HOLOS
ISSN 1807 - 1600

ANALYSIS OF NODAL STRESSES IN BLÉVOT AND FRÉMY TESTS

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Submitted May 22, 2023 - Accepted December 31, 2023
DOI: 10pts.15628/holos.2023.10840

ABSTRACT

For design of pile caps, strut and tie models are often adopted and have ample experimental support. Current norms present resistance limits different from the formulations proposed by the studies of Blévot and Frémy (1967), presenting conservative values. Thus, in order to analyze the behavior of the stresses in the nodal regions, an analytical analysis of the pile caps tested by Blévot and Frémy (1967) was carried out using the limits presented by the French researchers and those recommended by the main standard codes, in addition to other limits proposed by other researchers. With the results found, divergences in the results were observed.

KEYWORDS: Nodal stress, pile caps, strut-and-tie models.

ANÁLISE DAS TENSÕES NODAIS NOS ENSAIOS DE BLÉVOT E FRÉMY

RESUMO

Para o cálculo e dimensionamento de blocos sobre estacas, os modelos analíticos adotados com maior frequência são baseados em modelos tridimensionais de bielas e tirantes, estes que possuem um grande amparo experimental. As normatizações atuais apresentam limites de resistência diferentes das formulações propostas pelos estudos de Blévot e Frémy (1967), apresentando valores conservadores. Dessa forma, com o intuito de analisar o comportamento das tensões nas regiões nodais, realizou-se uma verificação analítica dos blocos sobre estacas ensaiados por Blévot e Frémy (1967) utilizando-se os limites apresentados pelos pesquisadores franceses, os recomendados pelas principais normatizações vigentes e os limites propostos por outros pesquisadores. Com os resultados encontrados foi observado divergências nos resultados.

PALAVRAS-CHAVE: Blocos sobre estacas, Modelos de bielas e tirantes, Tensões nodais.

1 INTRODUCTION

For the calculation and design of pile caps, linear and nonlinear three-dimensional models, as well as strut-and-tie models, are adopted. The latter is the most recommended and widely used model, as it is well-supported by experimental evidence, including tests conducted by Blévot and Frémy (1967).

The three-dimensional strut-and-tie method considers the existence of a truss inside the pile cap, composed of tension and compression bars connected through nodes, responsible for transmitting forces from the column to the piles. The forces acting on the compressed bars of the truss (struts) are resisted by concrete, while the forces acting on the tension bars (ties) are resisted by reinforcements.

Blévot (1957), Blévot and Frémy (1967) studied the behavior of pile caps through experimental analysis of pile caps with different numbers of piles. They concluded that the proposed models provided a consistent framework for the analysis and design of pile caps, suggesting safety limits for the inclination angle of struts and stresses in nodal regions.

Since then, the analysis of pile caps has been extensively studied, with various researchers proposing different limits for the elements, considering or not the longitudinal reinforcement ratio of the columns, depending on how the strut-and-tie method was applied.

1.1 Justification

The Brazilian Association of Technical Standards, ABNT NBR 6118 (2014), although not defining a specific method for the design of pile caps, suggests the adoption of the strut-and-tie method due to its idealization of the structural behavior of the caps.

ABNT NBR 6118 (2014), along with international standards, provides limits for stresses in nodal regions that align with the limits presented by Blévot and Frémy (1967). Therefore, this work is justified by the existence of discrepancies regarding stress limits and verification of pile caps.

This study serves as a complement to the work carried out by Tomaz, Delalibera, Giongo, and Gonçalves (2018).

1.2 Objective

The objective of this study was to evaluate the nodal stresses obtained from the tests conducted by Blévot and Frémy (1967), comparing them with the limits proposed by Schlaich and Schäfer (1991), as well as existing normative limits. Additionally, the study considered the multiaxial effect of concrete in the upper nodal zone, conducting a comparative analysis between these limits and the experimental results.

2 EXPERIMENTAL RESULTS USED

Blévot and Frémy (1967) proposed a methodology for calculating internal forces in pile caps and conducted tests with both reduced-scale models and full-scale models.

In total, 116 pile caps were tested, including 51 reduced-scale models of pile caps for four piles, 8 full-scale pile caps for four piles, 37 reduced-scale models of pile caps for three piles, 8 full-scale pile caps for three piles, 6 reduced-scale models of pile caps for two piles, and 6 full-scale pile caps for two piles.

The initial tests were conducted on reduced-scale models to determine the safety coefficients leading to the application of the strut-and-tie method. The models exhibited failures in the lower reinforcements due to punching shear at the center of the pile cap and/or near the piles. Additionally, various reinforcement configurations, theoretically effective in terms of safety against rupture and cracking, were analyzed.

Following the initial tests, Blévot and Frémy (1967) progressed to tests on full-scale models, incorporating observations from the reduced-scale models and responses regarding the effectiveness of different types of reinforcements. The results of the full-scale tests generally confirmed the findings from the reduced-scale models.

For both sets of tests, factors such as pile cap height, arrangement of reinforcements, and steel characteristics were examined. Material properties were controlled, and tests on concrete compression strength and tensile strength of the steels used were performed. Test results were recorded, emphasizing information relevant to this study, such as the inclination of struts relative to the horizontal plane, failure loads, and modes of failure.

The objective of the study was stress calculation, and for this purpose, the model developed by Blévot and Frémy (1967) was employed. Using this model requires the calculation of forces acting on the struts and the reactions at the piles, maintaining force equilibrium as presented in Figure 1.

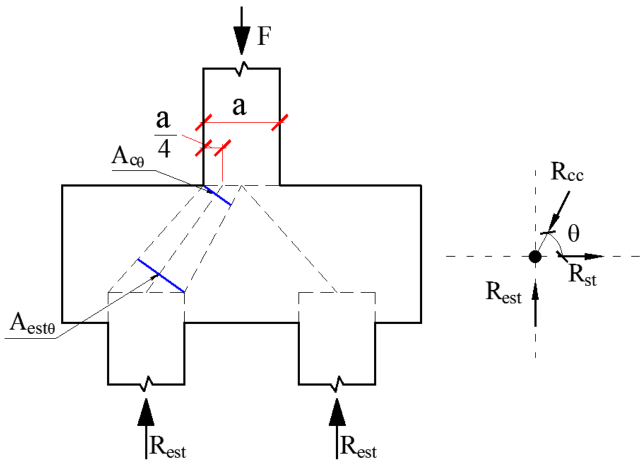

Figure 1: Force equilibrium in the lower nodal region for the calculation of Rst (resultant of the tensile force - tie) and Rcc (resultant of the compressive force - strut).

With the force equilibrium in the x and y directions (x in the horizontal direction and y in the vertical direction), the following equations are derived. Equations 1, 2 and 3 were used to determine the stresses acting on the struts and nodes according to the proposed strut-and-tie model. Blévot and Frémy's formulation (1967) involves the utilization of the values of the applied force on the column, the cross-sectional area of the column, and the cross-sectional area of the pile, both in relation to the strut inclination, as depicted in Figure 1.

$$R_{est} = \frac{Q_u}{n} \quad (1)$$

$$R_{est} = R_{cc} \times sen(\Theta) \quad (2)$$

$$R_{st} = R_{cc} \times \cos(\Theta) \quad (3)$$

Where Q_u is the ultimate load; n is the number of piles; R_{est} is the reaction of Q_u on each pile; R_{cc} is the resultant force in the compressed concrete; R_{st} is the resultant force in the tensioned steel, and Θ is the angle of inclination of the strut.

