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CALCULATIONS OF THREE TEST PROBLEMS BY THE 3-D TRANAL CODE.(U)

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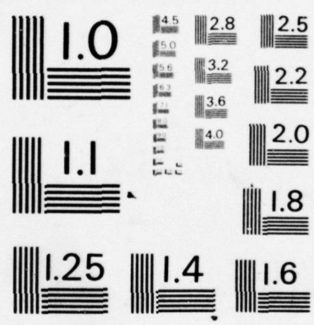

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CALCULATIONS OF THREE TEST PROBLEMS BY THE 3-D TRANAL CODE

Weidlinger Associates
110 East 59th Street
New York, New York 10022

April 1976

Final Report for Period April 1974—March 1976

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TRANAL Computer Program

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

TRANAL, a three-dimensional, finite element, transient nonlinear analysis code, was used to calculate a series of three simple test problems. Although the test problems are not three-dimensional, a number of different aspects of the code were checked including timing, data management, nonlinear cap model routine, applied air pressure routine (Brode fit), and mesh generation. The test problems were designed by the Space and Missile Systems Organization in conjunction with TRW personnel. NEXT PAGE

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20. ABSTRACT (Continued)

For two of the problems, TRANAL results are compared with results from LAYER, a two-dimensional, axisymmetric, finite difference code. The results compare quite well when the differences in code details are considered.

A third problem, which involves a hollow concrete cylinder embedded in a two-layer soil system (clay over shale), is also studied. The conclusion reached is that, for the prescribed airblast loading (nuclear type), the walls of the cylinder will not fail in compression during the first 100 milliseconds, which is probably the most critical period. However, this conclusion is based on a simple two-dimensional, axisymmetric problem; in order to understand this soil-structure interaction problem more fully, it is necessary to perform a complete three-dimensional analysis.

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I INTRODUCTION

During the last ten years, there has been considerable progress in the development of computer codes for three dimensional, transient, nonlinear analysis of soils and structures, Refs. [1] and [2]. Such codes can be used to study structural problems which are of interest in both civilian and military applications. A defense problem of much interest is the vulnerability of protective structures to high explosive and nuclear weapons. In particular, the vulnerability of underground missile silos is of primary concern to the United States Air Force (USAF).

The TRANAL code, Ref. [3], was developed by Weidlinger Associates (WA) under a previous Defense Nuclear Agency (DNA) contract with vulnerability problems in mind. In order to check certain capabilities of TRANAL, a series of three simple test problems were calculated. These three problems, which were designed by the Space and Missile Systems Organization (SAMSO) in conjunction with TRW personnel, were run as part of the current DNA contract and the results are reported herein. Some TRANAL - related code developments are also discussed.

II TRANAL DEVELOPMENTS

Although the basic TRANAL code has been operational since September 1974, there have been subsequent developments which are worth noting. These relate to graphics capability, data generation techniques, improvements in execution speed and more flexibility in its use for vulnerability problems for the USAF.

In order to run a large 3-D problem, it is frequently necessary to prepare a great deal of data before making a run. In a problem with complicated geometry and several different materials, it is not uncommon to prepare more than 10,000 data items. The preparation of such large amounts of data is usually an error prone task and various techniques are needed to reduce errors and speed data preparation. As a result, graphics capability and a data input aid, called region preprocessing, have been added to TRANAL.

Region Preprocessing

As outlined in Ref. [2], TRANAL is designed to use a technique referred to as zone processing in which a structural complex is subdivided into a set of substructures, called zones, and each zone is further subdivided into a set of elements. This two-level hierarchical procedure is used so that each substructure will fit into computer memory during the main calculational phase.

An extension of TRANAL which is referred to as region preprocessing is now operational. Each zone is subdivided into a set of regions which can be further subdivided into sets of elements. A region is a set of elements which all have the same material type. This three-level hierarchical procedure is used only during the data input phase of the calculation. Zone processing is still employed during the calculational phase.

Graphics Capability

The capability now exists to make plots of the elements in each zone, or of the regions defined in the problem set up. Thus, the coordinates and material layout produced by mappings and mesh generators can be viewed in order to check problem set up. The plotting routines used were obtained from library programs in the public domain. The main work was the adaptation of these routines to use the TRANAL data structures which are complicated by zone processing. Additional plotting capability for viewing results will be developed in the future when the need arises in a particular application.

