Skyline tension analysis in yarding operation: case studies in Italy

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Abstract:
A great deal of research in Italy has been directed toward field measurement of cable tension in cable yarding systems in order to facilitate initial tensioning of unloaded skylines or to provide means for avoiding overloading. Unfortunately, at present many cableway extraction systems are just based on the operators' experience and no calculation of the tension in skylines is carried out. This paper describes results of skyline tension analysis carried out in Italy in cable yarding operations or in lines set up in an experimental field. Measures on the skyline tension were recorded using load cells placed between rope and anchors. The data refer to 69 cableways, both single and multi-span. Tension variation was related to: initial tensioning, load, and line geometrical features. Data analysis provided functions to describe the tension variation in skylines and important recommendations for a safer use of the cableway extraction systems.

Keywords: cable yarding, standing skyline, payload analysis, skyline tension.

1 Introduction

Cable yarding plays a key role in steep terrain logging for an efficient forest management (Stampfer et al., 2009) and for reducing environmental impact. This system may reduce soil and water disturbance (Camp, 2002) and minimize damage to the residual stand (Kendrick and Sessions, 1991; Thompson et al., 1998).

In cable logging planning, one of the most important aspects is to determine the initial tensioning of skyline (unloaded tension) and the maximum log load (load weight) in relation to the defined constraints due to the line features. Tensions in the skyline must be within allowable limits when the carriage is located anywhere on the line (Brown and Sessions, 1996).

Analytical iterative methods for determining the maximum payload in standing skyline, based on different assumption, have been developed by many authors (Zingoli, 1959; Giordano, 1967; Falk, 1981; Kendrick and Sessions, 1991; Brown and Sessions, 1996). However, other authors stated that the result of analytical methods may have a low level of accuracy due to the high variability of the factors involved (Pestal, 1961), such as the elasticity of intermediate supports, that may balance the tension variation in the skyline. Empirical methods to determine initial tensioning and maximum log load (Pestal, 1961) or for measuring skyline tension and avoiding overloads (Sessions, 1976) have been also suggested. Little effort has been directed towards field measurements of skyline tension, so that information on tension increase due to the load in single and multi-span cable yarder is still limited.

This paper reports a summary of a-decade investigations carried out in Italy on standing skyline tensions in forest cable yarder based on gravitational system (Currò et al., 1989; Fabiano et al., 2002a, 2002b; Piegai and Verani 1993; Piegai et al.,1997; Piegai 1997). Sixty-nine lines based on gravitational extraction system, including both single-span and multi-span lines, were tested in experimental fields or forest yards. Data processing allowed us to determine the best functions to describe the skyline behaviour with different line designs, loads and initial tensioning. The results were used to give practical instructions to increase work safety with cable cranes.

2 Material and Methods

2.1 Ropes and geometrical features of the lines

Tension measurements were carried out on several ropes. The diameter of the ropes was 6 - 34 mm. The main strand construction was Seale, Warrington-Seale and Warrington, and the core of the ropes was mainly fiber. More details on the rope characteristics are shown in table 1.

Table 1: Specifications of skyline ropes applied in the study

Line	Ø	Strand construction	Wire	Core	Steel strength		Breaking strength C.R.		Weight	
N.	mm		N.		kg/mm²	N/mm²	kg	kN	kg/m	N/m
1 ÷ 5	6	Seale	114	Fiber	180	1770	2140	21.0	0.137	1.344
6 ÷ 9	12	Warrington-Seale	216	Metal	180	1770	9250	90.7	0.600	5.884
10 ÷ 13	14	Seale	114	Fiber	180	1770	11700	114.5	0.730	7.159
14 ÷ 23	14	Warrington-Seale	216	Metal	180	1770	12600	123.5	0.780	7.649
24 ÷ 35	16	Seale	114	Fiber	180	1770	15200	149.5	0.960	9.414
36 ÷ 46	18	Seale	114	Fiber	180	1770	19300	189.2	1.210	11.866
47 ÷ 53	20	Warrington-Seale	216	Fiber	180	1770	23800	233.6	1.520	14.906
54 ÷ 55	22	Seale	114	Fiber	180	1770	28800	282.7	1.800	17.652
56 ÷ 57	24	Seale	114	Fiber	180	1770	34300	336.4	2.150	21.084
58 ÷ 60	24	Warrington	114	Fiber	180	1770	34300	336.4	2.150	21.084
61	26	Seale	114	Fiber	180	1770	40300	394.9	2.520	24.713
62	26	Seale	114	Fiber	200	1960	44600	437.0	2.520	24.713
63	28	Warrington	114	Fiber	180	1770	46700	457.9	2.920	28.635
64	28	Seale	114	Fiber	180	1770	46700	457.9	2.920	28.635
65 e 67	30	Seale	114	Fiber	180	1770	53600	525.7	3.370	33.048
66	30	Warrington	114	Fiber	180	1770	53600	525.7	3.340	32.754
68	32	Warrington-Seale	186	Fiber	180	1770	61000	598.1	6.670	65.410
69	34	Warrington-Seale	186	Fiber	180	1770	68900	675.2	4.160	40.796

