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APPENDIX

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APPENDIX

Description of the Additional Subroutines and Modifications of NONSAP

In this section, the description of the additional subroutines and modifications of NONSAP (5) to accommodate the catenary element is briefly outlined.

Subroutines:

SCBL - To calculate the end forces in local coordinates of the catenary element by the flexibility iterative process.

RUSS - The tangent stiffness matrix of the catenary element is evaluated and the assembling process performed through statements number 760, 765, 790, to 761. It should be noted that this subroutine already exists in the NONSAP (5), but is modified to include the catenary element.

EQTCBL - To perform the equilibrium iteration of the Newton-Raphson method, the Kar method or the proposed technique.

EIKAR - To determine the modifying factor for the Kar method and the trial equilibrium state for the proposed iterative method.

Main Varibles:

APL1,ALP2,ALP4 - relate to the variable α_1, α_2 and α_4 in chapter 2, respectively.

ST - Element end force vector of catenary element in global coordinates.

S - The tangent stiffness matrix of the element in global coordinates.

RE - Unbalanced force vector.

DISP - Displacement vector in the previous load step.

DISPI - Incremental displacement vector at the current load step.

WV - Working vector for the displacement and the unbalanced force.

WR - Unbalanced force vector at the preceeding trial equilibrium load (used in the proposed technique only).

WP - External applied load vector at the current load step.

FAR - Scaling factor in the Kar method.

FA - Scaling factor obtained from the interpolation in the proposed technique.

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TABLES

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Table 4.1 Data of EXAMPLE PROBLEM 1

Description		Magnitude
Material proporties;		
modulus of elasticity, E	(ksf.)	$2.736X10^{6}$
cross-sectional area, A	(sq. ft.)	$5.509X10^{-3}$
Physical proporties;		
unit weight of cable	(kip./ft.)	$3.160X10^{-3}$
unstressed length of element a	(ft.)	412.8837
unstressed length of element b	(ft.)	613.0422
Load;		
concentrated live load appling downwards at node 2	(kip.)	8.000
Prescribed tolerance		$1.000X10^{-3}$

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Table 4.2 Relation between Z-displacement at node 2 (ft.) and cycle of iteration, EXAMPLE PROBLEM 1

Cycle no.	Newton-Raphson	Kar itertion	Proposed technique
1	-134.3581	-33.5890	-18.0056
2	-66.6933	-18.9570	-18.6870
3	-33.2922	-18.5020	-18.4664
4	-20.9686	-18.4664	
5	-18.7470		
6	-18.4664		
Final results	-18.4567 ft.	-18.4567 ft.	-18.4567 ft.
CPU time	0.33 sec.	0.32 sec.	0.29 sec.
PT	7.78×10^{-3}	1.44×10^{-3}	2.77×10^{-3}

PT : refers to the ratio of the norm of the unbalanced forces to that of the applied loads ($|\{\Delta P\}|/|\{P\}|$) after convergence

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Table 4.3 Final displacements at node 2, EXAMPLE PROBLEM 1

Sources	Displacements at node 2 (ft.)	
	Y	Z
Knudson (15)	-2.7720	-17.9510
NONSAP	-2.7932	-18.0439
Jayaraman & Knudson (13)	-2.8190	-18.4580
Proposed technique	-2.8195	-18.4567

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Table 4.4 Final Z-displacement at node 2 (ft.) at the end of each load step, EXAMPLE PROBLEM 2

Load step	Newton-Raphson	Kar itertion	Proposed technique
1	-5.5744	-5.5746	-15.6329
2	-12.2331	-12.2331	
3	-14.1789	-14.1789	
4	-15.6329	-15.6329	
Final results	-15.6329 ft.	-15.6329 ft.	-15.6329 ft.
CPU time	4.69 sec.	4.07 sec.	1.36 sec.

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Table 4.5 Data of EXAMPLE PROBLEM 3

Description		Magnitude
Material properties;		
modulus of elasticity, E	(ksf.)	$1.728\text{X}10^{6}$
cross-sectional area, A	(sq. ft.)	$1.578\text{X}10^{-3}$
Physical properties;		
unit weight of cable	(kip./ft.)	$1.000\text{X}10^{-4}$
unstressed length of element a	(ft.)	104.2
unstressed length of element b	(ft.)	99.8
Load;		
concentrated live load acting downwards at nodes 4,5,8,9	(kip.)	8.000
Prescribed tolerance		$1.0\text{X}10^{-4}$

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Table 4.5 Data of EXAMPLE PROBLEM 3 (cont.)

Node number	Coordinates of nodes at initial configuration, ft.					
	Assumed configuration			Self-weight configuration		
	X	Y	Z	X	Y	Z
1	0.000	100.000	0.000	0.000	100.000	0.0000
2	0.000	200.000	0.000	0.000	200.000	0.0000
3	100.000	0.000	0.000	100.000	0.000	0.0000
4	100.000	100.000	-30.000	100.247	100.247	-27.3377
5	100.000	200.000	-30.000	100.247	199.753	-27.3377
6	100.000	300.000	0.000	100.000	300.000	0.0000
7	200.000	0.000	0.000	200.000	0.000	0.0000
8	200.000	100.000	-30.000	199.753	100.247	-27.3377
9	200.000	200.000	-30.000	199.753	199.753	-27.3377
10	200.000	300.000	0.000	200.000	300.000	0.0000
11	300.000	100.000	0.000	300.000	100.000	0.0000
12	300.000	200.000	0.000	300.000	200.000	0.0000

Table 4.6 Relation between Z-displacement at node 4 (ft.) and cycle of iteration, EXAMPLE PROBLEM 3

Cycle no.	Newton-Raphson	Kar itertion	Proposed technique
1	-1175.1627	-293.7907	-4.0491
2	-765.2973	-49.1472	-4.1395
3	-40.5150	-26.3577	
4	-19.7633	-7.6120	
5	-9.2140	-4.7183	
6	-4.9869	-4.1399	
7	-4.1701	-4.1393	
8	-4.1393		
final results	-4.1393 ft.	-4.1393 ft.	-4.1393 ft.
CPU time	1.59 sec.	2.18 sec.	0.69 sec.
PT	4.28×10^{-5}	1.90×10^{-8}	3.22×10^{-4}

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Table 4.7 Final displacements at node 4 (ft.), EXAMPLE PROBLEM 3

Sources	Displacements at node 4 (ft.) (with reference to initial state)			DF
	X	Y	Z	
Knudson (15)	-0.1322*	-0.1322*	-1.4707*	-31.4707
NONSAP	-0.1325*	-0.1325*	-1.4717*	-31.4717
Jayaraman & Knudson (13)	-0.1300*	-0.1319*	-1.4643*	-31.4643
Proposed technique	-0.3822	-0.3822	-4.1393	-31.4770

* - Displacement is calculated based on the assumed initial configuration as given by ref.(13).

DF - Final Z-displacement (ft.) after self-weight and external load are applied (with reference to the X-Y plane)

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Table 4.8 Results of analyses using various numbers of subdivision of the first trial displacement, EXAMPLE PROBLEM 3

Case	NSFD	NTE	DFC	NT	CPU time(sec.)	PT
A	10	1	-0.3185	9	1.93	$3.269X10^{-5}$
B	100	1	-2.0123	4	0.92	$2.770X10^{-7}$
C	200	1	-3.1112	3	0.73	$1.033X10^{-4}$
D	300	2	-4.0491	2	0.69	$3.216X10^{-4}$
E	400	2	-3.9789	3	0.87	$3.640X10^{-8}$
F	500	2	-4.0201	2	0.69	$8.363X10^{-4}$
G	1000	4	-4.0575	2	0.89	$3.082X10^{-4}$

NSFD - refers to number of subdivision of the first trial displacement

DFC - refers to displacement at the end of the first iterative cycle

NTE - refers to number of trial equilibrium state employed

NT - refers to number of iterative cycle required for convergence

Table 4.9 Data of EXAMPLE PROBLEM 4

Description		Magnitude
Material proporties;		
modulus of elasticity, E	(ksf.)	3.312×10^{6}
cross-sectional area, A	(sq. ft.)	1.667×10^{-2}
Physical proporties;		
unit weight of cable	(kip./ft.)	8.170×10^{-3}
unstressed length of element a	(ft.)	14.9963
unstressed length of element b	(ft.)	14.9983
unstressed length of element c	(ft.)	14.9934
unstressed length of element d	(ft.)	14.9936
Load;		
concentrated dead load acting downwards at nodes 1,3,7,9	(kip.)	0.50112
concentrated dead load acting downwards at node 2,4,6,8	(kip.)	0.50053
concentrated dead load acting downwards at node 5	(kip.)	0.48577
concentrated live load acting downwards at node 3	(kip.)	200.000
Prescribed tolerance		1.0×10^{-3}

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Table 4.9 Data of EXAMPLE PROBLEM 4 (cont.)

