SE	a
	11100A SE	a,b
	11100A SW	b
	111203 SW	a
16	111313 SE	b

The available results do not show dramatic tension disparities clearly indicative of tendon distress. Relatively low tensions have been obtained for some tendons but the low values appear to affect evenly several tendons in the same grouping, suggesting systematic causes other than punctual distress. Nevertheless, the tendon segments listed in Table 3 are conservatively recommended for special attention in future examinations.

Finally, it is emphasized that vibration tests can only evaluate the tension state of the freely vibrating portion of the tendon. Damage including strand breakage may be present in the anchorage or other parts of the tendon, but would remain undetected if the force stretching the unbonded portion has been efficiently accommodated by intervening elements (e.g. grout in the anchorage, intermediate deviation blocks).

CONCLUSIONS

1. Vibrational testing was successfully conducted for about 90% of the tendon segment inventory scheduled for testing in the main span of the Sunshine Skyway Bridge.

2. Average estimated tension values agreed with those expected from design. Variability of results was comparable with that obtained in previous similar surveys of FDOT bridges.

3. Available results do not show dramatic tension disparities between continuing or directly opposed tendon segments that would be clearly indicative of tendon distress. Relatively low tensions have been obtained for some tendons but the low values appear to affect evenly several tendons in the same grouping, suggesting systematic causes other than punctual distress.

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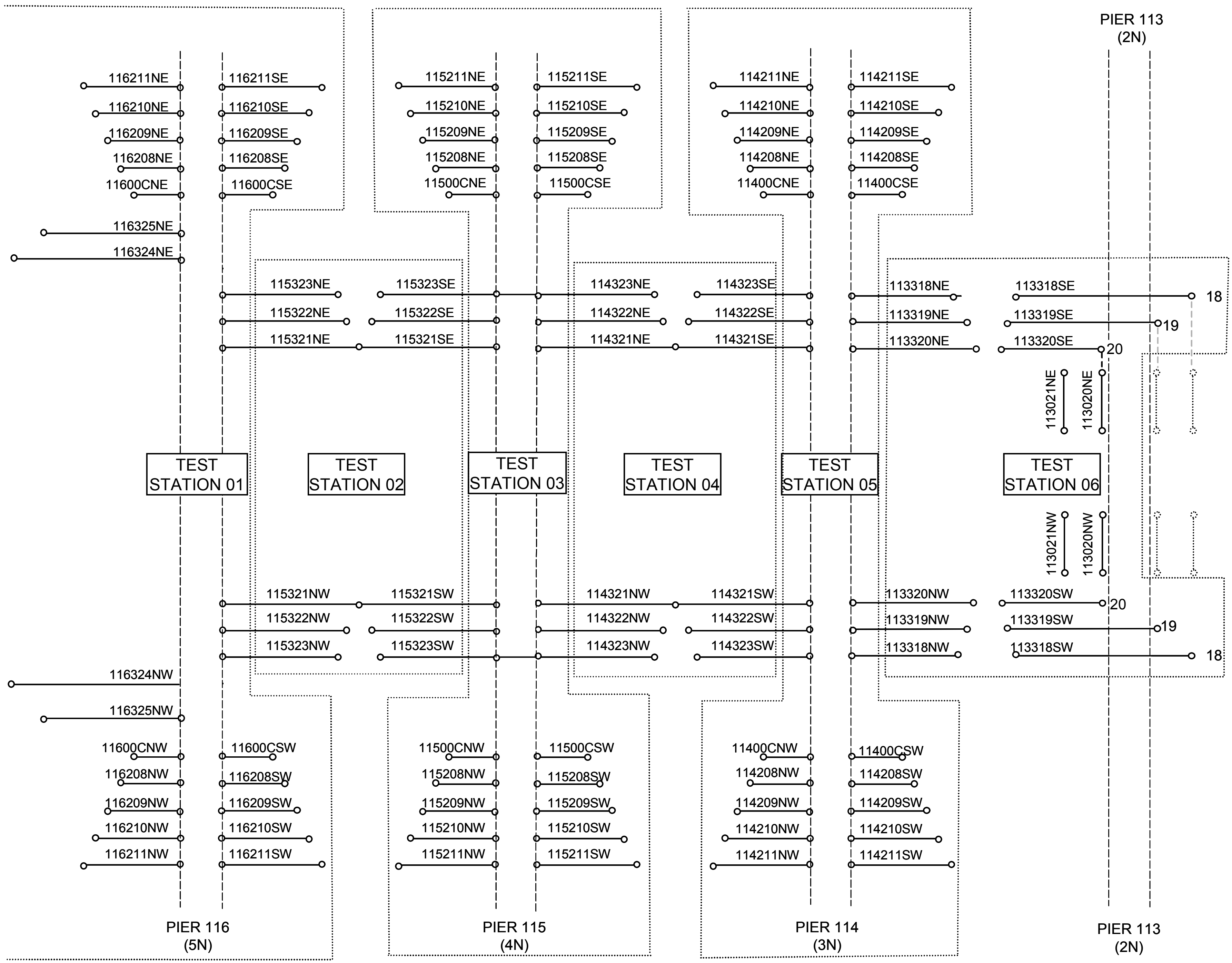
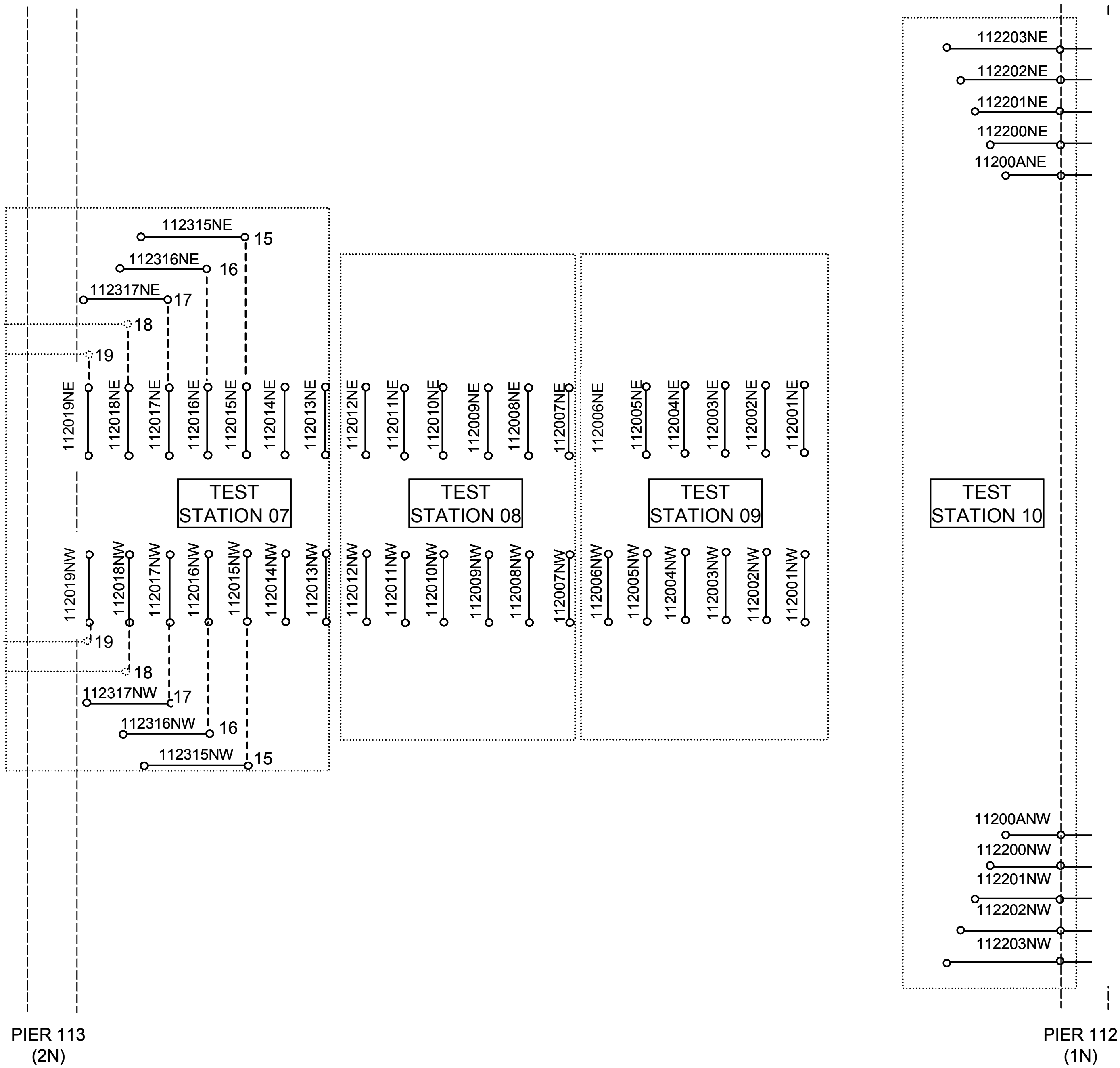
APPENDIX 1 - FIGURE A1 1/6