Execution Speed

TRANAL is currently operational on the CDC 6600 at New York University and on the CDC 7600 at Lawrence Berkeley Laboratory. Execution speed is less than 0.5 milliseconds per element per time step on the 7600; this includes the latest CAP model routine, Ref. [4], and all overhead due to data management.

At the current rate, a calculation requiring 10,000 elements and 1,000 time steps would cost about $1,500.00 ($1\frac{1}{2}$ hours of 7600 time) and could be expected to run overnight once the problem is set up.

In a recent preliminary calculation for the HARD PAN I-3 event, a full three dimensional calculation was made with 6156 elements (21,840 degrees of freedom) for 660 time steps. This calculation required 32 minutes of CDC 7600 time and cost $440.00 at the overnight rate (80%).

SAMSO Vulnerability Problems

Missile silo vulnerability studies are conducted by using an applied air blast loading to simulate a nearby nuclear explosion. Two air blast loading routines are now available in TRANAL. Both loadings are based on Brode's fits, Ref. [5], to a nuclear air burst. These two fits are the Brode direct fit and the Brode simple fit. In addition, two data generators have been built especially for the geometry of the missile silo vulnerability problem in order to reduce time and errors in the data generation process.

III SAMSO-TRW TEST PROBLEMS

In order to check out certain capabilities of TRANAL, a series of three simple test problems, designed by SAMSO and TRW personnel, have been calculated. These problems are designated by P1, P2 and P3.

Problem 1 (P1)

This problem, called P1, is the one dimensional, plain strain response of a half-space of shale covered by 20 feet of clay which is subjected to a pressure history corresponding to a one megaton surface burst at the 600 psi peak overpressure location (see Fig. 1).

Problem 2 (P2)

This problem called P2, is the two dimensional, axisymmetric response of a half-space of shale covered by 20 feet of clay subjected to a pressure history corresponding to a one megaton surface burst in ranges between 2,000 psi and 200 psi peak overpressure (see Fig. 2).

Problem 3 (P3)

This problem called P3, is the two dimensional, axisymmetric response of a hollow concrete cylinder embedded in 20 feet of clay overlying a shale half-space (see Fig. 3). The cylinder, which is flush with the clay surface, is 40 feet in length, 10 feet in radius and has 4 feet thick walls on the top and bottom and 2 feet thick side walls. The

