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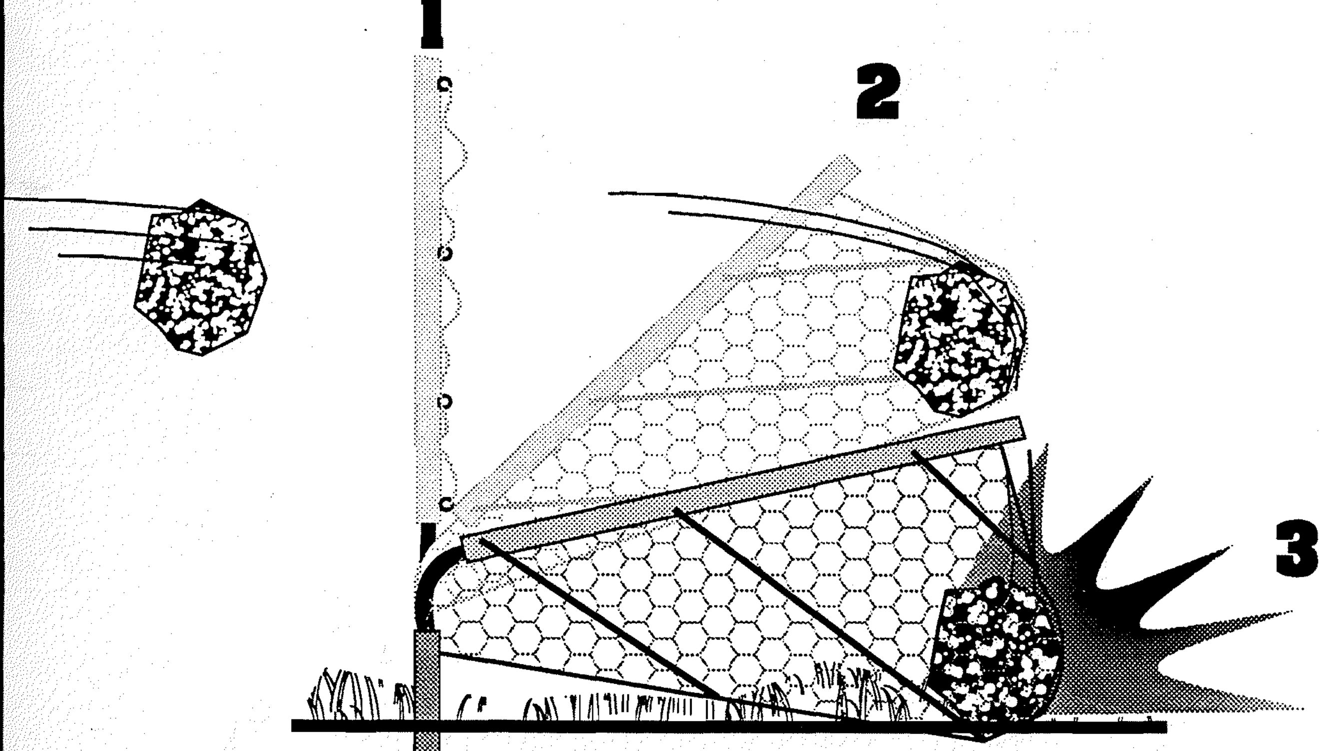
CDOT FLEX-POST ROCKFALL FENCE



REVIEW OF FIELD TESTS AND DEVELOPMENT OF DYNAMIC ANALYSIS PROGRAM FOR THE CDOH FLEX-POST ROCKFALL FENCE

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May, 1991

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16. Abstract

Field testing and dynamic analysis of a flexible rockfall protection structure is reported. Two prototype fence designs using the CDOH Flexpost were constructed and tested with freely falling rocks. Field tests were recorded on videotape. Rock sizes and weights were known, and reference points were marked on slopes and prototypes, allowing a quantification of rockfall velocities and energies, and prototype response. A large-deflection dynamic analysis program was developed and was used to compute fence response to rockfall impact cases equivalent to impacts observed in feild tests. Results of the analysis agree well with observed prototype response. Information for fence design, including forces in members and forces on post foundations are presented. The dependence of member force on rockfall energy is examined. Flexpost fence strength is presented as a curve of limiting rockfall velocity versus rock weight.

Implementation

The Colorado Flexpost Rockfall Fence is patented by the Colorado Department of Transportation. Any use of this or similar systems must be preapproved in writing by the Colorado Department of Transportation.

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Review of Field Tests and Development of Dynamic Analysis Program for CDOH Flexpost Fence

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Review of Field Tests and Development of Dynamic Analysis Program for CDOH Flexpost Fence

Introduction

In this study, the rockfall impact capacity of the CDOH Flexpost fence has been quantified in terms of maximum rock mass and velocity through a review of the performance of prototype fences in field tests, and through analysis of fence response to impact using a large deformation analysis program developed specifically for the Flexpost fence. The tasks of this study include a review of the videotapes of tests of prototype fences, extension of existing fence analysis routines, and calibration of the analysis through a comparison of predicted impact response of the fence to response observed in prototype tests.

All tasks have been successfully completed. Videotapes of the 1990 field tests have been reviewed, and from these videotapes, rockfall velocities, trajectories, and kinetic energies have been estimated. A general dynamic analysis program has been developed. The program is a non-linear, large deformation analysis program which includes explicit modelling of contact between the fence and the rock. The analysis program yields maximum forces in members, maximum forces in foundations, maximum rotations of posts, and a time history of fence deflections. Rockfall impacts observed in field tests were used as input load cases for the fence analysis program. Analysis results are consistent with fence performance in field tests.

This report includes a summary of data collected in videotape review, a description of the analytical model of the fence, a description of dynamic analysis solution sequence, a program listing, and maximum rock size and velocity for the present design of the fence.

CDOH Flexpost Fence

The Colorado Department of Highways has long sought to minimize rockfall hazard through development of better predictive tools and innovative protective structures. The Department's efforts include the development of state-of-the-art computational tools for prediction of rockfall energies and bounding heights using local topography and boulder population, and ongoing testing and design development of innovative structures to trap, slow, or deflect rockfalls. Among these structures are trenches, earth-filled timber cribs, geofabric wall barriers, resilient pendulums, and the Flexpost fence.

The Flexpost fence is a net of Maccaferri gabion mesh and intertwined steel cables supported on steel pipe posts. The posts are supported by spring elements constructed of 7 wire prestressing strand which can accommodate large post rotations without damage. Post rotations are limited by cable stays in the plane of the fence, but are not otherwise restricted. There are no cable stays out of the plane of the fence. The fence is a slender, two-dimensional structure. Large rotation capacity of the posts provides large deflection capacity for the fence, making the fence compliant. Compliance is a primary consideration in the design of rockfall mitigation structures. The input to a rockfall mitigation structure is energy, not force. Mitigation structures must dissipate the kinetic energy of falling rocks. Rigid structures which allow little defection must, by their nature, respond to impacts with high forces. Compliant structures will respond to the same impacts with lower force.

For minor impacts, the Flexpost fence absorbs rockfall energy through inertial resistance and through straining in mesh, cables, stays and posts. The fence structure itself absorbs the rockfall kinetic energy. For more severe impacts, inertia and stiffness remain, but a second mechanism is observed as well. Large, fast-moving rocks stretch the fence fabric taut. The taut fence imposes centripetal accelerations on rocks and can lead them to impacts with the ground. For severe impacts it is the earth, not the fence, that absorbs rockfall kinetic energy, provided that the fence has sufficient tensile strength to redirect the rock.

This second mechanism of Flexpost fence response was discussed in a 1990 study [1] of an early fence design. That study recommended the use of taller posts and a wider post spacing to increase overall flexibility of the fence, and to minimize forces in the fence fabric. Field

[1] G.Hearn, D.Hinzman, Analysis and Design Recommendations for the CDOH Flexpost Fence, June, 1990

trials of this larger Flexpost fence were conducted by CDOH near Rifle, Colorado during July and August of 1990 with notable success. The larger fence was able to capture large, fast moving rocks.

Having succeeded in its field trials, the Flexpost fence can be installed as a permanent rockfall mitigation structure at sites where the fence's capacity to catch rockfall is adequate for the hazard. To quantify the capacity of the Flexpost fence, impact conditions observed in field tests have been collected, an analysis program has been developed, and set of limiting rock weights and velocities have been computed based on field observations and on the results of analysis.

Field Tests:
Prototype Fences and General Observations

Two prototype Flexpost fence designs were built at a test site near Rifle, Colorado in the summer of 1990 (Fig. 1). Both prototypes were subjected to impacts by rocks of known size and weight (Fig. 2). The supply of test rocks included a range of weights from 145 lbs to 9700 lbs; rocks which hit the prototypes ranged from 256 lbs to 6040 lbs. The first prototype design was tested on July 10, 1990. This July prototype used 11 ft Flexposts, a post spacing of 16 ft in two middle panels, and a post spacing of 8 ft in two end panels. During tests on July 10, thirty-one rocks were dropped resulting in twelve impacts with the fence (Fig. 3,4). Of these twelve impacts, eight were stopped without damage to the fence, one tore the mesh fabric, and three overtopped the fence which at the time was partially held down by previous rockfalls. Translational kinetic energies of rock impacts ranged from 4,700 ft-lbs to 166,000 ft-lbs. The July prototype was not damaged by impacts with translational kinetic energies as high as 42,600 ft-lbs (a 1490 lb rock travelling at 43 ft/s), and was damaged by a rockfall at 44,100 ft-lbs (a 1550 lb rock travelling at 43 ft/s). The July prototype appeared to have sufficient strength, but the repeated rockfall impacts damaged the strands at the base of posts. By the end of testing, the Flexposts could no longer rebound after an impact, though the posts would stand vertical if righted. It appeared that the combination of extreme deformation of strands in bending, and tension in the post was the cause of damage to strands.

A second prototype with a revised design was tested on August 13, and again on August 21, 1990. This August prototype had the same post height and spacing as the July prototype, and had, in addition, diagonal cable stays in the plane of the fence between posts, connecting post tops to post foundations (Fig. 1). These stays take tensions during rockfall impact and protect the strands. The August prototype was tested by seventeen rockfall impacts out of thirty-nine attempts (Fig. 3,5,6). Of the impacts, thirteen were stopped without damage, two tore the mesh, one bent a Flexpost, one tore a diagonal stay, and one tore the top horizontal cable. Translational kinetic energy of the impact cases ranged from 2700 ft-lbs to 132,000 ft-lbs. The August prototype withstood an impact with a translational kinetic energy of 29,600 ft-lbs without damage, and was damaged by an impact of 58,700 ft-lbs. The Flexposts were able to rebound throughout the two testing days. The cable stays appeared to provide adequate protection for the strands.

Field Tests:

Data Reduction

Rockfall impacts were recorded by two videocameras, one a 'sweep' camera following the rock, and the other a 'fixed' camera focused on the Flexpost fence. Both cameras ran at 30 frames per second. Timescales were added to the videotapes after testing. The fence was marked with colored ribbons woven into the mesh to improve visibility. The slope of the test site was also marked with ribbons at 10 ft intervals extending a distance of 60 ft uphill from the fence. These ribbons were used as reference points for estimating rock velocity during videotape review. Rocks, in addition to their ID numbers, were painted with a pattern of dots so that rotational velocities could be estimated.

Videotapes of rockfall tests were reviewed to quantify impact conditions and fence response, and to provide input rockfall cases for the dynamic analysis program. Data obtained from the videotapes include:

- Rock translational velocity
- Rock rotational velocity
- Vertical angle of rock trajectory
- Horizontal angle of rock trajectory
- Location of impact on fence
- Post rotations in response to impact
- Damage to fence, if any

A coordinate system for reporting rockfall positions and velocities appears in Figs. 7,8. With data on rock size and weight, the data from the videotapes was used to compute translational and rotational kinetic energies of rockfalls (Figs. 9,10,11). Data on rockfall impact energies is summarized in Fig. 12,13. Post rotations are presented in Fig. 14,15,16.

Field Tests:

Conclusions

Field tests indicate that the impact capacity of the Flexpost fence is limited by the strength of the mesh. For impacts in the mesh, it is observed that the mesh will tear before other components fail, and this limit on mesh strength is clearly associated with a specific maximum kinetic energy. To be sure, other fence components were damaged in impacts. In separate impacts, a diagonal stay was torn, the top cable was torn, and a Flexpost was bent. In all cases the affected component had been hit directly by a rock. Neither the posts nor the stays are as compliant as the mesh, and during the top cable failure, the fence movement was restricted by other rocks lying in the mesh. Bent Flexposts, or the loss of individual stays will not immediately impair the overall performance of the fence, but a broken top cable is a serious loss. The likelihood of local damage to some components due to direct impacts will depend on site conditions and on maintenance intervals. While it might be argued that direct impacts with posts and stays are unlikely since the profile presented by these is only a small part of the overall area of the fence, it is possible that the site may include rockfall paths which concentrate impacts at a few locations along the fence. The possibility that fallen rocks accumulate in the fence and limit its deflection capability will depend on the rockfall activity of the site and on the frequency of maintenance cleaning. These concerns are site specific.

Dynamic Analysis Program

A FORTRAN program for analysis of Flexpost fence response to rockfall impact has been developed. The program uses a time-step approach to compute node displacements and member forces. The basic timestep is 1/100s. The rock is treated as a separate body, and the program uses information on rock position and fence geometry to compute a set of contact forces between the rock and the fence. These contact forces drive fence deformation and alter rock speed and trajectory. Output files include maximum forces in members with time of occurrence, and a complete description of the geometry of the fence at every tenth time step (more frequent output is possible).

The analytical model of the Flexpost fence is a lumped mass model of more than 300 nodes connected by a gridwork of mesh and cable members (Fig. 17,18). Nodes in the model occur at all post tops and foundation, in the mesh at post centerlines, and in the mesh at the midspan of mesh panels. Additional nodes 1 ft on center are placed in mesh panels near the location of rock impact. This close spacing of nodes is required to model the contact of the rock with the fence fabric (Fig. 19). Fence models with differing 'contact' panels have been prepared to handle various impact locations (Fig. 20).

Mesh and cable members can carry tensions only (negative strains produce a computed zero force value). Mechanical properties have been taken from manufacturers literature for cables, and developed from material tests for the Maccaferri gabion mesh. Flexposts can take axial tension or compression. Spring stiffness for posts rotations is taken as the bilinear relation reported previously. A detailed description of the analysis solution sequence and a program listing are contained in Appendix A.

Dynamic Analysis Program: Use and Results

Rockfall impact cases observed in field tests have been used as input to the dynamic analysis program. Fence deflections, forces in members and contact forces with the rock have been computed. Input load case are shown in Fig. 21. Results of the analysis are presented in Figs. 22 to 37. Analysis results are in good qualitative agreement with observed performance in field trials. Specifically, for impacts which damage the fence, analysis results indicate members forces in excess of the expected breaking strength.

Of particular interest are forces in the mesh. Member forces computed in the analysis should not be compared directly to mesh strength obtained from static tests. Instead, the average level of force per linear foot should be computed for mesh members surrounding the rock (a grid of four connected mesh members including the most highly stressed member is used). In this manner, plastic deformation of the mesh and redistribution of the forces among mesh members may be recognized. Using such an averaging procedure, force levels in the mesh have been computed for the input rockfall cases (Fig. 40). Average mesh force levels are in good agreement with a mesh breaking strength of about 2000 plf, with some obvious exceptions:

- August 13, Rock 40 and August 13, Rock 41 both tore the mesh. Computed mesh force is in excess of mesh strength, as expected.
- August 13, Rock 12 produced significant plastic deformation of mesh and cables, as noted on the videotape, and so the high mesh force indicates mesh deformation just short of a rupture.

- August 21, Rock 37 and August 21, Rock 14 have high computed mesh force without observed rupture in tests. It is possible that significant plastic deformation in the mesh had occurred, but was not noted.

Actual member forces may be somewhat lower than the analysis indicates because plastic deformation, and slip between mesh and cables (which will increase the length of mesh members) are not included explicitly in the analysis. However, the analysis program yields expected mesh force levels for nearly all impact cases, and correctly identifies all cases which will damage the mesh. It is a reliable, conservative analysis.

The influence of diagonal stays on member forces has been investigated through a reanalysis of cases August 13, Rock 64 and August 13, Rock 34 using a fence model without stays to allow a direct comparison between fences with and without stays. Results for these two special cases are presented in Figs. 38 and 39. Mesh and top cable forces are lower for the fence without stays (the fence is more flexible without stays). Intermediate cables C1, C2 and C3 also show lower forces but the differences are not always large. Bottom cable force will, in general, increase. Lack of diagonal stays eliminates an important load path for transfer of fabric forces to the foundations, and leaves much of this task to the bottom cable alone. Interior posts are always in compression when stays are present. Without stays interior posts may experience net tensions.

A study of limiting impact cases was undertaken. A relation between members forces and rockfall kinetic energy was sought which could provide guidance in evaluation of limiting cases. Also, for a given set of design parameters (i.e. member strength, post spacing, etc.), it was expected that limiting impact cases would be a function of position of impact, and especially of height of impact since the top of the fence can deflect more than the base. Analysis of hypothetical rockfall cases shows that member forces are proportional to the square root of kinetic energy, and that there is only a minor influence of impact position on member force. The second result can be understood from an examination of deflected shapes of the fence. Most rockfalls are ultimately stopped near the top of the mesh, even when the initial impact occurs near the bottom. Rocks impacting near the bottom of the mesh will deflect the fence, and the fence will in turn exert forces tending to lift the rock. As a result, the pocket which forms in the mesh to arrest the rock usually forms somewhere from the midheight to the top of the mesh. The fence ushers the rock to its more compliant region, and so the influence of initial impact height is minimized. Using this idea, plots of member forces versus the square root of kinetic energy were made for the various fence components, without regard to impact position, and in spite of some scatter, a linear dependence is apparent (Figs. 41 to 49). It is possible then to identify limiting rockfall mass and velocity directly from analysis results of observed impact cases. This curve of limiting rock velocity versus mass is presented in Figure 50 and indicates a limiting velocity of 41 ft/s for a 1000 lb rock, and a limiting velocity of 29 ft/s for a 2000 lb rock. Forces in other members corresponding to this limit state are listed below. .

Forces in Members for Limit State in Mesh (lbs)

Top Cable	5,500
Cable C3	3,800
Cable C2	6,900
Cable C1	5,500
Bottom Cable	10,600
Stay, End	9,200
Stay, Interior	5,800

For foundations at end posts, shear force at mesh limit can be expected to be about 5000 lbs, and uplift about 5700 bs. Interior post foundations will experience shear force of 3300 lbs and uplift of 800 lbs.

The curve for limiting rock velocities and masses may be compared to the limit curve generated last year for a Flexpost fence without stays. An adjustment to the previous limit curve must be made to account for the higher mesh forces which occur in a fence with stays. With such adjustment, the previous limit curve would indicate a limiting velocity of 43 ft/s for a 1000 lb rock, and a limiting velocity of 33 ft/s for a 2000 lb rock; reasonably good agreement.

Summary and Conclusions

This study has succeeded in quantifying the rockfall capacity of the present design configuration of the CDOH Flexpost fence, through an examination of the results of prototype tests and through a large-deformation dynamic analysis program developed specifically for the Flexpost fence. Analysis results agree with observed fence behavior, and are conservative. Limiting rock velocity as a function of rock mass has been determined by analysis and calibrated to field tests. Design information including member forces and forces on post foundations has been presented. The expected influence of diagonal stays on fence performance has been confirmed by the analysis.

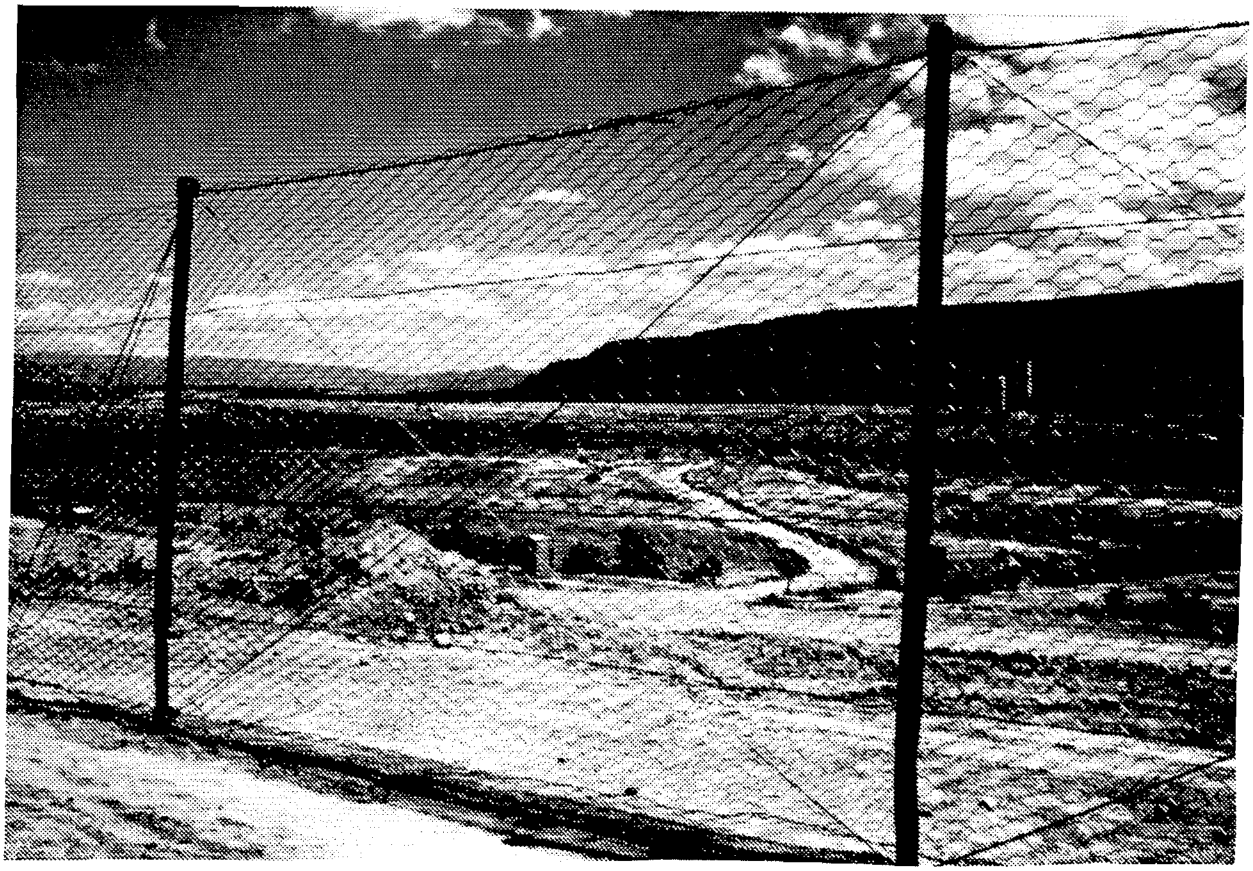
The limit curve for rock velocity and mass is based on breaking strength of the mesh. No provision has been made for a reserve strength capacity. Such a margin of safety may be introduced when evaluating specific sites for use of the Flexpost fence. That is, the limit on fence rockfall capacity should be compared to a maximum probable rockfall event as predicted by the Colorado Rockfall Simulation Program. A related concern of durability of the fence to repeated rockfall impacts should be studied further. The potential for channeling of rockfall paths to a few regions of the fence, and resulting local damage might compel a reduction in tolerable impact conditions.

Acknowledgements

This report, the data presented, the analytical tools developed, and the knowledge gained about Flexpost fence behavior are the result of the efforts of a number of talented people. At the University of Colorado, Diane Hinzman identified the bilinear stiffness characteristic of the post, and untangled a difficult problem of deformed geometries of the fence during impact in our 1990 study. Amy Schonbok reviewed videotapes of the prototype test, quantified the impact conditions, and was essential in the preparation of the figures for this report. Timothy Webb provided important help in the development of the analysis program.

The most important contribution has been made by the Colorado Department of Highways in its program of rockfall prediction and mitigation studies under the direction of Mr. Robert K. Barrett. Bob's creative and imaginative approach to rockfall problems has produced a number of new and inventive solutions, of which the Flexpost fence is just one. And Bob, I am sure, would want to acknowledge CDOH engineers Michael McMullen, Brandy Gilmore, Rick Andrew, and Ralph Trapani who have all made vital contributions.