Node number	Coordinates of nodes at initial configuration, ft.		
	X	Y	Z
1	15.0	15.0	-0.30619
2	15.0	36.0	-0.38926
3	15.0	45.0	-0.30619
4	30.0	15.0	-0.38926
5	30.0	30.0	-0.49859
6	30.0	45.0	-0.38926
7	45.0	15.0	-0.30619
8	45.0	30.0	-0.38926
9	45.0	45.0	-0.30619
10	0.0	15.0	0.00000
11	0.0	30.0	0.00000
12	0.0	45.0	0.00000
13	15.0	60.0	0.00000
14	30.0	60.0	0.00000
15	45.0	60.0	0.00000
16	60.0	45.0	0.00000
17	60.0	30.0	0.00000
18	60.0	15.0	0.00000
19	45.0	0.0	0.00000
20	30.0	0.0	0.00000
21	15.0	0.0	0.00000

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Table 4.10 Relation between Z-displacement at node 3 (ft.) and cycle of iteration, EXAMPLE PROBLEM 4

Cycle no.	Newton-Raphson	Kar itertion	Proposed technique
1	-31.3669	-7.8417	-1.7523
2	-12.9188	-4.8999	-2.7416
3	-8.3848	-2.7989	-2.5735
4	-5.7044	-2.9944	-2.5319
5	-4.0282	-2.5639	-2.5295
6	-3.0591	-2.5415	
7	-2.6431	-2.5298	
8	-2.5362	-2.5295	
9	-2.5296		
Final results	-2.5295 ft.	-2.5295 ft.	-2.5295 ft.
CPU time	5.96 sec.	7.24 sec.	3.99 sec.
PT	5.81×10^{-4}	6.37×10^{-4}	5.21×10^{-4}

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Table 4.11 Final displacements at nodes 3, 5, 6, 7, 8 and 9, EXAMPLE PROBLEM 4

Displacements (ft.)		Sources		
Node	Direction	Proposed technique	NONSAP	Kar (4)
3	X	-0.17365	-0.17359	Not given
	Y	0.17365	0.17359	Not given
	Z	-2.52954	-2.52908	-2.50000
5	X	-0.03239	-0.03240	Not given
	Y	0.03239	0.03238	Not given
	Z	-0.56827	-0.56735	Not given
				Not given
6	X	-0.14353	-0.14351	Not given
	Y	0.04853	0.04843	Not given
	Z	-1.11120	-1.11052	Not given
				Not given
7	X	-0.00336	-0.00336	Not given
	Y	0.00336	0.00336	Not given
	Z	-0.04540	-0.04478	Not given

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Table 4.11 Final displacements at nodes 3, 5, 6, 7, 8 and 9, EXAMPLE PROBLEM 4 (cont.)

Displacements (ft.)		Sources		
Node	Direction	Proposed technique	NONSAP	Kar (4)
8	X	-0.01718	-0.01733	Not given
	Y	0.00637	0.00637	Not given
	Z	-0.17811	-0.17755	Not given
9	X	-0.07486	-0.07484	Not given
	Y	0.01005	0.01004	Not given
	Z	-0.41048	-0.41014	Not given

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Table 4.12 Data of EXAMPLE PROBLEM 5

Description		Magnitude
Material properties;		
modulus of elasticity, E	(psi.)	$1.9X10^{7}$
cross-sectional area, A	(sq. in.)	0.3610
Physical proporties;		
unit weight of cable	(lb./in.)	0.106667
unstressed length of element a	(in.)	409.8004
unstressed length of element b,c	(in.)	899.7284
unstressed length of element d,e	(in.)	583.9186
unstressed length of element f,g	(in.)	915.9247
unstressed length of element h,i,j,k,l	(in.)	1151.8698
Load;		
concentrated live load at node 2	(lb.)	510.0
concentrated live load at node 4	(lb.)	510.0
concentrated live load at node 6	(lb.)	510.0
concentrated live load at node 8	(lb.)	3170.0
Prescribed tolerance		$1.0X10^{-4}$

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Table 4.12 Data of EXAMPLE PROBLEM 5 (cont.)

Node number	Coordinates of nodes at self-weight equilibrium configuration, (inch)	
	Y	Z
1	0.000	0.000
2	317.953	259.344
3	1012.617	833.294
4	1702.795	1412.435
5	2148.325	1791.135
6	2591.977	2172.037
7	3284.037	2773.820
8	3971.512	3380.848
9	4829.695	4151.614
10	5680.705	4930.312
11	6524.592	5716.745
12	7361.466	6510.720
13	8191.200	7312.050

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Table 4.13 Relation between Z-displacement at node 8 (inch) and cycle of iteration, EXAMPLE PROBLEM 5

Cycle no.	Newton-Raphson	Kar itertion	Proposed technique
1	-441.6319	-110.4080	-124.7506
2	-280.5442	-179.9662	-202.9092
3	-208.5303	-186.9410	-188.2583
4	-189.3491	-187.5759	-187.5854
5	-187.6088		
6	-187.5839		
Final results	-187.5840 in.	-187.5840 in.	-187.5840 in.
CPU time	1.66 sec.	1.36 sec.	1.37 sec.
PT	$5.27X10^{-4}$	$4.62X10^{-1}$	$1.93X10^{-2}$

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Table 4.14 Final displacements at node 2, 4, 6 and 8,

EXAMPLE PROBLEM 5

Displacements (in.)		Sources		
Node	Direction	Proposed technique*	NONSAP*	NONSAP (5)*
2	Y	29.8770	29.8059	29.7238
	Z	-36.0719	-36.0004	-36.0215
4	Y	136.4908	135.7660	135.6290
	Z	-160.9344	-160.1029	-160.0370
6	Y	188.9696	187.5736	187.4120
	Z	-219.8339	-218.2299	-218.1240
8	Y	245.1383	242.3343	242.1490
	Z	-279.2426	-276.0396	-275.8950

* - Final displacements after self-weight load and concentrated live loads are applied.

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Table 4.15 Data of EXAMPLE PROBLEM 6

Description		Magnitude
Material properties;		
modulus of elasticity, E	(ksf.)	3.812×10^{6}
cross-sectional area, A	(sq. ft.)	1.000×10^{-2}
Physical properties;		
unit weight of cable	(kip./ft.)	4.900×10^{-3}
unstressed length of element a	(ft.)	12.4758
unstressed length of element b	(ft.)	12.1003
unstressed length of element c	(ft.)	11.9725
unstressed length of element d	(ft.)	10.6720
unstressed length of element e	(ft.)	10.4955
Load;		
concentrated live load at all free nodes	(kip.)	13.498
Prescribed tolerance		1.000×10^{-3}

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Table 4.15 Data of EXAMPLE PROBLEM 6 (cont.)

Node number	Coordinates of nodes at self-weight equilibrium configuration, ft.		
	X	Y	Z
1	12.00016	10.49984	-1.29086
2	12.00002	21.00000	-1.97993
3	12.00016	31.50016	-1.29086
4	24.00006	10.49982	0.46903
5	24.00005	21.00000	-0.21985
6	24.00006	31.50018	0.46903
7	35.99994	10.49982	0.46903
8	35.99999	21.00000	-0.21985
9	35.99994	31.50018	0.46903
10	47.99984	10.49984	-1.29086
11	47.99998	21.00000	-1.97993
12	47.99984	31.50016	-1.29086
13	0.00000	10.50000	-4.81000
14	0.00000	21.00000	-5.50000
15	0.00000	31.50000	-4.81000
16	12.00000	42.00000	0.77000
17	24.00000	42.00000	2.53000
18	36.00000	42.00000	2.53000
19	48.00000	42.00000	0.77000

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Table 4.15 Data of EXAMPLE PROBLEM 6 (cont.)