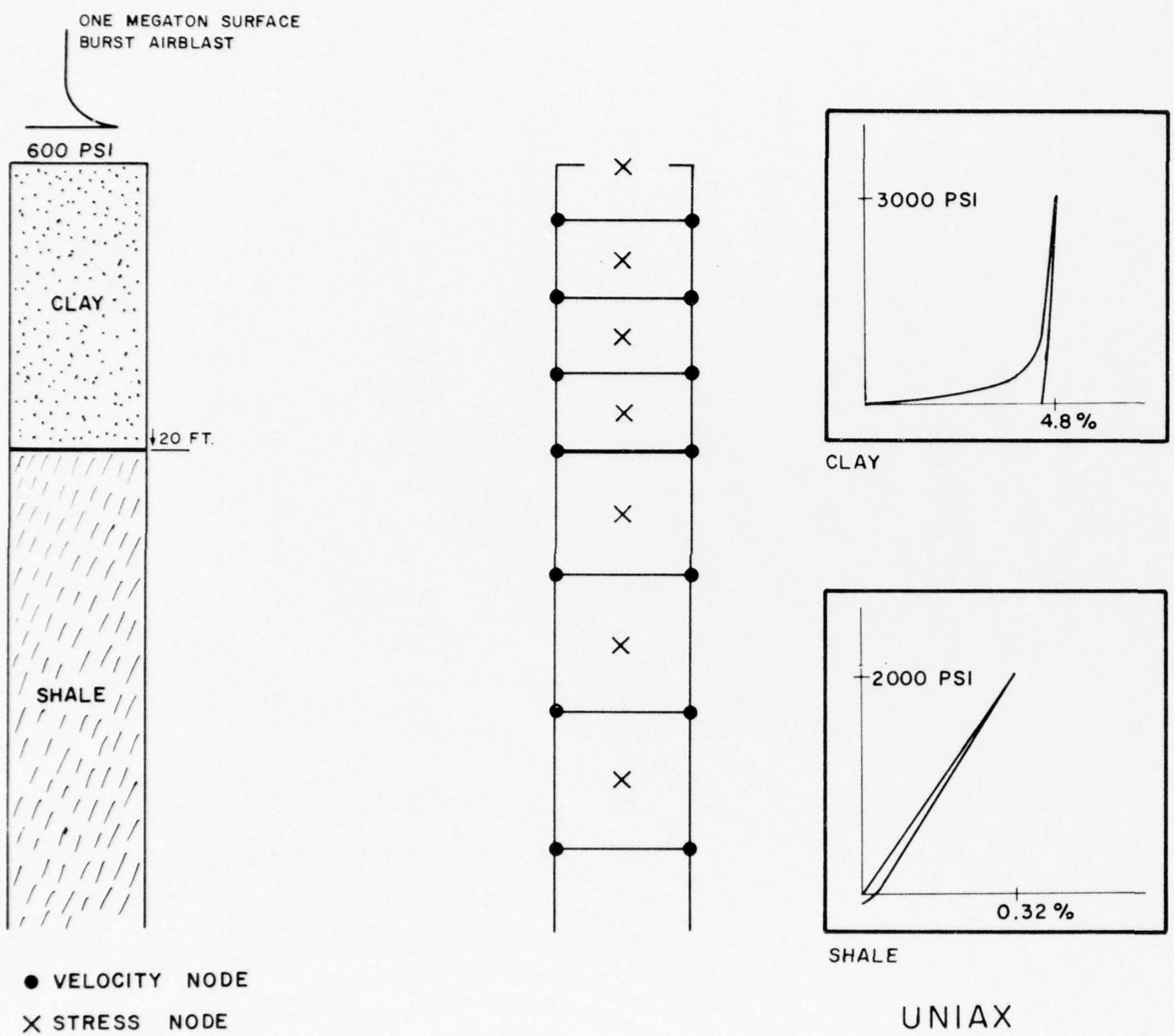


FIG. I PROBLEM I (PI)