George Hearn
Boulder, 1991

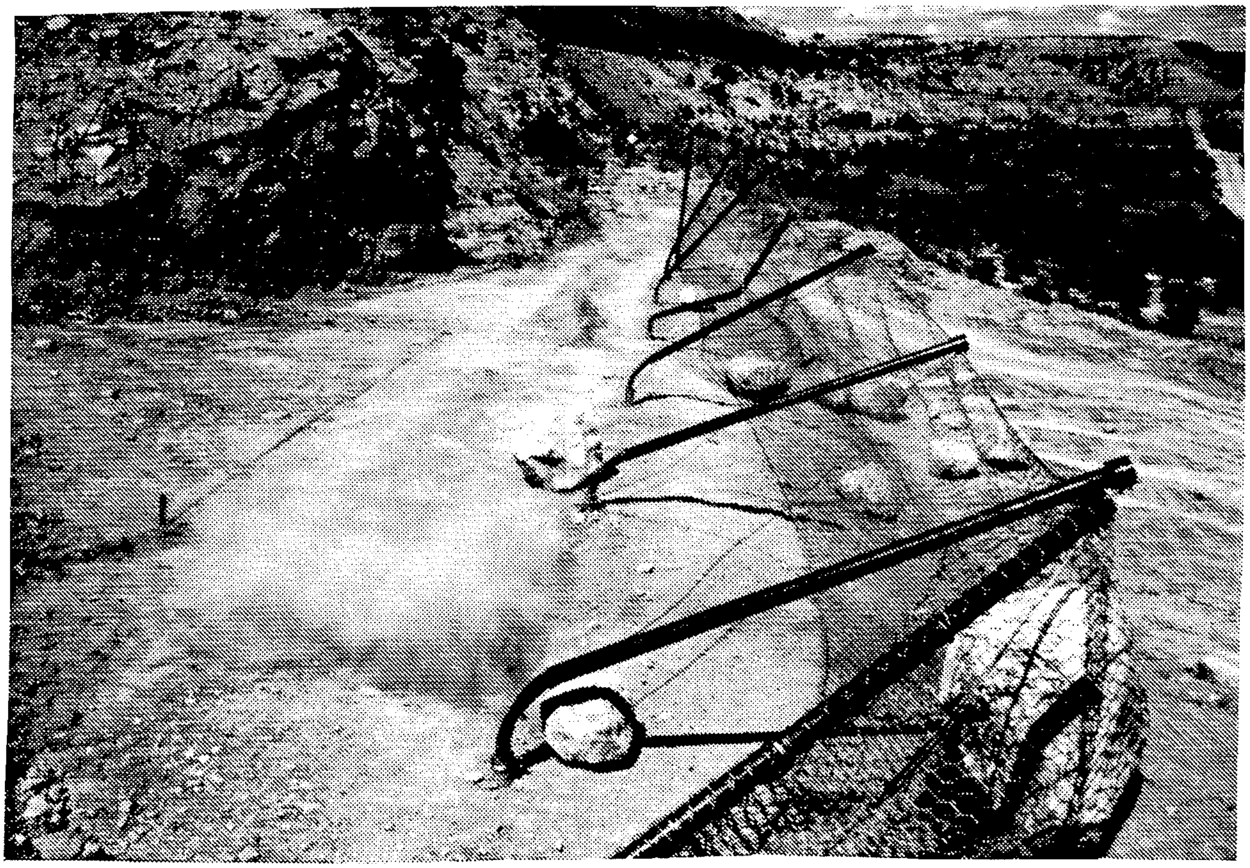


COLORADO FLEX-POST ROCKFALL FENCE

PHOTOGRAPH 1

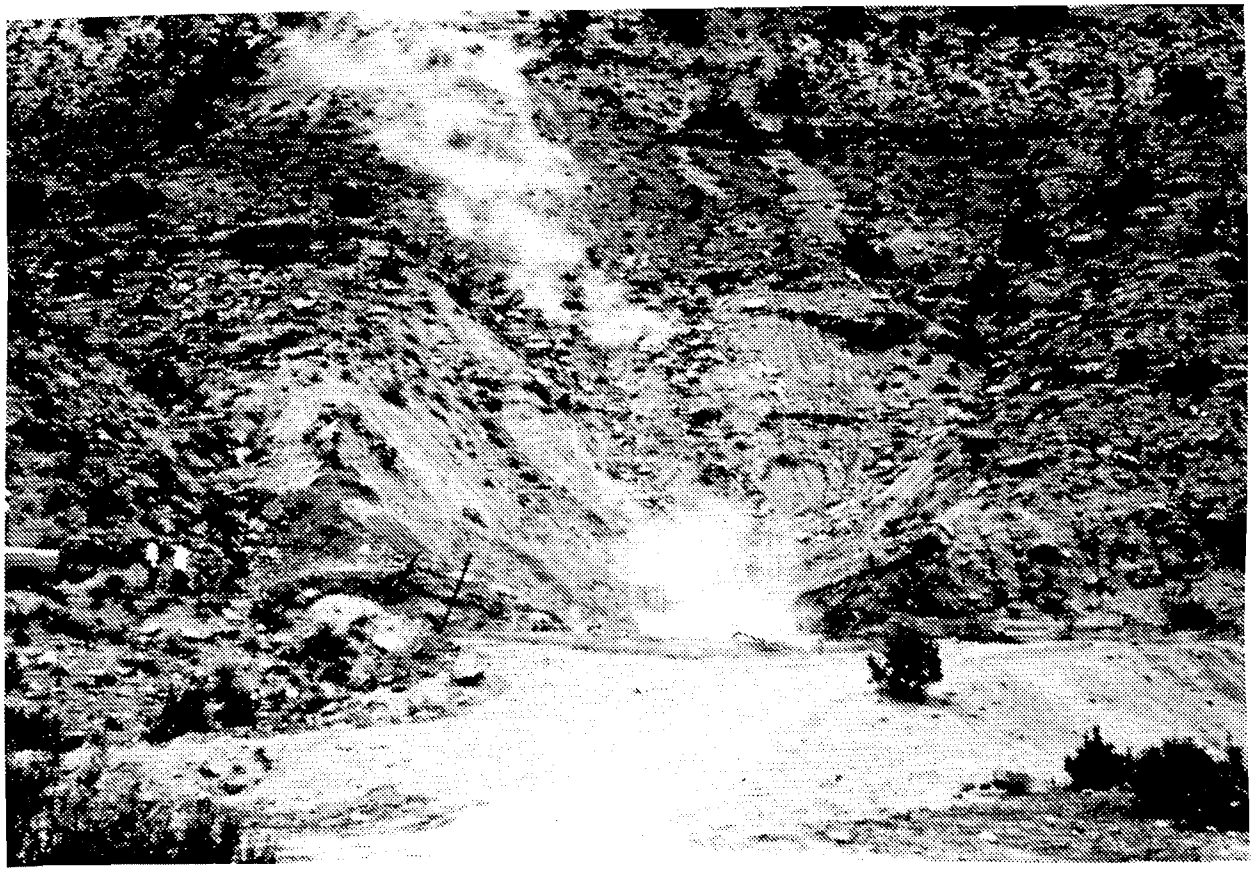
QUASI-STATIC TESTING

PHOTOGRAPH 2



COLORADO FLEX-POST ROCKFALL FENCE CATCHING A LARGE ROCK

PHOTOGRAPH 3



COLORADO ROCKFALL RESEARCH SITE NEAR RIFLE, COLORADO

PHOTOGRAPH 4

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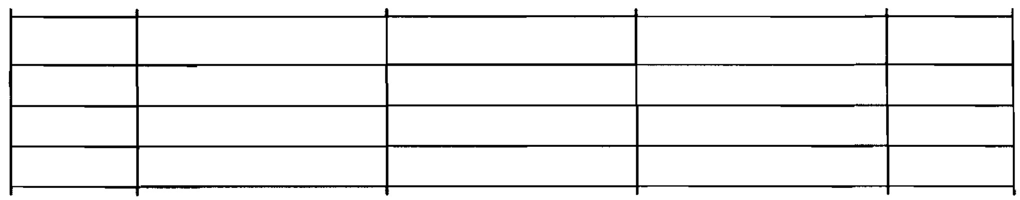
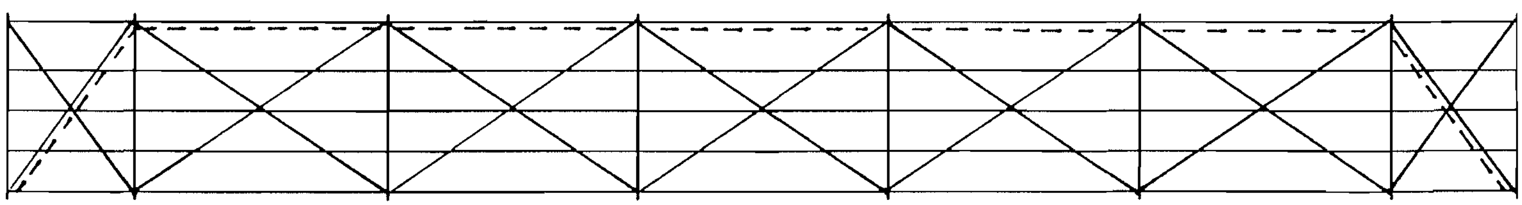
CDOH FLEXPOST FENCE

Prototype Schematics



July Prototype



August Prototype

– – – – – Prestressed Cable

Figure 1

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CDOH FLEXPOST FENCE

Prototype Tests

Rock Size and Mass

ROCK NO.	DIAMETER X (feet)	DIAMETER Y (feet)	DIAMETER Z (feet)	UNIT WEIGHT (pcf)	VOLUME (cu.feet)	WEIGHT (lbs)	MASS (slug)
1	3.5	3.5	3.5	170	22.5	3816	119
2				185			
3	3.5	1.4	1.8	185	4.62		27
4	4.0	3.2	2.9	185	19.4	3596	112
5	1.5	1.5	1.5	145	1.8	256	8
6	4.0	3.2	2.3	185	15.4	2852	89
7	3.0	2.2	1.6	170	5.5	940	29
8	2.3	1.5	1.3	162	2.4	380	12
9	3.5	2.4	2.3	160	10.1	1619	50
10	1.8	1.1	1.0	140	1.0	145	5
11	3.6	2.1	2.0	185	7.9	1465	46
12	2.5	2.5	2.3	180	7.5	1355	42
13	1.8	1.8	1.0	180	1.7	305	9
14	3.2	2.3	1.8	185	6.9	1283	40
15	1.7	1.6	0.9	160	1.3	205	6
16	1.7	1.4	0.9	185	1.1	207	6
17	5.0	4.5	2.5	160	29.5	4712	146
18	4.6	3.7	2.4	170	21.4	3636	113
19	3.8	3.0	2.5	185	14.9	2761	86
20	3.8	2.8	1.6	160	8.9	1426	44
21	2.3	1.8	1.5	180	3.3	585	18
22	2.3	2.1	1.3	185	3.3	608	19
23	3.7	2.9	1.6	166	9.0	1492	46
24	2.2	1.9	1.9	175	4.2	728	23
25	3.0	2.4	1.5	185	5.7	1046	33
26	3.0	2.0	1.5	170	4.7	801	25
27	1.8	1.5	0.8	185	1.1	209	7
28	2.4	2.3	1.0	160	2.9	462	14
29	3.0	2.4	2.2	185	8.3	1534	48
30	3.9	3.0	1.3	147	8.0	1171	36
31	2.2	2.0	1.4	185	3.2	597	19
32	2.5	2.3	2.0	160	6.0	963	30
33	5.1	3.0	3.1	185	24.8	4594	143
34	2.5	1.7	1.9	140	4.2	592	18
35	3.5	2.7	2.6	140	12.9	1801	56

Figure 2

University of Colorado at Boulder

CDOH FLEXPOST FENCE

Prototype Tests

Rock Size and Mass (cont.)

ROCK NO.	DIAMETER X (feet)	DIAMETER Y (feet)	DIAMETER Z (feet)	UNIT WEIGHT (pcf)	VOLUME (cu.feet)	WEIGHT (lbs)	MASS (slug)
36	2.5	2.5	2.3	185	7.5	1392	43
37	2.3	2.1	2.1	150	5.3	797	25
38	4.0	4.0	3.3	170	27.7	4700	146
39	4.7	4.5	2.6	170	28.8	4895	152
40	5.2	4.2	3.2	165	36.6	6038	188
41	2.8	2.8	2.3	160	9.4	1511	47
42	4.2	4.2	4.3	150	39.7	5957	185
43	5.2	4.4	3.5	185	41.9	7757	241
44	7.0	3.9	3.1				
45	3.7	3.0	2.0	175	11.6	2034	63
46	2.5	2.2	2.6	185	7.5	1385	43
47	2.7	2.6	2.4	175	8.8	1544	48
48	3.8	2.2	2.1	185	9.2	1701	53
49	4.7	2.9	2.7	147	19.3	2833	88
50	5.2	3.5	2.7	185	25.7	4760	148
51	5.6	3.8	3.5	170	39.0	6630	206
52	3.5	3.2	3.2	165	18.8	3096	96
53	3.3	3.0	1.5	185	7.8	1438	45
54	5.6	4.9	3.1	185	44.5	8240	256
55	4.3	3.8	3.2	147	27.4	4025	125
56	1.8	1.5	1.2	160	1.7	271	8
57	4.0	2.4	2.1	167	10.6	1763	55
58	2.3	1.8	1.6	147	3.5	510	16
59	2.1	1.5	1.2	175	2.0	346	11
60	4.5	4.5	4.2	170	44.5	7570	235
61	2.3	2.1	1.9	158	4.8	759	24
62	1.9	1.4	1.3	148	1.8	268	8
63	3.8	3.2	2.3	165	14.6	2416	75
64	2.5	2.2	1.4	148	4.0	597	19
65	2.9	2.6	1.3	185	5.1	949	30
66	2.9	2.5	2.0	140	7.6	1063	33
67	3.4	2.4	2.1	165	9.0	1480	46
68	5.8	4.8	3.7	180	53.9	9708	302
69	1.6	1.3	1.1	185	1.2	222	7
70	2.2	2.2	1.6	185	4.1	750	23

Figure 2 cont.

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Prototype Tests

Rockfall Summary

Date	Rock No.	Hit/Miss	Stopped or Not Stopped	Fence Condition
7/10/90	8	Miss	-	-
"	22	Hit	Stopped	No Damage
"	23	Hit	Not Stopped	No Damage
"	11	Miss	-	-
"	25	Miss	-	-
"	58	Miss	-	-
"	59	Miss	-	-
"	66	Miss	-	-
"	64	Hit	Stopped	No Damage
"	62	Miss	-	-
"	21	Miss	-	-
"	3	Miss	-	-
"	57	Miss	-	-
"	70	Hit	Stopped	No Damage
"	31	Hit	Stopped	No Damage
"	61	Miss	-	-
"	13	Miss	-	-
"	11	Miss	-	-
"	24	Miss	-	-
"	47	Hit	Not Stopped	Tore Mesh
"	45	Miss	-	-
"	63	Miss	-	-
"	29	Miss	-	-
"	46	Hit	Stopped	No Damage
"	4	Hit	Stopped	No Damage
"	48	Miss	-	-
"	41	Hit	Stopped	Held Fence Down
"	49	Miss	-	-
"	1	Hit	Not Stopped	Fence Already Down
"	65	Hit	Not Stopped	"
"	38	Hit	Not Stopped	"

Figure 3

Rockfall Summary (cont.)

Date	Rock No.	Hit/Miss	Stopped or Not Stopped	Fence Condition
8/13/90	5	Hit	Stopped	No Damage
"	2	Hit	Stopped	Tore Stay
"	40	Hit	Not Stopped	Tore Mesh
"	64	Hit	Not Stopped	Through Hole
"	24	Hit	Rolled Under	No Damage
"	58	Miss	-	-
"	26	Miss	-	-
"	36	Hit	Rolled Under	No Damage
"	66	Miss	-	-
"	62	Miss	-	-
"	48	Hit	Stopped	No Damage
"	37	Hit	Stopped	No Damage
"	26	Miss	-	-
"	41	Hit	Not Stopped	Tore Mesh
"	34	Hit	Stopped	No Damage
"	35	Miss	-	-
"	9	Hit	Rolled Under	No Damage
"	14	Miss	-	-
"	12	Hit	Stopped	Fabric Deformed
"	23	Miss	-	-
"	32	Miss	-	-
"	62	Miss	-	-
"	57	Miss	-	-
"	51	Miss	-	-
"	25	Miss	-	-
"	11	Miss	-	-
"	46	Miss	-	-
"	29	Miss	-	-
"	22	Miss	-	-
8/21/90	?	Hit	Stopped	No Damage
"	12	Miss	-	-
"	56	Miss	-	-
"	21	Miss	-	-
"	66	Miss	-	-
"	37	Hit	Stopped	No Damage
"	13	Hit	Stopped	Bent Post
"	14	Hit	Stopped	No Damage
"	64	Hit	Stopped	No Damage
"	70	Hit	Stopped	No Damage
"	4	Hit	Stopped	Held Fence Down

Figure 3 cont.

University of Colorado at Boulder

CDOH FLEXPOST FENCE

Fence Model

Rock Impact Locations

July 10, 1990

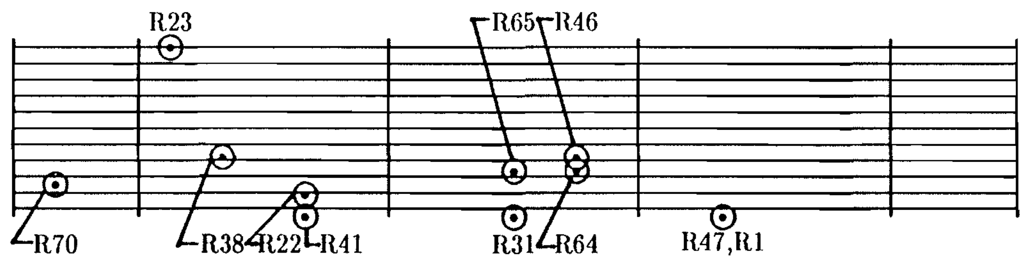


Figure 4

University of Colorado at Boulder

CDOH FLEXPOST FENCE

Fence Model

Rock Impact Locations

August 13, 1990

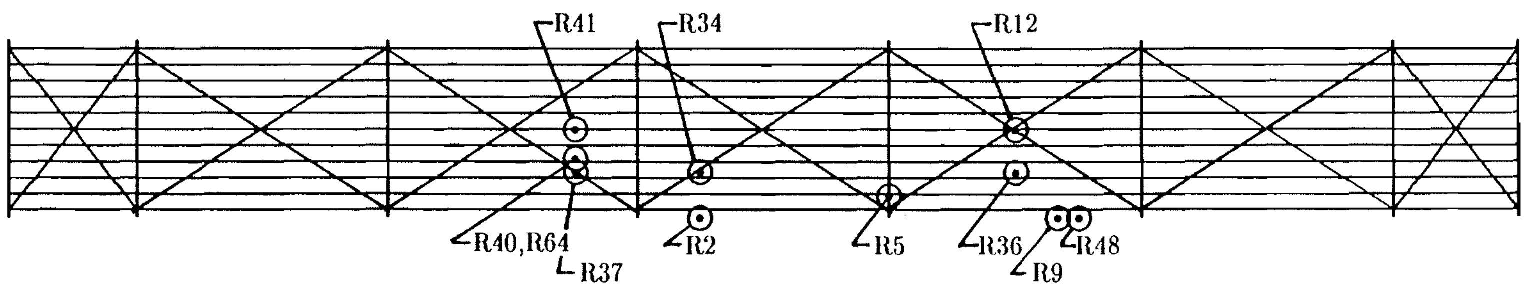


Figure 5

University of Colorado at Boulder

CDOH FLEXPOST FENCE

Fence Model

Rock Impact Locations

August 21, 1990

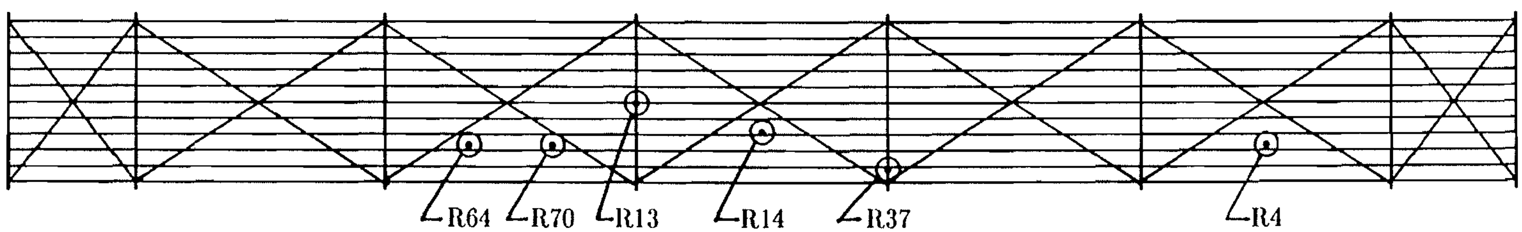


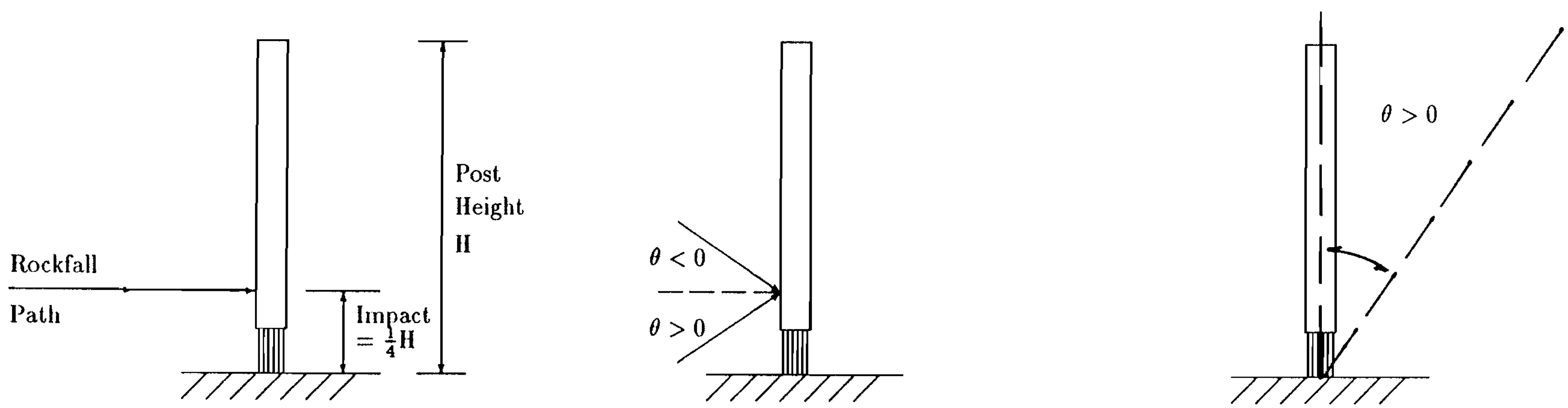
Figure 6

University of Colorado at Boulder

CDOH FLEXPOST FENCE

Prototype Tests

Coordinate System For Videotape Review



Position of Impact

Vertical Angle of Rock Trajectory

Post Deflection

Rockfall Vertical Coordinates and Trajectory

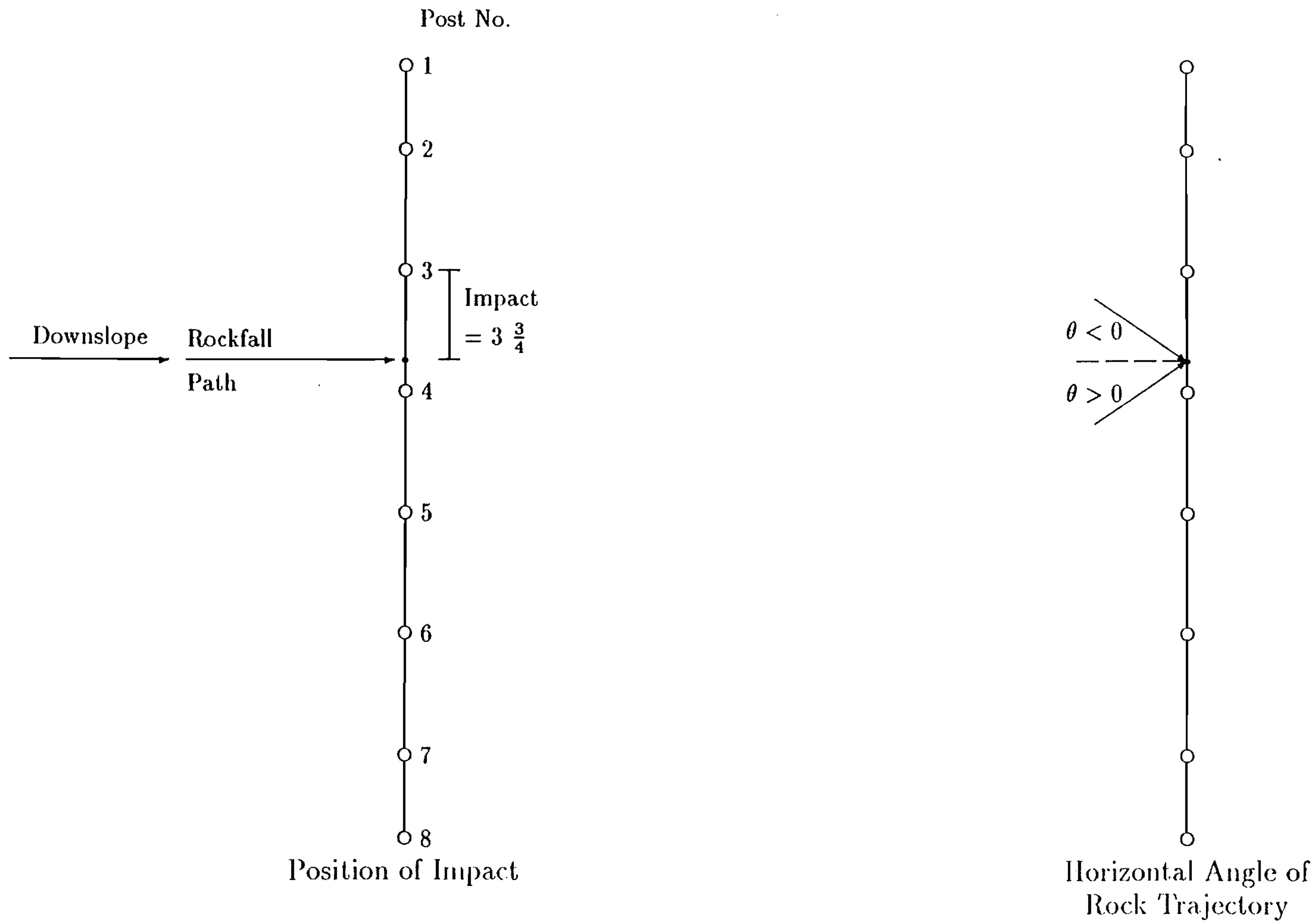
Figure 7

University of Colorado at Boulder

CDOH FLEXPOST FENCE

Prototype Tests

Coordinate System For Videotape Review



Rockfall Horizontal Coordinates and Trajectory

Figure 8

University of Colorado at Boulder

CDOH FLEXPOST FENCE

Prototype Tests

Rockfall Velocity and Energy

July 10, 1990

ROCK NO.	POSITION (feet)	TIME (sec)	VELOCITY (ft/s)	ANGULAR VELOCITY (rad/sec)	MASS (slug)	TRANSLAT'NL ENERGY (ft-lb)	I_ω (lb-ft-s^2)	ROTAT'NL ENERGY (ft-lb)	KINETIC ENERGY (ft-lb)
22	20	76.13			18.9	9,480	6.83	4,140	13,600
	10	76.47	30.0	33.0					
	0	76.77	33.3	36.7					
		AVG.	31.7	34.8					
23	30	126.83			46.4	42,600	33.81	11,300	53,900
	20	127.07	42.9	30.3					
	10	127.30	42.9	20.2					
	0	127.53	42.9	26.9					
		AVG.	42.9	25.8					
64	30	363.27			18.6	9,090	7.42	2,510	11,600
	20	363.57	33.3	20.9					
	10	363.93	27.3	25.7					
	0	364.23	33.3	31.4					
		AVG.	31.3	26.0					
70	30	611.17			23.3	9,260	9.33	4,440	13,700
	20	611.53	27.3	30.0					
	10	611.90	27.3	34.3					
	0	612.23	30.0	28.3					
		AVG.	28.2	30.8					
31	30	664.10			18.6	4,710	6.70	790	5,500
	20	664.53	23.1	18.1					
	10	664.97	23.1	14.5					
	0	665.43	21.4	13.5					
		AVG.	22.5	15.4					
47	30	910.37			48.0	44,100	32.44	17,200	61,200
	20	910.60	42.9	30.3					
	10	910.83	42.9	33.7					
	0	911.07	42.9	33.7					
		AVG.	42.9	32.5					

Figure 9

Rockfall Velocity and Energy
July 10, 1990 (cont.)