Node number	Coordinates of nodes at self-weight equilibrium configuration, ft.		
	X	Y	Z
20	60.00000	42.00000	-4.81000
21	60.00000	31.50000	-5.50000
22	60.00000	21.00000	-4.81000
23	48.00000	10.50000	0.77000
24	36.00000	0.00000	2.53000
25	24.00000	0.00000	2.53000
26	12.00000	0.00000	0.77000

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Table 4.16 Relation between Z-displacement at node 5 (ft.) and cycle of iteration, EXAMPLE PROBLEM 6

Cycle no.	Newton-Raphson	Kar itertion	Proposed technique
1	-0.1540	-0.3849	-0.1428
2	-0.1508	-0.1507	-0.1508
3		-0.1508	
Final results	-0.1508 ft.	-0.1508 ft.	-0.1508 ft.
CPU time	1.04 sec.	2.50 sec.	1.39 sec.
PT	$1.18X10^{-2}$	$1.66X10^{-3}$	$1.77X10^{-3}$

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Table 4.17 Final displacements at nodes 1, 2, 4 and 5, EXAMPLE PROBLEM 6

Displacements (ft.)		Sources		
Node	Direction	Proposed technique*	NONSAP*	Baron et.al.(8)
1	X	0.01974	0.01976	0.01990
	Y	-0.01139	-0.01138	-0.01150
	Z	-0.12247	-0.12256	-0.12300
2	X	0.02276	0.02278	0.02300
	Y	0.00000	0.00000	0.00000
	Z	-0.14149	-0.14158	-0.14300
4	X	0.00679	0.00680	0.00680
	Y	-0.01208	-0.01209	-0.01210
	Z	-0.12999	-0.13013	-0.13100
5	X	0.00782	0.00787	0.00790
	Y	0.00000	0.00000	0.00000
	Z	-0.15077	-0.15088	-0.15200

* : assumed unit weight of cable of $4.9X10^{-3}$ kip./ft.

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FIGURES

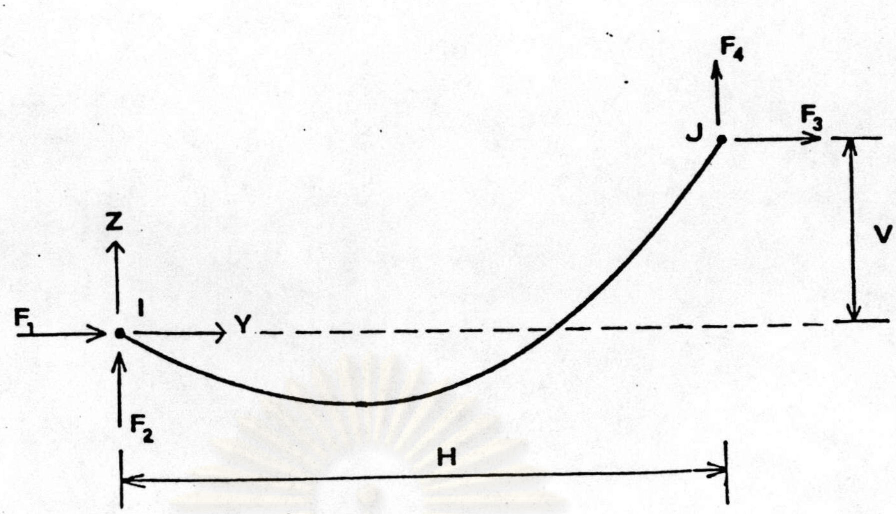

Figure 2.1 Cable element in local YZ plane

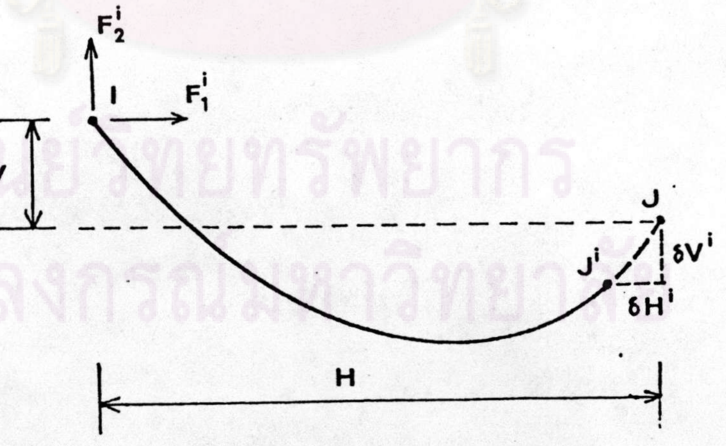

Figure 2.2 Cable configuration at step i

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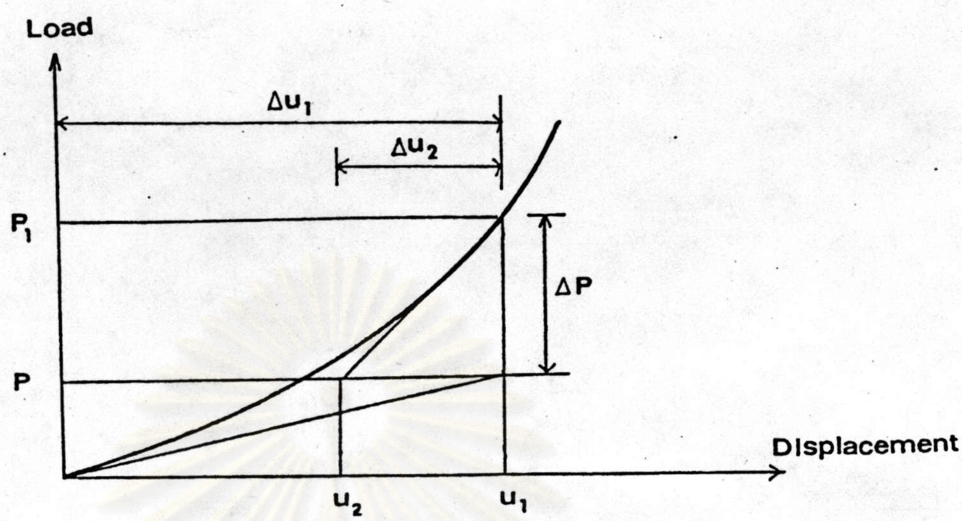