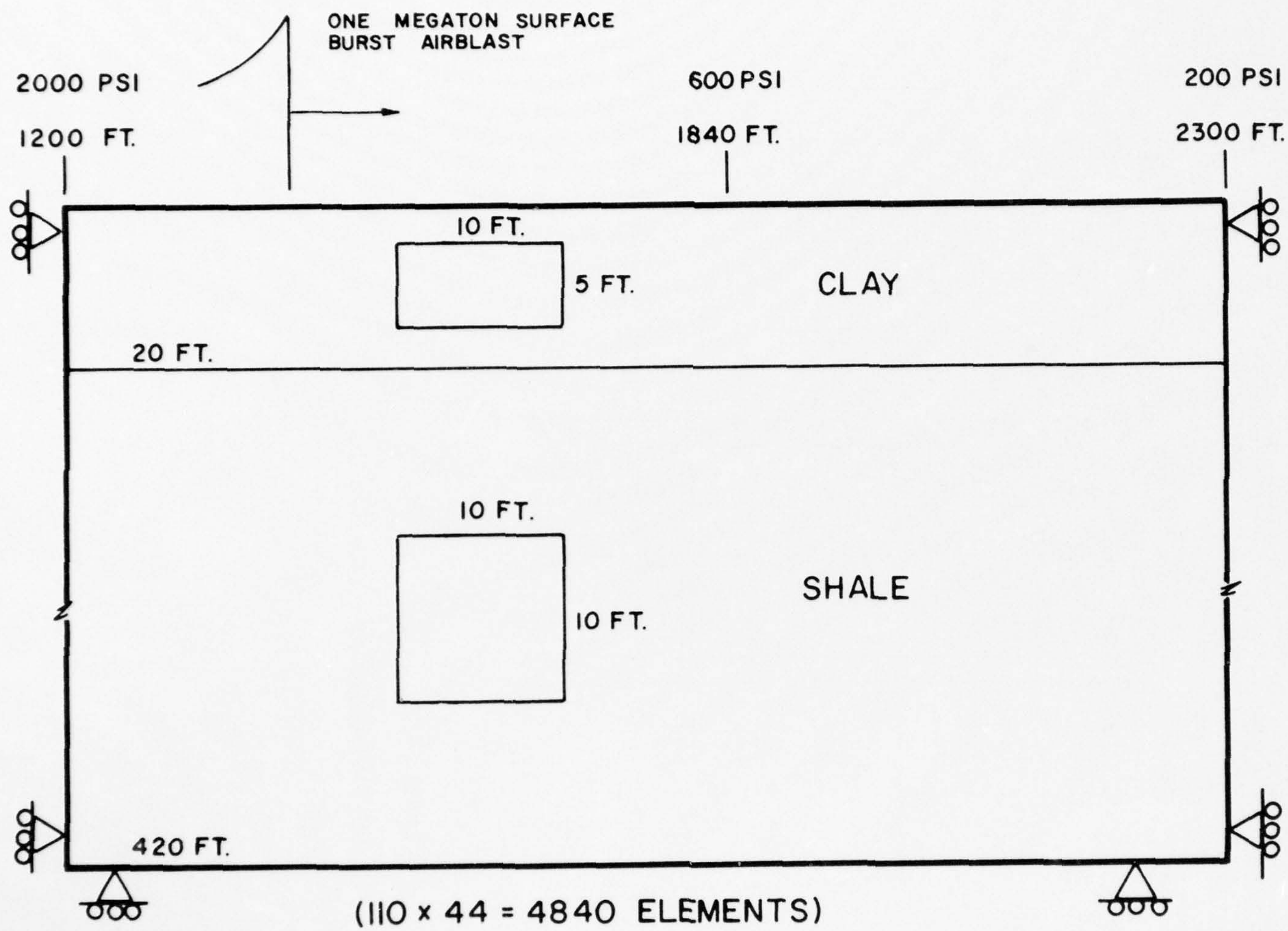


FIG. 2 PROBLEM 2 (P2)

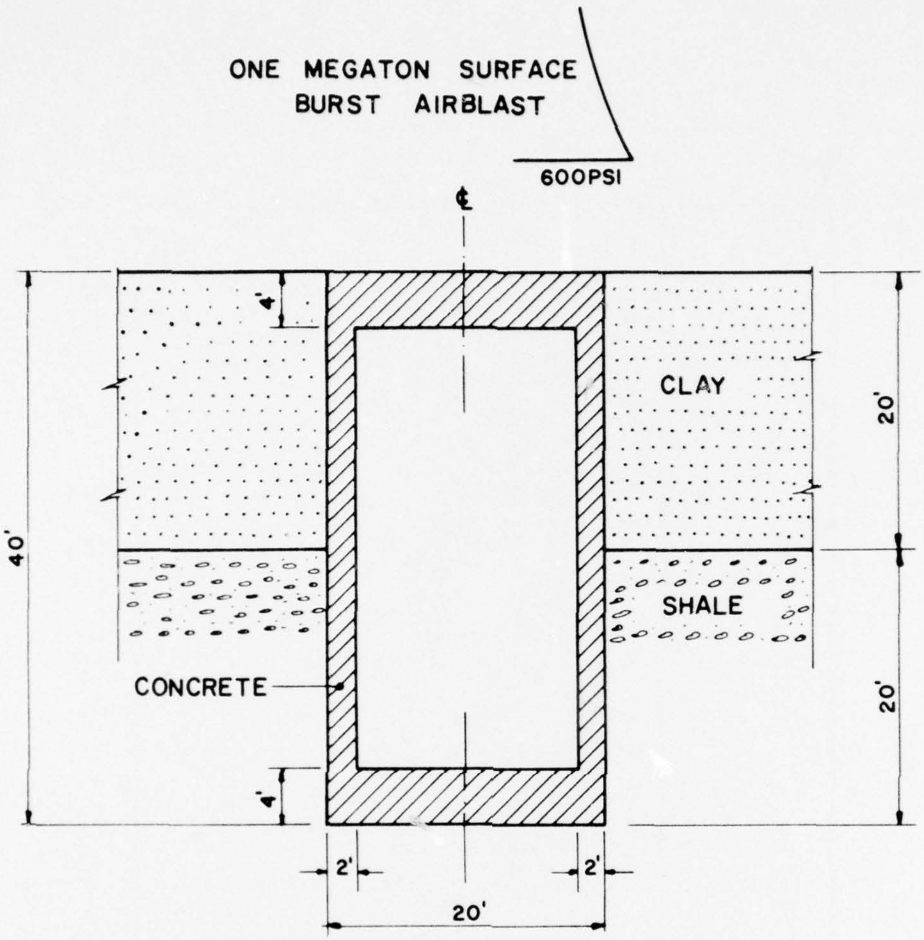


FIG. 3 PROBLEM 3 (P3)

clay/concrete surface is to be subjected everywhere to a pressure history corresponding to a one megaton surface burst at the 600 psi peak overpressure location.