Table 2: Geometrical features of the single-span lines monitored in the study

Line N.	Rope Ø mm	Length m	Slope %		Line N.	Rope Ø mm	Length m	Slope %
1	6	105	10		33	16	258	23
6	12	105	10		34	16	364	28
10	14	105	10		35	16	365	45
14	14	149	50		36	18	153	36
15	14	152	35		37	18	163	27
16	14	163	27		38	18	179	19
17	14	167	40		39	18	215	42
18	14	175	36		40	18	225	35
19	14	179	18		41	18	238	30
20	14	214	41		42	18	258	23
21	14	224	34		43	18	364	28
22	14	237	29		44	18	365	45
23	14	257	22		45	18	421	32
24	16	150	51		46	18	454	24
25	16	153	36		47	20	215	42
26	16	163	27		48	20	225	36
27	16	175	37		49	20	238	30
28	16	179	19		50	20	258	24
29	16	184	33		51	20	365	45
30	16	215	42		52	20	421	32
31	16	225	35		53	20	454	24
32	16	238	30		65	30	680	37

Forty-four cable yarders were single-span. The length of the lines was 105-680 m and the slope of the spans varied from 10 to 50% (Table 2). Twenty-five cable yarders were multi-span. Number of spans, total length of each line, and length and slope of each span are shown in table 3.

Table 3: Geometrical features of the multi-span lines monitored in the study

Line N.	Wire rope Ø mm	Total Length m	Av. Slope %	Span N.1 Length m	Span N.1 Slope %	Span N.2 Length m	Span N.2 Slope %	Span N.3 Length m	Span N.3 Slope %	Span N.4 Length m	Span N.4 Slope %	Span N.5 Length m	Span N.5 Slope %
2	6	105	10	57	11	48	9						
3	6	105	10	34	11	71	10						
4	6	105	10	23	11	82	10						
5	6	105	10	23	11	34	11	48	9				
7	12	105	10	27	11	78	10						
8	12	105	10	57	11	48	9						
9	12	105	10	27	11	29	11	49	9				
11	14	105	10	27	11	78	10						
12	14	105	10	57	11	48	9						
13	14	105	10	27	11	29	11	49	9				
54	22	1381	27	330	33	151	25	211	25	645	26	44	25
55	22	377	26	13	43	312	26	52	19				
56	24	893	36	20	0	373	41	449	40	17	26	34	15
57	24	892	36	392	39	449	40	17	26	34	15		
58	24	259	57	69	61	66	72	84	71	15	19	25	-4
59	24	358	29	11	44	81	36	114	27	115	28	37	16
60	24	303	30	270	33	33	9						
61	26	520	36	493	36	27	40						
62	26	1062	39	101	43	961	40						
63	28	287	31	63	35	204	29	20	25				
64	28	449	21	116	34	222	28	50	22	61	-16		
66	30	719	43	52	45	315	43	297	48	55	20		
67	32	1155	39	88	38	474	35	423	43	170	38		
68	32	520	19	47	38	364	19	75	17	34	-9		
69	34	1079	33	1000	34	17	33	32	36	30	12		

2.2 Tensions measurement

For measuring skyline tensions, the following instruments were used:

- HBM load cells: two 20-t cells (196kN), one 5-t cell (49kN), one 3-t cell (29kN), one 1-t cell (10kN);
- three digital strain meters (feeder/amplifier), model HBM DMD 20 (2) and DMD20A (1);
- two Delta-T (Delta-T Device LTD) data loggers.