The upper nodal stress can be calculated according to Equation 4, while the lower nodal stresses are calculated according to Equations 5, 6, and 7 for pile caps for two, three, and four piles, respectively.

$$Q_{zns} = \frac{Q_u}{A_c \times sen^2(\Theta)} \quad (4)$$

$$Q_{zni} = \frac{Q_u}{2 \times A_{est} \times sen^2(\Theta)} \quad (5)$$

$$Q_{zni} = \frac{Q_u}{3 \times A_{est} \times sen^2(\Theta)} \quad (6)$$

$$Q_{zni} = \frac{Q_u}{4 \times A_{est} \times sen^2(\Theta)} \quad (7)$$

Given that Q_u is the ultimate load; A_c is the cross-sectional area of the column; A_{est} is the cross-sectional area of the pile, and Θ is the angle of inclination of the strut.

2.1 Limits used for stress values

As the aim of the study was to compare the limits specified by standards with the experimental results obtained by Blévot and Frémy (1967), the limits proposed by the authors Blévot and Frémy (1967) and Schlaich and Schäfer (1991) were considered, as well as the limits established by the standards ABNT NBR 6118 (2014), Comisíon Permanente del Hormigón - CPH (2008), American Concrete Institute - ACI 318 (2014), and Comité Euro-International du Béton - CEB (2010).

All load factors were disregarded, such as the concrete strength reduction factor γ_c the Rüsch effect, and the coefficient α_{v2}.

Table 1 presents the limits used for the analysis of the results according to the nodal zone (upper or lower), based on f_c (compressive strength of concrete) and f_{ct} (tensile strength of concrete).

Table 1: Nodal stress limits without considering γ_c, the Rüsch effect and α_{v2}.

<table>
<tr><th colspan="4">Lower nodal zone limits</th></tr>
<tr><th>Authors</th><th>Pile cap for 4 piles</th><th>Pile cap for 3 piles</th><th>Pile cap for 2 piles</th></tr>
<tr><td>Blévot e Frémy (1967)</td><td colspan="3">f_c</td></tr>
<tr><td>Schlaich e Schäfer (1991)</td><td colspan="3">0,8 f_c</td></tr>
<tr><td>ABNT (2014)</td><td colspan="2">0,706 f_c</td><td>0,847 f_c</td></tr>
<tr><td>CPH (2008)</td><td colspan="2">0,824 f_c</td><td>0,824 f_c</td></tr>
<tr><td>ACI 318 (2014)</td><td colspan="2">0,6 f_c</td><td>0,8 f_c</td></tr>
<tr><td>CEB (2010)</td><td colspan="3">0,882 f_c</td></tr>
<tr><th colspan="4">Upper nodal zone limits</th></tr>
<tr><th>Authors</th><th>Pile cap for 4 piles</th><th>Pile cap for 3 piles</th><th>Pile cap for 2 piles</th></tr>
<tr><td>Blévot e Frémy (1967)</td><td>2,1 f_c</td><td>1,75 f_c</td><td>1,4 f_c</td></tr>
<tr><td>Schlaich e Schäfer (1991)</td><td colspan="3">1,1 f_c</td></tr>
<tr><td>ABNT (2014)</td><td colspan="3">f_c</td></tr>
<tr><td>CPH (2008)</td><td colspan="3">3,882 f_c</td></tr>
<tr><td>ACI 318 (2014)</td><td colspan="3">f_c</td></tr>
<tr><td>CEB (2010)</td><td colspan="3">1,176 f_c</td></tr>
<tr><td>Triple stress state</td><td colspan="3">f_c+ 4f_{ct}</td></tr>
</table>

According to Tomaz *et al.* (2018), the upper nodal region, the contact area between the pile cap and the column, is subjected to a triple stress state. Therefore, it is suggested that the stress limit for the upper nodal zone be equal to the resistance in the triple stress state, following the guidelines of ABNT NBR 6118 (2014). Thus, the limit considered in the triple stress state $\sigma_3 \geq \sigma_2 \geq \sigma_1$, is given by:

$$\sigma_3 = f_c + 4 \times \sigma_1 \tag{8}$$

Where σ1 ≥ -fct (where tensile stresses are considered negative).

Therefore, the limit value for stress in the upper nodal zone is greater than the value proposed by ABNT NBR 6118 (2014).

3 RESULTS AND DISCUSSIONS

The pile caps tested by Blévot and Frémy (1967) provided information regarding the failure load and the inclination angle of the struts. Utilizing Equations 1, 2, and 3, the reaction forces in each pile, in the struts, and in the ties were determined. The results are presented in Tables 2, 3, and 4.

Based on the obtained forces and the geometric properties of the pile caps, the Blévot and Frémy (1967) strut-and-tie method was applied to calculate nodal stresses. These stresses were subsequently compared with the limit stresses presented in Table 1. The values for these acting stresses are found in Tables 2, 3, and 4.

Table 2: Forces and acting stresses for the tests conducted by Blévot and Frémy (1967) for pile caps for two piles.

Pile cap Identification Number	R_{est} (kgf)	R_{cc} (kgf)	R_{st} (kgf)	σ_{zni} (kgf/cm²)	σ_{zns} (kgf/cm²)
Reduced model					
5,a	19250,00	26733,63	18550,59	189,42	330,01
5,b	16875,00	24510,47	17776,32	181,64	316,45
5 bis,a	12375,00	20379,19	16191,68	171,23	298,32
5 bis,b	9625,00	17982,68	15190,00	171,42	298,65
5 bis,c	13750,00	21848,97	16979,84	177,13	308,61
5 bis,d	10000,00	17772,70	14692,48	161,16	280,77
Full-Scale Model					
Pile cap Identification Number	R_{est} (kgf)	R_{cc} (kgf)	R_{st} (kgf)	σ_{zni} (kgf/cm²)	σ_{zns} (kgf/cm²)
2N1	105000,00	151153,44	108730,68	177,63	355,26
2N1 bis	162500,00	233927,94	168273,68	274,90	549,80
2N2	150000,00	185410,20	108981,38	187,09	374,17
2N2 bis	260000,00	324280,24	193798,03	330,17	660,33
2N3	225000,00	259807,62	129903,81	244,90	489,80
2N3 bis	300000,00	346410,16	173205,08	326,53	653,06

Table 3: Forces and acting stresses for the tests conducted by Blévot and Frémy (1967) for pile caps for three piles.

Pile cap Identification Number	R_{est} (kgf)	R_{cc} (kgf)	R_{st} (kgf)	σ_{zni} (kgf/cm²)	σ_{zns} (kgf/cm²)
Reduced model					
4,1	19083,33	29087,83	21952,86	226,21	591,16
4,2	19000,00	30861,12	24318,89	255,75	668,36
4,3	18916,67	28833,79	21761,14	224,23	586,00
6,1	38000,00	46338,52	26519,03	288,30	753,42
6,2	37333,33	46418,79	27584,90	294,47	769,54
6,3	39333,33	49691,93	30367,37	320,30	837,05
6,3 bis	31916,67	40192,43	24428,63	258,23	674,85
7N1	13000,00	27690,71	24449,44	300,93	786,44
7N2	14916,67	29833,33	25836,42	304,42	795,56
7N3	19833,33	30855,19	23636,45	244,91	640,03
7N4	21583,33	32898,46	24828,78	255,84	668,61
7N5	30000,00	37416,95	22361,31	238,10	622,23
7N6	35000,00	43653,11	26088,20	277,78	725,94
8,1	19383,33	25567,15	16672,30	172,06	449,65
8,2	14666,67	19433,52	12749,54	131,38	343,33
8,3	15000,00	20184,49	13506,06	138,58	362,15
8 bis,1	25000,00	32975,69	21503,39	221,92	579,94
8 bis,2	18083,33	23960,65	15719,60	161,98	423,31
8 bis,3	22750,00	30613,14	20484,19	210,17	549,25
13,a	25000,00	35988,91	25888,26	264,33	690,77
13,b	17833,33	25220,14	17833,33	181,97	475,56
13,c	23083,33	32644,76	23083,33	235,54	615,56