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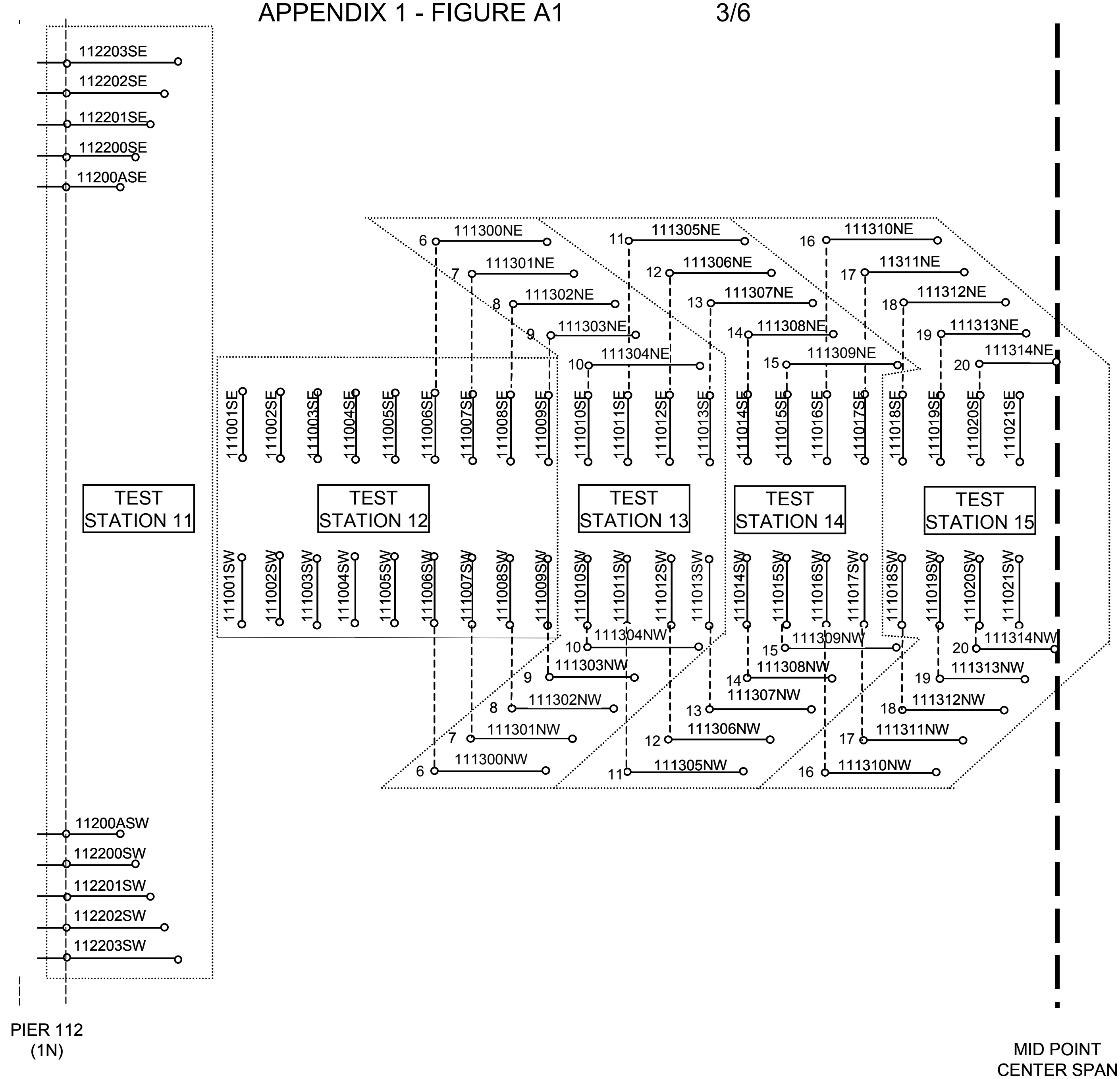
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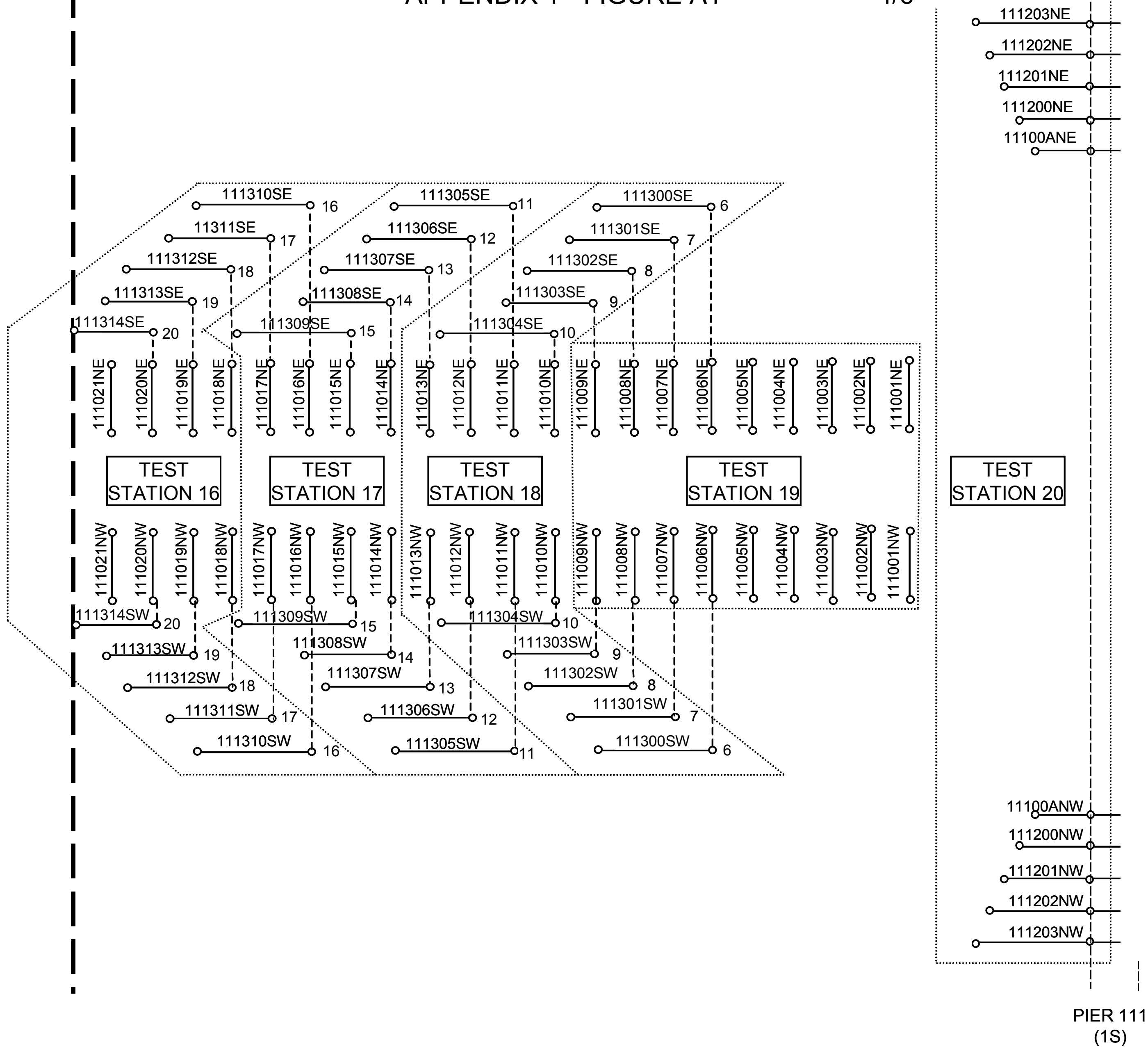
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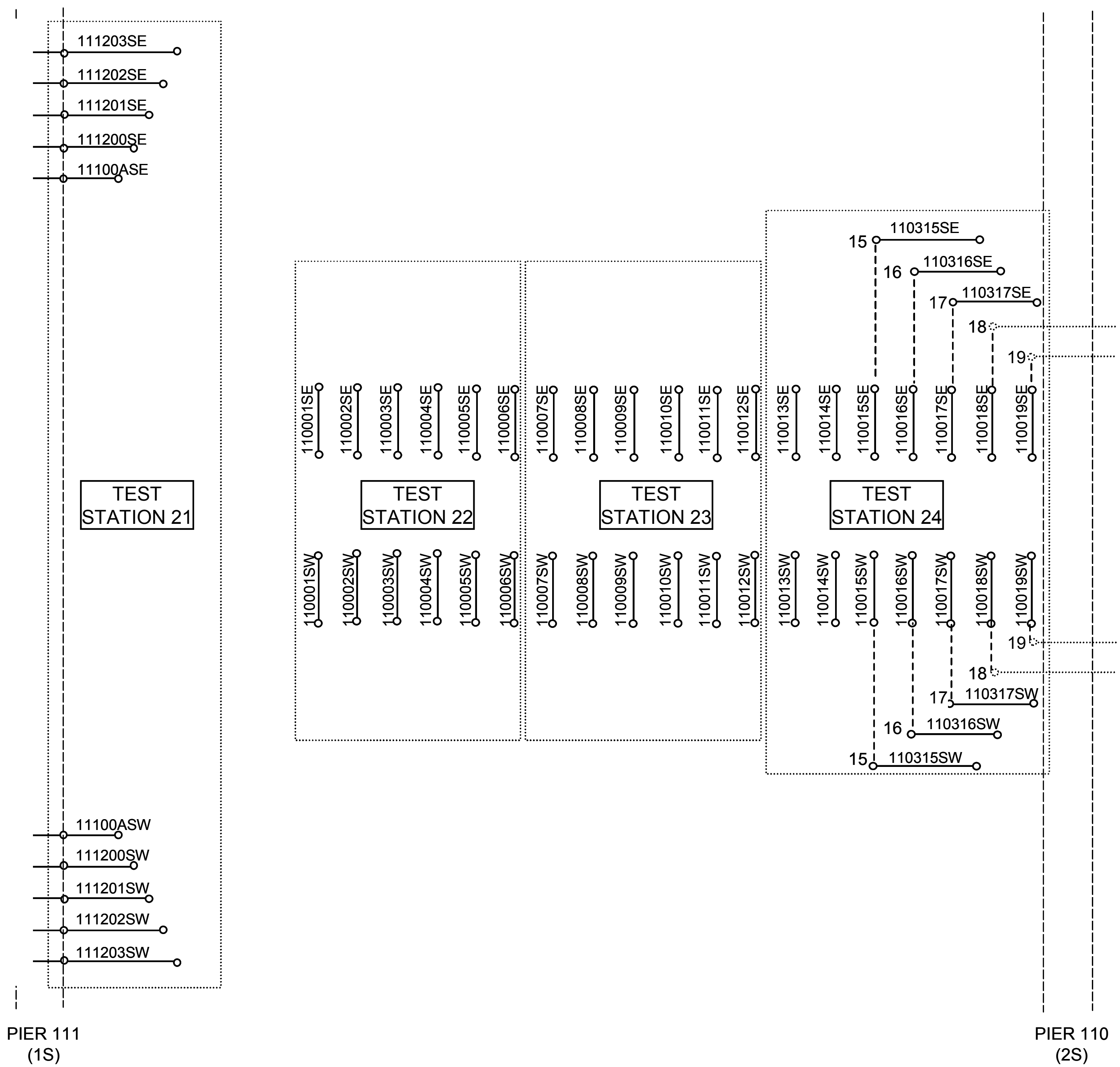
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110005SE
110006SE
TEST STATION 22
110001SW
110002SW
110003SW
110004SW
110005SW
110006SW
110007SE
110008SE
110009SE
110010SE
110011SE
110012SE
TEST STATION 23
110007SW
110008SW
110009SW
110010SW
110011SW
110012SW
15 110315SE
16 110316SE
17 110317SE
18
19
110013SE
110014SE
110015SE
110016SE
110017SE
110018SE
110019SE
TEST STATION 24
110013SW
110014SW
110015SW
110016SW
110017SW
110018SW
110019SW
19
18
17 110317SW
16 110316SW
15 110315SW
PIER 111
(1S)
PIER 110
(2S)