Tension in skyline was measured placing the load cells between skyline and anchors. When possible, the load cells were mounted both at uphill and downhill anchors. In other cases only one load cell was positioned at downhill or uphill anchor. The load cells were connected to the digital strain meters. The data logger recorded the data from the amplifier at a sampling interval of 1 second.

On each cable yarder line, the tensions were measured varying the initial tensioning (Tscar) and the load (P). The values of initial tensioning and the range of loads are shown in table 4 and 5. The maximum tension values of loaded skyline (Tcar), recorded for each line at different Tscar and P, were used in the data analysis.

2.3 Data analysis

The data analysis was carried out by means of a general description of the skyline behaviour under different conditions both for single span and multi span lines and a regression analysis.

Table 4: Values of initial tensioning (Tscar) and load weight (P) applied on the single-span lines

Line	Skyline		Initial tensioning	Load weight range	Load cells/Anchors position
N.	Ø mm	Breaking strenght kN	kN	daN	
1	6	21.0	2.0 - 3.9 - 5.9 - 7.8 - 9.8 - 11.8 - 13.7	25 - 150	Downhill (Dh)
6	12	90.7	14.7 - 19.6 - 24.5	43 - 334	Uphill (Uh)/ Downhill (Dh)
10	14	114.5	19.6 - 24.5	43 - 284	Uphill (Uh)/ Downhill (Dh)
14 ÷ 23	14	123.5	19.6 - 24.5 - 29.4 - 34.3	162 - 686	Uphill (Uh)/ Downhill (Dh)
24 ÷ 35	16	149.5	24.5 - 29.4 - 34.3 - 39.2 - 44.1	162 - 983	Downhill (Dh)
36 ÷ 46	18	189.2	29.4 - 34.3 - 39.2 - 44.1 - 49.1	180 - 1073	Downhill (Dh)
47 ÷ 53	20	233.6	39.2 - 46.1 - 52.0 - 58.9	233 - 1229	Downhill (Dh)
65	30	525.7	84.4 - 113.8 - 143.2	542 - 2136	Uphill (Uh)/ Downhill (Dh)

Table 5: Values of initial tensioning (Tscar) and load weight (P) applied on the multi-span lines

Line	Skyline		Initial tensioning	Load weight range	Load cells/Anchors position
N.	Ø mm	Breaking strenght kN	kN	daN	
2 ÷5	6	21.0	2.0 - 3.9 - 5.9 - 7.8 - 9.8 - 11.8 - 13.7	25 - 150	Downhill (Dh)
7 ÷ 9	12	90.7	14.7 - 19.6 - 24.5	43 - 335	Uphill (Uh)/ Downhill (Dh)
11 ÷ 13	14	114.5	19.6 - 24.5	42 - 336	Uphill (Uh)/ Downhill (Dh)
54	22	282.7	78.5 - 83.4 - 89.3 - 94.2	739 - 1641	Downhill (Dh)
55	22	282.7	49.1 - 60.8 - 68.7 - 76.5	196 - 1124	Uphill (Uh)/ Downhill (Dh)
56	24	336.4	112.8 - 126.5 - 140.3 - 151.1	269 - 1743	Downhill (Dh)
57	24	336.4	83.4 - 101.0 - 122.6	269 - 1716	Downhill (Dh)
58	24	336.4	60.8 - 74.6 - 86.3 - 109.9	365 - 1044	Uphill (Uh)/ Downhill (Dh)
59	24	336.4	69.7 - 84.4 - 98.1 - 111.8	269 - 1810	Uphill (Uh)/ Downhill (Dh)
60	24	336.4	58.9 - 78.5 - 88.3 - 103.0	792 - 2239	Uphill (Uh)/ Downhill (Dh)
61	26	394.9	84.4 - 93.2 - 103.0 - 113.8 - 120.7	255 - 1295	Downhill (Dh)
62	26	437.0	83.4 - 100.1 - 113.8 - 128.5	878 - 2483	Uphill (Uh)
63	28	457.9	94.2 - 117.7 - 133.4 - 140.3	949 - 3784	Uphill (Uh)/ Downhill (Dh)
64	28	457.9	88.3 - 97.1 - 105.9 - 115.8	542 - 1915	Uphill (Uh)
66	30	525.7	98.1 - 117.7 - 132.4 - 142.2	979 - 3212	Uphill (Uh)/ Downhill (Dh)
67	30	525.7	93.2 - 121.6 - 145.2 - 147.2	542 - 2423	Downhill (Dh)
68	32	598.1	105.0 - 115.8 - 125.6 - 133.4	793 - 2846	Uphill (Uh)/ Downhill (Dh)
69	34	675.2	122.6 - 137.3 - 157.0 - 176.6	553 - 2389	Uphill (Uh)/ Downhill (Dh)