Figure 3.1 Load-displacement curve, NEWTON-RAPHSON METHOD

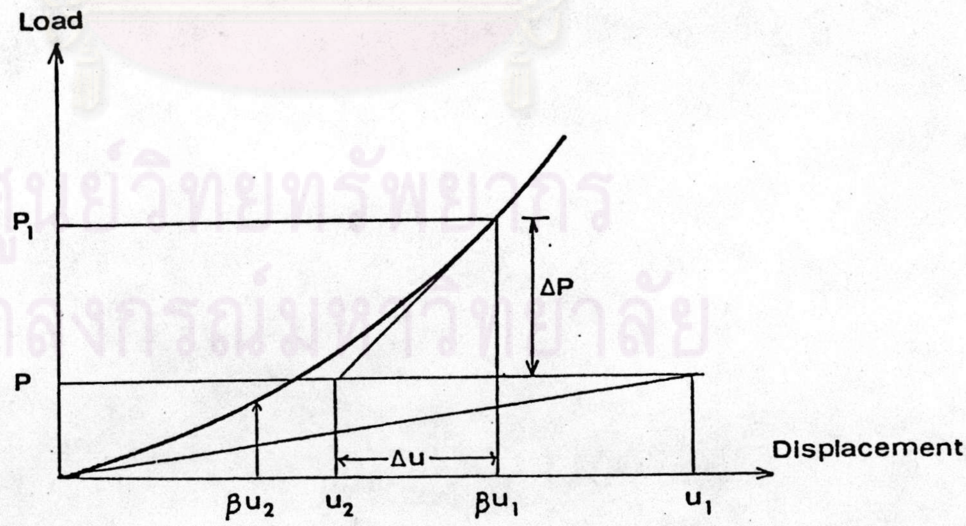

Figure 3.2 Load-displacement curve, UNDERRELAXATION METHOD

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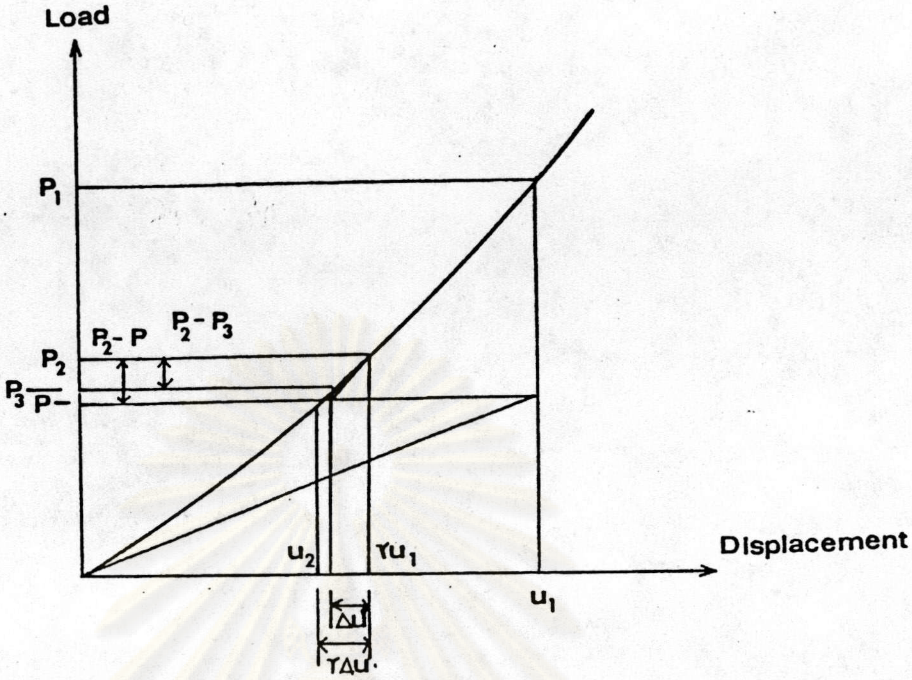

Figure 3.3 Load-displacement curve, KAR ITERATION PROCEDURE

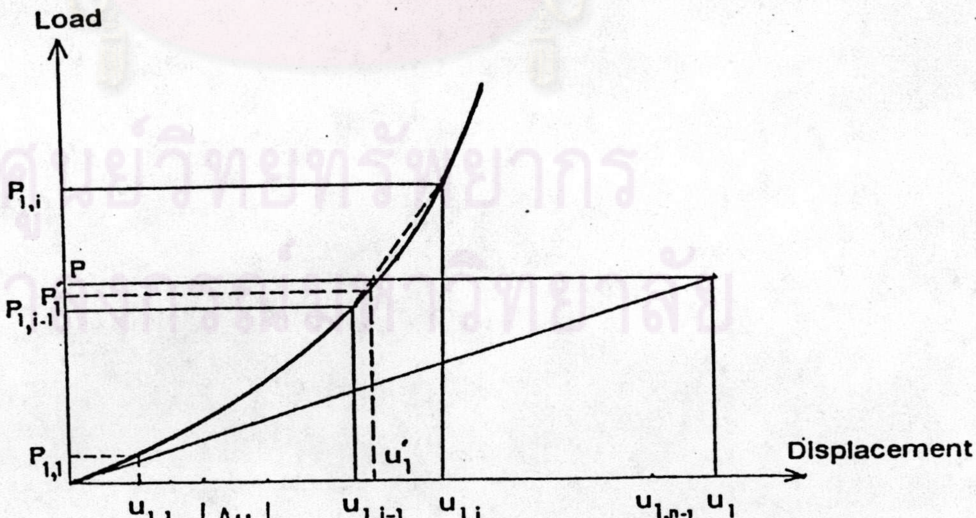

Figure 3.4 THE PROPOSED ITERATIVE IMPROVEMENT

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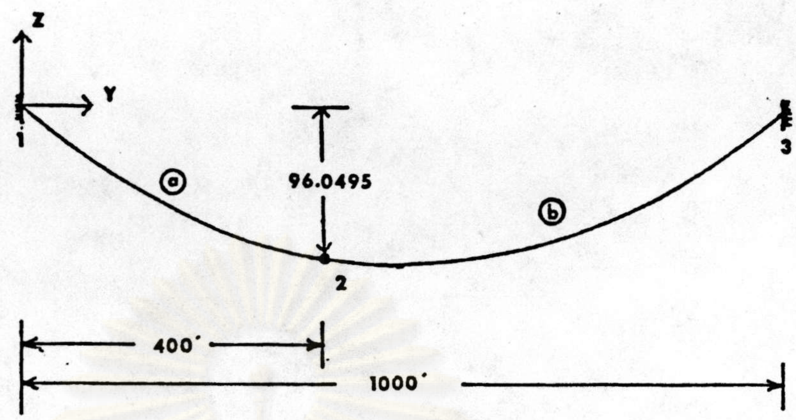