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13,d	21333,33	30169,89	21333,33	217,69	568,89
13,e	22250,00	31466,25	22250,00	227,04	593,33
13,f	16666,67	23570,23	16666,67	170,07	444,44
13,g	21000,00	29193,44	20279,46	207,06	541,12
13,h	15033,33	21524,92	15405,23	157,24	410,93
14,a	35583,33	43762,51	25475,16	274,60	717,62
14,b	30083,33	37569,82	22505,21	239,38	625,59
14,c	26666,67	32837,34	19161,94	206,31	539,15
14,d	26750,00	33064,82	19435,01	208,52	544,94
14,e	30083,33	37609,14	22570,79	239,89	626,90
14,f	28333,33	35324,45	21095,95	224,70	587,21
14,g	28416,67	35058,37	20532,47	220,68	576,70
14,h	27250,00	33480,25	19451,59	209,87	548,47
Full-Scale Model					
Pile cap Identification Number	R_{est} (kgf)	R_{cc} (kgf)	R_{st} (kgf)	σ_{zni} (kgf/cm²)	σ_{zns} (kgf/cm²)
3N1	140000,00	227397,69	179191,83	301,51	547,19
3N1 bis	166666,67	254042,18	191728,07	316,10	573,67
3N2	126666,67	205740,77	162125,94	272,80	495,08
3N2 bis	150000,00	228637,96	172555,26	284,49	516,30
3N3	206666,67	265930,31	167355,37	279,34	506,95
3N3 bis	226666,67	283817,42	170805,58	290,10	526,49
3N4	173333,33	223038,32	140362,57	234,28	425,18
3N4 bis	240000,00	283002,82	149968,64	272,42	494,39

Table 4: Forces and acting stresses for the tests conducted by Blévot and Frémy (1967) for pile caps for four piles.

Reduced Model					
Pile cap Identification Number	R_{est} (kgf)	R_{cc} (kgf)	R_{st} (kgf)	σ_{zni} (kgf/cm²)	σ_{zns} (kgf/cm²)
1,1	11850,00	16628,35	11665,31	119,05	414,82
1,2	15550,00	21124,93	14298,96	146,42	510,20
1,3	13812,50	18870,86	12857,85	131,54	458,34
1,4	6387,50	8658,10	5844,87	59,88	208,64
1,4	12525,00	17341,80	11994,27	122,51	426,86
2,1	14300,00	19108,01	12673,84	130,27	453,91
2,2	18125,00	24252,86	16114,77	165,57	576,93
2,3	15450,00	20955,48	14157,32	145,01	505,29
2,4	15575,00	20782,79	13760,22	141,49	493,01
3,1	11875,00	20058,68	16165,85	172,87	602,35
3,2	13500,00	23247,69	18926,30	204,25	711,71
3,3	12750,00	22118,82	18074,28	195,78	682,17
3,4	10875,00	20453,48	17322,80	196,27	683,88
1 A,1	28750,00	38036,47	24904,03	256,75	894,62
1 A,2	22500,00	29767,67	19490,11	200,93	700,14
1 A,2A	29437,50	38946,04	25499,56	262,89	916,02
1 A,3	29625,00	39194,10	25661,98	264,56	921,85
1 A,4	28937,50	38284,54	25066,45	258,42	900,46

3 A,1	20375,00	34664,02	28043,78	300,89	1048,43
3 A,2	22500,00	38279,29	30968,59	332,27	1157,77
3 A,3	16625,00	28149,07	22715,18	243,17	847,31
3 A,3 bis	21062,50	35662,54	28778,26	308,08	1073,48
3 A,4	21125,00	35940,00	29076,07	311,96	1087,02
Q,1	10200,00	17673,20	14432,67	156,23	544,39
Q,2	11250,00	14983,95	9897,29	101,82	354,80
Q,2 bis	12750,00	16981,81	11216,93	115,40	402,10
G,1	6250,00	15737,21	14442,90	202,17	704,45
G,2	7250,00	17686,25	16131,98	220,13	767,03
G,3	16250,00	25688,85	19896,09	207,20	721,96
G,4	46275,00	81616,43	67229,95	734,43	2559,09
G,5	21062,50	28729,30	19538,26	199,93	696,65
9 A,1	30000,00	65743,11	58499,20	735,06	2561,28
9 A,2	47500,00	103740,35	92226,95	1155,97	4027,91
9 A,3	42500,00	93041,09	82767,11	1039,21	3621,08
10, 1 a	21250,00	28999,14	19732,90	201,91	703,54
10, 1 b	20000,00	27126,83	18326,62	187,72	654,10
10, 2 a	18750,00	25171,36	16793,90	172,41	600,74
10, 2 b	20000,00	26912,65	18008,08	184,77	643,81
10, 3 a	19000,00	25832,55	17502,02	179,19	624,39
10, 3 b	18500,00	24754,65	16448,18	169,00	588,87
11, 1 a	14062,50	21193,32	15855,69	162,96	567,82
11, 1 b	12312,50	18249,15	13469,74	138,00	480,86
11, 2 a	13937,50	21443,01	16295,67	168,32	586,49
11, 2 b	14625,00	22132,66	16612,17	170,89	595,46
12, 1 a	21000,00	25636,27	14704,36	159,67	556,38
12, 2 b	17312,50	21119,19	12095,34	131,44	458,01
12, 2 a	18750,00	23045,48	13398,95	144,52	503,56
12, 2 b	16000,00	19503,83	11153,45	121,30	422,67
Full-Scale Model					
Pile cap Identification Number	R_{est} (kgf)	R_{cc} (kgf)	R_{st} (kgf)	σ_{zni} (kgf/cm²)	σ_{zns} (kgf/cm²)
4N1	175000,00	246841,99	174086,09	284,23	557,08
4N1 bis	167500,00	235772,34	165928,74	270,92	531,00
4N2	164500,00	231549,55	162956,88	266,06	521,49
4N2 bis	184750,00	263399,13	187740,61	306,55	600,85
4N3	162500,00	200861,05	118063,16	202,68	397,24
4N3 bis	225000,00	277658,30	162693,36	279,71	548,22
4N4	188250,00	234244,00	139399,39	237,94	466,36
4N4 bis	218750,00	270287,09	158756,25	272,63	534,35

It is noted, as presented by Tomaz *et al.* (2018), that when the load factor coefficients applied by the standards are disregarded, several limits become equal. This observation suggests that one of the reasons for the divergence in the proposed limits among standards stems from the adoption of safety factors that each institution and author adhere to. The limit stresses for the tested pile caps are presented in Tables 5 to 10.

Table 5: Limit stresses considered for the tests by Blévot and Frémy (1967) for pile caps for two piles in reduced-scale models (in kgf/cm²).

Pile cap Identification Number	Lower nodal zone limits					
	Blévot and Frémy (1967)	Schlaich e Schäfer (1991)	ABNT (2014)	CPH (2008)	ACI 318 (2014)	CEB (2010)
5,a	376,00	300,80	318,47	309,82	300,80	331,63
5,b	364,00	291,20	308,31	299,94	291,20	321,05
5 bis,a	237,00	189,60	200,74	195,29	189,60	209,03
5 bis,b	248,00	198,40	210,06	204,35	198,40	218,74
5 bis,c	238,00	190,40	201,59	196,11	190,40	209,92
5 bis,d	238,00	190,40	201,59	196,11	190,40	209,92

Pile cap Identification Number	Upper nodal zone limits						
	Blévot and Frémy (1967)	Schlaich and Schäfer (1991)	ABNT (2014)	CPH (2008)	ACI 318 (2014)	CEB (2010)	triple stress state
5,a	526,40	413,60	376,00	1459,63	376,00	442,18	438,51
5,b	509,60	400,40	364,00	1413,05	364,00	428,06	425,18
5 bis,a	331,80	260,70	237,00	920,03	237,00	278,71	282,96
5 bis,b	347,20	272,80	248,00	962,74	248,00	291,65	295,37
5 bis,c	333,20	261,80	238,00	923,92	238,00	279,89	284,09
5 bis,d	333,20	261,80	238,00	923,92	238,00	279,89	284,09

Table 6: Limiting stresses considered for the tests by Blévot and Frémy (1967) for pile caps for two piles in full-scale models (in kgf/cm²).