In the descriptive analysis the following parameters were used:

- the maximum skyline tension (Tmax). Tmax is calculated as ratio between the breaking strength of the rope and the safety factor, that usually varies from 2.5 to 3.5;

- The initial tensioning (Tscar), which in empirical methods (Pestal, 1961; Hippoliti et al., 1984) is a function of Tmax: Tscar = n × Tmax , where n = tension factor.

- The maximum load (Pmax), that in empirical methods (Pestal, 1961; Hippoliti et al.,1984) is a function of Tmax: Pmax = y × Tmax, where y = load factor;

- The tension in the loaded skyline (Tcar). It is the result of initial tensioning (Tscar) and tension increment (ΔT) due to the load: Tcar= Tscar + ΔT, where Tcar must be < Tmax;

- The tension increment index (TI): TI= ΔT/P.

Multiple linear regression was applied to find the relationship between Tcar and the other parameters. The regression analyses were applied separately for single and multi-span lines.

Considering the high variation range of tensions and loads, due to the different diameters (from 6 to 34 mm) of the ropes used in the study, Tcar (dependent variable), Tscar, and P values recorded for each rope were indexed dividing them by the breaking strength (CR) of the rope. As independent variable also the geometrical features of the lines were taken into account. In detail we considered:

- the span length (SL) and the span slope (Slope) in single-span lines;

- the span length (SL) and the ratio between the span and line length (Span%) in multi-span lines.

Regression analyses were carried out by the Statgraphics 5.1 software.

3 Results

3.1 Descriptive analysis

The data analysis showed that the tensions in skyline ropes depend on several factors; the most important ones are:

- initial tensioning (Tscar) related to the rope specifications;

- load weight (P);

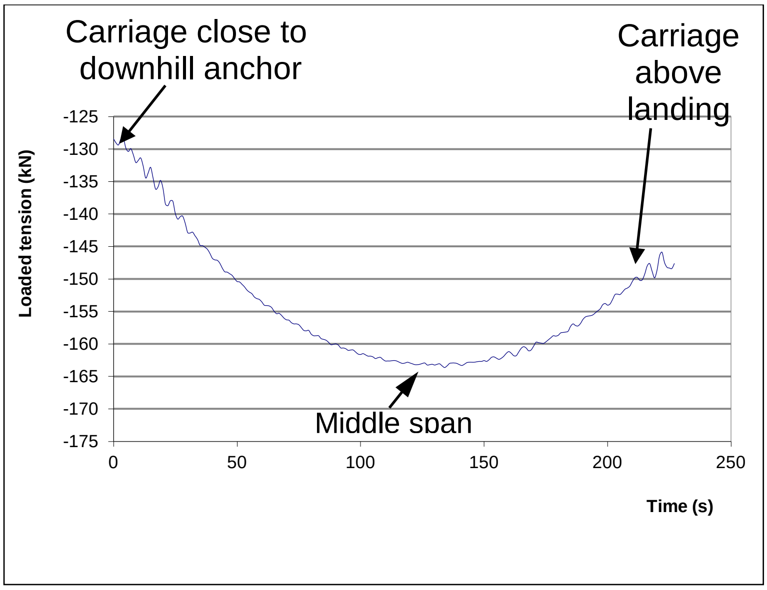
- geometrical features of the line.