ROCK NO.	POSITION (feet)	TIME (sec)	VELOCITY (ft/s)	ANGULAR VELOCITY (rad/sec)	MASS (slug)	TRANSLAT'NL ENERGY (ft-lb)	I_ω (lb-ft-s^2)	ROTAT'NL ENERGY (ft-lb)	KINETIC ENERGY (ft-lb)
46	30	1353.53			43.1	30,300	24.80	6,880	37,000
	20	1353.80	37.5	23.6					
	10	1354.07	37.5	23.6					
	0	1354.33	37.5	23.6					
		AVG.	37.5	23.6					
41	30	2313.10			47.0	39,600	31.74	18,600	58,200
	20	2313.37	37.5	35.3					
	10	2313.60	42.9	33.7					
	0	2313.83	42.9	33.7					
		AVG.	41.1	34.2					
1	30	2555.83			118.6	37,400	145.32	21,200	58,600
	20	2556.20	27.3	17.1					
	10	2556.60	25.0	19.6					
	0	2557.03	23.1	14.5					
		AVG.	25.1	17.1					
65	30	2661.13			29.5	27,100	15.61	6,140	33,200
	20	2661.37	42.9	30.3					
	10	2661.60	42.9	26.9					
	0	2661.83	42.9	26.9					
		AVG.	42.9	28.1					
38	30	2736.93			146.1	166,000	210.95	36,200	186,000
	20	2737.13	50.0	15.7					
	10	2737.37	42.9	20.2					
	0	2737.57	50.0	19.6					
		AVG.	47.6	18.5					

Figure 9 cont.

University of Colorado at Boulder

CDOH FLEXPOST FENCE

Prototype Tests

Rockfall Velocity and Energy

August 13, 1990

ROCK NO.	POSITION (feet)	TIME (sec)	VELOCITY (ft/s)	ANGULAR VELOCITY (rad/sec)	MASS (slug)	TRANSLAT'NL ENERGY (ft-lb)	I_ω (lb-ft-s^2)	ROTAT'NL ENERGY (ft-lb)	KINETIC ENERGY (ft-lb)
5	20	56.20			8.0	2,720	1.79	1,360	4,080
	10	56.60	25.0	39.3					
	0	56.97	27.3	38.6					
		AVG:	26.1	38.9					
2	20	127.03			*				
	10	127.57	18.8	17.7					
	0	128.10	18.8	17.7					
		AVG:	18.8	17.7					
40	20	166.83			187.7	132,000	331.09	243,000	375,000
	10	167.10	37.5	35.3					
	0	167.37	37.5	41.2					
		AVG:	37.5	38.3					
64	30	236.93			18.6	10,300	3.71	1,830	12,100
	20	237.23	33.3						
	10	237.53	33.3	31.4					
	0	237.83	33.3	31.4					
		AVG:	33.3	31.4					
36	20	415.23			43.3	4,220	24.93	959	5,180
	10	415.93	14.3	9.0					
	0	416.67	13.6	8.6					
		AVG:	13.0	8.8					
48	20	534.60			52.9	3,160	38.53	2,050	5,210
	10	535.40	12.5	11.8					
	0	536.47	9.4	8.8					
		AVG:	10.9	10.3					

* No rock size information

Figure 10

University of Colorado at Boulder

CDOH FLEXPOST FENCE

Prototype Tests

Rockfall Velocity and Energy

August 13, 1990 (cont.)

ROCK NO.	POSITION (feet)	TIME (sec)	VELOCITY (ft/s)	ANGULAR VELOCITY (rad/sec)	MASS (slug)	TRANSLAT'NL ENERGY (ft-lb)	I_ω (lb-ft-s^2)	ROTAT'NL ENERGY (ft-lb)	KINETIC ENERGY (ft-lb)
37	20	570.23			24.8	15,500	11.98	6,680	22,200
	10	570.53	33.3	31.4					
	0	570.80	37.5	35.3					
		AVG:	35.4	33.4					
41	20	646.17			47.0	58,700	31.74	15,700	74,400
	10	646.37	50.0	31.4					
	0	646.57	50.0	31.4					
		AVG:	50.0	31.4					
34	20	729.67			18.4	11,500	7.36	4,100	15,600
	10	729.93	37.5	35.3					
	0	730.23	33.3	31.4					
		AVG:	35.4	33.4					
9	20	809.63			50.3	5,660	36.68	2,550	8,200
	10	810.30	15.1	11.8					
	0	810.97	15.1	11.8					
		AVG:	15.1	11.8					
12	20	875.23			42.1	29,600	24.26	6,730	36,300
	10	875.50	37.5	23.6					
	0	875.77	37.5	23.6					
		AVG:	37.5	23.6					

Figure 10 cont.

University of Colorado at Boulder

CDOH FLEXPOST FENCE

Prototype Tests

Rockfall Velocity and Energy

August 21, 1990

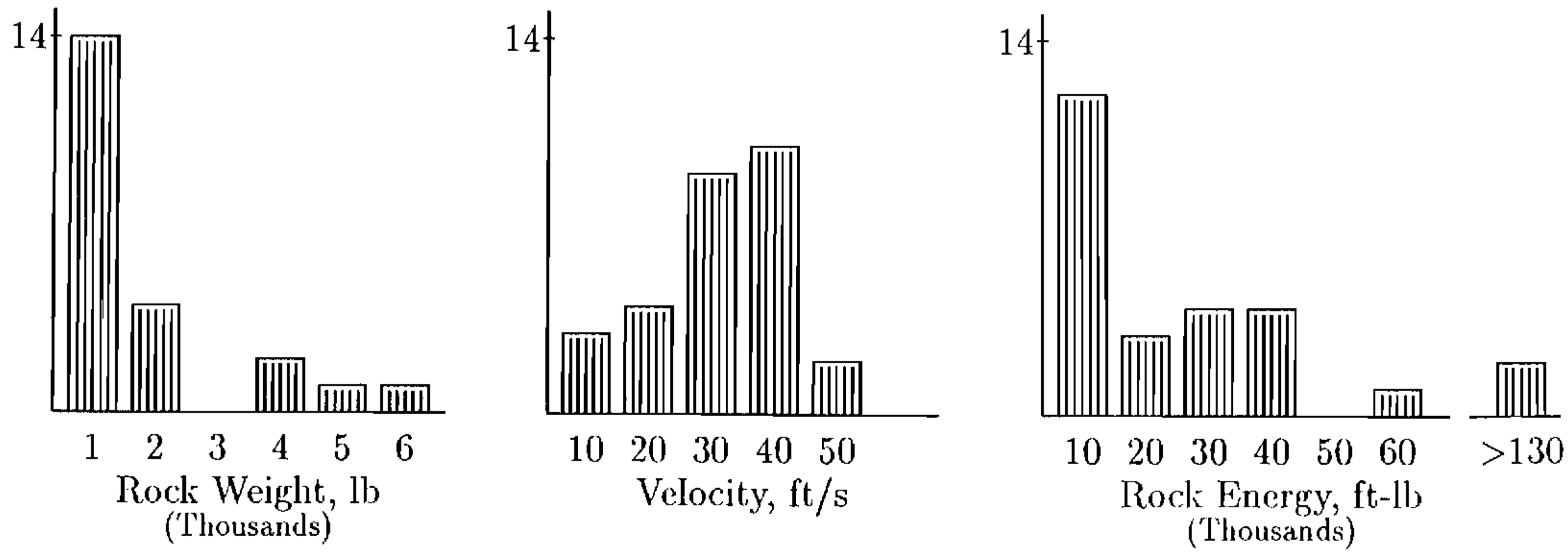
ROCK NO.	POSITION (feet)	TIME (sec)	VELOCITY (ft/s)	ANGULAR VELOCITY (rad/sec)	MASS (slug)	TRANSLAT'NL ENERGY (ft-lb)	I_ω (lb-ft-s^2)	ROTAT'NL ENERGY (ft-lb)	KINETIC ENERGY (ft-lb)
37	20.00	447.43			24.8	23,700	11.98	6,680	30,400
	10.00	447.63	50.0	31.4					
	0.00	447.90	37.5	35.3					
		AVG:	43.8	33.4					
13	20.00	470.27			9.5	5,270	2.14	468	5,740
	10.00	470.57	33.3	20.9					
	0.00	470.87	33.3	20.9					
		AVG:	33.3	20.9					
14	20.00	507.60			39.9	22,200	22.98	11,300	33500
	10.00	507.90	33.3	31.4					
	0.00	508.20	33.3	31.4					
		AVG:	33.3	31.4					
64	20.00	509.90			18.6	2,770	7.42	3,290	6,050
	10.00	510.53	15.8	29.8					
	0.00	511.07	18.8						
		AVG:	17.3	29.8					
70	20.00	540.83			23.3	9,560	9.33	2,310	11,900
	10.00	541.17	30.0	18.9					
	0.00	541.53	27.3	25.7					
		AVG:	28.6	22.3					
4	20.00	633.27			111.8	25,700	129.21	18,300	44,000
	10.00	633.73	21.4						
	0.00	634.20	21.4	16.8					
		AVG:	21.4	16.8					

Figure 11

University of Colorado at Boulder

CDOH FLEXPOST FENCE

Prototype Tests



Flexpost Field Tests

All Rockfalls

Figure 12

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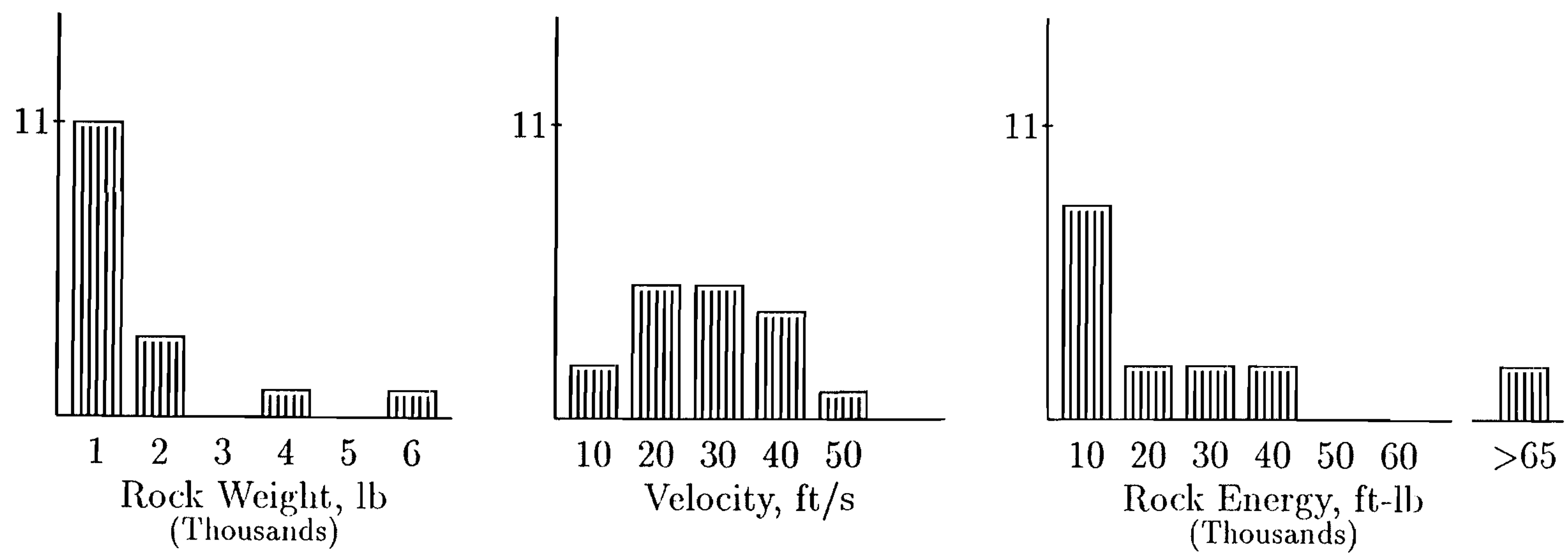
CDOH FLEXPOST FENCE

Prototype Tests



Flexpost Field Tests

Aug. 13 and Aug. 21

Figure 13

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CDOH FLEXPOST FENCE

Prototype Tests

Flexpost Deflections
July 10, 1990

ROCK NO.	IMPACT POSITION btwn post	IMPACT HEIGHT to fence	VERT. TRAJECT. degree	HORIZ. TRAJECT. degree	FLEX POST NO.	MAX DEFLEC. degree	TIME SWEEP frame	TIME FIXED frame
22	2 2/3	1/8	+20	-	-	-	1:16:24	24:42:16
					1	5	1:17:14	24:43:08
					2	20	1:17:10	24:43:05
					3	35	1:17:11	24:43:06
					4	5	1:17:12	24:43:06
23	2 1/8	top	-10	-	-	-	2:07:16	25:54:00
					2	35	2:07:28	25:54:13
64	3 3/4	1/4	+20	+20	-	-	6:04:09	30:17:27
					2	5	-	30:18:23
					3	30	6:05:04	30:18:22
					4	50	6:04:28	30:18:18
					5	20	6:05:08	30:18:26
70	1 1/3	3/16	0	-10	-	-	10:12:10	32:44:07
					1	50	10:12:25	32:44:24
					2	20	10:13:00	32:45:00
					3	10	10:12:28	32:44:25
31	3 1/2	0	+15	0	-	-	11:05:16	33:12:22
					1	5	11:05:25	33:13:02
					2	5	11:06:08	33:13:19
					3	20	11:06:15	33:13:22
					4	25	11:06:04	33:13:11
					5	5	11:06:08	33:13:15
47	4 1/3	0	0	-20	-	-	15:11:04	34:57:20
					1	10	-	34:58:02
					2	5	-	34:58:15
					3	15	-	34:58:14
					4	50	15:11:23	34:58:08
					5	50	15:11:25	34:58:10
					6	30	-	34:58:20
46	3 3/4	1/3	+20	0	-	-	22:34:14	36:15:20
					1	10	-	36:16:20
					2	10	22:35:16	36:16:17
					3	55	22:35:12	36:16:19
					4	85	22:35:11	36:16:17
					5	65	22:35:19	36:16:22
					6	30	22:35:24	36:16:24

Figure 14

University of Colorado at Boulder

CDOH FLEXPOST FENCE

Prototype Tests

Flexpost Deflections
July 10, 1990 (cont.)

ROCK NO.	IMPACT POSITION btwn post	IMPACT HEIGHT to fence	VERT. TRAJECT. degree	HORIZ. TRAJECT. degree	FLEX POST NO.	MAX DEFLEC. degree	TIME SWEEP frame	TIME FIXED frame
4	2	top	-30	-	-	-	-	36:53:00
					1	95	-	36:53:15
					2	100	-	36:53:20
					3	45	-	36:53:25
					4	20	-	36:54:03
41	2 2/3	0	0	0	-	-	25:12:09	38:33:29
					1	100	25:14:04	38:34:16
					2	100	25:13:28	38:34:17
					3	100	25:14:04	38:34:17
					4	110	25:13:07	38:34:27
					5	75	25:13:18	38:35:08
					6	55	25:13:18	38:35:08
1	4 1/3	0	0	-30	-	-	27:47:09	42:37:08
					1	50	27:48:15	42:38:05
					2	50	27:48:23	42:38:20
					3	110	27:48:07	42:38:07
					4	120	27:47:26	42:37:25
					5	110	27:48:01	42:38:00
					6	80	27:48:00	42:38:08
65	3 1/2	1/4	+10	0	-	-	28:48:24	44:21:28
					1	70	28:49:21	44:22:23
					2	90	28:49:26	44:22:28
					3	100	28:49:10	44:22:13
					4	115	28:49:16	44:22:20
					5	105	28:49:26	44:23:01
					6	80	28:50:05	44:23:09
38	2 1/3	1/3	-10	0	-	-	29:08:26	45:37:19
					1	90	-	45:37:26
					2	90	-	45:37:26
					3	110	29:09:09	45:38:01
					4	110	29:09:17	-
					5	75	29:10:09	-
					6	70	29:10:13	-

Figure 14 cont.

University of Colorado at Boulder

CDOH FLEXPOST FENCE

Prototype Tests

Flexpost Deflections
August 13, 1990

ROCK NO.	IMPACT POSITION btwn post	IMPACT HEIGHT to fence	VERT. TRAJECT. degree	HORIZ. TRAJECT. degree	FLEX POST NO.	MAX. DEFLEC. degree	TIME SWEEP frame	TIME FIXED frame
5	5	1/8	+10	0	-	-	56:29	11:12
					5	5	57:00	11:13
2	4 1/4	0	0	-10	-	-	2:08:03	44:14
					3	5	2:08:19	45:00
					4	10	2:08:19	45:00
40	3 3/4	1/3	+35	+10	-	-	2:47:11	1:06:17
					2	5	2:47:21	1:06:27
					3	10	2:47:20	1:06:26
					4	15	2:47:17	1:06:24
64	3 3/4	1/3	+20	+10	-	-	3:57:29	1:28:15
					4	10	3:58:03	1:28:20
24	4 1/2	1/4	0	-	-	-	-	1:49:06
					4	15	-	1:49:12
					5	10	-	1:49:12
36	5 1/2	1/4	0	-30	-	-	6:56:20	2:55:03
48	5 3/4	0	0	0	-	-	8:56:26	4:00:02
					5	3	8:56:28	4:00:05
37	3 3/4	1/4	+10	-5	-	-	9:30:25	4:16:06
					2	20	9:31:12	4:16:24
					3	30	9:31:10	4:16:22
					4	40	9:31:10	4:16:20
					5	25	9:31:11	4:16:22
					6	20	9:31:12	4:16:23
					7	10	9:31:15	4:16:25
41	3 3/4	1/2	-20	-	-	-	10:46:17	4:40:15
					1	15	10:47:01	4:40:28
					2	40	10:47:00	4:40:26
					3	40	10:46:25	4:40:21
					4	30	10:46:22	4:40:19
					5	20	10:46:24	4:40:22
					6	10	10:46:27	4:40:24

Figure 15

University of Colorado at Boulder

CDOH FLEXPOST FENCE

Prototype Tests

Flexpost Deflections
August 13, 1990 (cont.)

ROCK NO.	IMPACT POSITION btwn post	IMPACT HEIGHT to fence	VERT. TRAJECT. degree	HORIZ. TRAJECT. degree	FLEX POST NO.	MAX. DEFLEC. degree	TIME SWEEP frame	TIME FIXED frame
34	4 1/4	1/4	+15	0	-	-	12:10:09	5:06:28
					2	15	12:10:29	5:07:20
					3	20	12:10:25	5:07:16
					4	25	12:10:22	5:07:17
					5	15	12:10:26	5:07:14
					6	10	12:10:26	5:07:15
					7	5	12:10:29	5:07:19
9	5 2/3	0	0	+20	-	-	13:31:03	5:38:27
12	5 1/2	1/2	0	-	-	-	14:35:24	6:13:24
					1	20	14:36:16	6:14:17
					2	50	14:36:15	6:14:17
					3	70	14:36:16	6:14:16
					4	70	14:36:14	6:14:13
					5	75	14:36:18	6:14:18
					6	80	14:36:18	6:14:16
					7	60	14:36:21	6:14:21
					8	25	14:37:05	-

Figure 15 cont.

University of Colorado at Boulder

CDOH FLEXPOST FENCE

Prototype Tests

Flexpost Deflections

August 21, 1990

ROCK NO.	IMPACT POSITION btwn post	IMPACT HEIGHT to fence	VERT. TRAJECT. degree	HORIZ. TRAJECT. degree	FLEX POST NO.	MAX DEFLEC. degree	TIME SWEEP frame	TIME FIXED frame
37	5	1/8	+10	0	-	-	7:27:27	1:12:06
					2	20	7:28:28	-
					3	30	7:28:24	-
					4	35	7:28:24	1:13:04
					5	40	7:28:22	1:13:02
					6	35	7:28:24	1:13:02
					7	25	7:28:23	1:12:29
					8	5	7:28:23	-
13	4	1/2	-20	0	-	-	7:50:26	1:30:26
					1	35	7:51:12	1:31:11
					2	60	7:51:10	1:31:11
					3	70	7:51:14	1:31:13
					4	-	-	-
					5	70	7:51:19	1:31:21
					6	55	7:51:19	1:31:18
					7	45	7:51:19	1:31:20
					8	20	7:51:17	1:31:19
14	4 1/2	1/3	+25	-	-	-	8:28:10	2:15:20
					1	20	8:28:26	-
					2	45	8:28:27	2:16:11
					3	50	8:28:29	2:16:12
					4	55	8:29:01	2:16:10
					5	55	8:29:01	2:16:18
					6	40	8:29:11	2:16:09
					7	35	8:29:11	2:16:09
					8	15	8:29:16	2:16:07
64	3 1/3	1/4	+25	-	-	-	8:31:08	2:18:19
					1	10	8:31:27	-
					2	30	8:31:23	2:19:08
					3	40	8:31:28	2:19:08
					4	30	8:31:28	2:19:08

Figure 16

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CDOH FLEXPOST FENCE

Prototype Tests

Flexpost Deflections
August 21, 1990 (cont.)

ROCK NO.	IMPACT POSITION btwn post	IMPACT HEIGHT to fence	VERT. TRAJECT. degree	HORIZ. TRAJECT. degree	FLEX POST NO.	MAX DEFLEC. degree	TIME SWEEP frame	TIME FIXED frame
70	3 2/3	1/4	+30	-	-	-	9:01:22	3:54:00
					1	15	9:02:25	-
					2	40	9:02:19	3:54:27
					3	60	9:02:18	3:54:25
					4	80	9:02:17	3:54:23
					5	50	9:02:21	3:54:28
					6	40	9:02:22	3:55:00
					7	30	9:02:22	3:55:00
					8	10	9:02:24	3:55:03
4	6 1/2	1/4	+25	+20	-	-	10:34:09	5:00:28
					1	10	-	5:01:25
					2	45	-	5:01:24
					3	50	10:35:07	5:01:21
					4	55	-	5:01:19
					5	60	10:35:02	5:01:18
					6	60	10:35:00	5:01:15
					7	65	10:34:28	5:01:24
					8	50	10:34:29	5:01:25

Figure 16 cont.