APPENDIX 1 - FIGURE A1 6/6

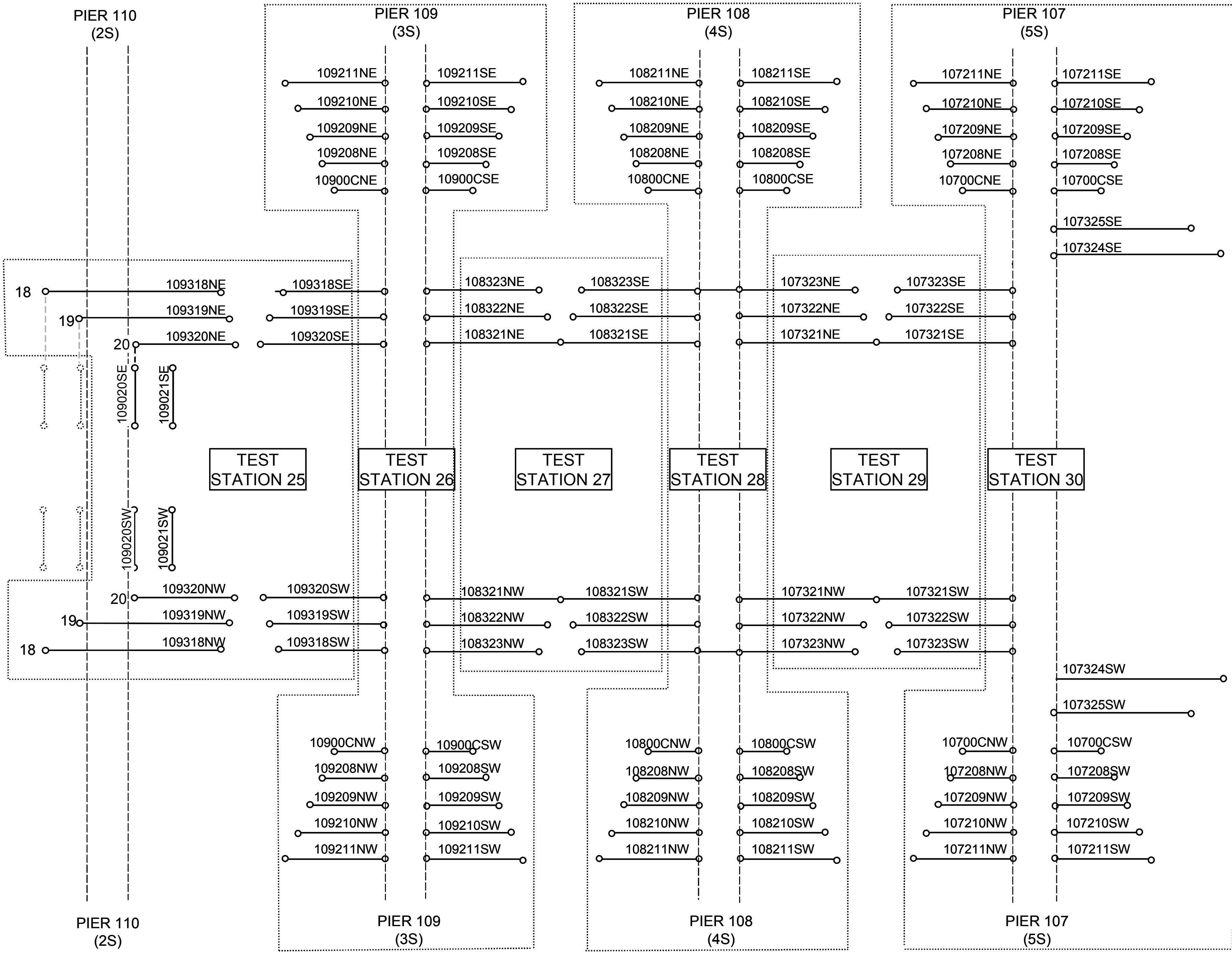

Table A1-1 Length of Unobstructed Tendon Segments (as LT in Figure 2a).

Tendon Name	Length (m)	Tendon Name	Length (m)
116211NE	19.88	115210NW	16.3
116210NE	16.3	115209NW	12.4
116209NE	12.71	115208NW	8.8
116208NE	9.22	11500CNW	5.637
11600CNE	5.71	115211SE	19.91
116325NE	27.66	115210SE	16.35
116324NE	31.24	115209SE	12.7
116211NW	19.92	115208SE	9.191
116210NW	16.31	11500CSE	5.73
116209NW	12.73	115211SW	19.85
116208NW	9.22	115210SW	16.26
11600CNW	5.75	115209SW	12.69
116325NW	27.66	115208SW	9.18
116324NW	31.25	11500CSW	5.69
116211SE	19.864	114323NE	27.628
116210SE	16.25	114322NE	31.257
116209SE	12.66	114321NE	34.674
116208SE	9.17	114323NW	27.636
11600CSE	5.67	114322NW	31.245
116211SW	19.85	114321NW	34.699
116210SW	16.28	114323SE	27.566
116209SW	12.72	114322SE	31.15
116208SW	9.2	114321SE	34.518
11600CSW	5.68	114323SW	27.563
115323NE	27.572	114322SW	31.152
115322NE	31.166	114321SW	34.525
115321NE	34.661	114211NE	19.92
115323NW	27.551	114210NE	16.35
115322NW	31.16	114209NE	12.73
115321NW	34.685	114208NE	9.19
115323SE	27.609	11400CNE	5.72
115322SE	31.186	114211NW	19.942
115321SE	34.55	114210NW	16.32
115323SW	27.598	114209NW	12.7
115322SW	31.218	114208NW	9.16
115321SW	34.552	11400CNW	5.64
115211NE	19.9	114211SE	19.86
115210NE	16.32	114210SE	16.26
115209NE	12.73	114209SE	12.69
115208NE	9.17	114208SE	9.17
11500CNE	5.65	11400CSE	5.77
115211NW	19.9	114211SW	19.9