In the single-span lines, the data highlighted that:

- the difference in the values of the tension measured between uphill and downhill anchor in unloaded single span skyline varied according to the theoretical method suggested by many authors (Pestal 1961; Giordano 1967; Samset 1979). That difference may be calculated multiplying the anchors drop (elevation gap in m) and the skyline rope weight per meter (kg/m; N/m);

- loaded skyline tension increases progressively when the loaded carriage moves from the anchors and reaches the maximum value when the carriage is in the middle of the span (Figure 1);

Figure 1 – Single-span line. Example of loaded skyline tension in relation to carriage positions



- Tscar and P being equal, the higher the span length, the higher the skyline tension increment (ΔT=Tcar - Tscar);

- span length and P being equal, ΔT decreases when Tscar increases;

- Tscar being equal, ΔT raises when P increases. This response is higher when low Tscar are applied.

In case of low Tscar (Tscar=1/3.5 Tmax), the TI values are 4.5 - 5. These values decrease to 1 – 1.5 for very high Tscar (Tscar = 2Tmax). Usually the TI value varies between 3 and 4.

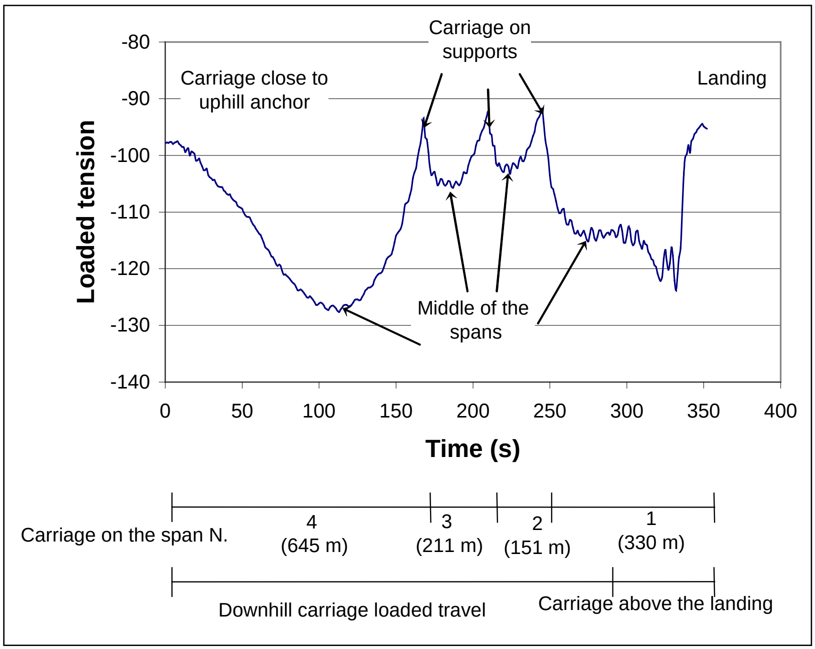
Nevertheless, when P being equal, the higher Tscar the higher Tcar, even though the higher Tscar the lower ΔT and TI.

In the multi - span lines the data highlighted that:

- the skyline tensions depend on the span length and they peak when the load is applied on the middle of the longest span of the line (Figure 2);

- the longest span location on the line (uphill, downhill or in the middle) does not affect the tension increment;

Figure 2 – Multi-span line. Example of loaded skyline tension in relation to carriage positions 4 spans line



- when the carriage travels on the saddle of the intermediate supports, the loaded skyline tension gets closer to the value of Tscar because the load weights on the intermediate supports;

- Tscar and P being equal, Tcar results lower than Tcar recorded in single-span lines both when the total length of the single and multi–span lines are equal and when the longest span of a multi-span line is equal to the length of a single-span line. This is due to the high resilience given by the intermediate supports to the whole cable yarder structure, as suggested by other authors (Pestal, 1961; Hippoliti et al., 1984).

- Tscar and P being equal, the higher the span length, the higher ΔT;

- for the same P value, the higher Tscar, the lower ΔT;

- for the same Tscar, the higher P, the higher ΔT. This response is higher when low Tscar are applied.