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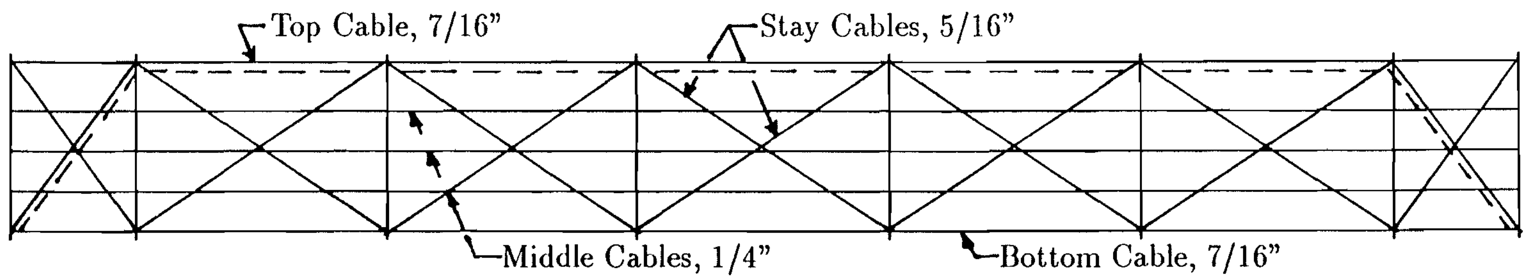
CDOH FLEXPOST FENCE

Fence Model

Cable Layout



– – – – – Prestressed Cable

Figure 17

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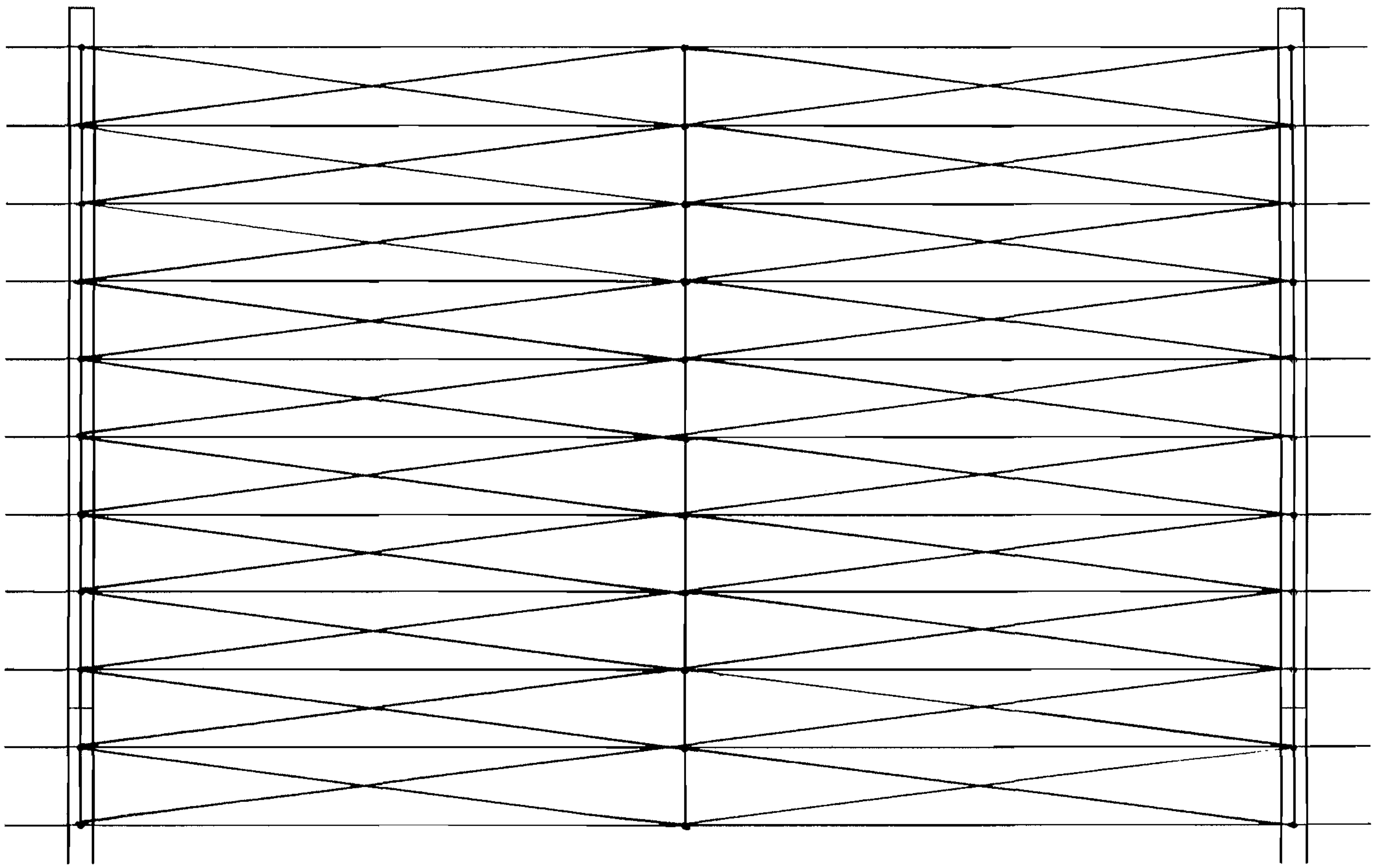
CDOH FLEXPOST FENCE

Fence Model

Node Locations and Mesh Members



(Stay cables not shown)

Figure 18

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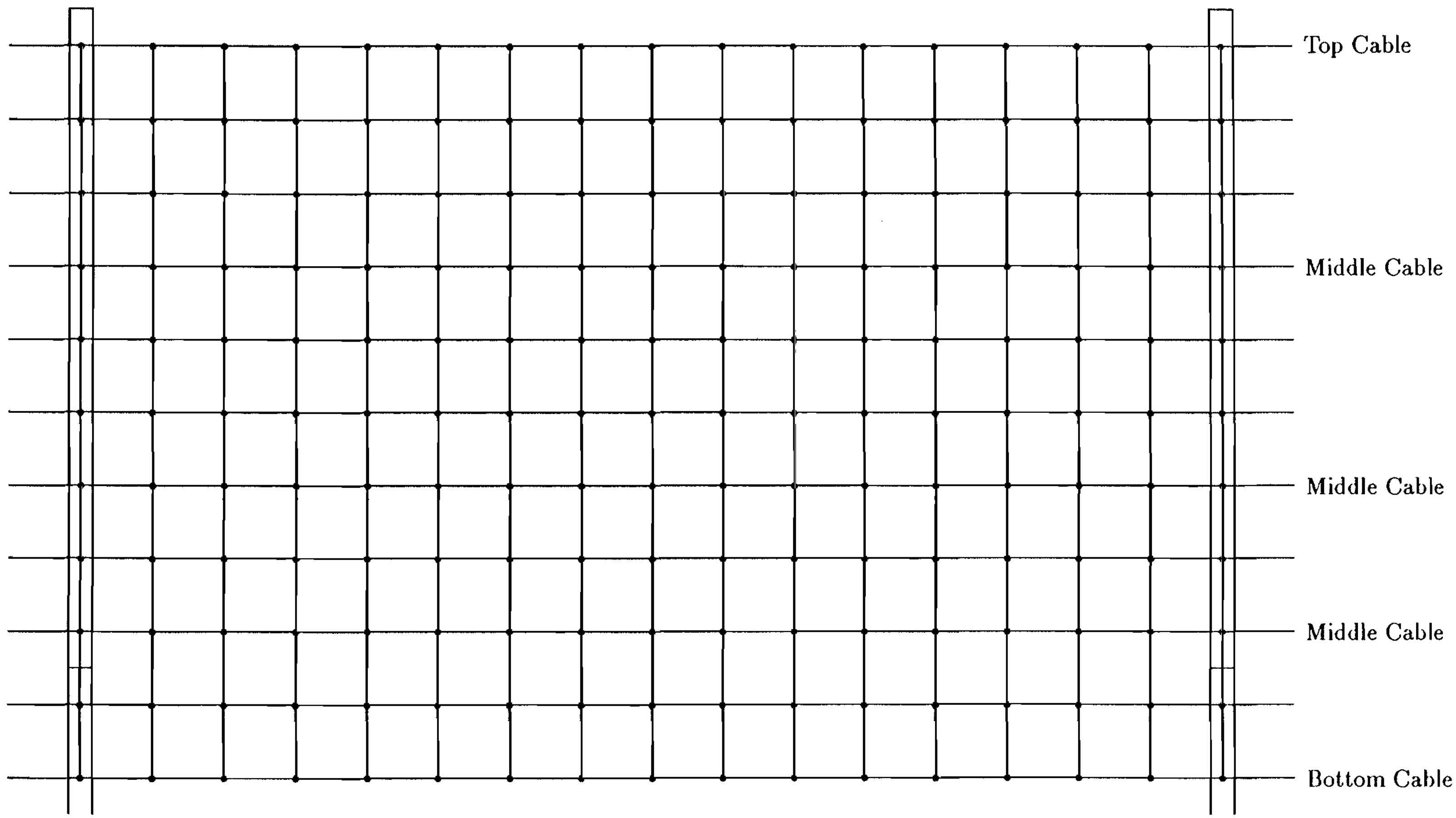
CDOH FLEXPOST FENCE

Fence Model

Mesh Members for Contact Problem



(Stay cables not shown)

Figure 19

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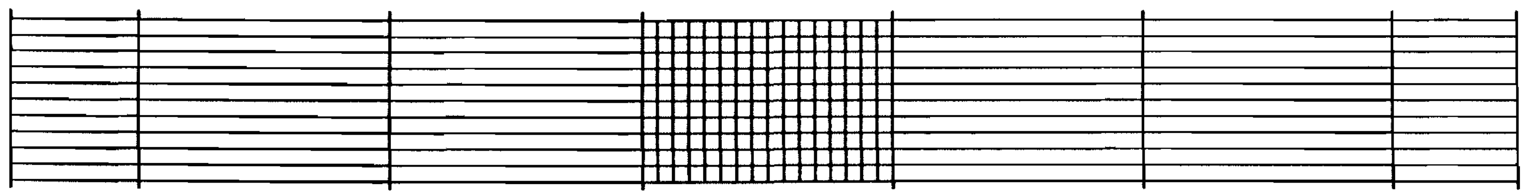
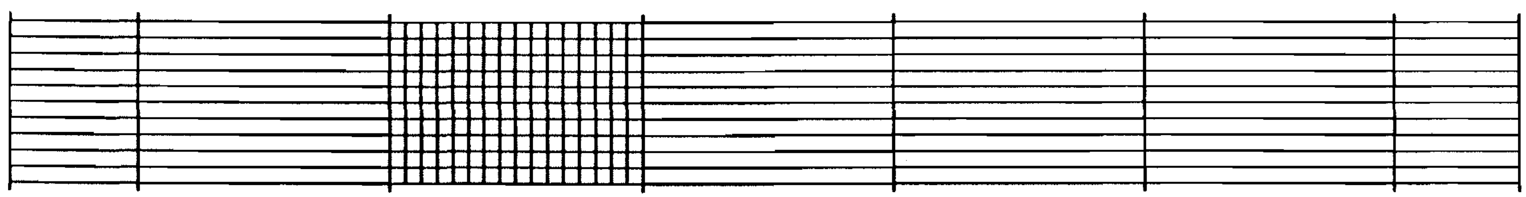
CDOH FLEXPOST FENCE

Fence Model

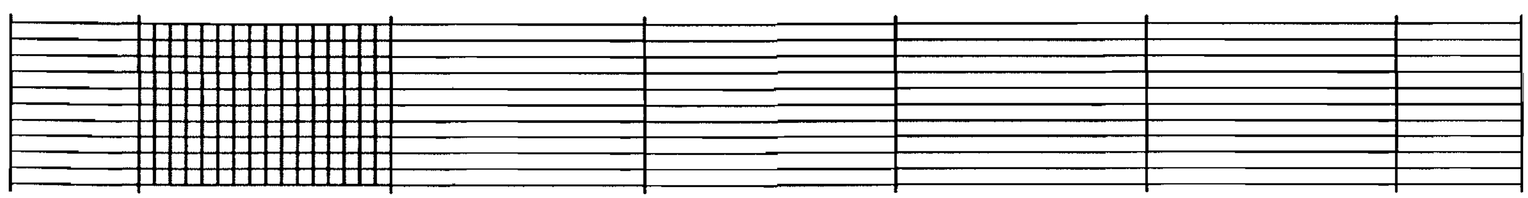
Models For Contact Problems



Model C1



Model C2



Model C3

Figure 20

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CDOH FLEXPOST FENCE

Prototype Tests

Impact Cases for Analysis

Date	Rock	Mass	Impact X	Location Y	Z	Impact VX	Velocity VY	VZ
		(slugs)	(ft)	(ft)	(ft)	(ft/s)	(ft/s)	(ft/s)
Aug.13	5	8.0	56	0	1	0.0	25.7	4.5
	40	188.0	36	0	4	-6.5	30.7	21.5
	64	18.6	36	0	4	-5.8	31.3	11.4
	36	43.2	64	0	3	6.5	11.3	0.0
	48	52.9	68	0	0	0.0	10.9	0.0
	37	24.8	36	0	3	3.1	34.9	6.1
	41	47.0	36	0	5	0.0	47.0	-17.1
	34	18.4	44	0	3	0.0	34.2	9.2
	9	50.3	67	0	1	-5.2	14.2	0.0
	12	42.1	64	0	5	0.0	37.5	0.0
Aug.21	37	24.4	56	0	1	0.0	43.1	7.6
	13	9.5	40	0	5	0.0	31.3	-11.4
	14	39.9	48	0	4	0.0	30.2	14.1
	64	18.6	29	0	3	0.0	15.7	7.3
	70	23.3	35	0	3	0.0	24.8	14.3
	4	112.0	80	0	3	-7.3	18.0	9.0

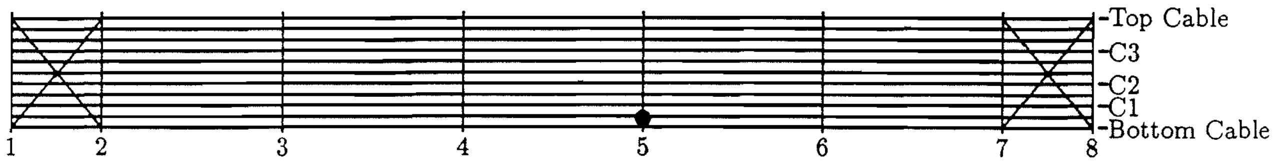
Figure 21

University of Colorado at Boulder

CDOH FLEXPOST FENCE

Analysis Results

August 13		Velocity	26.1 ft/s
Rock 5		Energy	4080 ft-lb



Fabric Forces

Member	Tension (lbs)
Mesh Vertical	1540
Mesh Horizontal	810
Top Cable	1560
C3	429
C2	598
C1	3860
Bottom Cable	3140
Stay (end)	1730
Stay	145

Posts

	Post 1	Post 2	Post 3	Post 4	Post 5	Post 6	Post 7	Post 8
Force (lbs)	441	-1350	-66	-179	-583	-190	-1380	1320
Rotation (deg)	2	-	-	-	-	-	-	3

Foundations

	1	2	3	4	5	6	7	8
Shear (lbs)	2130	83	108	37	-	-	123	2260
Axial (lbs) (+)	1690	-	34	-	-	-	-	2650
(-)	-	-1300	-	-179	-582	-188	-1310	-

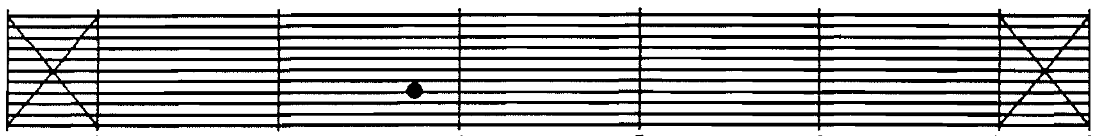
Figure 22

University of Colorado at Boulder

CDOH FLEXPOST FENCE

Analysis Results

August 13 Velocity 37.5 ft/s
Rock 40 Energy 375,000 ft-lb



Fabric Forces

Member	Tension (lbs)
Mesh Vertical	23800
Mesh Horizontal	13300
Top Cable	28600
C3	10900
C2	16400
C1	13500
Bottom Cable	39800
Stay (end)	26000
Stay	21900

Posts

	Post 1	Post 2	Post 3	Post 4	Post 5	Post 6	Post 7	Post 8
Force (lbs)	3370	-19500	-4380	3920	-15100	-14300	-27300	4450
Rotation (deg)	72	42	41	45	47	48	52	71

Foundations

	1	2	3	4	5	6	7	8
Shear (lbs)	27700	18500	2600	2500	14200	11200	18400	30900
Axial (lbs) (+)	15800	-	-	3020	8050	-	-	14500
(-)	-	-8840	-3560	-3340	-	-5620	-14100	-

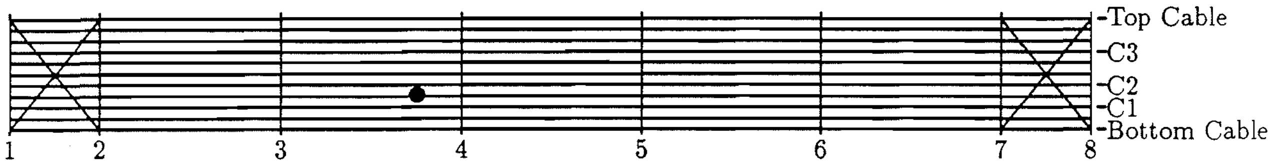
Figure 23

University of Colorado at Boulder

CDOH FLEXPOST FENCE

Analysis Results

August 13		Velocity	33.3 ft/s
Rock 64		Energy	12,100 ft-lb



Fabric Forces

Member	Tension (lbs)
Mesh Vertical	2570
Mesh Horizontal	955
Top Cable	6580
C3	3030
C2	3690
C1	2270
Bottom Cable	2580
Stay (end)	6930
Stay	2730

Posts

	Post 1	Post 2	Post 3	Post 4	Post 5	Post 6	Post 7	Post 8
Force (lbs)	486	-5570	-1990	-2340	-1670	-1380	-3510	536
Rotation (deg)	7	14	14	15	13	10	2	6

Foundations

	1	2	3	4	5	6	7	8
Shear (lbs)	4490	2130	327	785	1880	2320	1910	3480
Axial (lbs) (+)	5730	-	-	930	187	486	-	3950
(-)	-	-5060	-1980	-2340	-1110	-1380	-3510	-

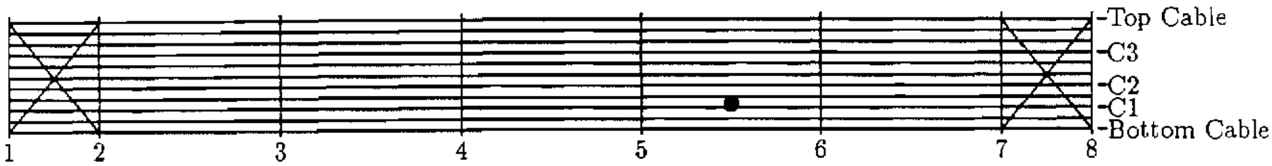
Figure 24

University of Colorado at Boulder

CDOH FLEXPOST FENCE

Analysis Results

August 13		Velocity	13.0 ft/s
Rock 36		Energy	5,180 ft-lb



Fabric Forces

Member	Tension (lbs)
Mesh Vertical	1970
Mesh Horizontal	860
Top Cable	3510
C3	1660
C2	2940
C1	3480
Bottom Cable	1890
Stay (end)	2480
Stay	860

Posts

	Post 1	Post 2	Post 3	Post 4	Post 5	Post 6	Post 7	Post 8
Force (lbs)	482	-1380	-155	-265	-475	-940	-2140	1400
Rotation (deg)	2	0	1	2	3	4	3	4

Foundations

	1	2	3	4	5	6	7	8
Shear (lbs)	1580	165	260	338	24	58	730	2360
Axial (lbs) (+)	1790	-	67	223	-	-	-	3270
(-)	-	-1290	-	-	-474	-940	-1740	-

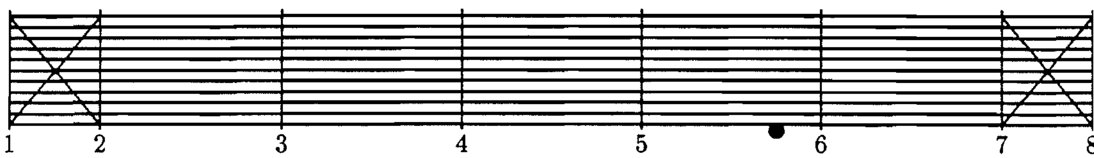
Figure 25

University of Colorado at Boulder

CDOH FLEXPOST FENCE

Analysis Results

August 13		Velocity	10.9 ft/s
Rock 48		Energy	5,210 ft-lb



Fabric Forces

Member	Tension (lbs)
Mesh Vertical	2270
Mesh Horizontal	1040
Top Cable	1640
C3	451
C2	797
C1	3020
Bottom Cable	4720
Stay (end)	1810
Stay	295

Posts

	Post 1	Post 2	Post 3	Post 4	Post 5	Post 6	Post 7	Post 8
Force (lbs)	90	-1300	-20	-80	-127	-510	-1550	854
Rotation (deg)	-	-	-	-	-	-	-	2

Foundations

	1	2	3	4	5	6	7	8
Shear (lbs)	1480	30	55	44	-	-	250	2120
Axial (lbs) (+)	1350	-	34	-	-	-	-	2170
(-)	-	-1290	-3	-52	-130	-510	-1410	-

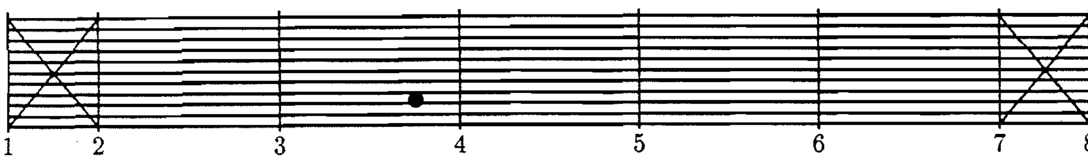
Figure 26

University of Colorado at Boulder

CDOH FLEXPOST FENCE

Analysis Results

August 13		Velocity	35.4 ft/s
Rock 37		Energy	22,200 ft-lb



Fabric Forces

Member	Tension (lbs)
Mesh Vertical	2350
Mesh Horizontal	1470
Top Cable	7590
C3	1500
C2	3190
C1	3770
Bottom Cable	3440
Stay (end)	6900
Stay	2970

Posts

	Post 1	Post 2	Post 3	Post 4	Post 5	Post 6	Post 7	Post 8
Force (lbs)	363	-5580	-2220	-3410	-1840	-1300	-3580	538
Rotation (deg)	8	13	14	15	12	11	5	8

Foundations

	1	2	3	4	5	6	7	8
Shear (lbs)	4690	2200	225	825	2520	2460	1820	4150
Axial (lbs) (+)	5530	-	-	212	398	620	-	3670
(-)	-	-5130	-2220	-3480	-1350	-1300	-3580	-

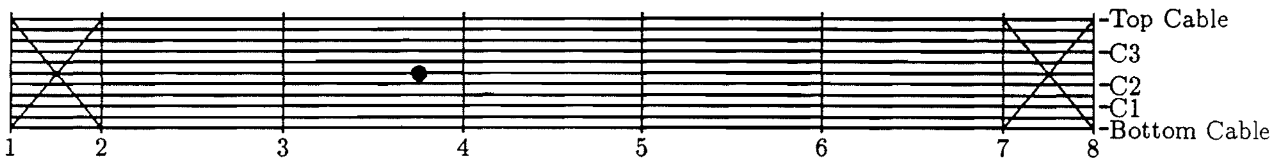
Figure 27

University of Colorado at Boulder

CDOH FLEXPOST FENCE

Analysis Results

August 13		Velocity	50.0 ft/s
Rock 41		Energy	74,400 ft-lb



Fabric Forces

Member	Tension (lbs)
Mesh Vertical	12400
Mesh Horizontal	3360
Top Cable	12900
C3	3940
C2	20100
C1	6020
Bottom Cable	12600
Stay (end)	15800
Stay	7070

Posts

	Post 1	Post 2	Post 3	Post 4	Post 5	Post 6	Post 7	Post 8
Force (lbs)	1600	-13000	-4680	-5320	-4260	-11300	-12900	4050
Rotation (deg)	36	40	42	43	44	35	34	46

Foundations

	1	2	3	4	5	6	7	8
Shear (lbs)	13900	5970	1840	1470	4550	6380	6040	16600
Axial (lbs) (+)	12800	-	-	-	1150	1300	-	13500
(-)	-	-11700	-4670	-5280	-3560	-9090	-12600	-