Table A1-1 Continued

Tendon Name	Length (m)	Tendon Name	Length (m)
114210SW	16.29	112006NE	4.55
114209SW	12.75	112005NE	4.55
114208SW	9.18	112004NE	4.55
11400CSW	5.68	112003NE	4.55
113318NE	27.592	112002NE	4.55
113319NE	31.188	112001NE	4.55
113320NE	34.927	112006NW	4.55
113318NW	27.586	112005NW	4.55
113319NW	31.177	112004NW	4.55
113320NW	34.928	112003NW	4.55
113021NE	4.26	112002NW	4.55
113020NE	4.26	112001NW	4.55
113021NW	4.26	112203NE	20.008
113020NW	4.26	112202NE	16.43
113320SE	10.216	112201NE	12.87
112019NE	4.26	112200NE	9.33
112018NE	4.26	11200ANE	5.84
112017NE	4.26	112203NW	20
112016NE	4.26	112202NW	16.43
112015NE	4.26	112201NW	12.84
112014NE	4.55	112200NW	6.817
112013NE	4.55	11200ANW	3.45
112019NW	4.26	112203SE	19.99
112018NW	4.26	112202SE	16.4
112017NW	4.26	112201SE	12.82
112016NW	4.26	112200SE	9.29
112015NW	4.26	11200ASE	5.84
112014NW	4.55	112203SW	20.05
112013NW	4.55	112202SW	16.43
112317NW	16.958	112201SW	12.85
112012NE	4.55	112200SW	9.35
112011NE	4.55	11200ASW	5.9
112010NE	4.55	111001SE	4.55
112009NE	4.55	111002SE	4.55
112008NE	4.55	111003SE	4.55
112007NE	4.55	111004SE	4.55
112012NW	4.55	111005SE	4.55
112011NW	4.55	111006SE	4.55
112010NW	4.55	111007SE	4.55
112009NW	4.55	111008SE	4.55
112008NW	4.55	111009SE	4.55
112007NW	4.55	111001SW	4.55

Table A1-1 Continued

Tendon Name	Length (m)	Tendon Name	Length (m)
111002SW	4.55	111020NW	4.55
111003SW	4.55	111019NW	4.55
111004SW	4.55	111018NW	4.55
111005SW	4.55	111017NE	4.55
111006SW	4.55	111016NE	4.55
111007SW	4.55	111015NE	4.55
111008SW	4.55	111014NE	4.55
111009SW	4.55	111017NW	4.55
111300NE	17.018	111016NW	4.55
111301NE	17.04	111015NW	4.55
111302NE	17.01	111014NW	4.55
111300NW	17.024	111013NE	4.55
111301NW	17.16	111012NE	4.55
111010SE	4.55	111011NE	4.55
111011SE	4.55	111010NE	4.55
111012SE	4.55	111013NW	4.55
111013SE	4.55	111012NW	4.55
111010SW	4.55	111011NW	4.55
111011SW	4.55	111010NW	4.55
111012SW	4.55	111009NE	4.55
111013SW	4.55	111008NE	4.55
111014SE	4.55	111007NE	4.55
111015SE	4.55	111006NE	4.55
111016SE	4.55	111005NE	4.55
111017SE	4.55	111004NE	4.55
111014SW	4.55	111003NE	4.55
111015SW	4.55	111002NE	4.55
111016SW	4.55	111001NE	4.55
111017SW	4.55	111009NW	4.55
111018SE	4.55	111008NW	4.55
111019SE	4.55	111007NW	4.55
111020SE	4.55	111006NW	4.55
111021SE	4.55	111005NW	4.55
111018SW	4.55	111004NW	4.55
111019SW	4.55	111003NW	4.55
111020SW	4.55	111002NW	4.55
111021SW	4.55	111001NW	4.55
111021NE	4.55	111203NE	20.03
111020NE	4.55	111202NE	16.43
111019NE	4.55	111201NE	12.86
111018NE	4.55	111200NE	9.35
111021NW	4.55	11100ANE	5.8

Table A1-1 Continued

Tendon Name	Length (m)	Tendon Name	Length (m)
111203NW	20	110016SE	4.55
111202NW	16.4	110017SE	4.55
111201NW	12.83	110018SE	4.55
111200NW	9.28	110019SE	4.55
11100ANW	5.76	110013SW	4.55
111203SE	20	110014SW	4.55
111202SE	16.37	110015SW	4.55
111201SE	12.82	110016SW	4.55
111200SE	9.32	110017SW	4.55
11100ASE	5.85	110018SW	4.55
111203SW	20.04	110019SW	4.55
111202SW	16.48	109318SE	27.581
111201SW	12.88	109319SE	31.173
111200SW	9.34	109320SE	34.881
11100ASW	5.86	109318SW	27.546
110001SE	4.55	109319SW	31.163
110002SE	4.55	109320SW	34.855
110003SE	4.55	109021SE	4.55
110004SE	4.55	109020SE	4.55
110005SE	4.55	109021SW	4.55
110006SE	4.55	109020SW	4.55
110001SW	4.55	109211NE	19.85
110002SW	4.55	109210NE	16.28
110003SW	4.55	109209NE	12.72
110004SW	4.55	109208NE	9.18
110005SW	4.55	10900CNE	5.7
110006SW	4.55	109211NW	19.91
110007SE	4.55	109210NW	16.28
110008SE	4.55	109209NW	12.7
110009SE	4.55	109208NW	9.2
110010SE	4.55	10900CNW	5.74
110011SE	4.55	109211SE	19.89
110012SE	4.55	109210SE	16.3
110007SW	4.55	109209SE	12.75
110008SW	4.55	109208SE	9.24
110009SW	4.55	10900CSE	5.74
110010SW	4.55	109211SW	19.9
110011SW	4.55	109210SW	16.33
110012SW	4.55	109209SW	12.76
110013SE	4.55	109208SW	9.27

Table A1-1 Continued

Tendon Name	Length (m)	Tendon Name	Length (m)
108322NE	31.224	107323NW	27.541
108321NE	34.85	107322NW	31.158
108323NW	27.633	107321NW	34.785
108322NW	31.223	107323SE	27.556
108321NW	34.858	107322SE	31.163
108323SE	27.549	107321SE	34.923
108322SE	31.164	107323SW	27.519
108321SE	34.849	107322SW	31.167
108323SW	27.546	107321SW	34.519
108322SW	31.157	107211NE	19.83
108321SW	34.841	107210NE	16.24
108211NE	19.87	107209NE	12.7
108210NE	16.29	107208NE	9.2
108209NE	12.72	10700CNE	5.68
108208NE	9.16	107211NW	19.8
10800CNE	5.72	107210NW	16.25
108211NW	19.85	107209NW	12.72
108210NW	16.27	107208NW	9.21
108209NW	12.74	10700CNW	5.7
108208NW	9.17	107211SE	19.82
10800CNW	5.73	107210SE	16.23
108211SE	19.87	107209SE	12.69
108210SE	16.29	107208SE	9.17
108209SE	12.71	10700CSE	5.74
108208SE	9.18	107211SW	19.8
10800CSE	5.69	107210SW	16.23
108211SW	19.85	107209SW	12.69
108210SW	16.26	107208SW	9.15
108209SW	12.71	10700CSW	5.67
108208SW	9.2	107325SE	27.571
10800CSW	5.68	107324SE	31.157
107323NE	27.537	107325SW	27.581