Pile cap Identification Number	Lower nodal zone limits					
	Blévot e Frémy (1967)	Schlaich e Schäfer (1991)	ABNT (2014)	CPH (2008)	ACI 318 (2014)	CEB (2010)
2N1	235,50	188,40	199,47	194,05	188,40	207,71
2N1 bis	440,00	352,00	372,68	362,56	352,00	388,08
2N2	278,00	222,40	235,47	229,07	222,40	245,20
2N2 bis	455,00	364,00	385,39	374,92	364,00	401,31
2N3	327,00	261,60	276,97	269,45	261,60	288,41
2N3 bis	470,00	376,00	398,09	387,28	376,00	414,54

Pile cap Identification Number	Upper nodal zone limits						
	Blévot and Frémy (1967)	Schlaich e Schäfer (1991)	ABNT (2014)	CPH (2008)	ACI 318 (2014)	CEB (2010)	triple stress state
2N1	329,70	259,05	235,50	914,21	235,50	276,95	281,26
2N1 bis	616,00	484,00	440,00	1708,08	440,00	517,44	509,42
2N2	389,20	305,80	278,00	1079,20	278,00	326,93	329,11
2N2 bis	637,00	500,50	455,00	1766,31	455,00	535,08	525,99
2N3	457,80	359,70	327,00	1269,41	327,00	384,55	383,96
2N3 bis	658,00	517,00	470,00	1824,54	470,00	552,72	542,54

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Table 7: Limiting stresses considered for the tests by Blévot and Frémy (1967) for pile caps for three piles in reduced-scale models (in kgf/cm²).

Pile cap Identification Number	Lower nodal zone limits					
	Blévot and Frémy (1967)	Schlaich e Schäfer (1991)	ABNT (2014)	CPH (2008)	ACI 318 (2014)	CEB (2010)
4,1	347,00	277,60	244,98	285,93	208,20	306,05
4,2	356,00	284,80	251,34	293,34	213,60	313,99
4,3	371,00	296,80	261,93	305,70	222,60	327,22
6,1	374,00	299,20	264,04	308,18	224,40	329,87
6,2	325,00	260,00	229,45	267,80	195,00	286,65
6,3	364,00	291,20	256,98	299,94	218,40	321,05
6,3 bis	250,00	200,00	176,50	206,00	150,00	220,50
7N1	283,00	226,40	199,80	233,19	169,80	249,61
7N2	235,00	188,00	165,91	193,64	141,00	207,27
7N3	220,00	176,00	155,32	181,28	132,00	194,04
7N4	177,00	141,60	124,96	145,85	106,20	156,11
7N5	238,00	190,40	168,03	196,11	142,80	209,92
7N6	238,00	190,40	168,03	196,11	142,80	209,92
8,1	232,00	185,60	163,79	191,17	139,20	204,62
8,2	232,00	185,60	163,79	191,17	139,20	204,62
8,3	275,00	220,00	194,15	226,60	165,00	242,55
8 bis,1	295,00	236,00	208,27	243,08	177,00	260,19
8 bis,2	291,00	232,80	205,45	239,78	174,60	256,66
8 bis,3	295,00	236,00	208,27	243,08	177,00	260,19
13,a	407,00	325,60	287,34	335,37	244,20	358,97
13,b	388,00	310,40	273,93	319,71	232,80	342,22
13,c	398,00	318,40	280,99	327,95	238,80	351,04
13,d	396,00	316,80	279,58	326,30	237,60	349,27
13,e	330,00	264,00	232,98	271,92	198,00	291,06
13,f	333,00	266,40	235,10	274,39	199,80	293,71
13,g	371,00	296,80	261,93	305,70	222,60	327,22
13,h	234,00	187,20	165,20	192,82	140,40	206,39
14,a	318,00	254,40	224,51	262,03	190,80	280,48
14,b	323,50	258,80	228,39	266,56	194,10	285,33
14,c	334,50	267,60	236,16	275,63	200,70	295,03
14,d	344,00	275,20	242,86	283,46	206,40	303,41
14,e	290,00	232,00	204,74	238,96	174,00	255,78
14,f	277,00	221,60	195,56	228,25	166,20	244,31
14,g	270,00	216,00	190,62	222,48	162,00	238,14
14,h	288,50	230,80	203,68	237,72	173,10	254,46

Pile cap Identification Number	Upper nodal zone limits						
	Blévot e Frémy (1967)	Schlaich e Schäfer (1991)	ABNT (2014)	CPH (2008)	ACI 318 (2014)	CEB (2010)	triple stress state
4,1	607,25	381,70	347,00	1347,05	347,00	408,07	406,26
4,2	623,00	391,60	356,00	1381,99	356,00	418,66	416,28
4,3	649,25	408,10	371,00	1440,22	371,00	436,30	432,96
6,1	654,50	411,40	374,00	1451,87	374,00	439,82	436,29

6,2	568,75	357,50	325,00	1261,65	325,00	382,20	381,72
6,3	637,00	400,40	364,00	1413,05	364,00	428,06	425,18
6,3 bis	437,50	275,00	250,00	970,50	250,00	294,00	297,62
7N1	495,25	311,30	283,00	1098,61	283,00	332,81	334,73
7N2	411,25	258,50	235,00	912,27	235,00	276,36	280,70
7N3	385,00	242,00	220,00	854,04	220,00	258,72	263,73
7N4	309,75	194,70	177,00	687,11	177,00	208,15	214,83
7N5	416,50	261,80	238,00	923,92	238,00	279,89	284,09
7N6	416,50	261,80	238,00	923,92	238,00	279,89	284,09
8,1	406,00	255,20	232,00	900,62	232,00	272,83	277,31
8,2	406,00	255,20	232,00	900,62	232,00	272,83	277,31
8,3	481,25	302,50	275,00	1067,55	275,00	323,40	325,75
8 bis,1	516,25	324,50	295,00	1145,19	295,00	346,92	348,18
8 bis,2	509,25	320,10	291,00	1129,66	291,00	342,22	343,70
8 bis,3	516,25	324,50	295,00	1145,19	295,00	346,92	348,18
13,a	712,25	447,70	407,00	1579,97	407,00	478,63	472,90
13,b	679,00	426,80	388,00	1506,22	388,00	456,29	451,84
13,c	696,50	437,80	398,00	1545,04	398,00	468,05	462,93
13,d	693,00	435,60	396,00	1537,27	396,00	465,70	460,71
13,e	577,50	363,00	330,00	1281,06	330,00	388,08	387,30
13,f	582,75	366,30	333,00	1292,71	333,00	391,61	390,65
13,g	649,25	408,10	371,00	1440,22	371,00	436,30	432,96
13,h	409,50	257,40	234,00	908,39	234,00	275,18	279,57
14,a	556,50	349,80	318,00	1234,48	318,00	373,97	373,91
14,b	566,13	355,85	323,50	1255,83	323,50	380,44	380,05
14,c	585,38	367,95	334,50	1298,53	334,50	393,37	392,32
14,d	602,00	378,40	344,00	1335,41	344,00	404,54	402,91
14,e	507,50	319,00	290,00	1125,78	290,00	341,04	342,58
14,f	484,75	304,70	277,00	1075,31	277,00	325,75	327,99
14,g	472,50	297,00	270,00	1048,14	270,00	317,52	320,13
14,h	504,88	317,35	288,50	1119,96	288,50	339,28	340,89

Table 8: Limiting stresses considered for the tests by Blévot and Frémy (1967) for pile caps for three piles in full-scale models (in kgf/cm²).