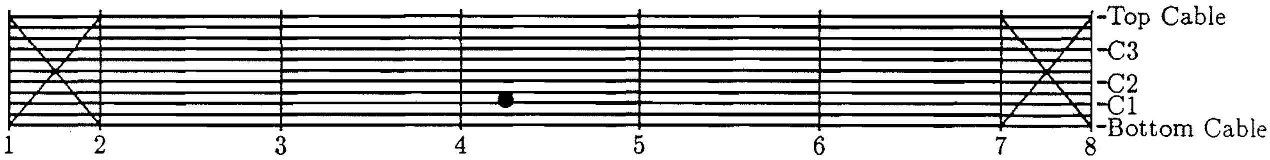
Figure 28

University of Colorado at Boulder

CDOH FLEXPOST FENCE

Analysis Results

August 13		Velocity	35.4 ft/s
Rock 34		Energy	15,600 ft-lb



Fabric Forces

Member	Tension (lbs)
Mesh Vertical	2450
Mesh Horizontal	1270
Top Cable	5510
C3	1870
C2	3474
C1	3910
Bottom Cable	3310
Stay (end)	3750
Stay	2410

Posts

	Post 1	Post 2	Post 3	Post 4	Post 5	Post 6	Post 7	Post 8
Force (lbs)	1020	-3100	-1420	-2410	-2070	-1520	-3000	423
Rotation (deg)	10	3	9	10	10	7	1	4

Foundations

	1	2	3	4	5	6	7	8
Shear (lbs)	3730	1880	1670	157	191	2040	2030	2940
Axial (lbs) (+)	3650	-	760	-	10	810	-	3190
(-)	-	-3100	-1120	-2410	-2070	-1130	-2990	-

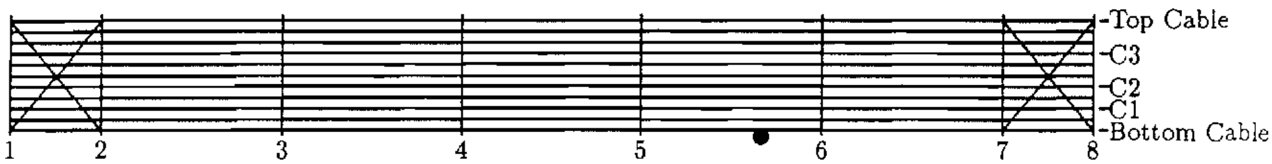
Figure 29

University of Colorado at Boulder

CDOH FLEXPOST FENCE

Analysis Results

August 13		Velocity	15.1 ft/s
Rock 9		Energy	8,200 ft-lb



Fabric Forces

Member	Tension (lbs)
Mesh Vertical	2000
Mesh Horizontal	1300
Top Cable	2080
C3	819
C2	1330
C1	3810
Bottom Cable	5660
Stay (end)	2220
Stay	480

Posts

	Post 1	Post 2	Post 3	Post 4	Post 5	Post 6	Post 7	Post 8
Force (lbs)	247	-1380	-194	-416	-684	-965	-2240	1030
Rotation (deg)	2	-	-	1	2	3	2	4

Foundations

	1	2	3	4	5	6	7	8
Shear (lbs)	1830	131	228	239	27	42	400	2640
Axial (lbs) (+)	1560	-	17	200	-	-	-	2680
(-)	-	-1310	-76	-278	-683	-964	-2000	-

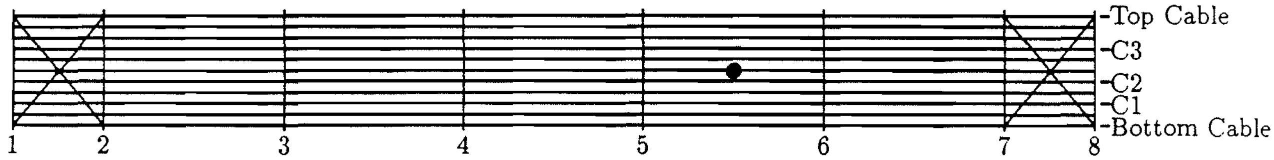
Figure 30

University of Colorado at Boulder

CDOH FLEXPOST FENCE

Analysis Results

August 13		Velocity	37.5 ft/s
Rock 12		Energy	36,300 ft-lb



Fabric Forces

Member	Tension (lbs)
Mesh Vertical	4600
Mesh Horizontal	1040
Top Cable	7970
C3	9950
C2	8690
C1	4000
Bottom Cable	5950
Stay (end)	8960
Stay	3800

Posts

	Post 1	Post 2	Post 3	Post 4	Post 5	Post 6	Post 7	Post 8
Force (lbs)	563	-6070	-2290	-2290	-3200	-3300	-7240	2630
Rotation (deg)	12	18	19	22	26	27	22	27

Foundations

	1	2	3	4	5	6	7	8
Shear (lbs)	6220	3200	3220	2630	575	630	2980	9540
Axial (lbs) (+)	6380	-	610	630	-	-	-	7930
(-)	-	-6060	-2230	-1790	-3180	-3290	-6580	-

Figure 31

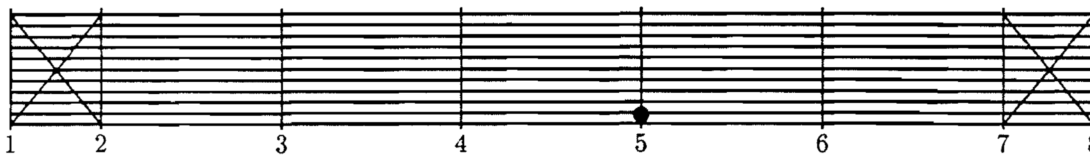
University of Colorado at Boulder

CDOH FLEXPOST FENCE

Analysis Results

August 21 — Velocity 43.8 ft/s

Rock 37 — Energy 30,400 ft-lb



Fabric Forces

Member	Tension (lbs)
Mesh Vertical	4460
Mesh Horizontal	1420
Top Cable	5450
C3	948
C2	1390
C1	5970
Bottom Cable	10400
Stay (end)	3800
Stay	2530

Posts

	Post 1	Post 2	Post 3	Post 4	Post 5	Post 6	Post 7	Post 8
Force (lbs)	1430	-2630	-1170	-1800	-2270	-1460	-3330	2990
Rotation (deg)	8	5	7	8	8	8	7	12

Foundations

	1	2	3	4	5	6	7	8
Shear (lbs)	4490	1190	1930	358	184	155	2140	3970
Axial (lbs) (+)	3660	-	490	735	-	-	-	5920
(-)	-	-2630	-1160	-1700	-2270	-1460	-2850	-

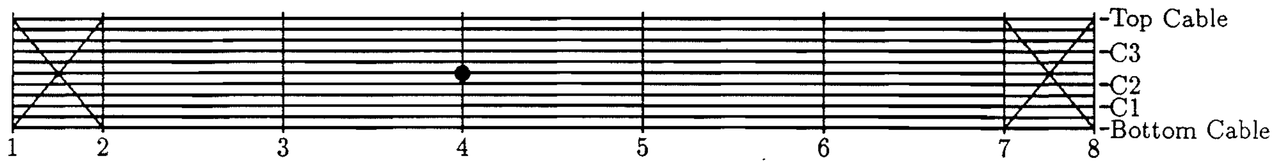
Figure 32

University of Colorado at Boulder

CDOH FLEXPOST FENCE

Analysis Results

August 21		Velocity	33.3 ft/s
Rock 13		Energy	5,740 ft-lb



Fabric Forces

Member	Tension (lbs)
Mesh Vertical	3450
Mesh Horizontal	885
Top Cable	4230
C3	1590
C2	3780
C1	3820
Bottom Cable	2070
Stay (end)	2860
Stay	1530

Posts

	Post 1	Post 2	Post 3	Post 4	Post 5	Post 6	Post 7	Post 8
Force (lbs)	919	-2340	-970	-3340	-870	-490	-1820	700
Rotation (deg)	4	-	4	7	4	-	-	3

Foundations

	1	2	3	4	5	6	7	8
Shear (lbs)	2400	1300	20	250	25	1210	690	2340
Axial (lbs) (+)	3100	-	-	-	10	360	-	2470
(-)	-	-1670	-970	-3340	-870	-	-1410	-

Figure 33

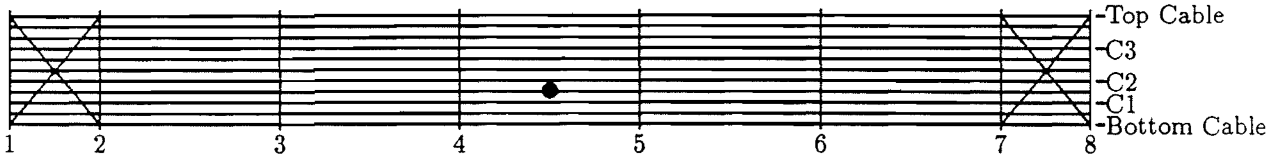
University of Colorado at Boulder

CDOH FLEXPOST FENCE

Analysis Results

August 21
Rock 14

Velocity 33.3 ft/s
Energy 33,500 ft-lb



Fabric Forces

Member	Tension (lbs)
Mesh Vertical	8720
Mesh Horizontal	5010
Top Cable	17700
C3	3680
C2	3690
C1	8240
Bottom Cable	12600
Stay (end)	13900
Stay	9380

Posts

	Post 1	Post 2	Post 3	Post 4	Post 5	Post 6	Post 7	Post 8
Force (lbs)	2580	-10900	-4380	-5690	-6050	-5220	-11900	2870
Rotation (deg)	44	34	43	42	42	43	34	44

Foundations

	1	2	3	4	5	6	7	8
Shear (lbs)	16200	7090	5000	3810	3980	5050	8060	14600
Axial (lbs) (+)	11400	-	670	3	90	1070	-	12800
(-)	-	-8450	-3270	-4230	-4550	-3500	-7300	-

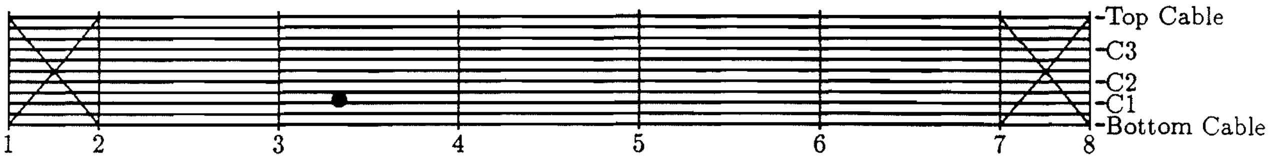
Figure 34

University of Colorado at Boulder

CDOH FLEXPOST FENCE

Analysis Results

August 21		Velocity	17.3 ft/s
Rock 64		Energy	6,050 ft-lb



Fabric Forces

Member	Tension (lbs)
Mesh Vertical	1290
Mesh Horizontal	766
Top Cable	2120
C3	902
C2	3790
C1	2640
Bottom Cable	1710
Stay (end)	2310
Stay	552

Posts

	Post 1	Post 2	Post 3	Post 4	Post 5	Post 6	Post 7	Post 8
Force (lbs)	766	-1850	-1220	-681	-185	-77	-1370	170
Rotation (deg)	3	1	3	1	1	-	-	3

Foundations

	1	2	3	4	5	6	7	8
Shear (lbs)	1480	468	60	20	267	188	106	1290
Axial (lbs) (+)	2300	-	-	8	298	49	-	1440
(-)	-	-1590	-1220	-681	-	-	-1320	-

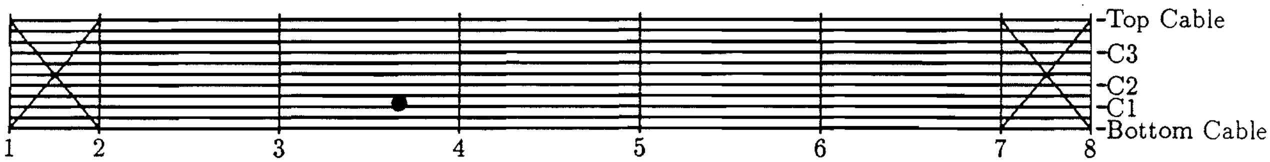
Figure 35

University of Colorado at Boulder

CDOH FLEXPOST FENCE

Analysis Results

August 21		Velocity	28.6 ft/s
Rock 70		Energy	11,900 ft-lb



Fabric Forces

Member	Tension (lbs)
Mesh Vertical	2340
Mesh Horizontal	1010
Top Cable	5560
C3	3760
C2	4700
C1	2740
Bottom Cable	2300
Stay (end)	4450
Stay	1820

Posts

	Post 1	Post 2	Post 3	Post 4	Post 5	Post 6	Post 7	Post 8
Force (lbs)	743	-3610	-1390	-1800	-1140	-1040	-2440	1040
Rotation (deg)	5	7	9	11	9	4	1	5

Foundations

	1	2	3	4	5	6	7	8
Shear (lbs)	2870	1200	114	204	1140	1540	1200	2710
Axial (lbs) (+)	3660	-	-	370	1000	270	-	2840
(-)	-	-3220	-1390	-1800	-	-990	-2150	-

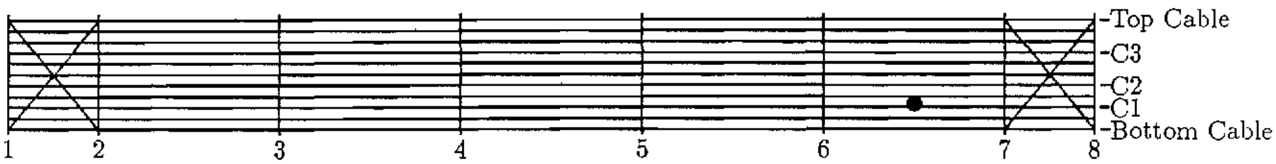
Figure 36

University of Colorado at Boulder

CDOH FLEXPOST FENCE

Analysis Results

August 21		Velocity	21.4 ft/s
Rock 4		Energy	44,000 ft-lb



Fabric Forces

Member	Tension (lbs)
Mesh Vertical	7900
Mesh Horizontal	4200
Top Cable	17400
C3	6000
C2	12400
C1	10500
Bottom Cable	15100
Stay (end)	32300
Stay	8600

Posts

	Post 1	Post 2	Post 3	Post 4	Post 5	Post 6	Post 7	Post 8
Force (lbs)	3240	-11300	-4220	-1920	-6500	-10200	-26200	2420
Rotation (deg)	87	62	64	53	48	46	47	78

Foundations

	1	2	3	4	5	6	7	8
Shear (lbs)	21300	7250	3730	3630	7250	7300	17400	28200
Axial (lbs)	12200	-	-	515	840	-	-	18500
(-)	-	-11400	-2030	-1720	-3140	-7250	-19200	-

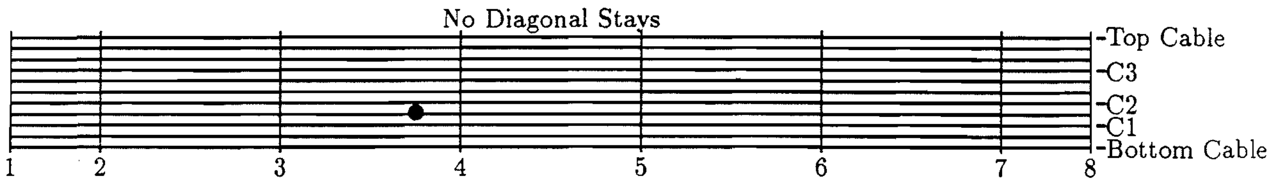
Figure 37

University of Colorado at Boulder

CDOH FLEXPOST FENCE

Analysis Results

August 13		Velocity	33.3 ft/s
Rock 64		Energy	12,100 ft-lb



Fabric Forces

Member	Tension (lbs)
Mesh Vertical	1810
Mesh Horizontal	887
Top Cable	2300
C3	1910
C2	3970
C1	1610
Bottom Cable	3540
Stay (end)	-
Stay	-

Posts

	Post 1	Post 2	Post 3	Post 4	Post 5	Post 6	Post 7	Post 8
Force (lbs)	339	499	830	-753	554	-243	-264	370
Rotation (deg)	8	2	11	15	5	2	2	8

Foundations

	1	2	3	4	5	6	7	8
Shear (lbs)	1130	18	164	84	50	7	7	1260
Axial (lbs) (+)	363	499	814	378	552	-	-	403
(-)	-	-	-	-753	-	-243	-264	-

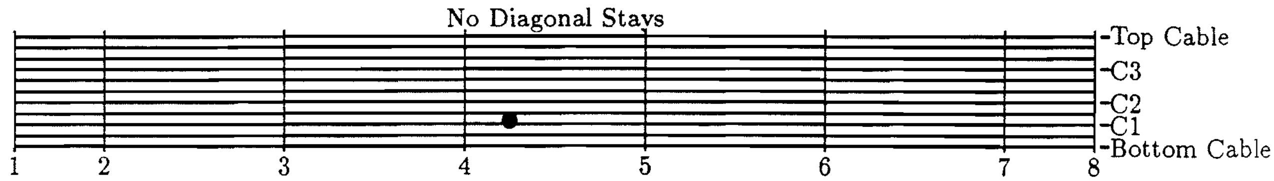
Figure 38

University of Colorado at Boulder

CDOH FLEXPOST FENCE

Analysis Results

August 13		Velocity	35.4 ft/s
Rock 34		Energy	15,600 ft-lb



Fabric Forces

Member	Tension (lbs)
Mesh Vertical	1830
Mesh Horizontal	735
Top Cable	1670
C3	1110
C2	2870
C1	3100
Bottom Cable	3310
Stay (end)	-
Stay	-

Posts

	Post 1	Post 2	Post 3	Post 4	Post 5	Post 6	Post 7	Post 8
Force (lbs)	436	-297	652	-922	-580	-1670	-551	534
Rotation (deg)	12	2	6	14	10	3	1	7

Foundations

	1	2	3	4	5	6	7	8
Shear (lbs)	2130	8	67	152	44	59	10	2030
Axial (lbs) (+)	500	-	649	-	283	-	-	564
(-)	-	-296	-	-920	-580	-1670	-550	-

Figure 39

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CDOH FLEXPOST FENCE

Average Forces in Mesh

Date	Rock No.	Maximum Member Force (lbs)	Average Mesh Force (plf)
Aug. 13	5	1540	890
"	40	23800	15100
"	64	2570	1560
"	36	1970	1320
"	48	2270	1520
"	37	2350	1530
"	41	12400	5420
"	34	2450	1500
"	9	2000	1500
"	12	4600	2510
Aug. 21	37	4460	2630
"	13	3450	1590
"	14	8720	5710
"	64	1290	980
"	70	2340	1290
"	4	7900	4450
No Stays	64	1810	1160
"	34	1830	850

Figure 40

University of Colorado at Boulder

CDOH FLEXPOST FENCE

Analysis Results

Vertical Mesh Members

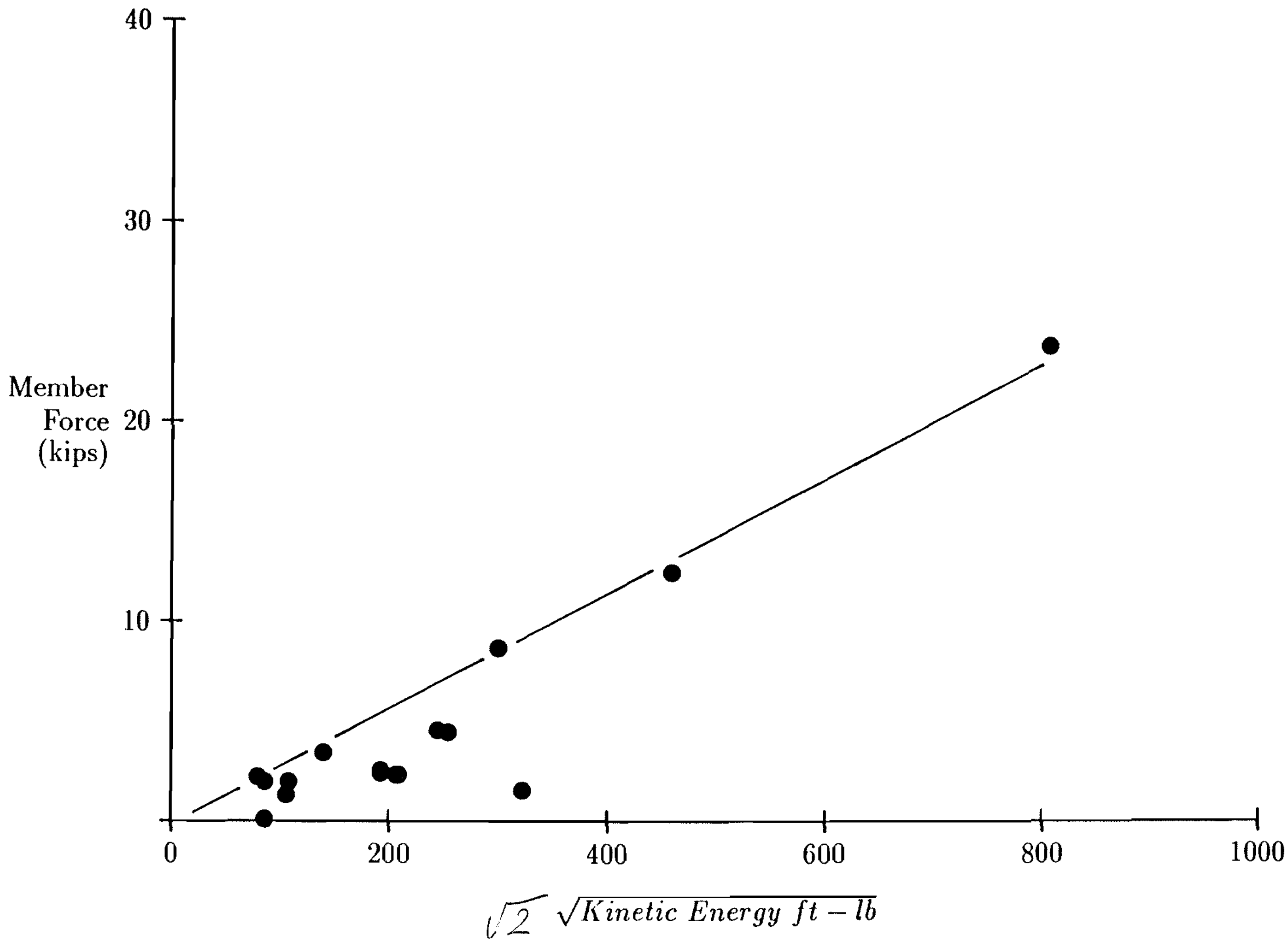

Figure 41

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CDOH FLEXPOST FENCE
Analysis Results