Table A1-2 Length of Tendon Segments Obstructed as in Figure 2b

Tendon Name	L2 (m)	L2+L1 (m)	LT (m)
113318SE	10.206	11.141	16.519
113319SE	10.239	11.125	16.724
113318SW	10.181	11.147	16.620
113319SW	10.138	11.132	16.731
113320SW	10.225	11.151	16.615
113320SE	10.216	11.171	16.746
112317NE	10.323	11.287	16.920
112316NE	10.234	11.170	16.807
112315NE	10.225	11.174	16.659
112316NW	10.179	11.153	16.773
112315NW	10.218	11.152	16.541
111303NE	10.181	11.140	17.114
111304NE	10.183	11.167	16.814
111302NW	10.176	11.172	17.029
111303NW	10.185	11.158	17.133
111304NW	10.160	11.121	16.814
111305NE	10.177	11.149	16.660
111306NE	10.190	11.175	16.680
111307NE	10.166	11.091	16.675
111308NE	10.185	11.135	16.696
111309NE	10.214	11.144	16.775
111305NW	10.200	11.185	16.785
111306NW	10.216	11.183	16.708
111307NW	10.195	11.167	16.729
111308NW	10.195	11.181	16.786
111309NW	10.234	11.181	16.828
111310NE	10.267	11.161	16.725
111311NE	10.254	11.193	16.713
111312NE	10.264	11.171	16.711
111313NE	10.220	11.173	16.692
111314NE	6.752	8.106	13.383
111310NW	10.223	11.176	16.734
111311NW	10.182	11.184	16.716
111312NW	10.217	11.212	16.720
111313NW	10.191	11.175	16.700
111314NW	6.787	7.733	13.420
111310SE	10.207	11.184	16.686
111311SE	10.183	11.159	16.701
111312SE	10.221	11.154	16.740

Table A1-2 Continued

Tendon Name	L2 (m)	L2+L1 (m)	LT (m)
111313SE	10.155	11.109	16.686
111314SE	6.578	7.572	13.158
111310SW	10.208	11.146	16.673
111311SW	10.179	11.156	16.674
111312SW	10.215	11.174	16.725
111313SW	10.169	11.082	16.663
111314SW	6.562	7.548	13.137
111305SE	10.200	11.178	16.643
111306SE	10.205	11.131	16.655
111307SE	10.233	11.180	16.677
111308SE	10.214	11.174	16.674
111309SE	10.166	11.118	16.678
111305SW	10.219	11.129	16.641
111306SW	10.169	11.120	16.634
111307SW	10.201	11.154	16.673
111308SW	10.178	11.111	16.662
111309SW	10.153	11.107	16.667
111300SE	10.162	11.139	17.033
111301SE	10.168	11.126	17.043
111302SE	10.184	11.137	17.057
111303SE	10.152	11.129	17.024
111304SE	10.171	11.126	16.689
111300SW	10.186	11.124	17.030
111301SW	10.172	11.100	17.013
111302SW	10.161	11.100	17.009
111303SW	10.165	11.115	17.021
111304SW	10.180	11.160	16.644
110317SE	10.348	11.258	16.819
110316SE	10.182	11.121	16.614
110315SE	10.112	11.086	16.609
110317SW	10.330	11.299	16.812
110316SW	10.164	11.118	16.628
110315SW	10.137	11.094	16.717
109318NE	10.214	11.154	16.712
109319NE	10.178	11.111	16.808
109320NE	10.176	11.085	16.756
109318NW	10.211	11.176	16.824
109319NW	10.171	11.111	16.808
109320NW	10.181	11.116	16.790

Table A2- Estimated Tensions and Disparities

Stations 1 to 15: From North End of Main Span to Mid Point.

Test Station	Tendon Type	Estimated Force (KN/strand)				Estimated Force (kips/strand)				Force Disparity (Difference/Average)			
		NE	SE	NW	SW	NE	SE	NW	SW	E (S-N)	W (S-N)	S (E-W)	N (E-W)
1	**116211**	119.6	113.7	108.1	NA	26.9	25.6	24.3	NA	-5%			10%
	116210	119.8	117.9	97.1	97.4	26.9	26.5	21.8	21.9	-2%	0%	19%	21%
	116209	123.0	122.8	122.1	126.0	27.6	27.6	27.5	28.3	0%	3%	-3%	1%
	116208	97.5	91.8	100.9	95.1	21.9	20.6	22.7	21.4	-6%	-6%	-4%	-3%
	11600C	99.2	93.5	119.7	124.9	22.3	21.0	26.9	28.1	-6%	4%	-29%	-19%
	116325	107.3		109.2		24.1		24.5					-2%
	116324	113.3		112.2		25.5		25.2					1%
2	**115323**	118.6	114.5	122.0	118.5	26.7	25.7	27.4	26.6	-3%	-3%	-3%	-3%
	115322	111.5	113.4	108.0	111.0	25.1	25.5	24.3	25.0	2%	3%	2%	3%
	115321	NT	NT	104.0	NT	NT	NT	23.4	NT				
3	**115211**	115.8	117.1	117.6	123.5	26.0	26.3	26.4	27.8	1%	5%	-5%	-2%
	115210	116.6	111.7	114.0	112.7	26.2	25.1	25.6	25.3	-4%	-1%	-1%	2%
	115209	114.8	NA	109.3	108.4	25.8	NA	24.6	24.4		-1%		5%
	115208	NA	99.4	109.1	109.4	NA	22.3	24.5	24.6		0%	-10%	
	11500C	103.5	106.0	102.4	101.0	23.3	23.8	23.0	22.7	2%	-1%	5%	1%
4	**114323**	113.0	112.5	111.4	111.6	25.4	25.3	25.1	25.1	0%	0%	1%	1%
	114322	NT	111.9	NT	110.7	NT	25.2	NT	24.9			1%	
	114321	NT	118.7	NT	110.3	NT	26.7	NT	24.8			7%	
5	**114211**	118.2	115.3	110.6	114.8	26.6	25.9	24.9	25.8	-2%	4%	0%	7%
	114210	111.2	113.2	106.1	111.4	25.0	25.5	23.9	25.1	2%	5%	2%	5%
	114209	103.1	103.0	102.5	111.8	23.2	23.2	23.0	25.1	0%	9%	-8%	1%
	114208	112.4	111.3	102.4	99.0	25.3	25.0	23.0	22.3	-1%	-3%	12%	9%
	11400C	100.2	106.5	104.4	96.1	22.5	24.0	23.5	21.6	6%	-8%	10%	-4%
6	**113318**	117.3	NA	116.3	108.3	26.4	NA	26.2	24.4		-7%		1%
	113319	108.1	112.4	114.2	110.4	24.3	25.3	25.7	24.8	4%	-3%	2%	-5%
	113320	NT	NA	NT	104.2	NT	NA	NT	23.4				
	113021	115.6		117.0		26.0		26.3					-1%
	113020	120.6		114.8		27.1		25.8					5%
7	**112317**	NA		118.7		NA		26.7					
	112316	114.9		110.3		25.8		24.8					4%
	112315	105.2		106.6		23.7		24.0					-1%
	112019	111.2		NT		25.0		NT					
	112018	115.2		117.2		25.9		26.4					-2%
	112017	113.9		119.2		25.6		26.8					-5%
	112016	117.1		115.0		26.3		25.9					2%
	112015	101.7		106.3		22.9		23.9					-4%
	112014	118.3		115.1		26.6		25.9					3%
	112013	120.5		119.9		27.1		27.0					0%
8	**112012**	116.6		121.7		26.2		27.4					-4%
	112011	123.6		118.8		27.8		26.7					4%
	112010	116.3		118.1		26.1		26.5					-2%
	112009	117.7		118.8		26.5		26.7					-1%
	112008	118.3		112.4		26.6		25.3					5%
	112007	121.6		119.4		27.3		26.8					2%
9	**112006**	119.9		120.1		27.0		27.0					0%
	112005	118.4		116.6		26.6		26.2					2%
	112004	120.4		122.5		27.1		27.5					-2%
	112003	121.5		118.0		27.3		26.5					3%
	112002	120.6		114.6		27.1		25.8					5%
	112001	125.5		123.7		28.2		27.8					2%