Surface Pressure Time History

The pressure time history applied to the surface in all problems was based on the Brode simple fit, Ref. [5]. The response was calculated for 100 milliseconds after the time the 600 psi peak overpressure begins, which is roughly 108 milliseconds after the detonation of the one megaton surface burst. Thus, response curves for all calculations begin somewhat after 0.1 seconds and extend past 0.2 seconds.

Material Models

Material models for the clay and shale were represented by the soil CAP model, Ref. [6], in compression with mean stress, σ_m, limited in tension. Uniaxial compression curves for the clay and the shale are illustrated in Fig. 1. The concrete in P3 was represented by a linearly elastic model in compression with mean stress limited in tension. Since the stresses in the concrete never exceeded the assumed value of compressive failure (6,000 psi), this model is considered adequate for P3. Values of the parameters used for the three materials are given in Table I.

TABLE I. CAP MODEL PARAMETERS (Model as described in Ref. [6])

	Clay	Shale	Concrete
ρ(pcf)	120	137	150
K(ksi)	340	540	1600
G(ksi)	85	115	1250
A(ksi)	0.1	0.866	-
B(ksi^{-1})	1.5	2.5	-
C(ksi)	0.07	0.361	-
D(ksi^{-1})	2.0	0.5	-
W	0.04	0.0005	-
R	3.0	3.0	-
σ_m(ksi) (tension cutoff)	0.010	1.5	0.667

Calculational Grids and Time Steps

Based upon previous experience with problems of this type and due to the desire to keep the calculational cost down, it was decided that a coarse mesh would be adequate for these problems. The meshes for problems P1, P2 and P3 are illustrated in Figs. 1, 2 and 4, respectively. The time increment for P1 and P2 was 1 millisecond and for P3 was 0.4 milliseconds. Thus, 250 time steps were used in P3 and only 100 time steps in P1 and P2. The P3 mesh had 1,089 elements and was run without using external storage. The P2 mesh had 4,840 elements and thus required external storage, since fewer than 2,000 elements fit in main memory at one time. Variable mesh generation was tested in P3 whereas P1