Figure 4.1 Isolated cable at self-weight shape, EXAMPLE PROBLEM 1,2

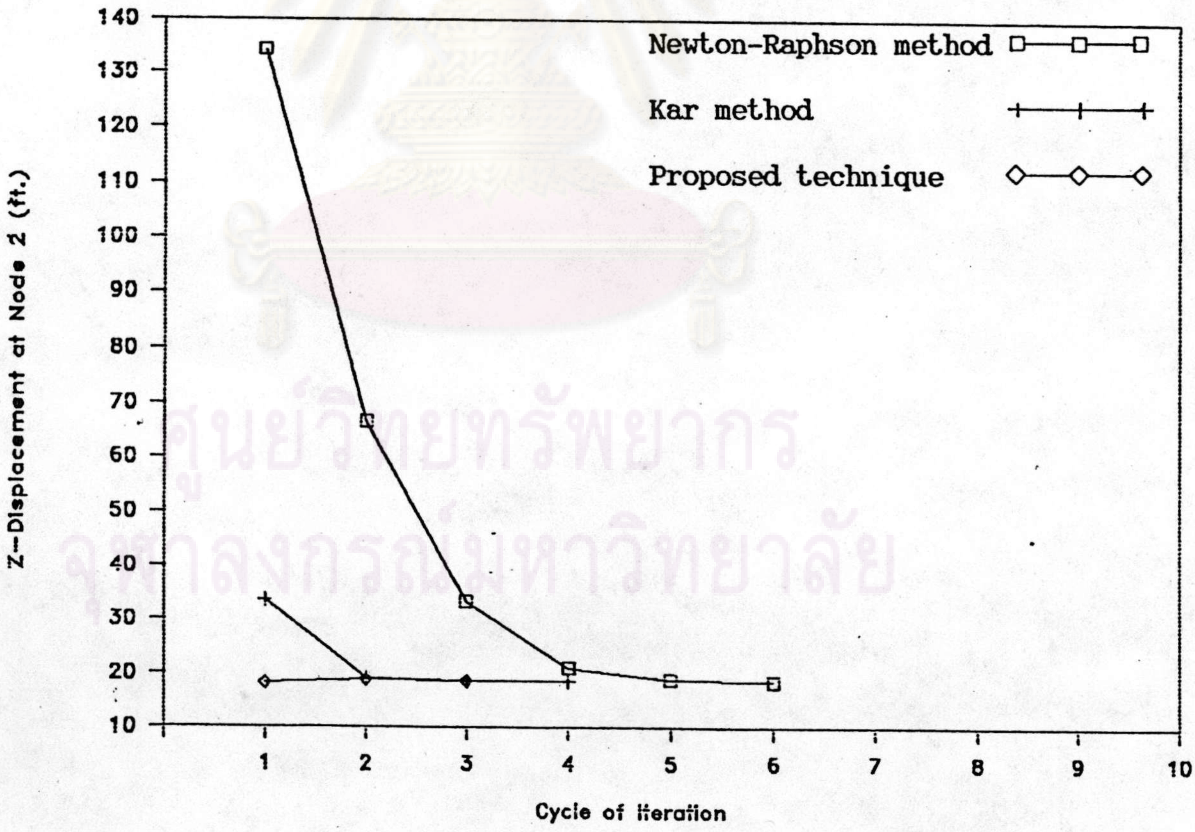

Figure 4.2 Speed of convergence of each iterative method, EXAMPLE PROBLEM 1

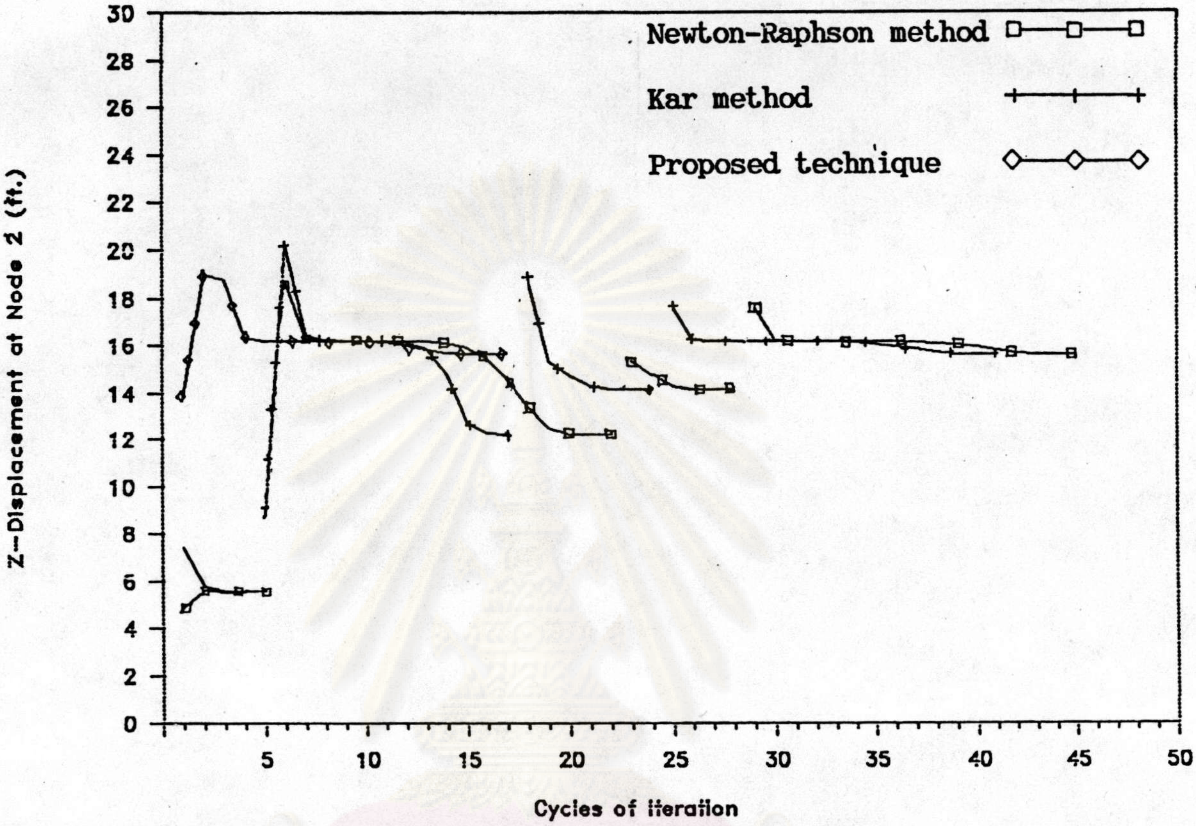

Figure 4.3 Speed of convergence of each iterative method, EXAMPLE PROBLEM 2

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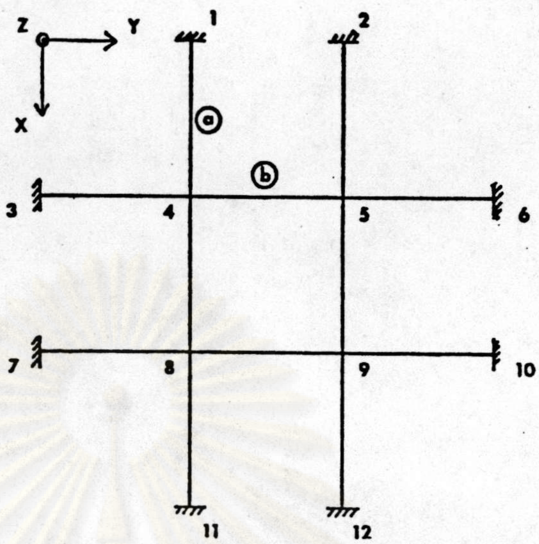