Notes: Shaded cells: tested obstructed tendon segments (shade on cell frame only indicates obstruction as in Figure 1). NA: tendon segment tested but with data not suitable for analysis. NT: tendon segment not tested due to excessive obstruction or accessibility issues. Blank cells (in tendon listing) : no tendon segment in that category.

Table A2 Continued

Test Station	Tendon Type	Estimated Force (KN/strand)				Estimated Force (kips/strand)				Force Disparity (Difference/Average)			
		NE	SE	NW	SW	NE	SE	NW	SW	E (S-N)	W (S-N)	S (E-W)	N (E-W)
10/11	**112203**	108.3	102.4	105.3	109.9	24.3	23.0	23.7	24.7	-6%	4%	-7%	3%
	112202	108.5	107.7	102.1	108.9	24.4	24.2	22.9	24.5	-1%	6%	-1%	6%
	112201	96.8	96.2	108.2	99.2	21.8	21.6	24.3	22.3	-1%	-9%	-3%	-11%
	112200	106.2	101.6	108.9	102.2	23.9	22.8	24.5	23.0	-4%	-6%	-1%	-3%
	11200A	91.3	101.5	NA	90.3	20.5	22.8	NA	20.3	11%		12%	
12	**111001**		123.1		119.4		27.7		26.8			3%	
	111002		117.3		121.8		26.4		27.4			-4%	
	111003		123.4		117.5		27.7		26.4			5%	
	111004		119.6		120.8		26.9		27.2			-1%	
	111005		120.7		124.1		27.1		27.9			-3%	
	111006		122.7		119.2		27.6		26.8			3%	
	111007		114.0		110.1		25.6		24.8			3%	
	111008		124.8		116.8		28.1		26.3			7%	
	111009		115.7		116.9		26.0		26.3			-1%	
13	**111300**	117.2		114.3		26.3		25.7					2%
	111301	112.4		115.4		25.3		25.9					-3%
	111302	116.1		111.4		26.1		25.1					4%
	111303	115.3		113.3		25.9		25.5					2%
	111304	NA		112.6		NA		25.3					
	111010		115.3		118.6		25.9		26.7			-3%	
	111011		124.7		114.0		28.0		25.6			9%	
	111012		119.3		115.2		26.8		25.9			4%	
	111013		114.0		114.4		25.6		25.7			0%	
14	**111305**	112.7		113.5		25.3		25.5					-1%
	111306	111.4		113.0		25.0		25.4					-1%
	111307	114.4		120.6		25.7		27.1					-5%
	111308	110.1		115.5		24.8		26.0					-5%
	111309	113.6		118.9		25.5		26.7					-5%
	111014		119.9		NT		27.0		NT				
	111015		117.9		118.6		26.5		26.7			-1%	
	111016		114.6		113.9		25.8		25.6			1%	
	111017		NT		NT		NT		NT				
15	**111310**	105.7		108.5		23.8		24.4					-3%
	111311	109.2		107.4		24.6		24.1					2%
	111312	100.7		108.2		22.6		24.3					-7%
	111313	102.1		100.3		23.0		22.6					2%
	111314	NA		NA		NA		NA					
	111018		NT		NT		NT		NT				
	111019		NT		115.0		NT		25.9				
	111020		NT		NT		NT		NT				
	111021		114.4		120.7		25.7		27.1			-5%	

Mid Point

Table A2 Continued

Stations 30 to 16: From South End of Main Span to Mid Point.