Horizontal Mesh Members

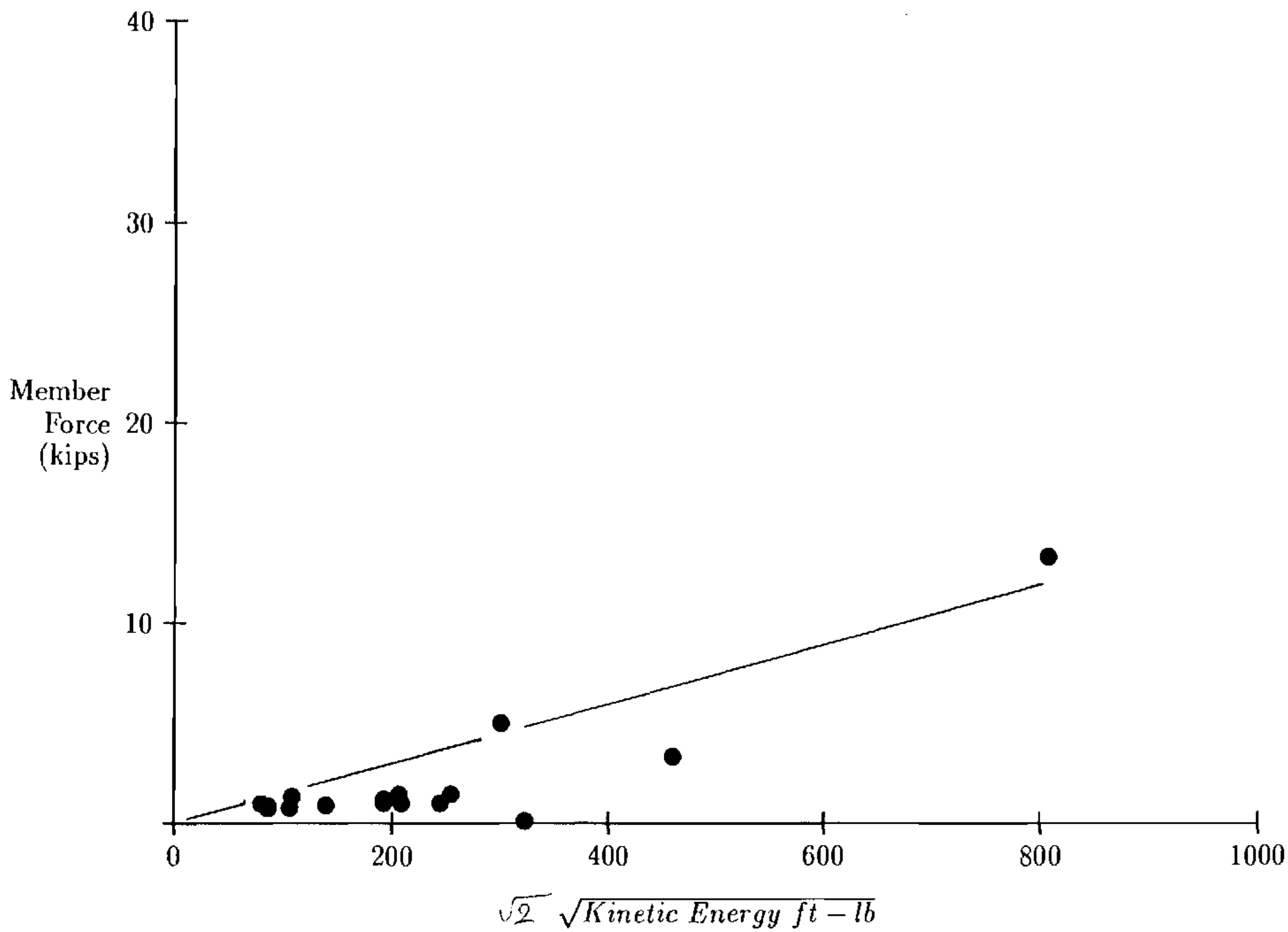

Figure 42

University of Colorado at Boulder

CDOH FLEXPOST FENCE

Analysis Results

Top Cable

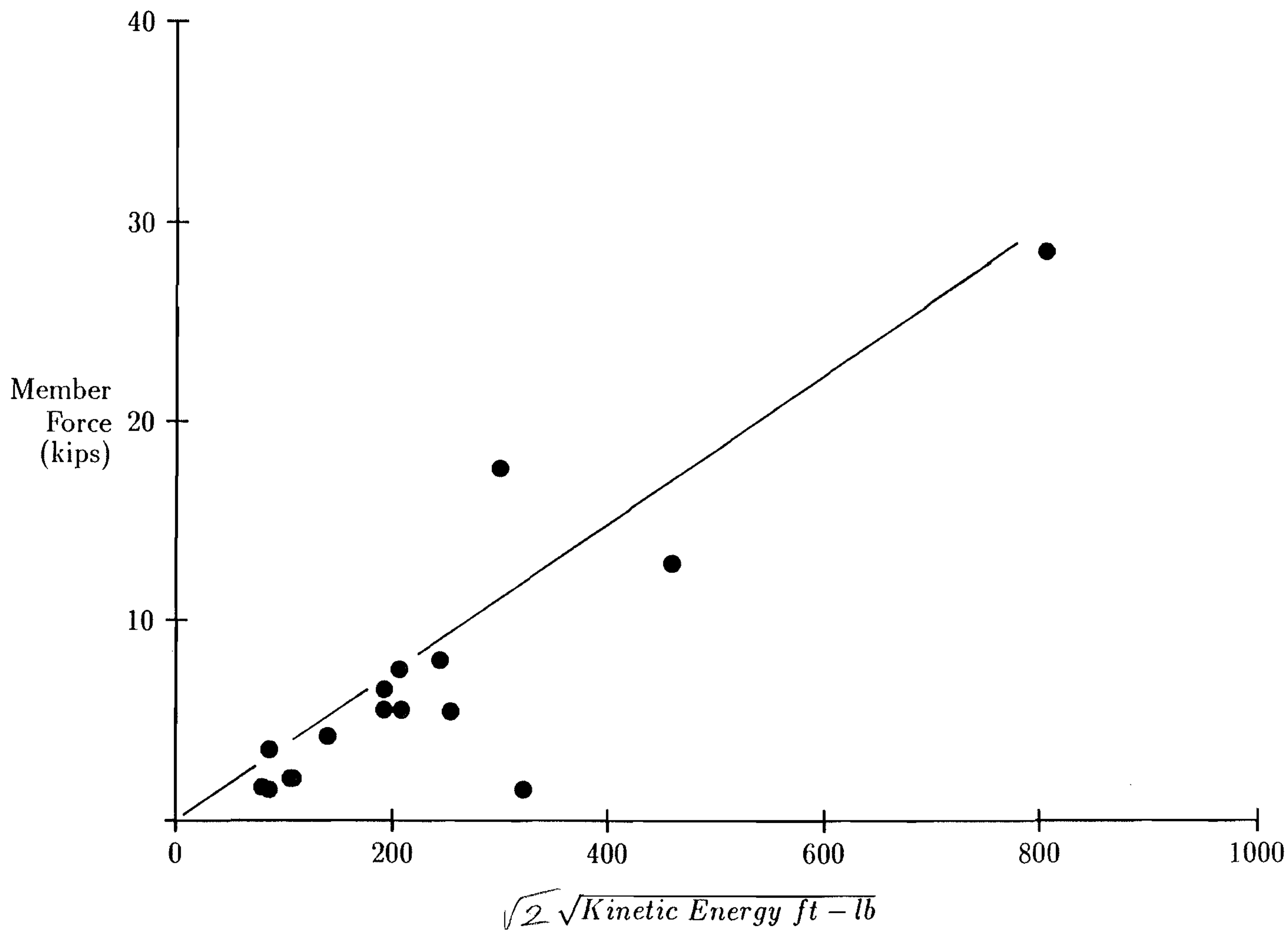

Figure 43

University of Colorado at Boulder

CDOH FLEXPOST FENCE

Analysis Results

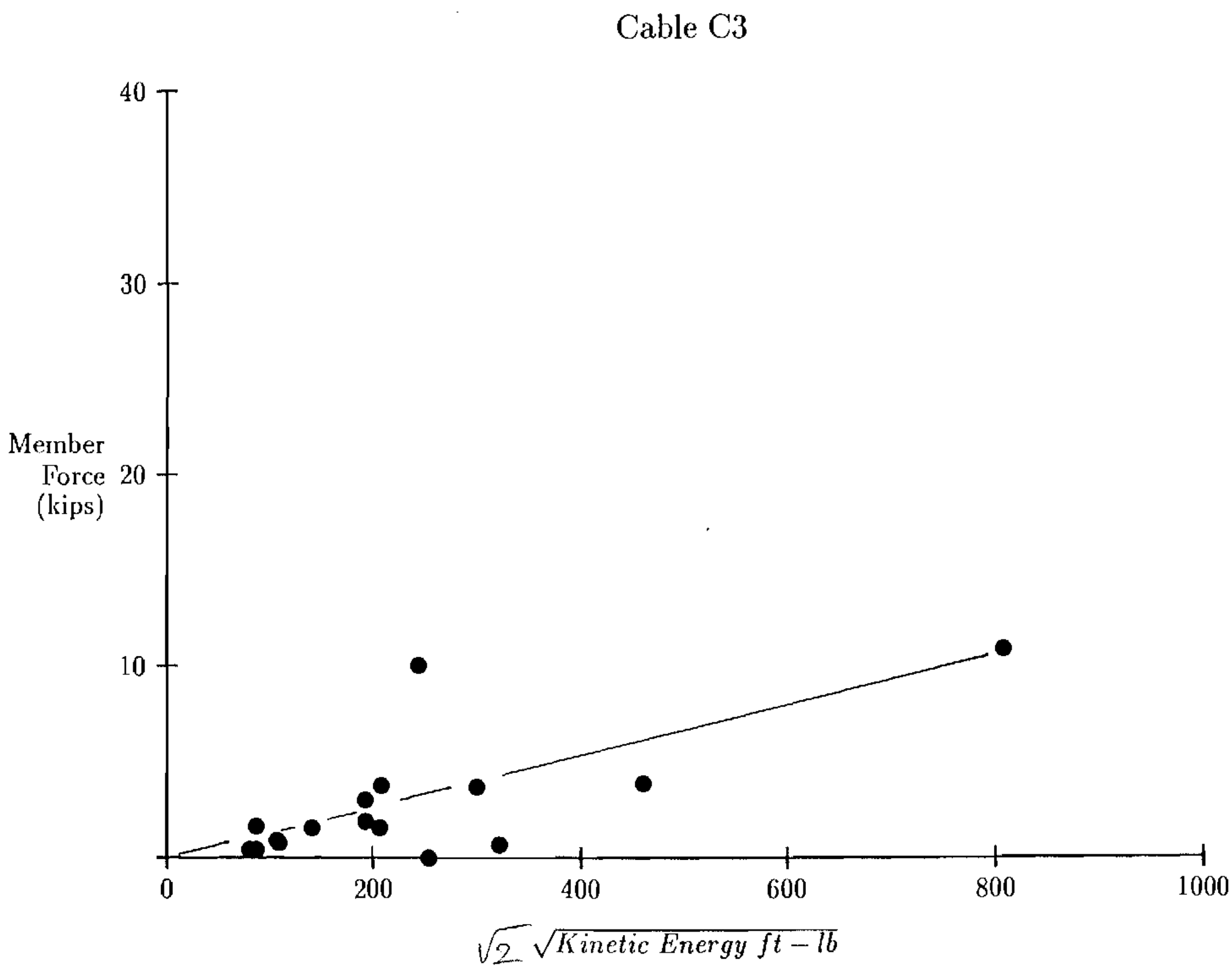

Figure 44

University of Colorado at Boulder

CDOH FLEXPOST FENCE

Analysis Results

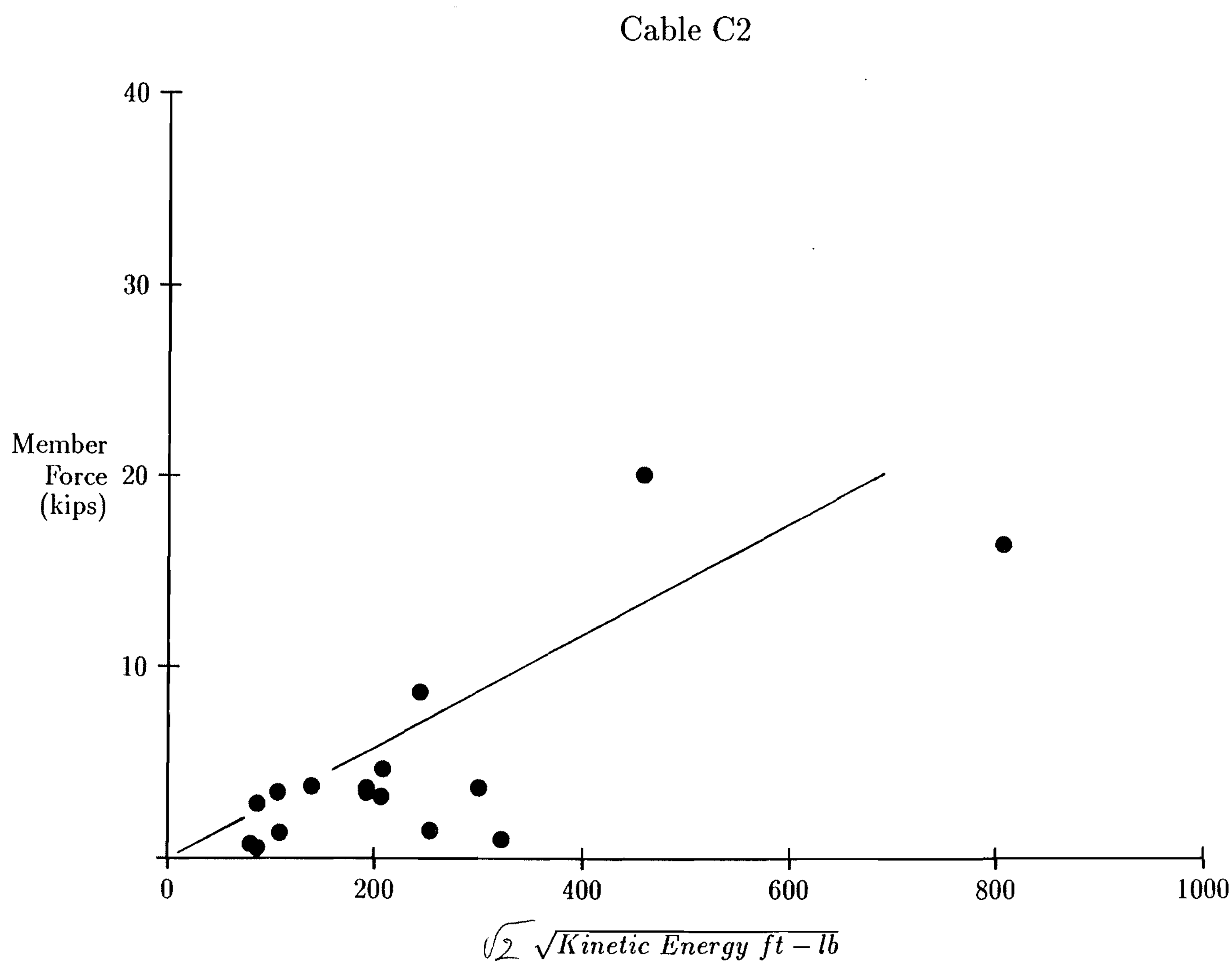

Figure 45

University of Colorado at Boulder

CDOH FLEXPOST FENCE

Analysis Results

Cable C1

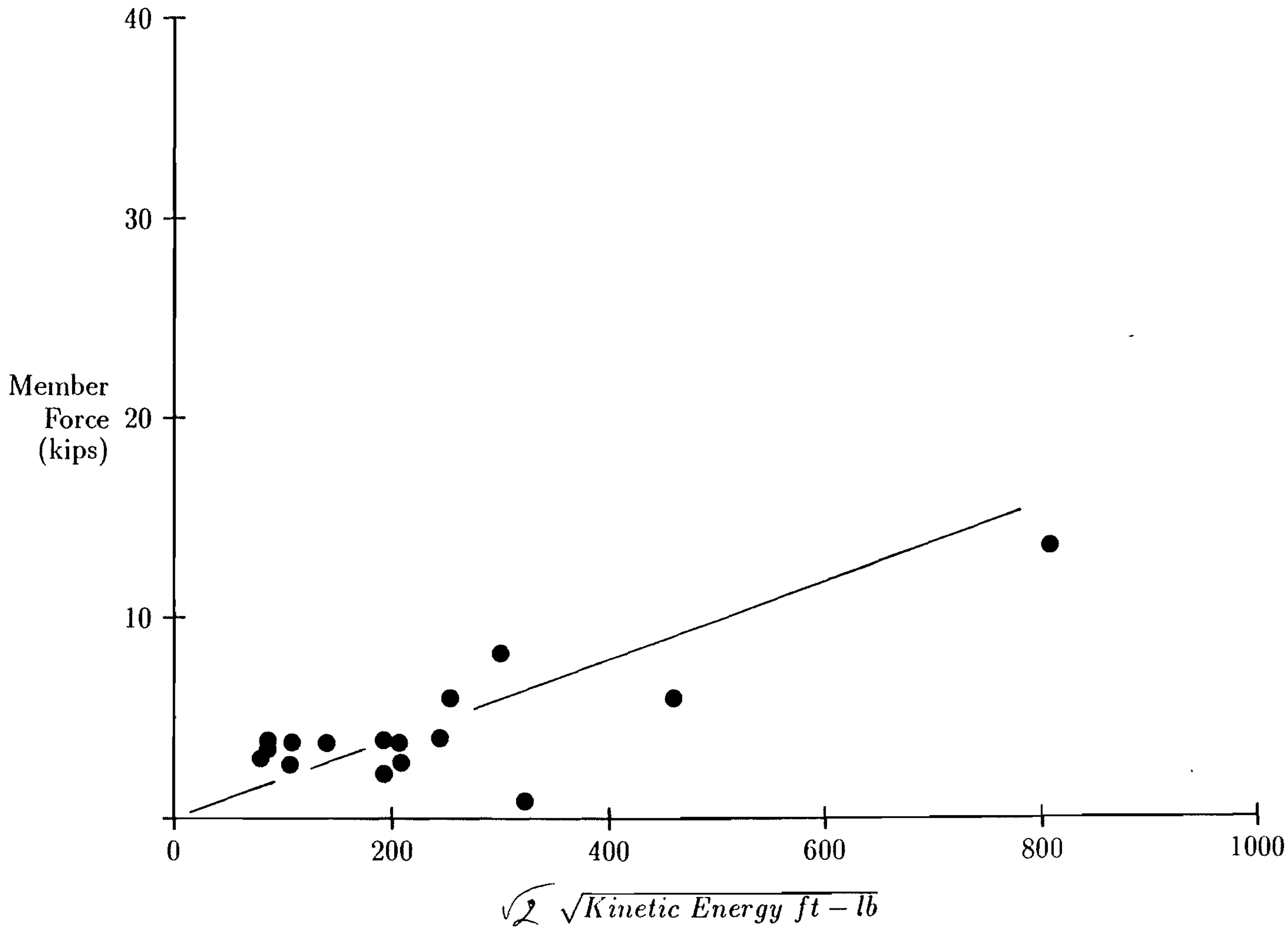

Figure 46

University of Colorado at Boulder

CDOH FLEXPOST FENCE

Analysis Results

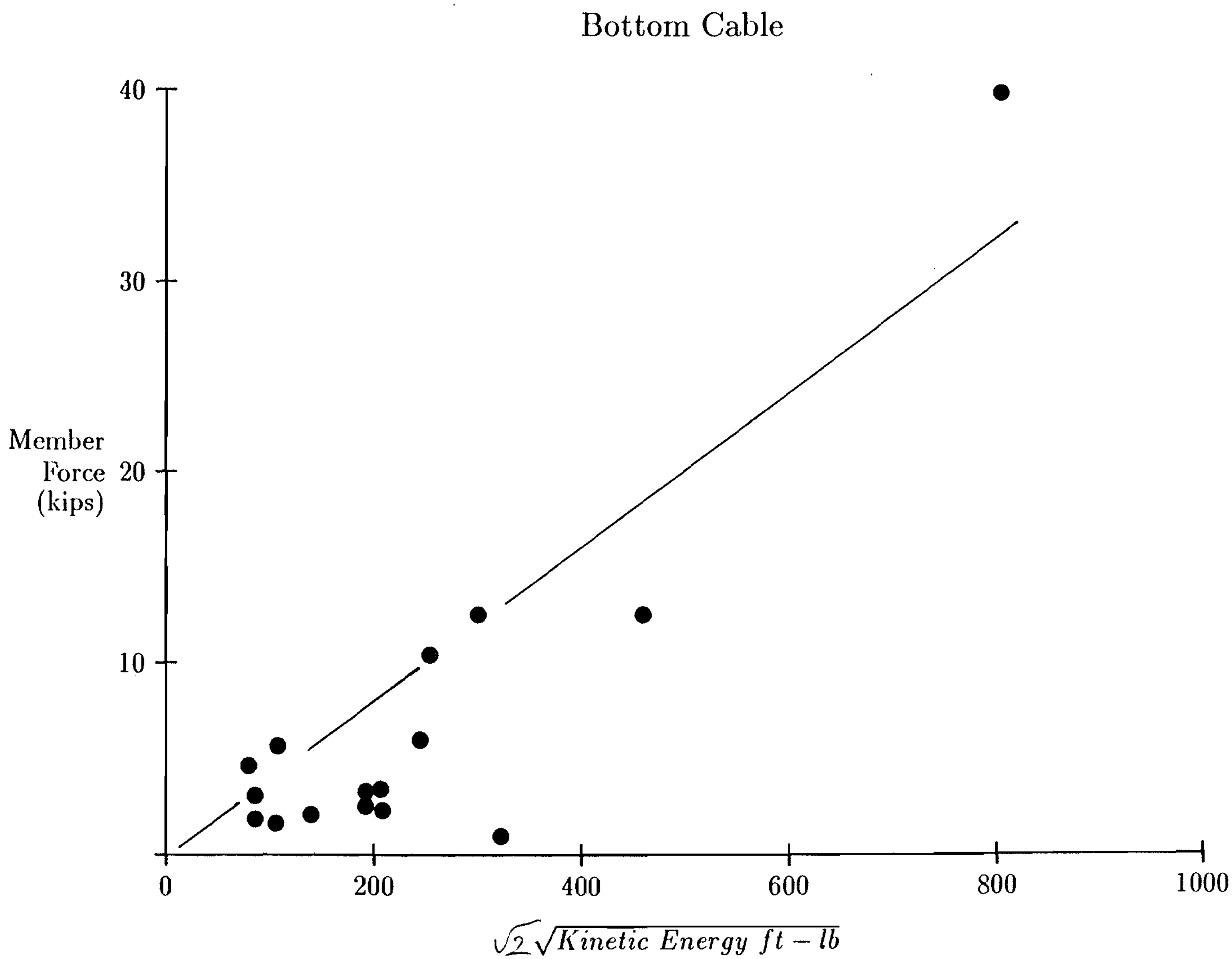

Figure 47

University of Colorado at Boulder

CDOH FLEXPOST FENCE

Analysis Results

Stay - End

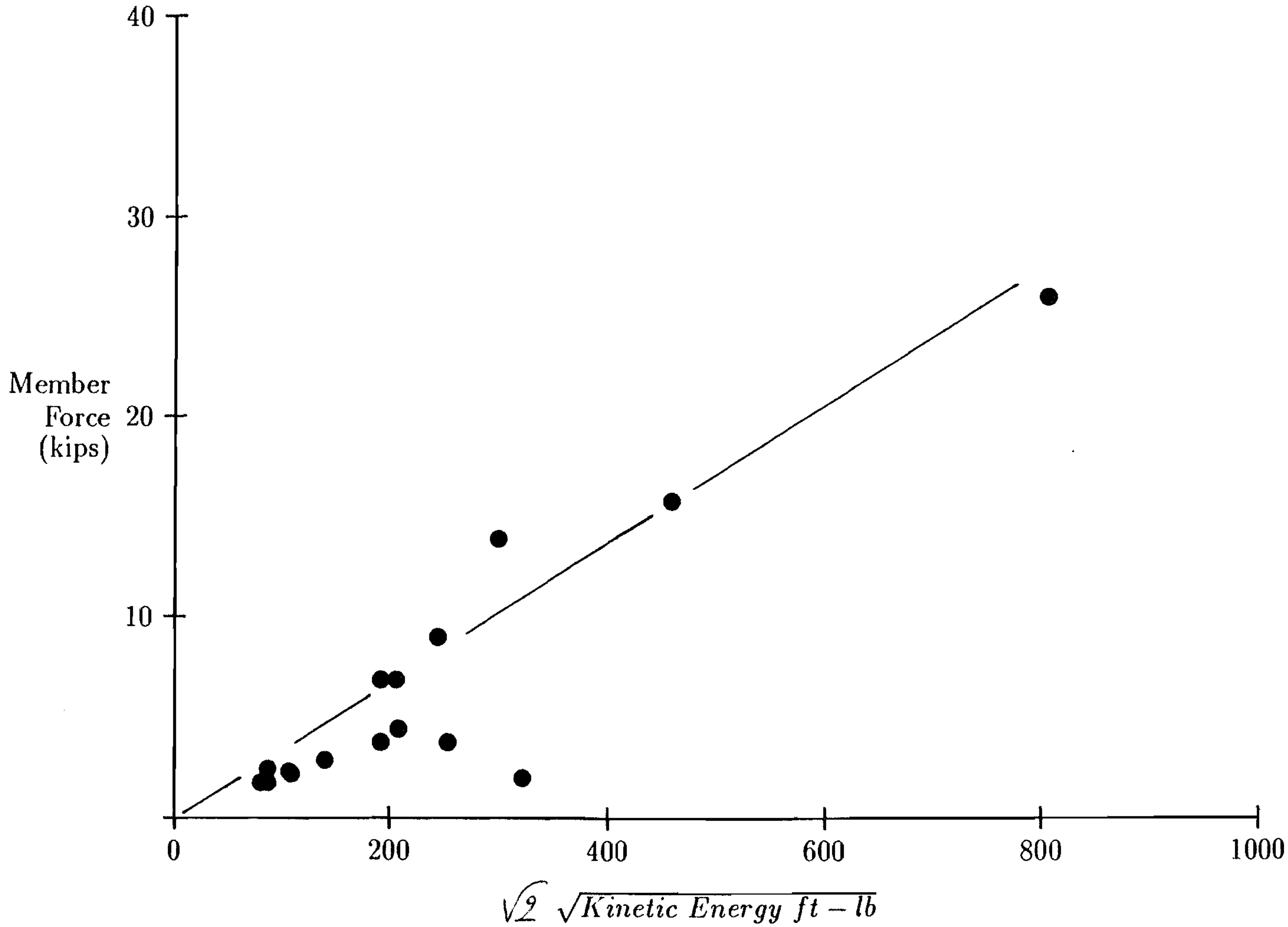

Figure 48

University of Colorado at Boulder

CDOH FLEXPOST FENCE

Analysis Results

Stay

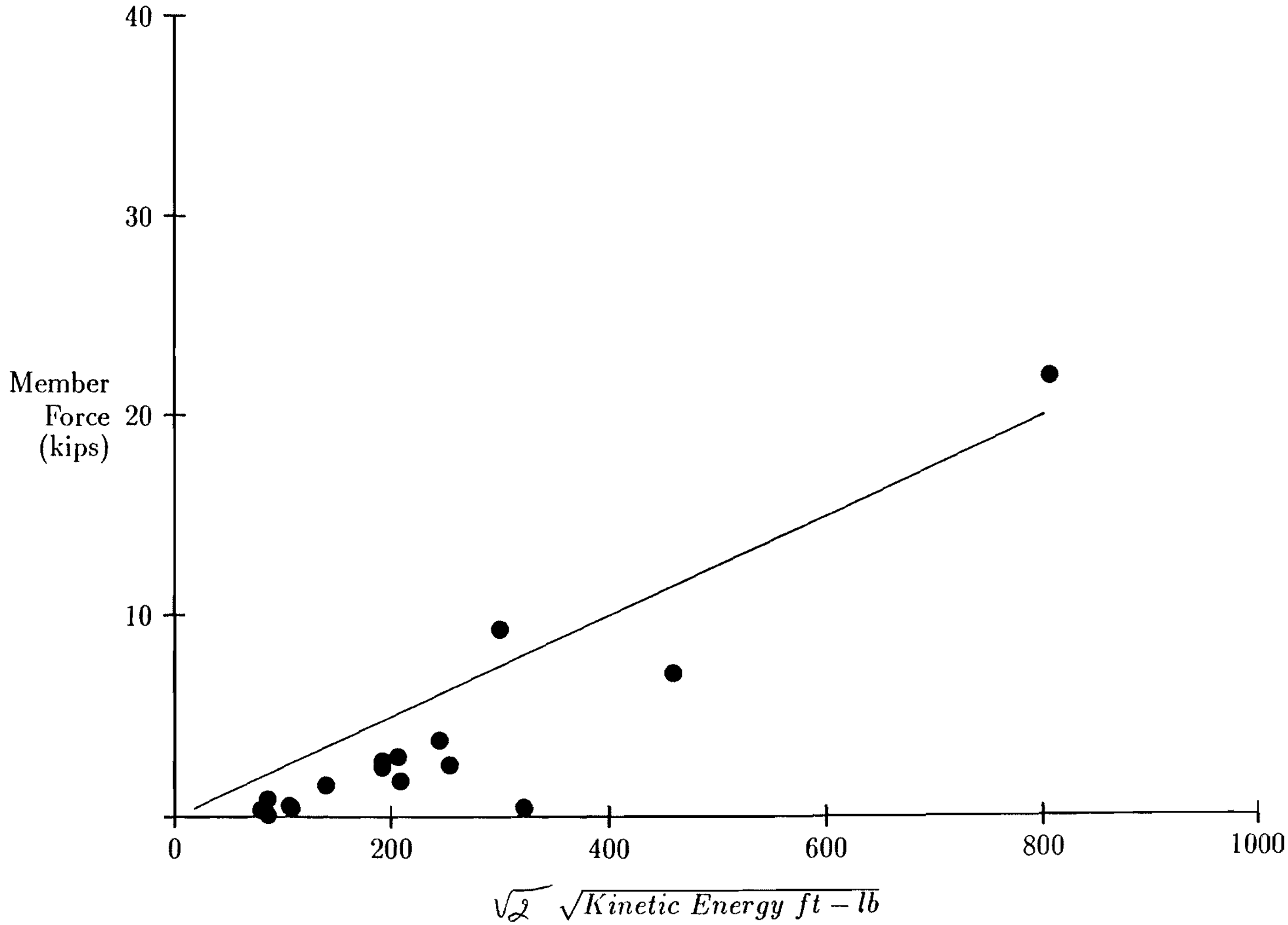

Figure 49

University of Colorado at Boulder

CDOH FLEXPOST FENCE

Analysis Results

Limits for Rock Mass and Velocity

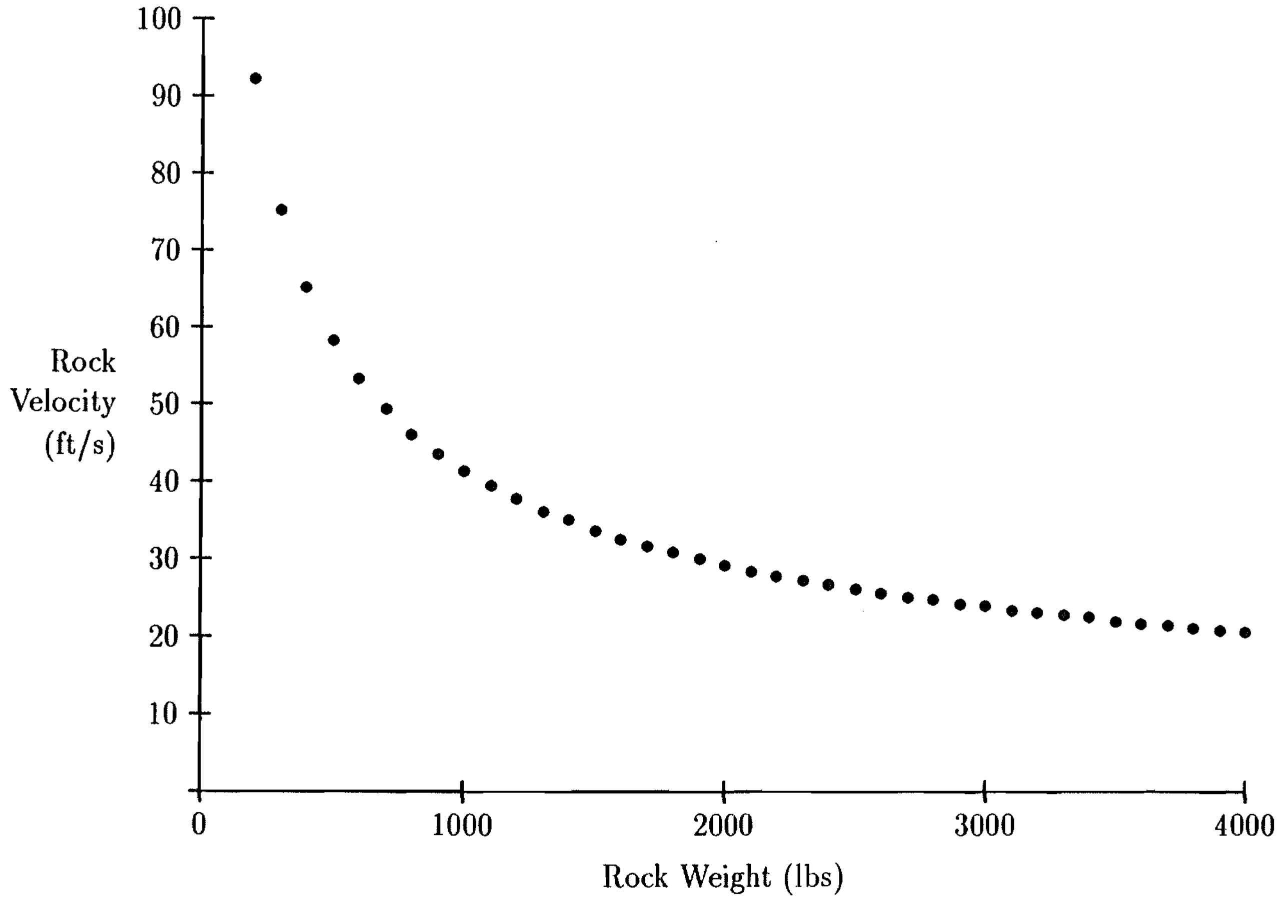

Figure 50

Appendix A

Analysis Solution Sequence

The analysis program attempts, through a series of iterations and progressive estimates of the position and velocity of nodes in the fence model, to obtain an equilibrium solution for the equation of motion

$$[M]A + [K]X = F$$

where

$[M]$	= Mass matrix
$[K]$	= Stiffness matrix
$\{A\}$	= Acceleration vector
$\{X\}$	= Position vector
$\{F\}$	= External force vector

The stiffness of the fence changes significantly during the course of a rockfall impact because of large changes in fence geometry and large changes in tension in mesh and cable members. Forces acting on nodes also change significantly. In combination, these effects demand a stepwise solution. Fence response to impact is assumed to be linear for small displacements, and this in turn requires a small time step for the dynamic solution.

The analysis computation begins with a known equilibrium state a time t_1. That is, all node positions, velocities, and accelerations, all member forces, and all external forces are known. The computation seeks a new equilibrium state at time t_2, which is separated from t_1 by a small time step $\triangle t$.

$$t_2 = t_1 + \triangle t$$

Node positions and velocities for t_1 and t_2 are related as

$$X_2 = X_1 + \frac{1}{2}(V_1 + V_2)\triangle t$$

$$V_2 = V_1 + \frac{1}{2}(A_1 + A_2)\triangle t$$

where
X_1 = node position vector at t_1
X_2 = node position vector at t_2
V_1 = node velocity vector at t_1
V_2 = node velocity vector at t_2
A_1 = node acceleration vector at t_1
A_2 = node acceleration vector at t_2

These relations can be solved for V_2 and A_2.

$$V_2 = \frac{2}{\triangle t}(X_2 - X_1) - V_1$$

$$A_2 = \frac{4}{(\triangle t)^2}(X_2 - X_1) - \frac{4}{\triangle t}V_1 - A_1$$

The computation does not employ global stiffness and mass matrices.

Instead, local stiffness matrices are computed and node positions X_2 are adjusted individually. The local force vector F_2 is the resultant of external forces and any imbalance in member forces at the node. The computation uses a current estimate of X_2 for a node (computed from X_1 and V_1 at the start), and computes the lengths and forces for members connected to the node. The resultant of the member forces is added to external forces at the node to form F_2. Acceleration A_2 is computed from X_1, X_2, V_1, and A_1 as above. With these, an adjustment to the estimated X_2 is computed as

$$\{\triangle X_2\} = [K]^{-1}\{\{F_2\} - [M]\{A_2\}\}$$

For the adjusted X_2, forces F_2 and accelerations A_2 are recomputed and further adjustments to X_2 are made. The process stops when equilibrium in state t_2 is within a specified tolerance. The computation proceeds from node to node throughout the fence making single adjustment to the X_2 position of each node and continuing with the next node. The computation repeats this cycle through the fence until equilibrium is satisfied at all nodes.

Once an equilibrium solution has been reached for state 2, time is advanced, and the newly computed equilibrium state becomes the new state 1, and a next equilibrium state is sought.

$$t_1 \leftarrow t_1 + \triangle t$$

$$X_1 \leftarrow X_2$$

$$V_1 \leftarrow V_2$$

$$A_1 \leftarrow A_2$$

A program listing follows this appendix.

Contact Forces

Rocks are modelled as deformable bodies of linear spring stiffness. The spring stiffness assigned to rocks is not related to actual material stiffness, nor is it suggested that impact with a Flexpost fence will significantly deform rocks. Rather, a linear spring stiffness is a useful construction for introducing a variable external contact force, and produces reasonable deformed shapes for the fence. The spring stiffness of the rock is computed as

$$K_{Rock} = \frac{Max\ Contact\ Force}{Rock\ Radius}$$

The maximum contact force is computed at the start of the analysis as the force required to halt the rock in one time step.

If a node's position X_2 places it within the interior of the rock, the distance D from the node to the center of the rock is computed, the vector of direction cosines R_x from the rock center to the node is established, and a vector of contact forces C is assigned to the node

$$C_i = K_{Rock} \frac{(Radius - D)}{Radius} R_{xi}$$

Local stiffness of the node $[K_o]$ is modified as well so that changing contact forces