Pile cap Identification Number	**Lower nodal zone limits**					
	Blévot e Frémy (1967)	Schlaich e Schäfer (1991)	ABNT (2014)	CPH (2008)	ACI 318 (2014)	CEB (2010)
3N1	453,50	362,80	320,17	373,68	272,10	399,99
3N1 bis	453,50	362,80	320,17	373,68	272,10	399,99
3N2	376,50	301,20	265,81	310,24	225,90	332,07
3N2 bis	437,00	349,60	308,52	360,09	262,20	385,43
3N3	463,00	370,40	326,88	381,51	277,80	408,37
3N3 bis	409,00	327,20	288,75	337,02	245,40	360,74
3N4	326,50	261,20	230,51	269,04	195,90	287,97
3N4 bis	424,50	339,60	299,70	349,79	254,70	374,41

Pile cap Identification Number	Upper nodal zone limits						
	Blévot e Frémy (1967)	Schlaich e Schäfer (1991)	ABNT (2014)	CPH (2008)	ACI 318 (2014)	CEB (2010)	triple stress state
3N1	793,63	498,85	453,50	1760,49	453,50	533,32	524,33
3N1 bis	793,63	498,85	453,50	1760,49	453,50	533,32	524,33
3N2	658,88	414,15	376,50	1461,57	376,50	442,76	439,07
3N2 bis	764,75	480,70	437,00	1696,43	437,00	513,91	506,10
3N3	810,25	509,30	463,00	1797,37	463,00	544,49	534,82
3N3 bis	715,75	449,90	409,00	1587,74	409,00	480,98	475,12
3N4	571,38	359,15	326,50	1267,47	326,50	383,96	383,40
3N4 bis	742,88	466,95	424,50	1647,91	424,50	499,21	492,28

Table 9: Limiting stresses considered for the tests by Blévot and Frémy (1967) for pile caps for four piles in reduced-scale models (in kgf/cm²).

Pile cap Identification Number	Lower nodal zone limits					
	Blévot e Frémy (1967)	Schlaich e Schäfer (1991)	ABNT (2014)	CPH (2008)	ACI 318 (2014)	CEB (2010)
1,1	291,00	232,80	205,45	239,78	174,60	256,66
1,2	278,50	222,80	196,62	229,48	167,10	245,64
1,3	313,00	250,40	220,98	257,91	187,80	276,07
1,4	318,50	254,80	224,86	262,44	191,10	280,92
1,4	291,00	232,80	205,45	239,78	174,60	256,66
2,1	326,00	260,80	230,16	268,62	195,60	287,53
2,2	328,20	262,56	231,71	270,44	196,92	289,47
2,3	380,50	304,40	268,63	313,53	228,30	335,60
2,4	373,30	298,64	263,55	307,60	223,98	329,25
3,1	321,00	256,80	226,63	264,50	192,60	283,12
3,2	372,00	297,60	262,63	306,53	223,20	328,10
3,3	309,00	247,20	218,15	254,62	185,40	272,54
3,4	325,50	260,40	229,80	268,21	195,30	287,09
1 A,1	266,00	212,80	187,80	219,18	159,60	234,61
1 A,2	368,00	294,40	259,81	303,23	220,80	324,58
1 A,2A	332,50	266,00	234,75	273,98	199,50	293,27
1 A,3	366,00	292,80	258,40	301,58	219,60	322,81
1 A,4	329,00	263,20	232,27	271,10	197,40	290,18
3 A,1	291,50	233,20	205,80	240,20	174,90	257,10
3 A,2	392,00	313,60	276,75	323,01	235,20	345,74
3 A,3	320,00	256,00	225,92	263,68	192,00	282,24
3 A,3 bis	461,00	368,80	325,47	379,86	276,60	406,60
3 A,4	324,00	259,20	228,74	266,98	194,40	285,77
Q,1	339,00	271,20	239,33	279,34	203,40	299,00
Q,2	307,50	246,00	217,10	253,38	184,50	271,22
Q,2 bis	210,00	168,00	148,26	173,04	126,00	185,22
G,1	131,50	105,20	92,84	108,36	78,90	115,98
G,2	131,50	105,20	92,84	108,36	78,90	115,98
G,3	220,50	176,40	155,67	181,69	132,30	194,48
G,4	306,00	244,80	216,04	252,14	183,60	269,89

G,5	184,00	147,20	129,90	151,62	110,40	162,29
9 A,1	272,70	218,16	192,53	224,70	163,62	240,52
9 A,2	408,10	326,48	288,12	336,27	244,86	359,94
9 A,3	344,00	275,20	242,86	283,46	206,40	303,41
10, 1 a	346,00	276,80	244,28	285,10	207,60	305,17
10, 1 b	431,10	344,88	304,36	355,23	258,66	380,23
10, 2 a	339,30	271,44	239,55	279,58	203,58	299,26
10, 2 b	314,30	251,44	221,90	258,98	188,58	277,21
10, 3 a	283,80	227,04	200,36	233,85	170,28	250,31
10, 3 b	333,80	267,04	235,66	275,05	200,28	294,41
11, 1 a	268,80	215,04	189,77	221,49	161,28	237,08
11, 1 b	194,80	155,84	137,53	160,52	116,88	171,81
11, 2 a	308,60	246,88	217,87	254,29	185,16	272,19
11, 2 b	300,00	240,00	211,80	247,20	180,00	264,60
12, 1 a	207,80	166,24	146,71	171,23	124,68	183,28
12, 2 b	218,80	175,04	154,47	180,29	131,28	192,98
12, 2 a	324,30	259,44	228,96	267,22	194,58	286,03
12, 2 b	261,00	208,80	184,27	215,06	156,60	230,20

Pile cap Identification Number	**Upper nodal zone limits**						
	Blévot e Frémy (1967)	Schlaich e Schäfer (1991)	ABNT (2014)	CPH (2008)	ACI 318 (2014)	CEB (2010)	triple stress state
1,1	611,10	320,10	291,00	1129,66	291,00	342,22	343,70
1,2	584,85	306,35	278,50	1081,14	278,50	327,52	329,68
1,3	657,30	344,30	313,00	1215,07	313,00	368,09	368,32
1,4	668,85	350,35	318,50	1236,42	318,50	374,56	374,47
1,4	611,10	320,10	291,00	1129,66	291,00	342,22	343,70
2,1	684,60	358,60	326,00	1265,53	326,00	383,38	382,84
2,2	689,22	361,02	328,20	1274,07	328,20	385,96	385,30
2,3	799,05	418,55	380,50	1477,10	380,50	447,47	443,51
2,4	783,93	410,63	373,30	1449,15	373,30	439,00	435,51
3,1	674,10	353,10	321,00	1246,12	321,00	377,50	377,26
3,2	781,20	409,20	372,00	1444,10	372,00	437,47	434,07
3,3	648,90	339,90	309,00	1199,54	309,00	363,38	363,85
3,4	683,55	358,05	325,50	1263,59	325,50	382,79	382,28
1 A,1	558,60	292,60	266,00	1032,61	266,00	312,82	315,63
1 A,2	772,80	404,80	368,00	1428,58	368,00	432,77	429,62
1 A,2A	698,25	365,75	332,50	1290,77	332,50	391,02	390,09
1 A,3	768,60	402,60	366,00	1420,81	366,00	430,42	427,40
1 A,4	690,90	361,90	329,00	1277,18	329,00	386,90	386,19
3 A,1	612,15	320,65	291,50	1131,60	291,50	342,80	344,26
3 A,2	823,20	431,20	392,00	1521,74	392,00	460,99	456,27
3 A,3	672,00	352,00	320,00	1242,24	320,00	376,32	376,14
3 A,3 bis	968,10	507,10	461,00	1789,60	461,00	542,14	532,61
3 A,4	680,40	356,40	324,00	1257,77	324,00	381,02	380,61
Q,1	711,90	372,90	339,00	1316,00	339,00	398,66	397,34
Q,2	645,75	338,25	307,50	1193,72	307,50	361,62	362,17
Q,2 bis	441,00	231,00	210,00	815,22	210,00	246,96	252,40
G,1	276,15	144,65	131,50	510,48	131,50	154,64	162,53