Figure 4.4 Cable net at plan view, EXAMPLE PROBLEM 3

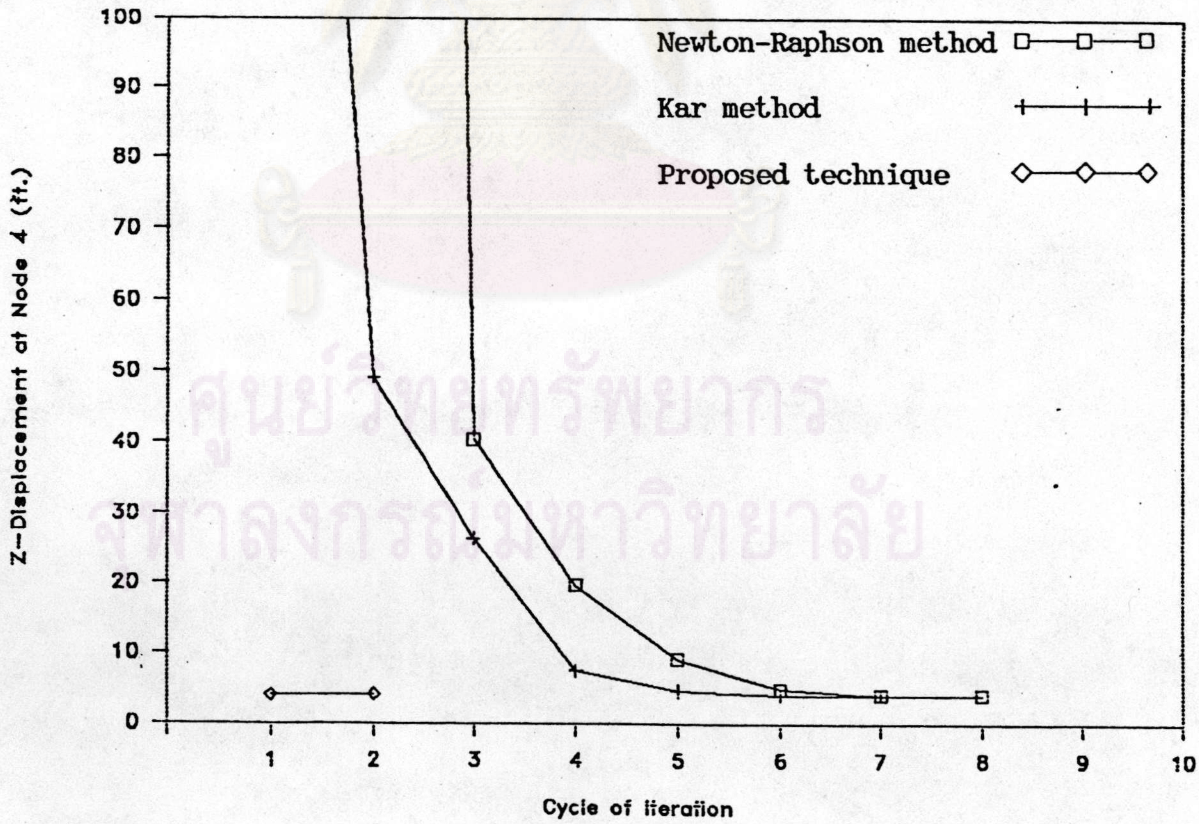

Figure 4.5 Speed of convergence of each iterative method, EXAMPLE PROBLEM 3

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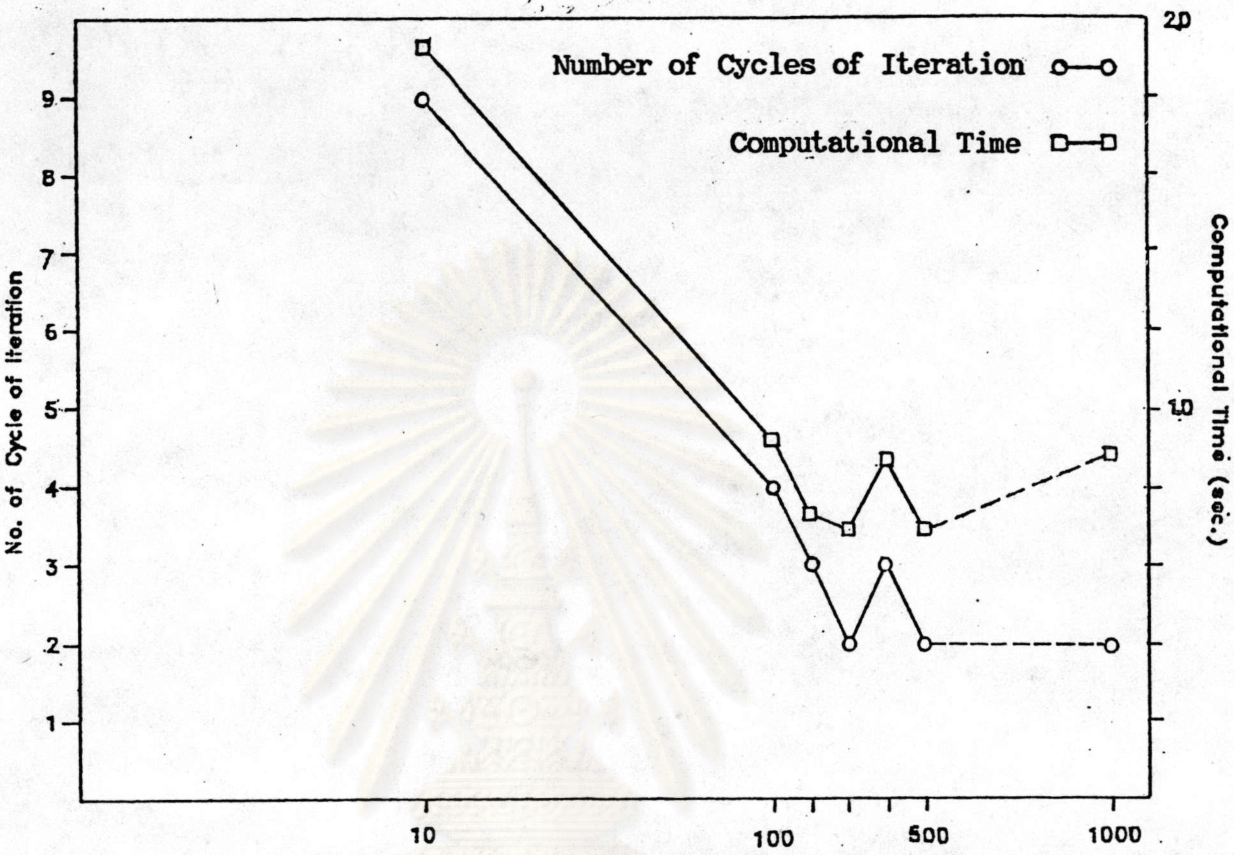

Number of Subdivisions of the First Trial Displacement

Figure 4.6 Rate of convergence v.s. number of subdivision of the first trial displacement, EXAMPLE PROBLEM 3

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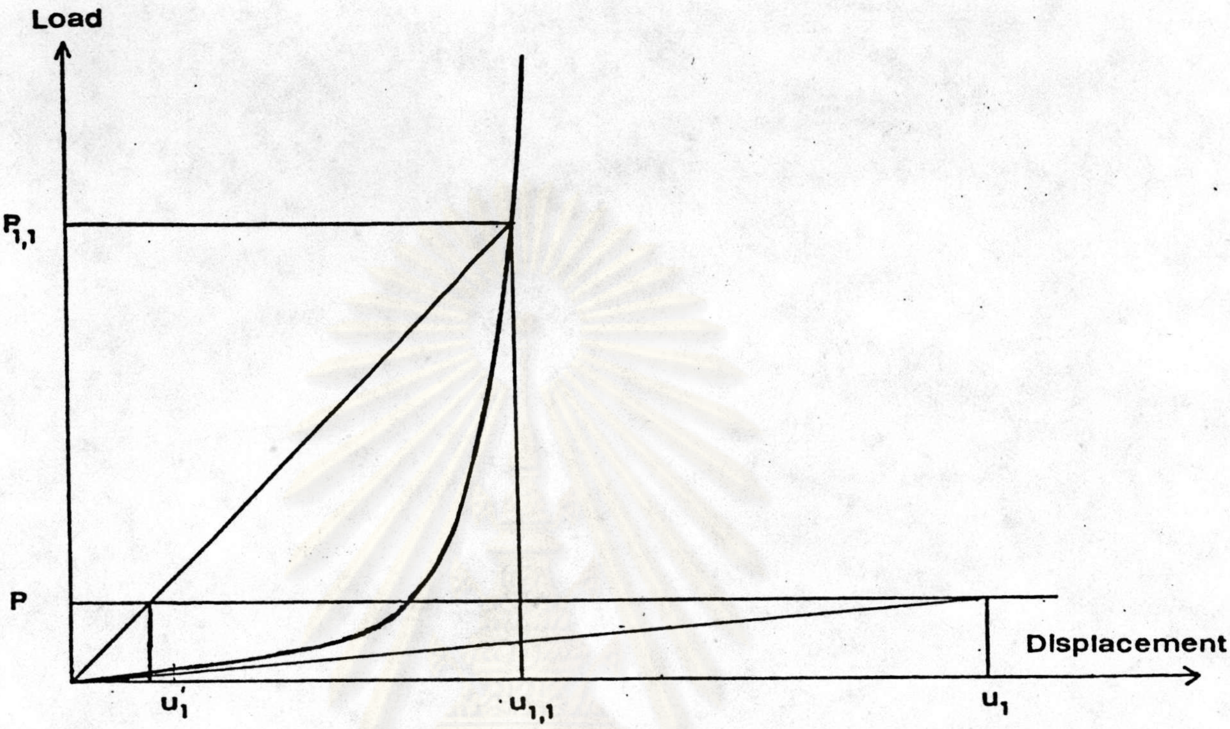

Figure 4.7 Displacement at the end of the first iterative cycle in case of small number of subdivisions, EXAMPLE PROBLEM 3

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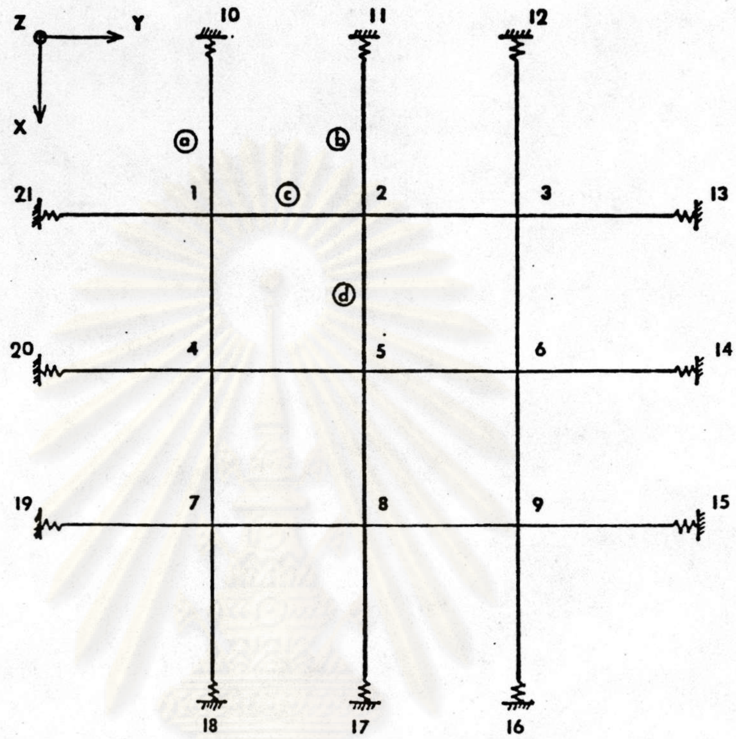