$$[K_{Node}] = [K_o] + K_{Rock}[I]\{R_x\}$$

Other approaches to the contact problem have been tried in this study. Early attempts concentrated on methods to exclude fence nodes from the interior of the rock. In such approaches, nodes intruding on rocks are moved to a position on the surface of the rock using geometric criteria. The geometry adjustment used 1) a vector connecting the rock center and the node, or 2) a vector associated with the least resistance to node movement based on local stiffness. Both approaches produced large imbalances of forces in members, and slowed the solution sequence.

```
      PROGRAM FLEXPOST

C*********************************************************************
C    DEFINITION OF VARIABLES
C*********************************************************************
C
C    ACCL(NNODE,3,2)      ACCELERATION VECTOR FOR NODES, GLOBAL
C                         FIRST INDEX IS NODE NUMBER
C                         SECOND INDEX DENOTES XYZ
C                         THIRD INDEX DENOTES TIME STATE
C                         1 - BEGINNING OF TIME STEP, t1
C                         2 - END OF TIME STEP, t2
C
C    AMAG                 MAGNITUDE OF ACCELERATION, TEMPORARY
C
C    ANG                  POST ROTATION IN RADIANS, TEMPORARY
C
C    AREA(MTYPE)          CROSS SECTION AREA OF MEMBERS, BY MEMBER
C                         TYPE
C
C    CONPTS(24)           INTEGER ARRAY OF NODE NUMBERS CURRENTLY IN
C                         CONTACT WITH ROCK
C
C    CONS(NNODE,10)       CONNECTIVITY ARRAY, LIST OF NODES AND
C                         CONNECTED MEMBERS
C
C    D                    TEMPORARY STORAGE VARIABLE
C
C    D1                   TEMPORARY STORAGE VARIABLE
C
C    D2                   TEMPORARY STORAGE VARIABLE
C
C    DEAD                 MAXIMUM POSSIBLE CONTACT FORCE BETWEEN
C                         ROCK AND NODES
C                         COMPUTED AS FORCE REQUIRED TO HALT ROCK IN
C                         ONE TIME STEP (A DEAD STOP)
C
C    DT                   TIME STEP FOR COMPUTATION, 1/100 S
C
C    DUM                  STRING VARIABLE FOR TITLES
C
C    DX(3)                VECTOR OF NODE DISPLACEMENTS, TEMPORARY
C
C    DXMAX                MAXIMUM NODE DISPLACEMENT LIMIT IN ONE
C                         ITERATION
C
C    E                    INTEGER VARIABLE FOR MEMBER END NODE
C
```

```
C     F0                    INITIAL FORCE IN MEMBER, TEMPORARY
C                           FOR LOCAL STIFFNESS COMPUTATION
C
C     F1                    FINAL FORCE IN MEMBER, TEMPORARY
C                           FOR LOCAL STIFFNESS COMPUTATION
C
C     FORC(NNODE,3,2)       FORCE VECTOR FOR NODES, GLOBAL
C                           RESULTANT OF MEMBER FORCES AND CONTACT
C                           FIRST INDEX IS NODE NUMBER
C                           SECOND INDEX DENOTES XYZ
C                           THIRD INDEX DENOTES TIME STATE
C                           1 - BEGINNING OF TIME STEP, t1
C                           2 - END OF TIME STEP, t2
C
C     FORCE                 FORCE IMBALANCE AT NODE, USED TO CHECK
C                           CONVERGENCE OF SOLUTION
C
C     FOUND(PPOST*2,3,4)    VECTOR OF MAXIMUM FORCES ON FOUNDATIONS
C                           FIRST INDEX IS FOUNDATION NUMBER
C                           SECOND INDEX DENOTES XYZ, FOR MAX
C                           THIRD INDEX CONTAINS XYZ FORCES AND
C                           TIME OF OCCURRENCE OF MAX FORCE
C
C     FOUNDT(PPOST*2,3,4)   TEMPORARY STORAGE FOR MAXIMUM FORCES ON
C                           FOUNDATIONS
C                           ARRAY VARIABLES DEFINED FOR FOUND(,,)
C
C     FR                    FORCE IN MEMBER, TEMPORARY
C
C     GDX(3)                UNIT DISPLACEMENT VECTOR FOR LOCAL
C                           STIFFNESS COMPUTATION
C
C     GEOM(NNODE,3,2)       POSITION VECTOR FOR NODES, GLOBAL
C                           FIRST INDEX IS NODE NUMBER
C                           SECOND INDEX DENOTES XYZ
C                           THIRD INDEX DENOTES TIME STATE
C                           0 - BEFORE IMPACT
C                           1 - BEGINNING OF TIME STEP, t1
C                           2 - END OF TIME STEP, t2
C
C     LENGTH                MEMBER LENGTH, TEMPORARY
C
C     MASS(NNODE)           ARRAY OF NODE MASSES
C
C     MB                    INTEGER VARIABLE FOR MEMBER NUMBER
C
C     MEM0(MMEM)            ARRAY OF INITIAL LENGTHS OF MEMBERS
C
```

```
C     MEM(MMEM)                ARRAY OF CURRENT LENGTHS OF MEMBERS
C                              UNDER LOAD
C
C     MEMB(MMEM,4)             MEMBER INCIDENCES ARRAY
C                              FIRST INDEX IS MEMBER NUMBER
C                              FOR SECOND INDEX
C                              = 1 MEMBER START NODE
C                              = 2 MEMBER END NODE
C                              = 3 MEMBER TYPE
C                              = 4 MEMBER INITIAL LENGTH (SLACK MEMBERS)
C
C     MEMF(MMEM,2)             ARRAY OF MAXIMUM MEMBER FORCES
C                              FIRST INDEX IS MEMBER NUMBER
C                              FOR SECOND INDEX
C                              = 1 TIME OF MAX FORCE
C                              = 2 MAX FORCE
C
C     MEMFT(MMEM)              TEMPORARY STORAGE FOR MAXIMUM MEMBER
C                              FORCES
C
C     MLEN(MMEM)               ARRAY OF MAXIMUM MEMBER LENGTHS
C
C     NLIST(NNODE)             ORDERED LIST OF NODE NUMBERS FOR
C                              COMPUTATION.  ITERATION PROCEEDS FIRST IN
C                              FENCE FABRIC, NEXT IN POSTS, AND LAST IN
C                              FOUNDATIONS.
C
C     NTYPE(NNODES)            ARRAY FOR NODE TYPES
C                              VALUES FOR NTYPE:
C                              1 - COMMON NODE
C                              2 - END MESH, LEFT SIDE
C                              3 - END MESH, RIGHT SIDE
C                              4 - TOP OF POST
C                              5 - BOTTOM OF POST
C
C     PRESTR(MTYPE)            PRESTRESS FORCE IN MEMBER, BY MEMBER TYPE
C
C     PRO(PPOST*2,2)           ARRAY FOR MAXIMUM POST ROTATIONS
C                              FIRST INDEX IS POST NUMBER
C                              FOR SECOND INDEX
C                              = 1 TIME OF MAX ROTATION
C                              = 2 MAX ROTATION
C
C     PROT(PPOST*2)            TEMPORARY STORAGE FOR MAXIMUM POST
C                              ROTATIONS
C
C     RADIUS                   RADIUS OF ROCK
C
```

```
C     RNODE                    INTEGER INDEX FOR ROCK IN ARRAYS ACCL,
C                              FORC, GEOM, AND VEL
C
C     S                        INTEGER VARIABLE FOR MEMBER START NODE
C
C     STIFF(3)                 LOCAL STIFFNESS MATRIX FOR NODES
C
C     T                        INTEGER VARIABLE FOR MEMBER TYPE
C
C     VEC(NNODE)               NODE/ROCK CONTACT ARRAY
C                              = 0 FOR NO CONTACT
C                              > 0 FOR CONTACT OF NODE WITH ROCK
C                              VALUE OF VEC() EXPRESSES FRACTIONAL
C                              INTRUSION OF CURRENT NODE POSITION ON ROCK
C                              RADIUS
C
C     VEL(NMAX,3,2)            VELOCITY OF NODES, GLOBAL
C                              SECOND VARIABLE DENOTES XYZ
C                              THIRD VARIABLE DENOTES TIME STATE
C                              1 - BEGINNING OF TIME STEP
C                              2 - END OF TIME STEP
C
C     VF                       TEMPORARY STORAGE FOR CONTACT FORCE COMPUTATION
C
C     VMAG                     MAGNITUDE OF VELOCITY
C
C     YA                       YOUNG'S MODULUS
C
C***********************************************************************

      DOUBLE PRECISION GEOM(320,3,2),FORC(320,3),VEL(320,3,2)
      DOUBLE PRECISION ACCL(320,3,2),RESID(320,3)
      DOUBLE PRECISION GDX(3),VEC(320)
      DOUBLE PRECISION MASS(320),MEM0(540),LENGTH
      DOUBLE PRECISION PRESTR(20),AREA(20),R(3),MEM(540)
      DOUBLE PRECISION RADIUS,DT,DETER,VMAG,AMAG,DEAD,D
      DOUBLE PRECISION ANG,FR,YA,F0,F1,FORCE
      DOUBLE PRECISION VF,DIR,RJ,FRAC,D1,D2
      DOUBLE PRECISION STIFF(3)
      DOUBLE PRECISION DX(3),DXMAX,DXX
      DOUBLE PRECISION MLEN(540),MEMF(540,2),MEMFT(540),PRO(20,2)
      DOUBLE PRECISION PROT(20),FOUND(20,3,4),FOUNDT(20,30,4)

      INTEGER MEMB(540,4),S,E,T,MB,RNODE,CONPTS(24)
      INTEGER CONS(320,10)

      CHARACTER*40 DUM
```

```
C***********************************************************************
C
C    SET CONSTANTS FOR COMPUTATION
C         YOUNGS MODULUS YA = 20,000,000 psi
C         TIME STEP         DT = 0.01 s
C         START TIME        TM = 0 s
C         CONVERGENCE       FCONV = 100 lbs
C
C***********************************************************************

      YA=20000000
      DT=0.01
      FCONV=100

C***********************************************************************
C
C         OPEN FILES FOR INPUT / OUTPUT
C              MODEL.PRN -    FENCE GEOMETRY, CONNECTIVITY, AND
C                             MEMBER PROPERTIES
C              ROCK.DAT -     ROCK SPEED, MASS, AND IMPACT LOCATION
C              RFORCE.PRN -   OUTPUT FILE OF CONTACT FORCES, ROCK
C                             POSITION, AND ROCK VELOCITY AS A
C                             FUNCTION OF TIME
C              FMEMS.PRN -    OUTPUT FILE OF MAXIMUM MEMBER
C                             FORCES, FOUNDATION FORCES, AND POST
C                             ROTATIONS
C              FOUTS.PRN -    OUTPUT FILE OF FENCE DEFLECTED SHAPE
C
C***********************************************************************

      OPEN(UNIT=10,FILE='MODEL.PRN',STATUS='OLD')
      OPEN(UNIT=11,FILE='FOUTS.PRN',STATUS='NEW')
      OPEN(UNIT=12,FILE='RFORCE.PRN',STATUS='NEW')
      OPEN(UNIT=14,FILE='FMEMS.PRN',STATUS='NEW')
      OPEN(UNIT=15,FILE='ROCK.DAT',STATUS='OLD')

C***********************************************************************
C
C    READ TITLE OF FENCE MODEL
C
C***********************************************************************

      READ(10,10000)DUM
10000 FORMAT(A8)
```

```
C***********************************************************************
C
C    READ NODE NUMBER, INITIAL POSITION, MASS AND TYPE
C         ND = -1 INDICATES END OF NODE DATA
C
C***********************************************************************

      DO 100 I=1,1000
      READ(10,*)ND,X,Y,Z,A,T
      IF (ND.LT.(0)) THEN
      GOTO 110
      ENDIF
      GEOM(ND,1,0)=X
      GEOM(ND,2,0)=Y
      GEOM(ND,3,0)=Z
      GEOM(ND,1,1)=X
      GEOM(ND,2,1)=Y
      GEOM(ND,3,1)=Z
      GEOM(ND,1,2)=X
      GEOM(ND,2,2)=Y
      GEOM(ND,3,2)=Z
      IF (ND.GT.NUMNODE) THEN
      NUMNODE=ND
      ENDIF
      MASS(I)=A
      NTYPE(I)=T
  100 CONTINUE

C***********************************************************************
C
C    READ NODE NUMBERS FOR POSTS AND FOUNDATIONS AT ENDS OF FENCE
C    USED FOR CONSTRAINT CONDITIONS
C
C***********************************************************************

  110 READ(10,*)TL,BL,TR,BR

C***********************************************************************
C
C    READ MEMBER NUMBER, TYPE, START NODE, END NODE, AND INITIAL
C         LENGTH (IF SLACK)
C
C***********************************************************************

      DO 120 I=1,1000
      READ(10,*)MB,T,S,E,LENGTH

      IF (MB.LT.0) THEN
```

```
      GOTO 130
      ENDIF

      MEMB(MB,1)=MB
      MEMB(MB,2)=T
      MEMB(MB,3)=S
      MEMB(MB,4)=E

      IF (MB.GT.NUMMEMB) THEN
      NUMMEMB=MB
      ENDIF

      IF (LENGTH.GT.0.) THEN
      MEM0(MB)=LENGTH
      MEM(MB)=LENGTH
      GOTO 120
      ENDIF

C***********************************************************************
C
C    COMPUTE MEMBER LENGTH
C
C***********************************************************************

      MEM0(MB)=0
      MEM0(MB)=(GEOM(S,1,1)-GEOM(E,1,1))**2
      MEM0(MB)=MEM0(MB)+(GEOM(S,2,1)-GEOM(E,2,1))**2
      MEM0(MB)=MEM0(MB)+(GEOM(S,3,1)-GEOM(E,3,1))**2
      MEM0(MB)=(MEM0(MB))**(0.5)
      MEM(MB)=MEM0(MB)

  120 CONTINUE

C***********************************************************************
C
C    READ MEMBER PROPERTIES
C         TYPE, AREA, PRESTRESS FORCE
C
C***********************************************************************

  130 DO 140 I=1,100
      READ(10,*)T,A,P
      IF(T.LE.0) THEN
      GOTO 150
      ENDIF
      AREA(T)=A
  140 PRESTR(T)=P
```

```
  150 CLOSE(10)

C***********************************************************************
C
C    ESTABLISH CONNECTIVITY ARRAYS FOR NODES
C         CONS(NODE, MEMBER)
C
C***********************************************************************

      DO 160 I=1,NUMMEMB
      S=MEMB(I,3)
      DO 170 J=1,10
      IF (CONS(S,J).EQ.0) THEN
      CONS(S,J)=I
      GOTO 180
      ENDIF
  170 CONTINUE

  180 E=MEMB(I,4)
      DO 190 J=1,10
      IF (CONS(E,J).EQ.0) THEN
      CONS(E,J)=I
      GOTO 160
      ENDIF
  190 CONTINUE
  160 CONTINUE

10010 FORMAT(A38)

C***********************************************************************
C
C    ESTABLISH ITERATION LIST FOR NODES ORDERED BY TYPE
C         1 - COMMON NODE
C         2 - END MESH, LEFT SIDE
C         3 - END MESH, RIGHT SIDE
C         4 - TOP OF POST
C         5 - BOTTOM OF POST
C
C***********************************************************************

      ITY=1
      DO 200 J=1,5
      DO 200 I=1,NUMNODE
      IF (NTYPE(I).EQ.J) THEN
      NLIST(ITY)=I
      ITY=ITY+1
      ENDIF
  200 CONTINUE
```

```
C***********************************************************************
C
C    FOR ROCK, POSITION, VELOCITY, ACCELERATION, AND FORCE DATA ARE
C    STORED AT END OF NODE ARRAYS
C
C***********************************************************************

     RNODE=NUMNODE+1

C***********************************************************************
C
C    READ ANALYSIS TITLE
C    READ ROCK MASS, ROCK INITIAL POSITION, ROCK INITIAL VELOCITY
C
C***********************************************************************

      READ(15,10010)DUM
      READ(15,*)MASS(RNODE),RADIUS
      READ(15,*)X,Y,Z
      GEOM(RNODE,1,1)=X
      GEOM(RNODE,2,1)=Y
      GEOM(RNODE,3,1)=Z
      READ(15,*)X,Y,Z
      VEL(RNODE,1,1)=X
      VEL(RNODE,2,1)=Y
      VEL(RNODE,3,1)=Z

      CLOSE(15)

C***********************************************************************
C
C    WRITE ANALYSIS TITLE AND INITIAL ROCK POSITION TO OUTPUT FILES
C
C***********************************************************************

      WRITE(11,*)DUM
      WRITE(11,*)(GEOM(RNODE,J,1),J=1,3)
      WRITE(12,*)DUM
      WRITE(14,*)DUM

C***********************************************************************
C
C    COMPUTE FORCE REQUIRED TO HALT ROCK IN FIRST TIME STEP.  THIS
C    IS THE UPPER BOUND ON CONTACT FORCE FOR THE COMPUTATION.
C
C***********************************************************************

      VMAG=0
```

```
      AMAG=0
      DO 210 J=1,3
      VMAG=VEL(RNODE,J,1)**2+VMAG
  210 AMAG=ACCL(RNODE,J,1)**2+AMAG

      VMAG=(VMAG)**(.5)
      AMAG=(AMAG)**(.5)
      DEAD=MASS(RNODE)*(2*VMAG/DT+AMAG)

C************************************************************************
C
C     OUTER (ROCK) ITERATION LOOP
C          NITS - AN ITERATION COUNTER USED FOR DIAGNOSTICS
C
C************************************************************************

  220 NITS=NITS+1

C************************************************************************
C
C     COMPUTE ROCK POSITION AT END OF TIME STEP
C
C************************************************************************

      DO 230 J=1,3
      GEOM(RNODE,J,2)=GEOM(RNODE,J,1)+(VEL(RNODE,J,1)+
     +VEL(RNODE,J,2))*DT/2
  230 FORC(RNODE,J)=0

C************************************************************************
C
C     INNER (FENCE) ITERATION LOOP
C          ITS - AN ITERATION COUNTER FOR DIAGNOSTICS
C
C************************************************************************

  240 ITS=ITS+1

C************************************************************************
C