Generally in multi-span lines, both for high and low mounting tension, the maximum TI values recorded were lower than the TI recorded in the single span lines. The TI values were between 2.5 and 3 in two-span lines and between 2 and 2.5 in three or more span lines. The higher Tscar, the lower TI.

3.2 Regression analysis

Single-span lines

By considering several independent variables (Tscar/CR; P/CR; SL and Slope), the following multiple linear regression models were applied to both uphill and downhill anchors data:

1) $Tcar/CR = a + (b \times Tscar/CR) + (c \times P/CR)$

2) $Tcar/CR = a + (b \times Tscar/CR) + (c \times P/CR) + (d \times SL)$

3) $Tcar/CR = a + (b \times Tscar/CR) + (c \times P/CR) + (d \times SL) + (e \times Slope)$

The output of the regression analyses (Table 6 and 7) describes the relationship between Tcar/CR and the independent variables.

Since p<0.001 for all models, there was a statistical significant relationship between the variables. The high value of R-squared indicated that all the models explain more than 97% of the Tcar/CR variability.

The linear regression models showed lower errors for the uphill anchor.

Table 6 – Output of the regression analyses for single-span lines – downhill anchor – N.=1557, R² = coefficient of determination; S.E. = Standard error

Function	Factors					R^2	S.E.	Predicted/Observed Max difference (%)	
	a Cost	b x TS/CR	c x P/CR	d x SL	e x Slope			+	-
1	0.05314	0.75921	3.50972			0.977	0.0094	10.7	-11.3
2	0.03770	0.76970	3.54544	0.00005		0.983	0.0080	11.9	-11.6
3	0.05517	0.75512	3.54768	0.00005	-0.04807	0.988	0.0066	11.6	-11.2

Table 7 - Output of the regression analyses for single-span lines – uphill anchor – N.=114, R² = coefficient of determination; S.E. = Standard error

Function	Factors					R^2	S.E.	Predicted/Observed Max difference (%)	
	a cost	b x TS/CR	c x P/CR	d x SL	e x Slope			+	-
1	0.04220	0.79888	3.47109			0.970	0.0083	5.3	-5.9
2	0.04555	0.75152	3.43653	0.00003		0.985	0.0057	5.9	-5.1
3	0.04954	0.75036	3.53831	0.00004	-0.02059	0.989	0.0051	6.1	-3.4

Multi-span lines

Multiple linear regression analyses were carried out using Tcar/CR measured when the load was in the longest span. In fact, the maximum tension increments occur when the load is in the middle of the longest span. The longest span affects all the line behaviour.

By considering several independent variables (Tscar/CR; P/CR; SL; Span%), the following multiple linear regression models were applied to both uphill and downhill anchors data:

4) Tcar/CR = a + (b×Tscar/CR) + (c×P/CR)

5) Tcar/CR = a + (b×Tscar/CR) + (c×P/CR) + (dxSL)

6) Tcar/CR = a + (b×Tscar/CR) + (c×P/CR) + (e×Span%)

7) Tcar/CR = a + (b×Tscar/CR) + (c×P/CR) + (d×SL) + (e×Span%)

The output of the regression analyses (Table 8 and 9) describes the relationship between Tcar/CR and the independent variables.

Since p<0.001 for all models, there was a statistical significant relationship between the variables. The high value of R-squared indicated that all the models explain more than 92% of the Tcar/CR variability.

The linear regression models showed lower errors for the uphill anchor.