Figure 4.8 A syncastic net at plan view, EXAMPLE PROBLEM 4

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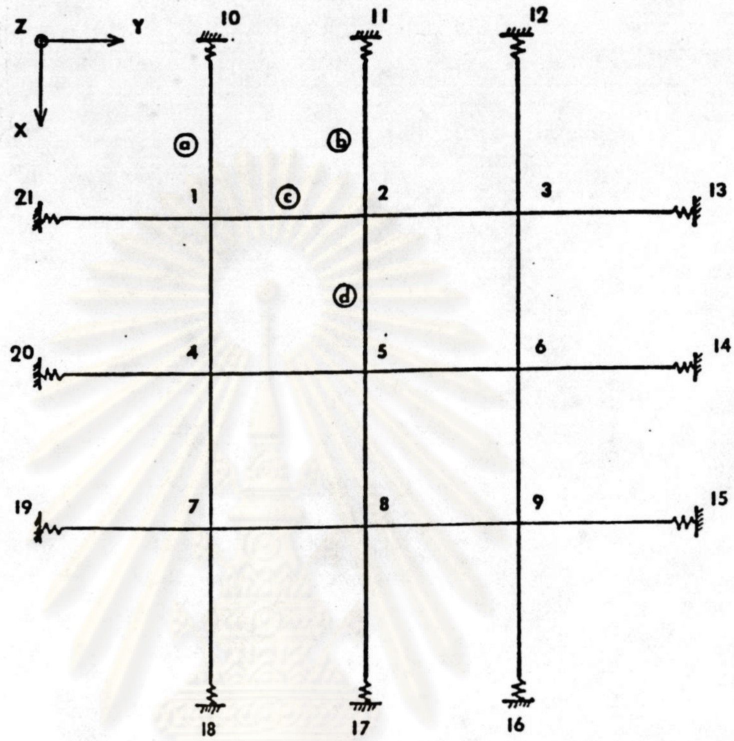

Figure 4.8 A syncastic net at plan view, EXAMPLE PROBLEM 4

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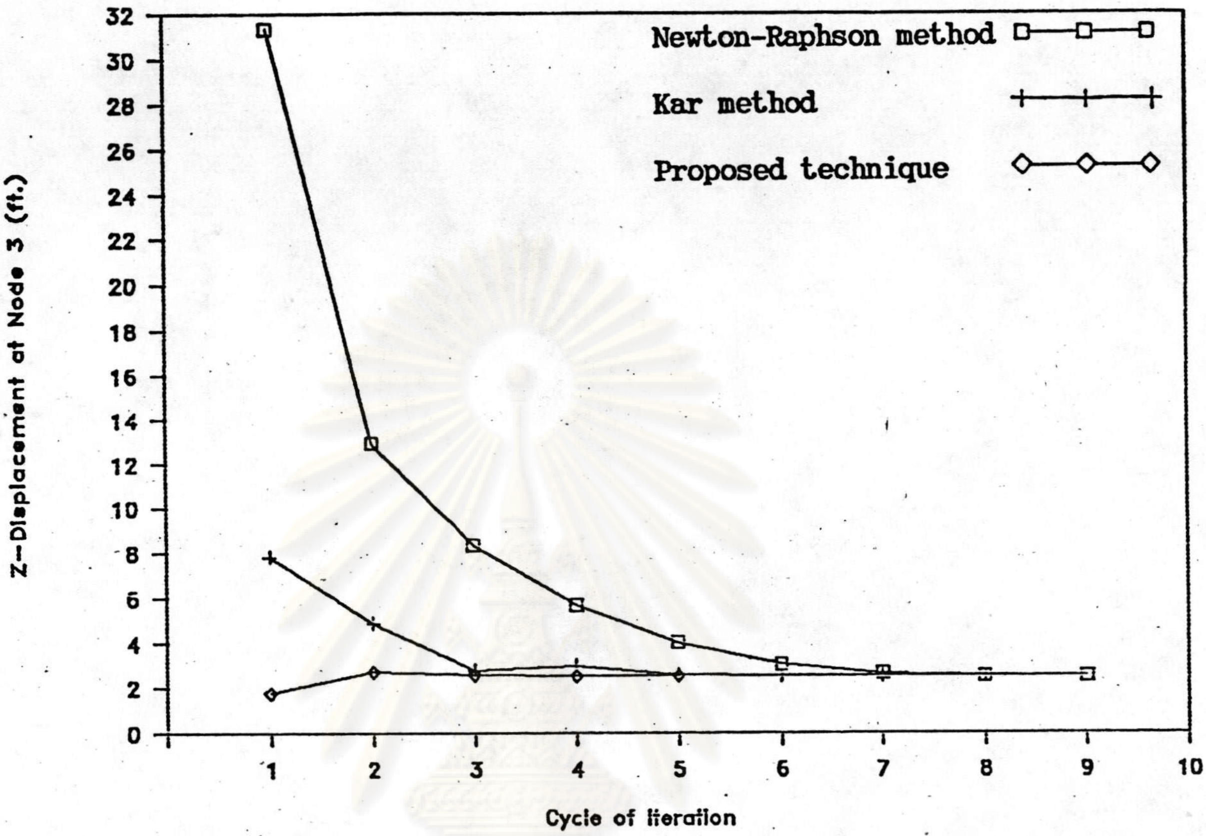

Figure 4.9 Speed of convergence of each iterative method, EXAMPLE PROBLEM 4

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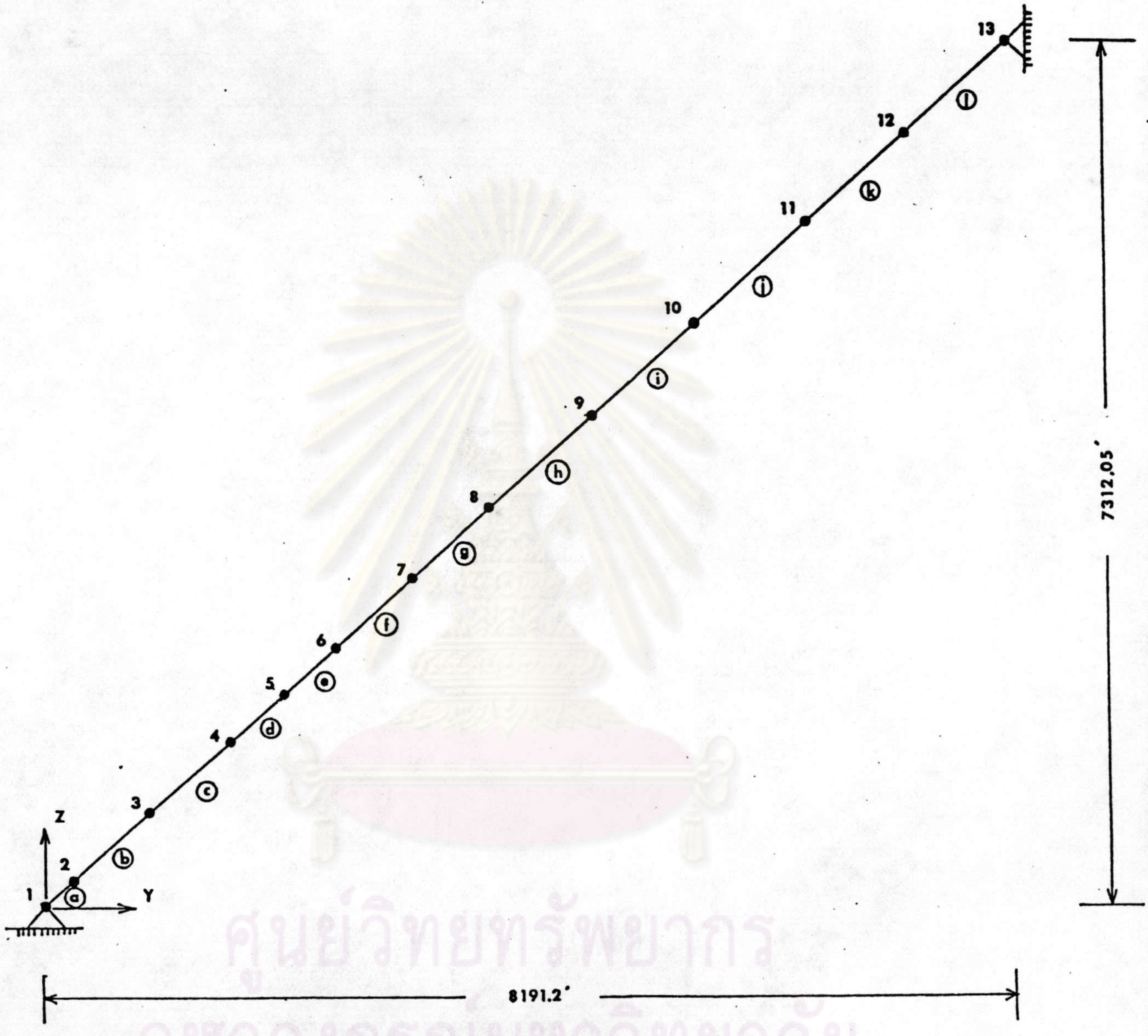