C     SET ALL NODE FORCES TO ZERO
C
C************************************************************************

      DO 250 I=1,NUMNODE
      DO 250 J=1,3
  250 FORC(I,J)=0.
```

```
      DO 260 II=I,NUMNODE
      I=NLIST(II)

      IF (NTYPE(I).EQ.5) THEN
      GOTO 260
      ENDIF

C************************************************************************
C
C    CHECK ON CONTACT FOR INDIVIDUAL NODE
C
C    VEC(I) EXPRESSES INTERFERENCE OF ROCK AND NODE AS A FRACTION
C    OF THE ROCK RADIUS
C
C************************************************************************

      VEC(I)=0

      DO 270 J=1,3
      D=ABS(GEOM(I,J,2)-GEOM(RNODE,J,2))
      IF (D.LT.RADIUS) THEN
      GOTO 280
      ENDIF
  270 CONTINUE
      GOTO 290

  280 D=0
      DO 300 J=1,3
  300 D=D+(GEOM(I,J,2)-GEOM(RNODE,J,2))**2
      D=(D)**(.5)
      IF (D.LT.RADIUS) THEN
      VEC(I)=(RADIUS-D)/RADIUS
      ENDIF

C************************************************************************
C
C COMPUTE LOCAL STIFFNESS FOR NODE
C         i    SET LOCAL STIFFNESS TO ZERO
C         ii   IMPOSE UNIT DISPLACEMENTS IN X,Y,Z
C         iii  COMPUTE RESULTING MEMBER FORCES
C         iv   COMPUTE SPRING CONSTANTS
C
C************************************************************************

  290 DO 310 J=1,3
  310 STIFF(J)=0.

      DO 320 J=1,3
```

```
      GDX(1)=GEOM(I,1,2)
      GDX(2)=GEOM(I,2,2)
      GDX(3)=GEOM(I,3,2)
      GDX(J)=GDX(J)+0.1

      DO 320 K=1,10

      M=CONS(I,K)
      E=MEMB(M,3)
      T=MEMB(M,2)
      IF (E.EQ.I) THEN
      E=MEMB(M,4)
      ENDIF

      IF (M.EQ.0) THEN
      GOTO 320
      ENDIF

      LENGTH=0

      F0=AREA(T)*YA*(MEM(M)-MEM0(M))/MEM0(M)+PRESTR(T)


      DO 330 L=1,3
  330 LENGTH=LENGTH+(GDX(L)-GEOM(E,L,2))**2
      LENGTH=SQRT(LENGTH)

      F1=AREA(T)*YA*(LENGTH-MEM0(M))/MEM0(M)+PRESTR(T)

      STIFF(J)=STIFF(J)+ABS((F1-F0)/.1*(GEOM(E,J,2)-
     +GDX(J))/MEM0(M))
  320 CONTINUE

C**********************************************************************
C
C     FOR NODES IN CONTACT WITH ROCK, ADD SPRING STIFFNESS OF
C     CONTACT FORCE
C
C**********************************************************************

      IF (VEC(I).NE.0) THEN
      D=ABS(RADIUS*(1-VEC(I)))

      DO 340 J=1,3
      DXX=(GEOM(RNODE,J,2)-GEOM(I,J,2))/D
  340 STIFF(I,J)=STIFF(I,J)+ABS(DEAD/RADIUS*DXX)
      ENDIF
```

```
C***********************************************************************
C
C    ADD INERTIAL TERMS
C
C***********************************************************************

      STIFF(1)=STIFF(1)+MASS(I)*4/DT/DT
      STIFF(2)=STIFF(2)+MASS(I)*4/DT/DT
      STIFF(3)=STIFF(3)+MASS(I)*4/DT/DT

C***********************************************************************
C
C    COMPUTE FORCES ACTING ON NODE
C
C***********************************************************************

      DO 350 K=1,10

      M=CONS(I,K)
      E=MEMB(M,3)
      T=MEMB(M,2)

      IF (I.EQ.E) THEN
      E=MEMB(M,4)
      ENDIF

      IF (M.EQ.0) THEN
      GOTO 360
      ENDIF

C***********************************************************************
C
C    COMPUTE POST ROTATION
C
C***********************************************************************

      IF ((T.EQ.1).OR.(T.EQ.2)) THEN
      E=I-1
      D=(GEOM(I,1,2)-GEOM(E,1,1))**2+GEOM(I,2,2)**2
      D=SQRT(D)
      ANG=ASIN(D/10)
      FR=0

C***********************************************************************
C
C    FORCE FROM STRANDS IN POST
C
C***********************************************************************
```

```
      IF (ANG.GT.0) THEN
      FR=(2300+1600*ANG)/10
      FORC(I,1)=FORC(I,1)+FR*(GEOM(E,1,1)-GEOM(I,1,2))/10
      FORC(I,2)=FORC(I,2)-FR*(GEOM(I,2,2))/10
      FORC(I,3)=FORC(I,3)+FR*(10-GEOM(I,3,2))/10
      ENDIF

C***********************************************************************
C
C    ELASTIC STRETCH IN POST
C
C***********************************************************************

      FR=AREA(T)*YA*(MEM(M)-MEM0(M))/MEM0(M)+PRESTR(T)

      GOTO 370
      ENDIF

C***********************************************************************
C
C    ELASTIC STRETCH IN MEMBERS
C
C***********************************************************************

      FR=AREA(T)*YA*(MEM(M)-MEM0(M))/MEM0(M)+PRESTR(T)

C***********************************************************************
C
C    MESH AND CABLES TAKE NO COMPRESSION
C
C***********************************************************************

      IF (FR.LT.0.) THEN
      FR=0.
      ENDIF

  370 DO 380 J=1,3
      FORCE=FR*(GEOM(E,J,2)-GEOM(I,J,2))/MEM(M)
  380 FORC(I,J)=FORC(I,J)+FORCE

  350 CONTINUE

C***********************************************************************
C
C    ADD CONTACT FORCES
C
C***********************************************************************
```

```
  360 IF (VEC(I).NE.0.) THEN

      DO 390 J=1,3

      IF ((GEOM(I,J,2)-GEOM(RNODE,J,2)).EQ.0.) THEN
      GOTO 390
      ENDIF

      VF=(GEOM(I,J,2)-GEOM(RNODE,J,2))/RADIUS*DEAD*VEC(I)
      FORC(I,J)=FORC(I,J)+VF

  390 CONTINUE

      ENDIF

      IF (NTYPE(I).EQ.2) THEN
      RJ=GEOM(I,3,0)
      DO 400 J=1,3
      FORC(BL,J)=FORC(BL,J)+FORC(I,J)*(10-RJ)/10
  400 FORC(TL,J)=FORC(TL,J)+FORC(I,J)*RJ/10
      ENDIF

      IF (NTYPE(I).EQ.3) THEN
      RJ=GEOM(I,3,0)
      DO 410 J=1,3
      FORC(BR,J)=FORC(BR,J)+FORC(I,J)*(10-RJ)/10
  410 FORC(TR,J)=FORC(TR,J)+FORC(I,J)*RJ/10
      ENDIF

C************************************************************************
C
C    COMPUTE CURRENT VALUE OF ACCELERATION FROM GEOMETRY DATA
C    COMPUTE NET FORCE ON NODE (AFTER ACCELERATION)
C
C************************************************************************

      DO 420 J=1,3
      ACCL(I,J,2)=(GEOM(I,J,2)-GEOM(I,J,1))*4/DT/DT-
     +4*VEL(I,J,1)/DT-ACCL(I,J,1)
  420 FORC(I,J)=FORC(I,J)-MASS(I)*ACCL(I,J,2)

C************************************************************************
C
C    ADJUST NODE POSITION FOR END OF TIME STEP
C
C************************************************************************

      DXMAX=0
```

```
      DO 430 J=1,3
      DX(J)=FORC(I,J)/(STIFF(J))
      IF (ABS(DX(J)).GT.DXMAX) THEN
      DXMAX=ABS(DX(J))
      ENDIF
  430 CONTINUE

C***********************************************************************
C
C    LIMIT LARGEST NODE DISPLACEMENT TO 0.1 FT
C    SCALE OTHER DISPLACEMENTS
C
C***********************************************************************

      IF (DXMAX.GT.0.1) THEN
      DXMAX=DXMAX/0.1
      ENDIF

      IF (DXMAX.EQ.0) THEN
      DXMAX=1
      ENDIF

      DO 440 J=1,3
      DX(J)=DX(J)*ABS(DX(J)/DXMAX)
      GEOM(I,J,2)=GEOM(I,J,2)+DX(J)/2
  440 ACCL(I,J,2)=ACCL(I,J,2)+DX(J)*2/DT/DT

C***********************************************************************
C
C    CONSTRAIN DISPLACEMENTS FOR FABRIC NODES ON END POSTS
C
C***********************************************************************

      IF (NTYPE(I).EQ.2) THEN
      RJ=GEOM(I,3,0)
      DO 450 J=1,3
      D1=GEOM(TL,J,2)-GEOM(BL,J,1)
  450 GEOM(I,J,2)=GEOM(BL,J,1)+D1*RJ/10
      ENDIF

      IF (NTYPE.EQ.3) THEN
      RJ=GEOM(I,3,0)
      DO 460 J=1,3
      D2=GEOM(TR,J,2)-GEOM(BR,J,1)
  460 GEOM(I,J,2)=GEOM(BR,J,1)+D2*RJ/10
      ENDIF
```

```
C***********************************************************************
C
C     COMPUTE NEW LENGTHS FOR MEMBERS ATTACHED TO NODE
C
C***********************************************************************

      DO 470 K=1,10

      M=CONS(I,K)
      E=MEMB(M,3)
      T=MEMB(M,2)

      IF (I.EQ.E) THEN
      E=MEMB(M,4)
      ENDIF

      IF (M.EQ.0) THEN
      GOTO 260
      ENDIF

      LENGTH=0
      DO 490 J=1,3
  490 LENGTH=LENGTH+(GEOM(I,J,2)-GEOM(E,J,2))**2

      MEM(M)=SQRT(LENGTH)

  470 CONTINUE

  260 CONTINUE

C***********************************************************************
C
C     CHECK ON EQUILIBRIUM FOR FENCE
C     SET NODE FORCES TO ZERO
C
C***********************************************************************

      DO 500 I=1,NUMNODE+1
      FORC(I,1)=0
      FORC(I,2)=0
  500 FORC(I,3)=0

C***********************************************************************
C
C     COMPUTE FORCES IN MEMBERS, AND APPLY FORCES TO NODES
C
C***********************************************************************
```

```
      DO 510 I=1,NUMMEMB

      S=MEMB(I,3)
      E=MEMB(I,4)
      T=MEMB(I,2)

C***********************************************************************
C
C    FOR POSTS, COMPUTE SPRING FORCE
C
C***********************************************************************

      IF ((T.EQ.1).OR.(T.EQ.2)) THEN
      D=(GEOM(S,1,1)-GEOM(E,1,2))**2+GEOM(E,2,2)**2
      D=SQRT(D)
      ANG=ASIN(D/10)
      FR=0

C***********************************************************************
C
C    STORE POST ROTATION FOR LATER COMPARISON AGAINST MAXIMUM
C    ROTATION
C
C***********************************************************************

      PROT(E)=ANG

      IF (ANG.GT.0) THEN
      FR=(2300+1600*ANG)/10
      FORC(E,1)=FORC(E,1)-FR*(GEOM(E,1,2)-GEOM(S,1,1))/10
      FORC(E,2)=FORC(E,2)-FR*(GEOM(E,2,2))/10
      FORC(E,3)=FORC(E,3)+FR*(10-GEOM(E,3,2))/10
      ENDIF

      FR=AREA(T)*YA*(MEM(I)-MEM0(I))/MEM0(I)+PRESTR(T)

      GOTO 520
      ENDIF

      FR=AREA(T)*YA*(MEM(I)-MEM0(I))/MEM0(I)+PRESTR(T)

C***********************************************************************
C
C    MESH AND CABLES TAKE NO COMPRESSION
C
C***********************************************************************

      IF (FR.LT.0.) THEN
```

```
      FR=0.
      ENDIF

  520 DO 530 J=1,3
      FORC(S,J)=FORC(S,J)+FR*(GEOM(E,J,2)-GEOM(S,J,2))/MEM(I)
  530 FORC(E,J)=FORC(E,J)+FR*(GEOM(S,J,2)-GEOM(E,J,2))/MEM(I)

C***********************************************************************
C
C     STORE MEMBER FORCE FOR LATER COMPARISON AGAINST MAXIMUM MEMBER
C     FORCE
C
C***********************************************************************

      MEMFT(I)=FR

  510 CONTINUE

C***********************************************************************
C
C     ADD CONTACT FORCES
C
C***********************************************************************

      DO 540 II=1,NUMNODE

      I=NLIST(II)

      IF (NTYPE(I).EQ.5) THEN
      DO 580 J=1,3
      DO 590 JJ=1,3
  590 FOUNDT(I,J,JJ)=FORC(I,JJ)
  580 FOUNDT(I,J,4)=TM
      GOTO 540
      ENDIF

      IF (VEC(I).NE.0.) THEN

      DO 550 J=1,3
      D=RADIUS(1-VEC(I))
      IF ((GEOM(I,J,2)-GEOM(RNODE,J,2)).EQ.0.) THEN
      GOTO 550
      ENDIF

      VF=(GEOM(I,J,2)-GEOM(RNODE,J,2))/D/RADIUS*DEAD
     +*VEC(I)
      FORC(RNODE,J)=FORC(RNODE,J)-VF
      FORC(I,J)=FORC(I,J)+VF
```

```
  550 CONTINUE

      ENDIF

      IF (NTYPE(I).EQ.2) THEN
      RJ=GEOM(I,3,0)
      DO 560 J=1,3
      FORC(BL,J)=FORC(BL,J)+FORC(I,J)*(10-RJ)/RJ
  560 FORC(TL,J)=FORC(TL,J)+FORC(I,J)*RJ/10
      ENDIF

      IF (NTYPE(I).EQ.3) THEN
      RJ=GEOM(I,3,0)
      DO 570 J=1,3
      FORC(BR,J)=FORC(BR,J)+FORC(I,J)*(10-RJ)/RJ
  570 FORC(TR,J)=FORC(TR,J)+FORC(I,J)*RJ/10
      ENDIF

  540 CONTINUE

C************************************************************************
C
C     SET ITFLAG FOR CONVERGENCE CHECK IN FENCE
C          ITFLAG = 0 CONVERGENCE IS SATISFIED
C          ITFLAG = 1 CONVERGENCE NOT SATISFIED
C
C************************************************************************

      ITFLAG=0

      DO 600 II=1,NUMNODE

      IF (NTYPE(II).EQ.5) THEN 600

      DO 610 J=1,3
      FORCE=(FORC(I,J)-MASS(I)*ACCL(I,J,2))
      IF (ABS(FORCE).GT.FCONV) THEN
      ITFLAG=1
      ENDIF
  610 CONTINUE

  600 CONTINUE

C************************************************************************
C
C     IF CONVERGENCE NOT SATISFIED, RETURN TO FENCE ITERATION
C
C************************************************************************
```

```
      IF (ITFLAG.NE.0) THEN
      GOTO 240
      ENDIF

C*********************************************************************
C
C    FENCE CONVERGENCE SATISFIED, SET FENCE ITERATION COUNTER TO
C    ZERO
C
C*********************************************************************

      ITS=0

C*********************************************************************
C
C    FOR FENCE IN EQUILIBRIUM, USE CONTACT FORCES TO ADJUST
C    ROCK VELOCITY, ACCELERATION AND POSITION
C
C*********************************************************************

      DO 620 J=1,3
      ACCL(RNODE,J,2)=4*(GEOM(RNODE,J,2)-GEOM(RNODE,J,1))
     +/DT/DT-4*VEL(RNODE,J,1)/DT-ACCL(RNODE,J,1)
      FORCE=FORC(RNODE,J)-ACCL(RNODE,J,2)*MASS(RNODE)
      IF (ABS(FORCE).GT.FCONV) THEN
      ITFLAG=1
      ENDIF
  620 CONTINUE

C*********************************************************************
C
C    IF CONVERGENCE NOT SATISFIED AT ROCK, UPDATE ROCK POSITION,
C    VELOCITY AND ACCELERATION, AND RETURN TO ITERATION
C
C*********************************************************************

      IF (ITFLAG.NE.0) THEN
      DO 630 J=1,3
      ACCL(RNODE,J,2)=FORC(RNODE,J)/MASS(RNODE)
      VEL(RNODE,J,2)=VEL(RNODE,J,1)+(ACCL(RNODE,J,1)+
     +ACCL(RNODE,J,2))*DT/2
  630 CONTINUE
      GOTO 220
      ENDIF
```

```
C*********************************************************************
C
C    CONVERGENCE SATISFIED AT ROCK AND FENCE, MOVE END OF TIME STEP
C    VALUES TO BEGINNING OF TIME STEP, ADVANCE TIME, OUTPUT VALUES
C
C*********************************************************************

      DO 640 I=1,NUMNODE+1
      DO 640 J=1,3
      FORC(I,J)=0
      VEL(I,J,1)=VEL(I,J,1)+DT/2*(ACCL(I,J,1)+ACCL(I,J,2))
      GEOM(I,J,1)=GEOM(I,J,2)
  640 ACCL(I,J,1)=ACCL(I,J,2)

C*********************************************************************
C
C    OUTPUT CONTACT FORCES, ROCK POSITION AND ROCK VELOCITY
C
C*********************************************************************

      WRITE(12,*)TM
      WRITE(12,*)(FORC(RNODE,J),J=1,3)
      WRITE(12,*)(GEOM(RNODE,J,2),J=1,3)
      WRITE(12,*)(VEL(RNODE,J,2),J=1,3)

C*********************************************************************
C
C    OUTPUT MAXIMUM MEMBER FORCES, MAXIMUM POST ROTATIONS AND
C    MAXIMUM FOUNDATION FORCES
C
C*********************************************************************

      REWIND(14)
      WRITE(14,*)DUM

      DO 650 I=1,NUMMEMB
      IF (ABS(MEMFT(I)).GT.ABS(MEMF(I,2))) THEN
      MEMF(I,2)=MEMFT(I)
      MEMF(I,1)=TM
      MLEN(I)=MEM(I)
      ENDIF
      WRITE(14,10020)I,MEMF(I,1),MEMF(I,2),MLEN(I)/MEM0(I)
  650 CONTINUE
10020 FORMAT(I5,4(F15.4))

      WRITE(14,*)-1

      DO 660 I=1,NUMNODE
```

```
      IF (NTYPE(I).EQ.4) THEN
      IF (ABS(PROT(I)).GT.ABS(PRO(I,2))) THEN
      PRO(I,2)=PROT(I)
      PRO(I,1)=TM
      ENDIF
      WRITE(14,10020)I,PRO(I,1),PRO(I,2)
      ENDIF

      IF (NTYPE(I).EQ.5) THEN
      DO 670 J=1,3
      IF (ABS(FOUNDT(I,J,J)).GT.ABS(FOUND(I,J,J))) THEN
      DO 680 K=1,4
  680 FOUND(I,J,K)=FOUNDT(I,J,K)
      ENDIF
      ENDIF
      WRITE(14,10020)I,(FOUND(I,J,K),K=1,4)
  670 CONTINUE
      ENDIF

  660 CONTINUE
C************************************************************************
C
C     CHECK FOR END OF ANALYSIS RUN
C     VFLAG IS SET TO 6 (REQUIRING 6 ADDITIONAL TIME STEPS) ONCE
C     ROCK VELOCITY NORMAL TO THE FENCE HAS BECOME NEGATIVE.
C
C************************************************************************

      VFLAG=VFLAG-1
      IF (VFLAG.EQ.0) THEN
      SFLAG=1
      ENDIF
      IF (VFLAG.LT.O) THEN
      IF (VEL(RNODE,2,2).LT.0) THEN
      VFLAG=6
      ENDIF
      ENDIF

      TM=TM+DT

      TT=TM-TP
      IF (SFLAG.EQ.1) THEN
      GOTO 690
      ENDIF
      IF ((TT).LT.(0.0999)) THEN
      GOTO 700
      ENDIF
  690 NITS=0
```

```
      TP=TM
      WRITE(11,10030)TM
      DO 710 I=1,NUMNODE+1
      WRITE(11,10030)GEOM(I,1,2),GEOM(I,2,2),GEOM(I,3,2)
10030 FORMAT(3(F6.2,1X))
  710 CONTINUE
      WRITE(11,*)-1,-1,-1

C***********************************************************************
C
C    CHECK FOR END OF ANALYSIS CONDITION
C    RETURN TO ANALYSIS
C
C***********************************************************************

  700 ITS=0
      IF (SFLAG.NE.1) THEN
      NITS=0
      GOTO 220
      ENDIF

      STOP

      END
```