Test Station	Tendon Type	Estimated Force (KN/strand)				Estimated Force (kips/strand)				Force Disparity (Difference/Average)			
		SE	NE	SW	NW	SE	NE	SW	NW	E (N-S)	W (N-S)	S (E-W)	N (E-W)
30	107211	119.0	124.8	112.1	119.8	26.7	28.1	25.2	26.9	5%	7%	6%	4%
	107210	99.8	95.1	107.6	104.2	22.4	21.4	24.2	23.4	-5%	-3%	-8%	-9%
	107209	104.5	109.8	104.9	97.7	23.5	24.7	23.6	22.0	5%	-7%	0%	12%
	107208	94.7	101.0	106.5	103.9	21.3	22.7	23.9	23.4	6%	-2%	-12%	-3%
	10700C	88.8	92.6	103.7	91.6	20.0	20.8	23.3	20.6	4%	-12%	-16%	1%
	107325	109.4		NA		24.6		NA					
	107324	128.9		NA		29.0		NA					
29	107323	116.7	113.2	116.8	115.5	26.2	25.4	26.3	26.0	-3%	-1%	0%	-2%
	107322	NT	NA	NT	110.2	NT	NA	NT	24.8				
	107321	NT	117.2	NT	132.1	NT	26.3	NT	29.7				-12%
28	108211	102.8	97.5	96.1	95.9	23.1	21.9	21.6	21.5	-5%	0%	7%	2%
	108210	101.4	98.0	93.6	95.8	22.8	22.0	21.0	21.5	-3%	2%	8%	2%
	108209	99.1	99.5	104.2	99.4	22.3	22.4	23.4	22.3	0%	-5%	-5%	0%
	108208	96.5	97.3	92.1	95.3	21.7	21.9	20.7	21.4	1%	3%	5%	2%
	10800C	82.0	89.8	86.2	88.6	18.4	20.2	19.4	19.9	9%	3%	-5%	1%
27	108323	127.9	121.9	NT	120.6	28.7	27.4	NT	27.1	-5%			1%
	108322	109.9	111.4	107.6	110.3	24.7	25.1	24.2	24.8	1%	2%	2%	1%
	108321	106.1	106.4	NT	112.7	23.8	23.9	NT	25.3	0%			-6%
26	109211	118.7	116.2	102.6	97.8	26.7	26.1	23.1	22.0	-2%	-5%	15%	17%
	109210	101.3	97.6	112.2	98.2	22.8	22.0	25.2	22.1	-4%	-13%	-10%	-1%
	109209	98.3	94.7	96.3	92.6	22.1	21.3	21.7	20.8	-4%	-4%	2%	2%
	109208	91.1	84.8	87.6	85.1	20.5	19.1	19.7	19.1	-7%	-3%	4%	0%
	10900C	81.7	84.3	85.9	87.2	18.4	18.9	19.3	19.6	3%	2%	-5%	-3%
25	109318	123.4	112.0	119.9	114.9	27.7	25.2	27.0	25.8	-10%	-4%	3%	-2%
	109319	NT	114.9	NT	111.3	NT	25.8	NT	25.0				3%
	109320	NT	115.3	NT	NA	NT	25.9	NT	NA				
	109021	115.1		112.4		25.9		25.3				2%	
	109020	NT		115.8		NT		26.0					
24	110317	113.2		123.1		25.4		27.7				-8%	
	110316	117.3		118.9		26.4		26.7				-1%	
	110315	119.0		117.8		26.7		26.5				1%	
	110019	117.6		NT		26.4		NT					
	110018	116.8		NT		26.3		NT					
	110017	NT		NT		NT		NT					
	110016	NT		111.9		NT		25.2					
	110015	115.8		113.3		26.0		25.5				2%	
	110014	116.4		117.5		26.2		26.4				-1%	
	110013	121.6		120.7		27.3		27.1				1%	
23	110012	118.3		121.4		26.6		27.3				-3%	
	110011	120.2		121.2		27.0		27.2				-1%	
	110010	117.4		120.4		26.4		27.1				-3%	
	110009	119.1		118.1		26.8		26.6				1%	
	110008	118.3		116.0		26.6		26.1				2%	
	110007	113.6		117.8		25.5		26.5				-4%	
22	110006	120.6		116.7		27.1		26.2				3%	
	110005	124.6		121.7		28.0		27.4				2%	
	110004	119.2		112.5		26.8		25.3				6%	
	110003	127.3		125.6		28.6		28.2				1%	
	110002	121.5		115.4		27.3		25.9				5%	
	110001	125.6		125.7		28.2		28.3				0%	

Table A2 Continued

Test Station	Tendon Type	Estimated Force (KN/strand)				Estimated Force (kips/strand)				Force Disparity (Difference/Average)			
		SE	**NE**	**SW**	**NW**	**SE**	**NE**	**SW**	**NW**	**E (N-S)**	**W (N-S)**	**S (E-W)**	**N (E-W)**
20/21	111203	106.0	115.8	108.1	122.2	23.8	26.0	24.3	27.5	9%	12%	-2%	-5%
	111202	106.2	106.8	113.2	102.6	23.9	24.0	25.5	23.1	1%	-10%	-6%	4%
	111201	100.6	112.3	103.1	NA	22.6	25.2	23.2	NA	11%		-3%	
	111200	100.3	105.2	100.9	NA	22.5	23.6	22.7	NA	5%		-1%	
	11100A	84.4	96.8	91.5	95.8	19.0	21.8	20.6	21.5	14%	5%	-8%	1%
19	111001		118.6		127.4		26.7		28.6				-7%
	111002		122.2		116.3		27.5		26.1				5%
	111003		130.7		124.2		29.4		27.9				5%
	111004		123.3		121.5		27.7		27.3				1%
	111005		115.5		117.1		26.0		26.3				-1%
	111006		115.4		119.1		25.9		26.8				-3%
	111007		117.9		115.5		26.5		26.0				2%
	111008		116.0		115.4		26.1		25.9				1%
	111009		117.7		117.9		26.5		26.5				0%
18	111300	NA		114.1		NA		25.7					
	111301	115.3		109.7		25.9		24.7				5%	
	111302	116.0		111.0		26.1		25.0				4%	
	111303	109.5		110.6		24.6		24.9				-1%	
	111304	113.2		107.9		25.5		24.3				5%	
	111010		114.8		117.0		25.8		26.3				-2%
	111011		117.8		NT		26.5		NT				
	111012		NT		122.2		NT		27.5				
	111013		NT		NT		NT		NT				
17	111305	113.3		NA		25.5		NA					
	111306	113.9		110.3		25.6		24.8				3%	
	111307	111.3		114.8		25.0		25.8				-3%	
	111308	117.8		117.6		26.5		26.4				0%	
	111309	113.4		112.1		25.5		25.2				1%	
	111014		NT		119.7		NT		26.9				
	111015		NT		119.9		NT		27.0				
	111016		NT		115.9		NT		26.1				
	111017		NT		NT		NT		NT				
16	111310	110.1		113.6		24.8		25.5				-3%	
	111311	107.7		108.2		24.2		24.3				0%	
	111312	107.6		108.3		24.2		24.4				-1%	
	111313	99.5		102.5		22.4		23.0				-3%	
	111314	NA		NA		NA		NA					
	111018		NT		NT		NT		NT				
	111019		NT		NT		NT		NT				
	111020		NT		117.6		NT		26.4				
	111021		120.0		117.4		27.0		26.4				2%

Mid Point

UNIT CONVERSIONS TABLE

CONVERSION FACTORS, US CUSTOMARY TO METRIC UNITS

Multiply	***by***	***to obtain***
inch	25.4	mm
foot	0.3048	meter
square inches	645	square mm
cubic yard	0.765	cubic meter
pound/cubic yard	0.593	kg/cubic meter
inch^2/year	2.046 10^{-7}	cm^2/sec
gallon/cubic yard	4.95	liter/cubic meter
standard cubic feet/hour	466.67	ml/minute
ounces	28.35	gram
pound	0.454	kilogram
pound (lb)	4.448	newtons
kip (1000 lb)	4.448	kilo newton (kN)
kilo newton (kN)	0.22481	kip (1000 lb)
pound/in^2	0.0069	MPa
kip/in^2	6.895	MPa
ft-kip	1.356	kN-m
in-kip	0.113	kN-m