Figure 4.10 Isolated prestressed cable, EXAMPLE PROBLEM 5

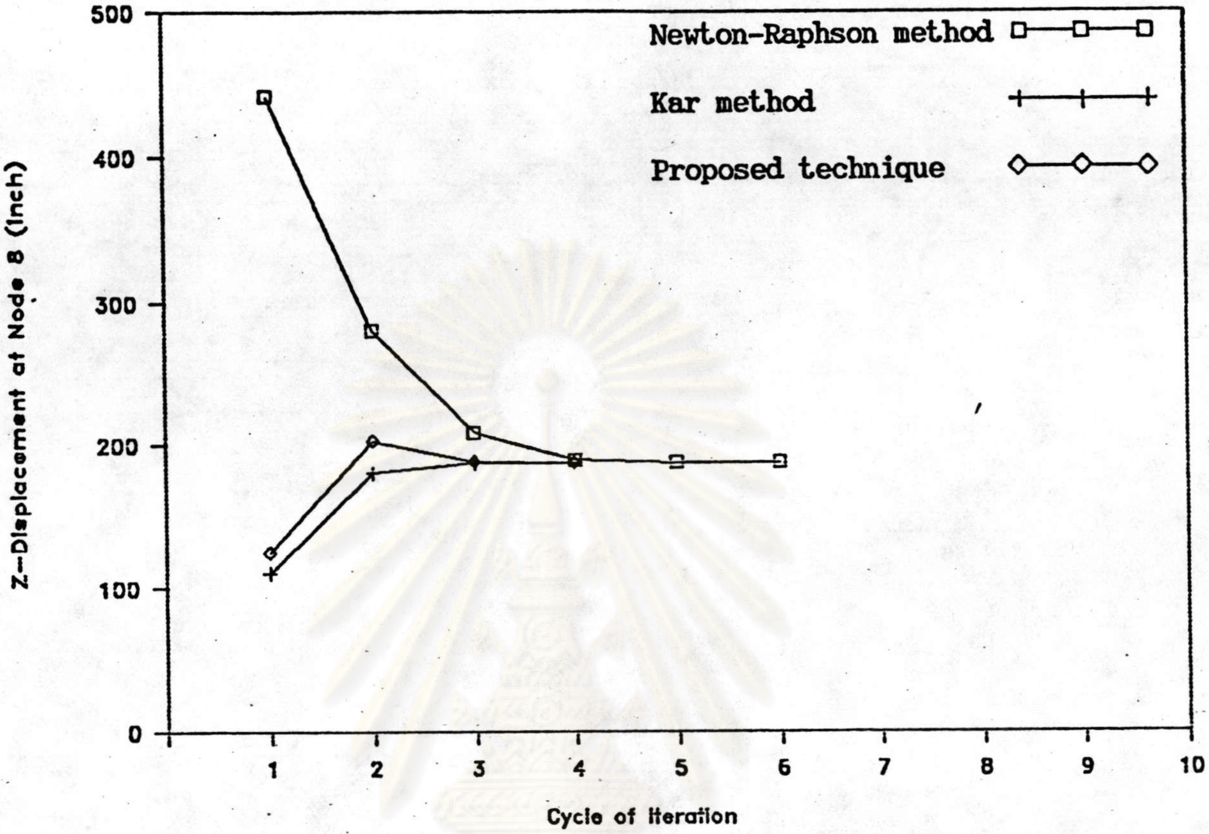

Figure 4.11 Speed of convergence of each iterative method, EXAMPLE PROBLEM 5

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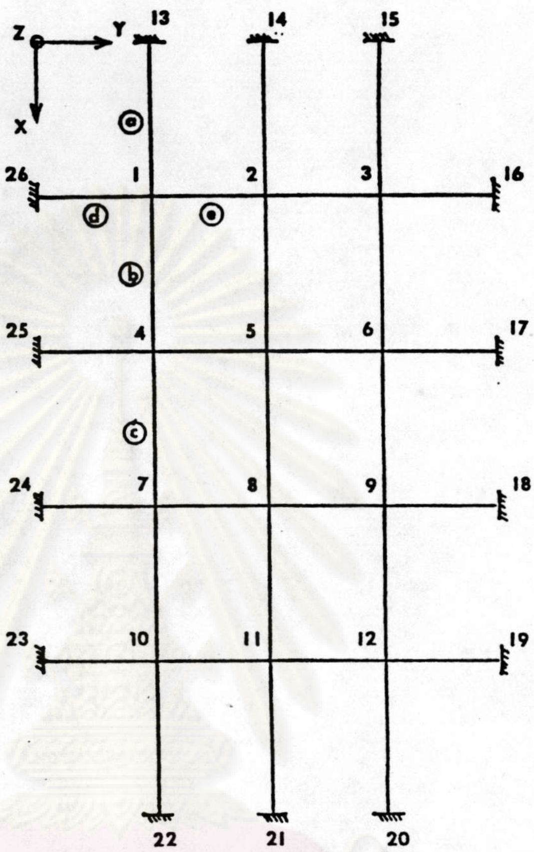

Figure 4.12 Saddle-shape cable net at plan view , EXAMPLE PROBLEM 6

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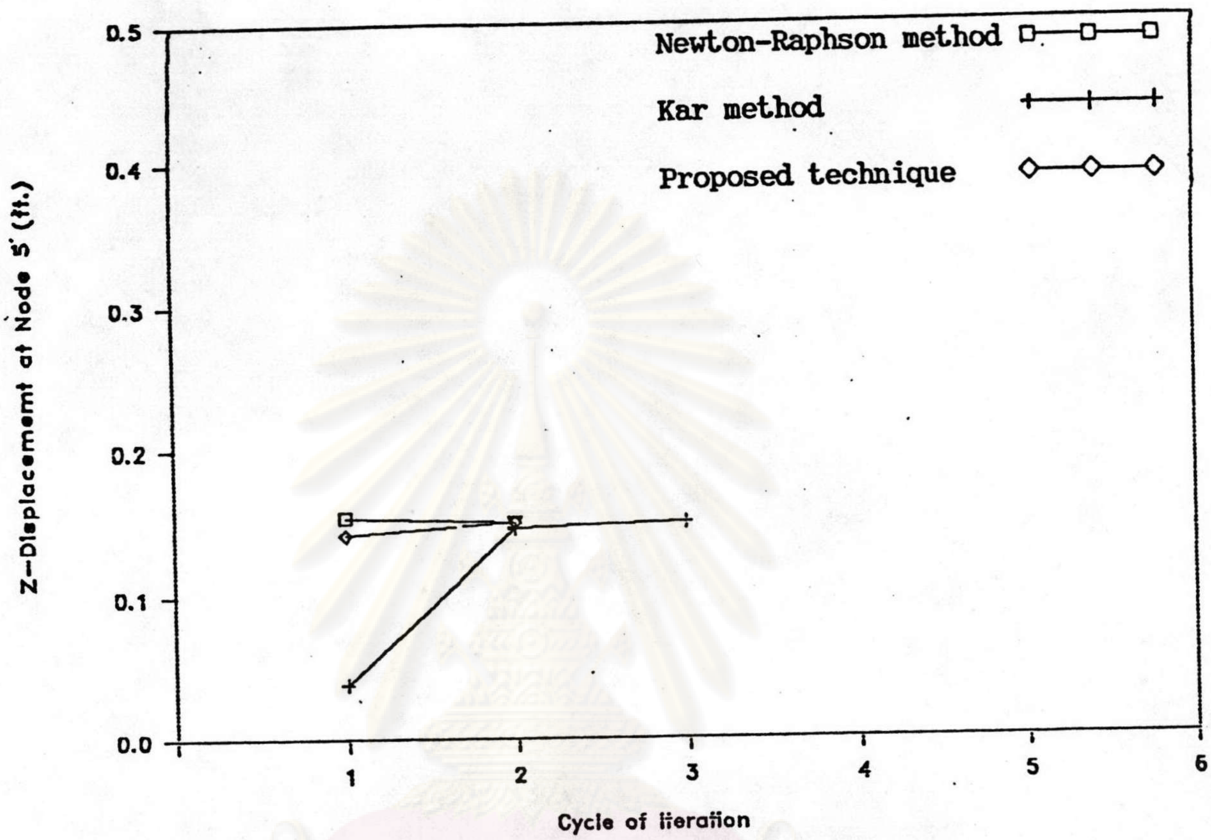

Figure 4.13 Speed of convergence of each iterative method, EXAMPLE PROBLEM 6

VITA

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