Table 8 – Output of the regression analyses for multi-span lines – downhill anchor – data related to the longest span – N.= 1485, R² = coefficient of determination; S.E. = Standard error

Function	Factors					R^2	S.E.	Predicted/Observed Max difference (%)	
	a Cost	b TS/CR	c P/CR	d Span%	e SL			+	-
4	0.04538	0.81559	2.57603			0.965	0.0228	21.4	-18.8
5	0.03299	0.82131	2.61359		0.00004	0.971	0.0209	15.0	-19.7
6	-0.01212	0.82432	2.57296	0.09004		0.984	0.0156	16.6	-14.0
7	-0.01371	0.82648	2.59204	0.08282	0.00002	0.985	0.0150	16.9	-15.2

Table 9 – Output of the regression analyses for multi-span lines – uphill anchor – data related to the longest span – N.= 587, R² = coefficient of determination; S.E. = Standard error

Function	Factors					R^2	S.E.	Predicted/Observed Max difference (%)	
	a Cost	b TS/CR	c P/CR	d Span%	E SL			+	-
4	0.03451	0.79589	3.09188			0.922	0.0190	19.0	-10.3
5	0.03089	0.78088	2.91798		0.00004	0.954	0.0145	15.5	-10.8
6	-0.02472	0.85139	2.86113	0.08345		0.979	0.0099	9.9	-9.3
7	-0.01850	0.84105	2.84614	0.07344	0.00001	0.980	0.0097	10.2	-9.2

4 Discussion

A different behavior of the single- and multi-span lines was observed. Generally, multi-span lines show lower skyline tension increment, Tscar and P being equal.

All the independent variables applied in the model affect the skyline rope behaviour both in single-span (Tscar, P, SL and Slope) and in multi-span lines (Tscar, P, SL and Span%).

The behaviour of multi-span skylines is similar to those of single-span lines when the longest span reaches almost the total length of the line.

All the multiple regression models gave good results ($p<0.001$). In single-span lines, the best results were obtained by function 3 for uphill anchor, even though it may overestimate Tcar/CR. In multi-span lines, the best results were obtained by function 7 for uphill anchor, even though the predicted results showed a lower accuracy compared to those of single-span function 3.

The application of the multiple regression models for single-span lines highlighted that:

1. initial tensioning should vary between 3/5÷2/3 Tmax (that corresponds to 0.20 and 0.22 Tscar/CR);
2. the load weight should vary between:
   - 1/11-1/9 Tmax (0.030-0.035 P/CR) to respect a safety factor S=3. The higher P (1/9 Tmax), the lower Tscar (3/5 Tmax);
   - 1/7-1/6 Tmax (0.055-0.050 P/CR) to respect a safety factor S=2.5. The higher P (1/6 Tmax), the lower Tscar (3/5 Tmax);
3. long lines permit lower load than short lines;
4. in single-span lines, the tension increment index (TI) is usually between 3.5 and 4.5 depending on the length of the line, with higher increments on long lines and low Tscar. On over 700 metres line length, TI may be higher than 5.

The application of multiple regression models for the multi-span lines highlighted that:

- respecting the safety factors 3 and 2.5, multi-span lines permit higher Tscar and P than single-span lines;
- when the length of the main span is 2/3 of the total length of the line, tension increments are very similar to the values recorded in single-span lines. Nevertheless, applying mounting tensions similar to the maximum Tscar for single-span lines (2/3 Tmax; TS/CR=0.220), higher P are permitted (P/CR=0.035 - 1/9 Tmax rather than 0.030 - 1/11 Tmax). Higher Tscar (TS/CR=0.250 - 3/4 Tmax) needs a P reduction (P/CR=0.030 - 1/11 Tmax);
- higher Tscar (TS/CR=0.250 - 3/4 Tmax) and P are permitted (P/CR=0.035-0.040 – load factor 1/9-1/8) in case of two equal-length spans on the line or when the main span length is lower than 40-60% of the total length of the line;
- in case of 3 or more spans on the line (main span length < 30-40% of the total length of the line), higher Tscar are permitted (TS/CR=0.270 - 4/5 di Tmax) with P equal to 1/9 Tmax (P/CR=0.035).

On multi-span lines, generally, it is important to apply a higher mounting tension than in single-span lines to avoid skyline deflections on intermediate supports and troubles with the carriage traveling on the support saddles.

In conclusion, the linear regressions models allowed to suggest rules for a safer use of standing skyline, on the basis of field measurements. In particular, a safety factor equal to 3 is recommended and corresponds to the factor that is usually adopted in forest operation (Hippoliti et al., 1984). When the safety factor is lower than 3, tension monitoring systems or self-regulating mechanisms, such as adjustable skyline brakes or tensioning devices, are recommended.

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