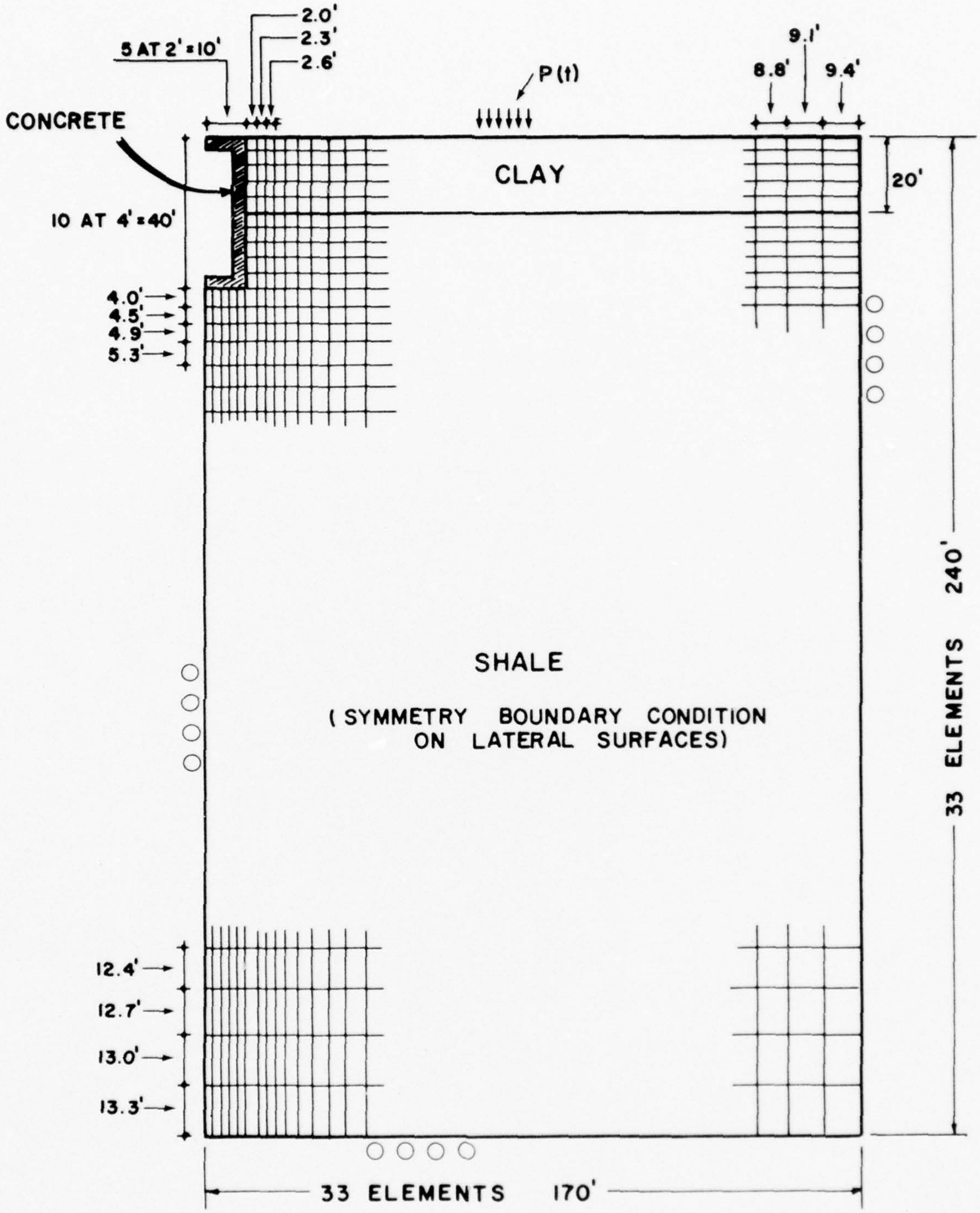


FIG. 4 PROBLEM P3 - FINITE ELEMENT MESH

and P2 used only two mesh sizes. Thus, a variety of important features of the code were exercised. The cost of running problems P1, P2 and P3 on the CDC 6600 was less than $2.00, $150.00 and $75.00, respectively.

IV NUMERICAL RESULTS

Problem P1

The vertical velocity and displacement histories for problem P1 from TRANAL at a depth of 2.9 ft are shown in Fig. 5. Also shown in this figure are the corresponding results from the LAYER code. The results from TRANAL and LAYER compare quite well when the coarseness of the mesh and other code details are considered. Some of the differences can be ascribed to

- time phasing details in applied surface loading
- different modeling of tensile behavior
- different approximation techniques (finite element and fintie difference)

The maximum velocity of about 360 in/sec is quite close to the theoretical value expected from simple, one dimensional shock considerations. This value can be obtained by using the shock condition

$$\Delta v = \frac{\Delta p}{\sqrt{\rho M}}$$

where Δp is the jump in pressure at the shock front, Δv is the jump in particle velocity, ρ is the material density and M is the secant modulus (Rayleigh line slope) corresponding to the shock loading of the material. From the stress-strain curve in Fig. 1, the 600 psi level corresponds to a strain of about 0.04; thus M = 15 ksi. The clay density, in consistent units, is $\rho = .18$. Since $\Delta p = .6$ ksi, the value of Δv is about 360 in/sec.