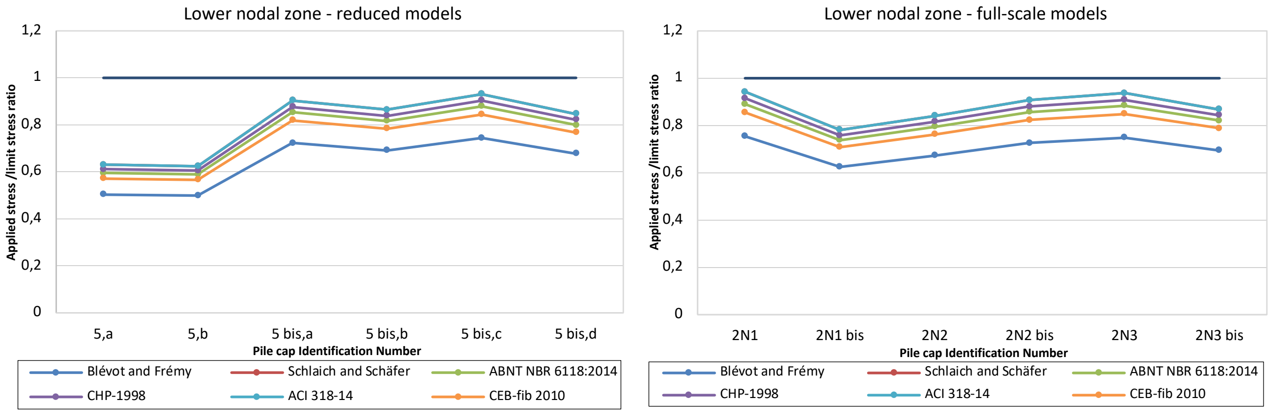
G,2	276,15	144,65	131,50	510,48	131,50	154,64	162,53
G,3	463,05	242,55	220,50	855,98	220,50	259,31	264,30
G,4	642,60	336,60	306,00	1187,89	306,00	359,86	360,49
G,5	386,40	202,40	184,00	714,29	184,00	216,38	222,82
9 A,1	572,67	299,97	272,70	1058,62	272,70	320,70	323,16
9 A,2	857,01	448,91	408,10	1584,24	408,10	479,93	474,12
9 A,3	722,40	378,40	344,00	1335,41	344,00	404,54	402,91
10, 1 a	726,60	380,60	346,00	1343,17	346,00	406,90	405,14
10, 1 b	905,31	474,21	431,10	1673,53	431,10	506,97	499,58
10, 2 a	712,53	373,23	339,30	1317,16	339,30	399,02	397,68
10, 2 b	660,03	345,73	314,30	1220,11	314,30	369,62	369,77
10, 3 a	595,98	312,18	283,80	1101,71	283,80	333,75	335,62
10, 3 b	700,98	367,18	333,80	1295,81	333,80	392,55	391,54
11, 1 a	564,48	295,68	268,80	1043,48	268,80	316,11	318,78
11, 1 b	409,08	214,28	194,80	756,21	194,80	229,08	235,12
11, 2 a	648,06	339,46	308,60	1197,99	308,60	362,91	363,40
11, 2 b	630,00	330,00	300,00	1164,60	300,00	352,80	353,78
12, 1 a	436,38	228,58	207,80	806,68	207,80	244,37	249,90
12, 2 b	459,48	240,68	218,80	849,38	218,80	257,31	262,37
12, 2 a	681,03	356,73	324,30	1258,93	324,30	381,38	380,94
12, 2 b	548,10	287,10	261,00	1013,20	261,00	306,94	310,01

Table 10: Limiting stresses considered for the tests by Blévot and Frémy (1967) for pile caps for four piles in full-scale models (in kgf/cm²).

Pile cap Identification Number	Lower nodal zone limits						
	Blévot e Frémy (1967)	Schlaich e Schäfer (1991)	ABNT (2014)	CPH (2008)	ACI 318 (2014)	CEB (2010)	
4N1	372,50	298,00	262,99	306,94	223,50	328,55	
4N1 bis	408,00	326,40	288,05	336,19	244,80	359,86	
4N2	371,00	296,80	261,93	305,70	222,60	327,22	
4N2 bis	341,50	273,20	241,10	281,40	204,90	301,20	
4N3	341,50	273,20	241,10	281,40	204,90	301,20	
4N3 bis	393,00	314,40	277,46	323,83	235,80	346,63	
4N4	353,50	282,80	249,57	291,28	212,10	311,79	
4N4 bis	423,00	338,40	298,64	348,55	253,80	373,09	
Pile cap Identification Number	**Upper nodal zone limits**						
	Blévot e Frémy (1967)	Schlaich e Schäfer (1991)	ABNT (2014)	CPH (2008)	ACI 318 (2014)	CEB (2010)	triple stress state
4N1	782,25	409,75	372,50	1446,05	372,50	438,06	434,62
4N1 bis	856,80	448,80	408,00	1583,86	408,00	479,81	474,01
4N2	779,10	408,10	371,00	1440,22	371,00	436,30	432,96
4N2 bis	717,15	375,65	341,50	1325,70	341,50	401,60	400,13
4N3	717,15	375,65	341,50	1325,70	341,50	401,60	400,13
4N3 bis	825,30	432,30	393,00	1525,63	393,00	462,17	457,38

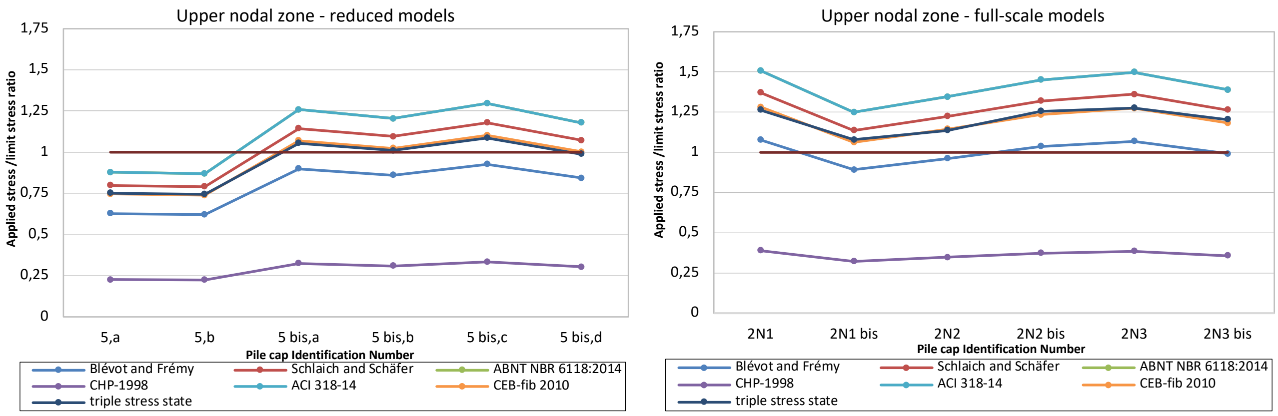
4N4	742,35	388,85	353,50	1372,29	353,50	415,72	413,49
4N4 bis	888,30	465,30	423,00	1642,09	423,00	497,45	490,62

For the analysis of correlations between the applied stresses and the presented limits, the ratio between the applied stress and the limit stress was examined. Considering the failure type of each pile caps, the closer this ratio is to 1, the closer the adopted limit is to the actual failure. These relationships are presented in Figures 2 to 7.



a) b)

Figure 2: The relationship between the applied stress and the limit stress in the lower nodal zone for pile caps for two piles tested by Blévot and Frémy (1967) – a) Reduced models; b) Full-scale models.



a) b)

Figure 3: The relationship between the applied stress and the limit stress in the upper nodal zone for pile caps for two piles tested by Blévot and Frémy (1967) – a) Reduced models; b) Full-scale models.

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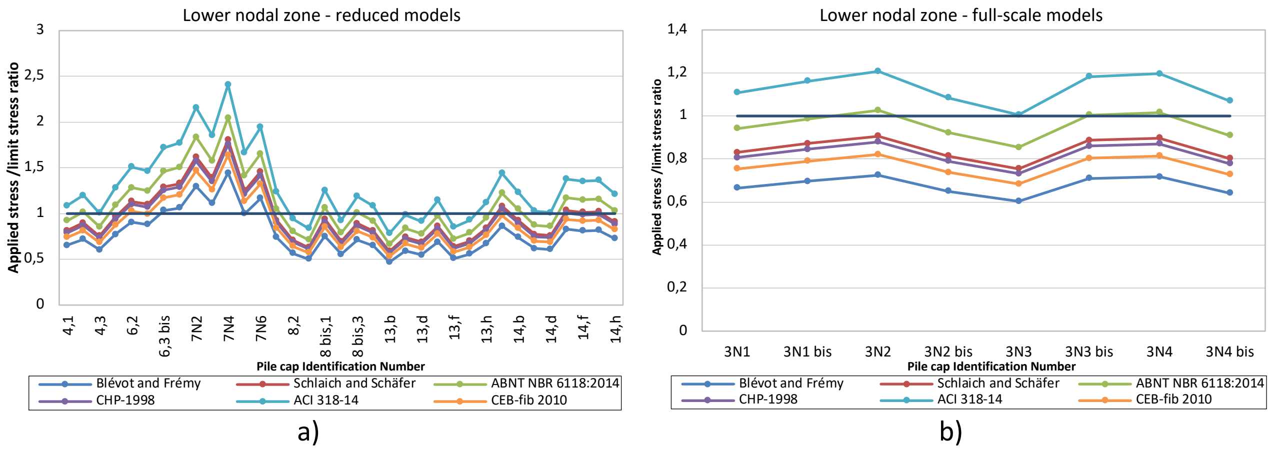


Figure 4: The relationship between the applied stress and the limit stress in the lower nodal zone for pile caps for three piles tested by Blévot and Frémy (1967) – a) Reduced models; b) Full-scale models.

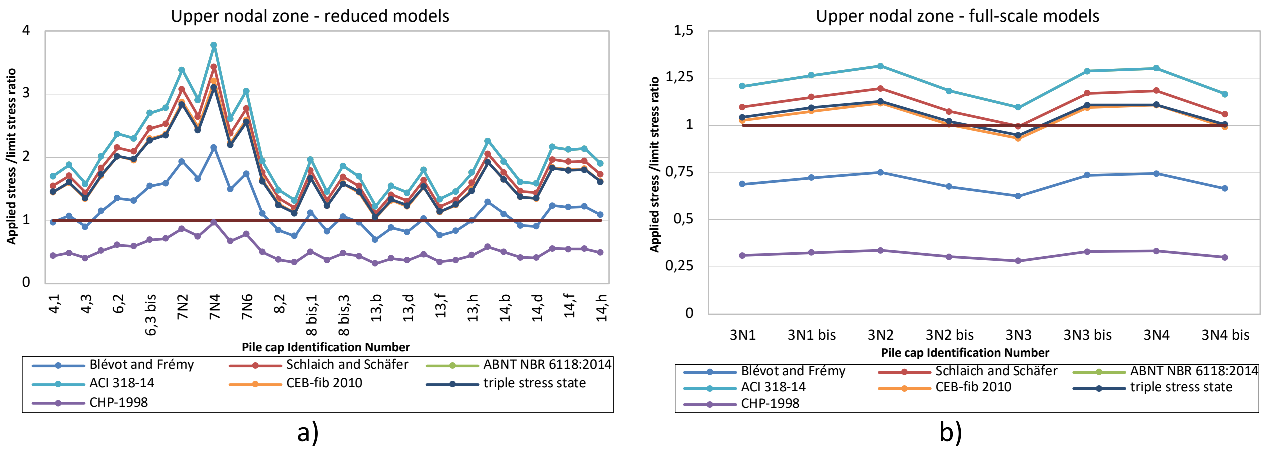


Figure 5: The relationship between the applied stress and the limit stress in the upper nodal zone for pile caps for three piles tested by Blévot and Frémy (1967) – a) Reduced models; b) Full-scale models.

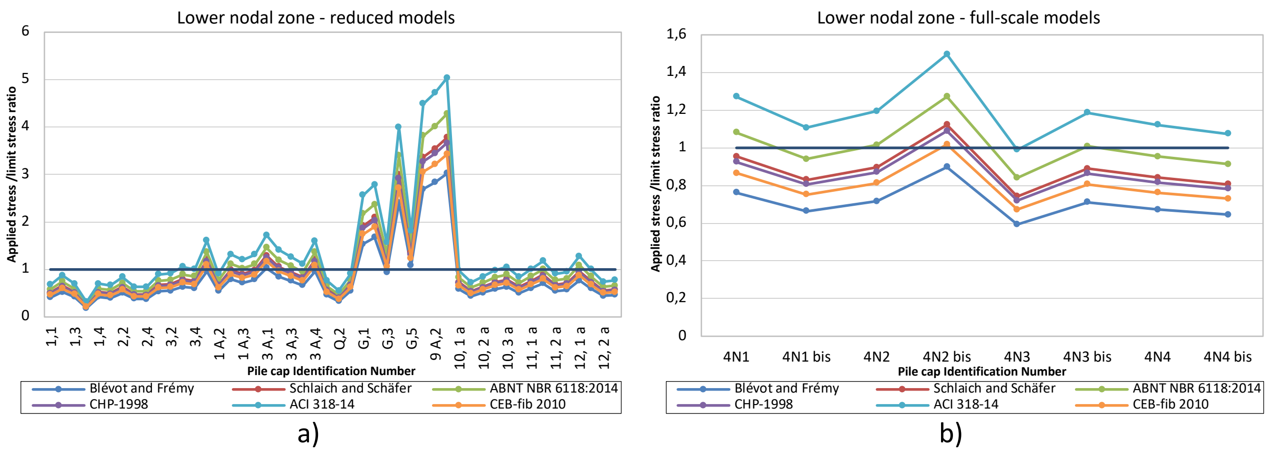
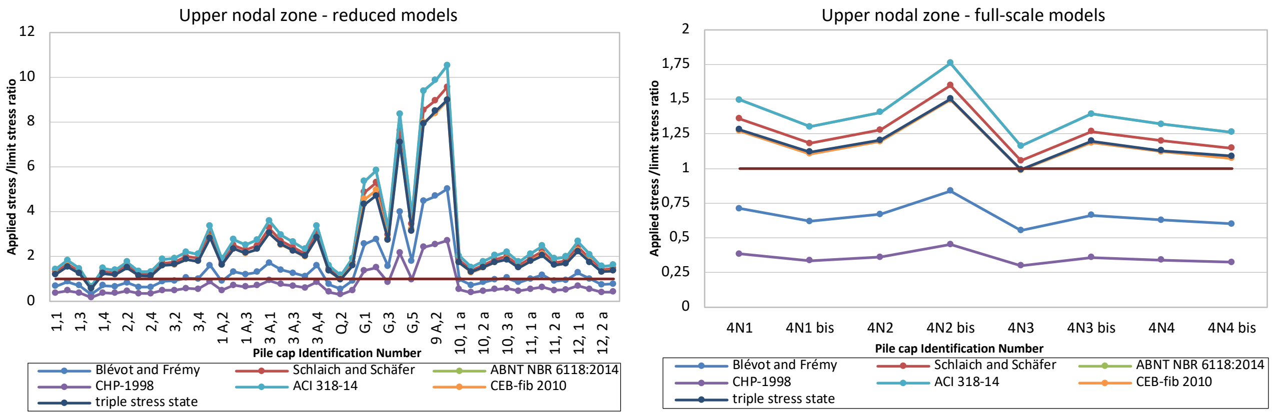