Although not shown in this report, time histories at

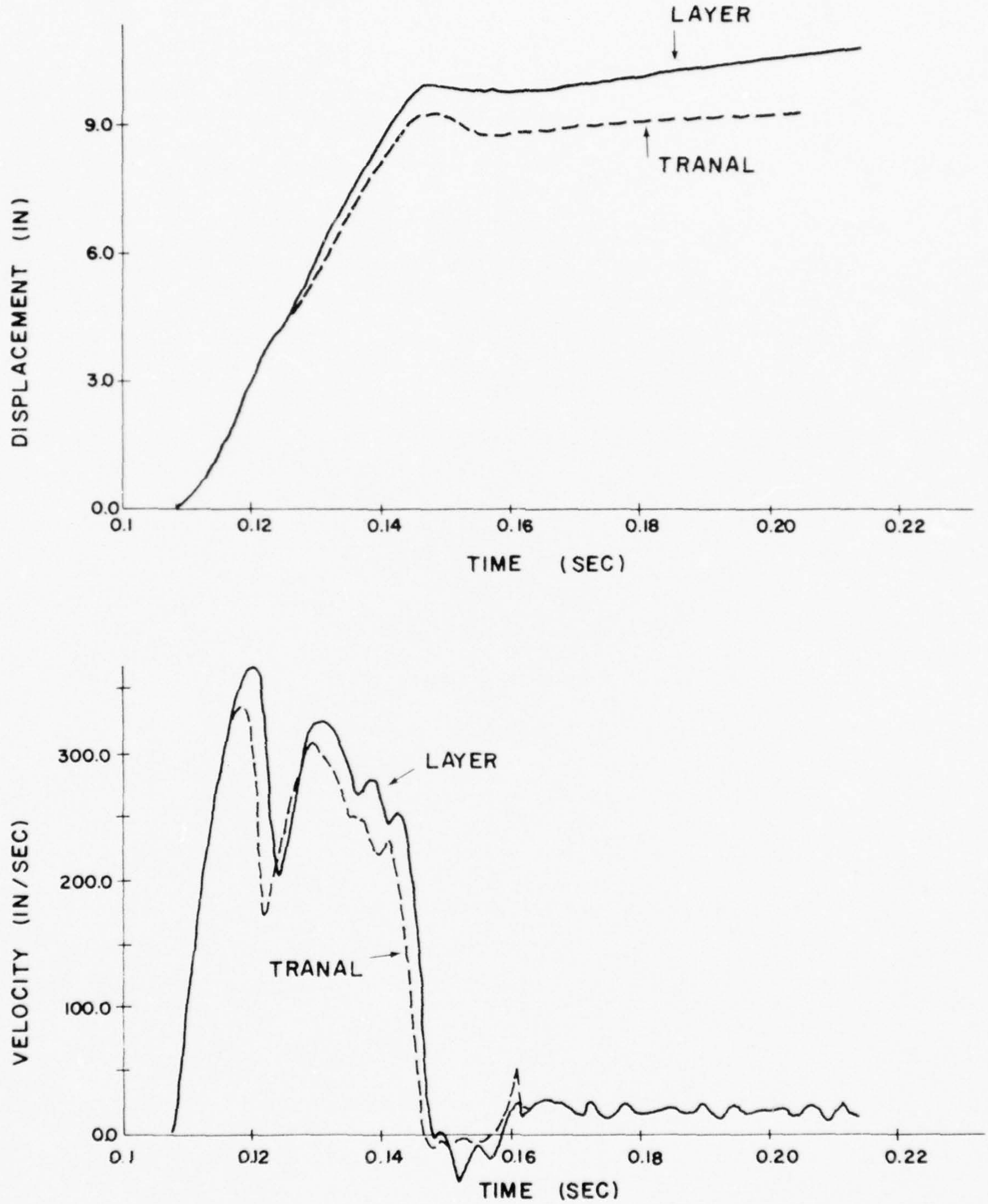


FIG. 5 PROBLEM P1 - VERTICAL RESPONSE AT DEPTH = 2.9 FT.

other depths compare equally well when TRANAL and LAYER results are examined. Additional comparisons are presented in the following discussion of the two dimensional problem P2.

Problem P2

Velocity and displacement histories in both the radial and vertical directions are shown in Figs. 6-10. Corresponding time histories from the LAYER code are also shown in these figures. Once again the agreement is seen to be quite good when the factors mentioned for problem P1 are considered.