Figure 6: The relationship between the applied stress and the limit stress in the inner nodal zone for pile caps for four piles tested by Blévot and Frémy (1967) – a) Reduced models; b) Full-scale models.



a) b)

Figure 7: The relationship between the applied stress and the limit stress in the upper nodal zone for pile caps for four piles tested by Blévot and Frémy (1967) – a) Reduced models; b) Full-scale models.

The analysis of the graphs reveals discrepancies among the adopted limits. It is evident that among the reduced-scale and full-scale models, there are significant differences in which limit closely approximates the experimental failure.

For pile caps for two piles, according to the observations by Blévot and Frémy (1967), tests of reduced-scale models predominantly exhibited failures through inclined cracks at the top (diagonal tension failure of the strut) and, in some models, after the crushing of the struts. Analyzing the graphs, it is noticeable that all limits for the lower nodal zones were above the stresses acting on the pile caps, with limit values closely grouped together, and the limits proposed by ACI 318 (2014) being closer to the applied stresses.

Regarding the upper nodal zone, the limits proposed by CPH (2008) deviated from experimental behavior, showing limits 50% higher than the stresses acting on the pile caps at the time of failure. This observation may extend to other models and pile caps. On the other hand, the limits proposed by ABNT NBR 6118 (2014) and ACI 318 (2014) were equal due to the considerations regarding coefficients, presenting the lowest limit values among those analyzed. This trend may also extend to other models and pile caps. The triple stress state and the limit proposed by CEB (2010) showed limit values very close to the behavior of the stresses acting on the pile cap.

For full-scale pile caps for two piles, practically all failures occurred in the upper nodal zone. Similar to the tests on reduced-scale models, limits in the lower nodal zones were higher than the stresses acting on the pile caps, with the values proposed by ACI 318 (2014) being the closest to the applied stresses. Concerning the upper nodal zone, it is noted that the limits proposed by Blévot and Frémy (1967) showed values closer to the stresses acting on the pile caps.

For pile caps for three piles, tests with reduced-scale models generally exhibited failures through inclined cracks (diagonal tension) or on the lower face of the pile cap. Among the presented limits, those proposed by ACI 318 (2014) had the lowest limit values in the lower nodal zone. For the lower nodal zone, the limits of ABNT NBR 6118 (2014) showed values closer to the stresses acting on the pile caps. In the upper nodal zone, it was observed that the limits proposed by Blévot and Frémy (1967) had values that were closer to the stresses acting on the pile caps.

For full-scale pile caps for three piles, the majority of failures occurred due to inclined cracks, presenting cracks on the lower face and on the lateral faces, according to Blévot and Frémy (1967). In the lower nodal zone, similar to the reduced-scale model, the limits proposed by ABNT NBR 6118 (2014) showed values closer to the stresses acting on the pile caps. Regarding the upper nodal zone, it is observed that the triple stress state and the limit proposed by CEB (2010) had limit values very close to each other and close to the values of the stresses acting on the pile caps.

Concerning the pile caps for four piles in reduced-scale models, Blévot and Frémy (1967) observed that the majority of failures occurred on the lower face, starting from one or more piles, forming inclined cracks. In the lower nodal zone, the limits proposed by ACI 318 (2014) resulted in values closer to the stresses acting on the pile cap. In the upper nodal zone, the limits proposed by Blévot and Frémy (1967) showed values close to the stresses acting on the pile caps.

Finally, for full-scale pile caps for four piles, like the reduced-scale models, Blévot and Frémy (1967) observed that the majority of failures were caused by inclined cracks (diagonal tension), starting from one or more piles. In the lower nodal zone, the limits proposed by ABNT NBR 6118 (2014) showed values close to the stresses acting on the pile caps. In the upper nodal zone, none of the adopted limits showed values relatively close to the stresses acting, with the triple stress state and the limit proposed by CEB (2010) being the ones with values closest to these stresses.

It was observed that the limits proposed by Schlaich and Schäfer (1991) showed consistent values in all tests.

4 CONCLUSIONS

Analyzing the various adopted limit values, it was found that there is a discrepancy among them. This demonstrates that, depending on the adopted limit, one may consider the pile cap to be either verified or not with respect to the failure force.

With the analysis of the results and observations related to the tests conducted by Blévot and Frémy (1967) and the adopted limit values, it is noted that some limits have values much higher than the stresses acting on the pile caps. Therefore, if these limits were adopted for design, although they meet the safety criteria defined by standards, it is observed that the stresses acting for pile cap failure would be lower than these limits. Thus, even though it meets the safety criteria, the pile cap failure occurs with stresses lower than those limit values.

The adopted limit values should be analyzed according to the type of pile cap. Some conclusions that can be inferred from the results of the limit stresses are presented below.

- The limit proposed by the Spanish standard CPH (2008) for the upper nodal zone presents high limit values compared to other limits and the stresses acting on the pile caps. Therefore, caution is needed when considering this limit, as the pile caps tested by Blévot and Frémy (1967) exhibited failures with nodal stresses approximately 50% lower than the values allowed by this standard.

- When the weighting coefficients for long-term and design actions are disregarded, the limits proposed by ABNT NBR 6118 (2014) and ACI 318 (2014) for the upper nodal zone become equal. These limits have values relatively lower than the other limits and the stresses acting on the pile caps.
- In the lower nodal zone, for all cases, the limits proposed by ABNT NBR 6118 (2014) and ACI 318 (2014) show better results, with values that are closer to the stresses acting on the pile caps, making them suitable for an analysis that prioritizes safety, efficiency, and economy.
- In the upper nodal zone, three proposed limits show better results: Blévot and Frémy (1967), CEB (2010), and considering the triple stress state.

5 ACKNOWLEDGMENTS

To the Research Foundation of the State of Minas Gerais – FAPEMIG, CAPES, and the Master’s Program in Civil Engineering, affiliated with the Federal University of Uberlandia, we express our gratitude.

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HOW TO CITE THIS ARTICLE

Delalibera, R. G., Silva, J. C. G., & Giongo, J. S. (2023). ANÁLISE DAS TENSÕES NODAIS NOS ENSAIOS DE BLÉVOT E FRÉMY. HOLOS, 7(39). https://doi.org/10.15628/holos.2023.10840

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Editor: Fábio Augusto Procópio Paiva

Submitted May 22, 2023
Accepted December 31, 2023
Published December 31, 2023