The largest percentage difference seems to appear in Fig. 7, where the maximum radial velocity at the near surface point is more than 100 in/sec in the TRANAL calculation and only 70 in/sec in the LAYER calculation. The displacements are, however, better. This is normally the case in finite difference and finite element wave propagation calculations of this type. Generally speaking, maximum velocities are less reliable than displacements since the nature of wave motion is that displacements are continuous whereas velocities may be discontinuous. This is particularly the case near boundaries and interfaces. In addition, peak values of velocity (vertical and radial) are sensitive to the introduction of viscosity. Neither the LAYER or the TRANAL calculation used artificial viscosity. Furthermore, modification of the rise time of the applied surface loading can affect the peak velocity. In both calculations, the rise time was not modified so that the effective rise time of the load was controlled by the speed of the load and the mesh size. Slight differences in phasing of the applied

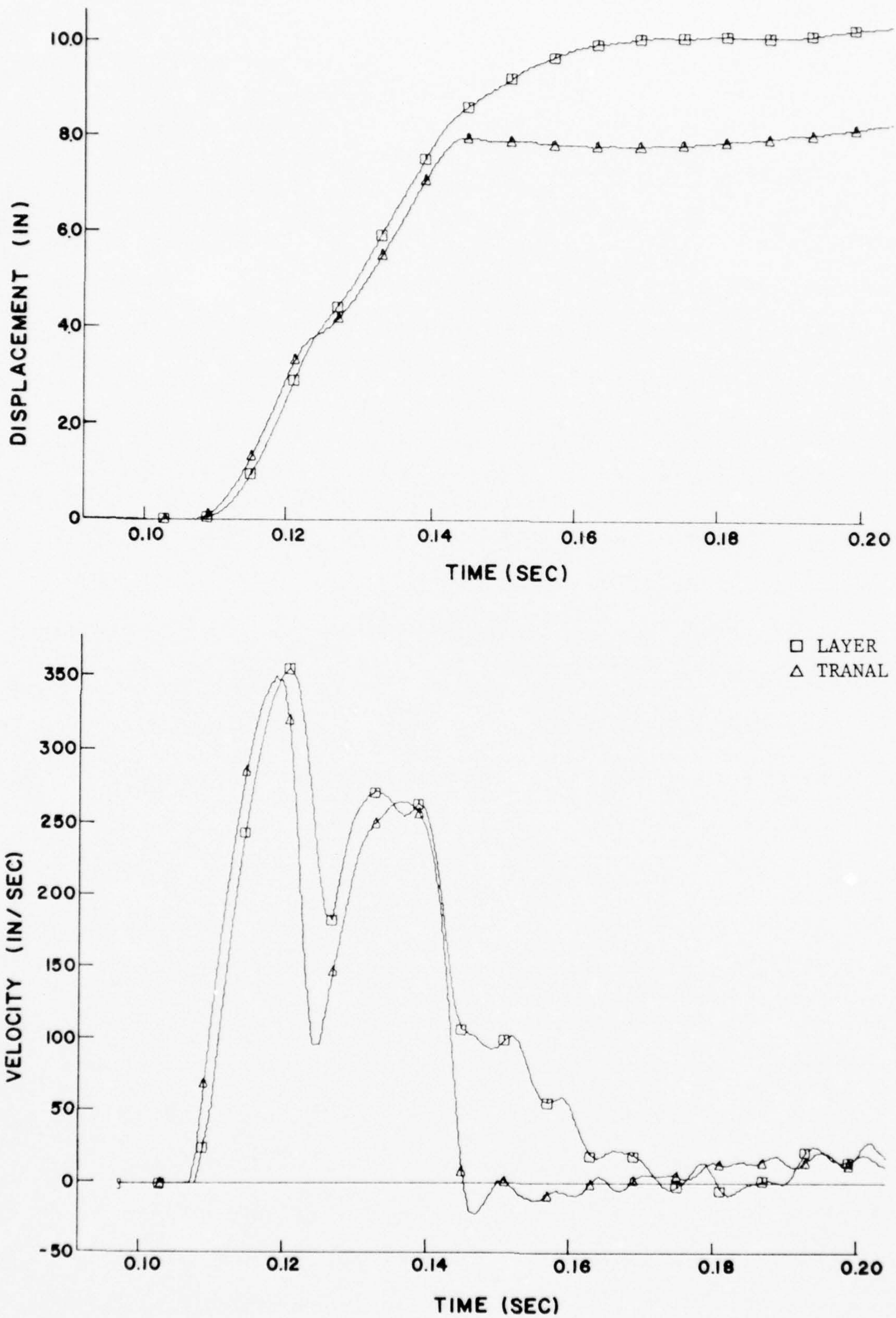


FIG. 6 PROBLEM P2 - VERTICAL RESPONSE AT RANGE = 1840 FT.
DEPTH = 2.9 FT

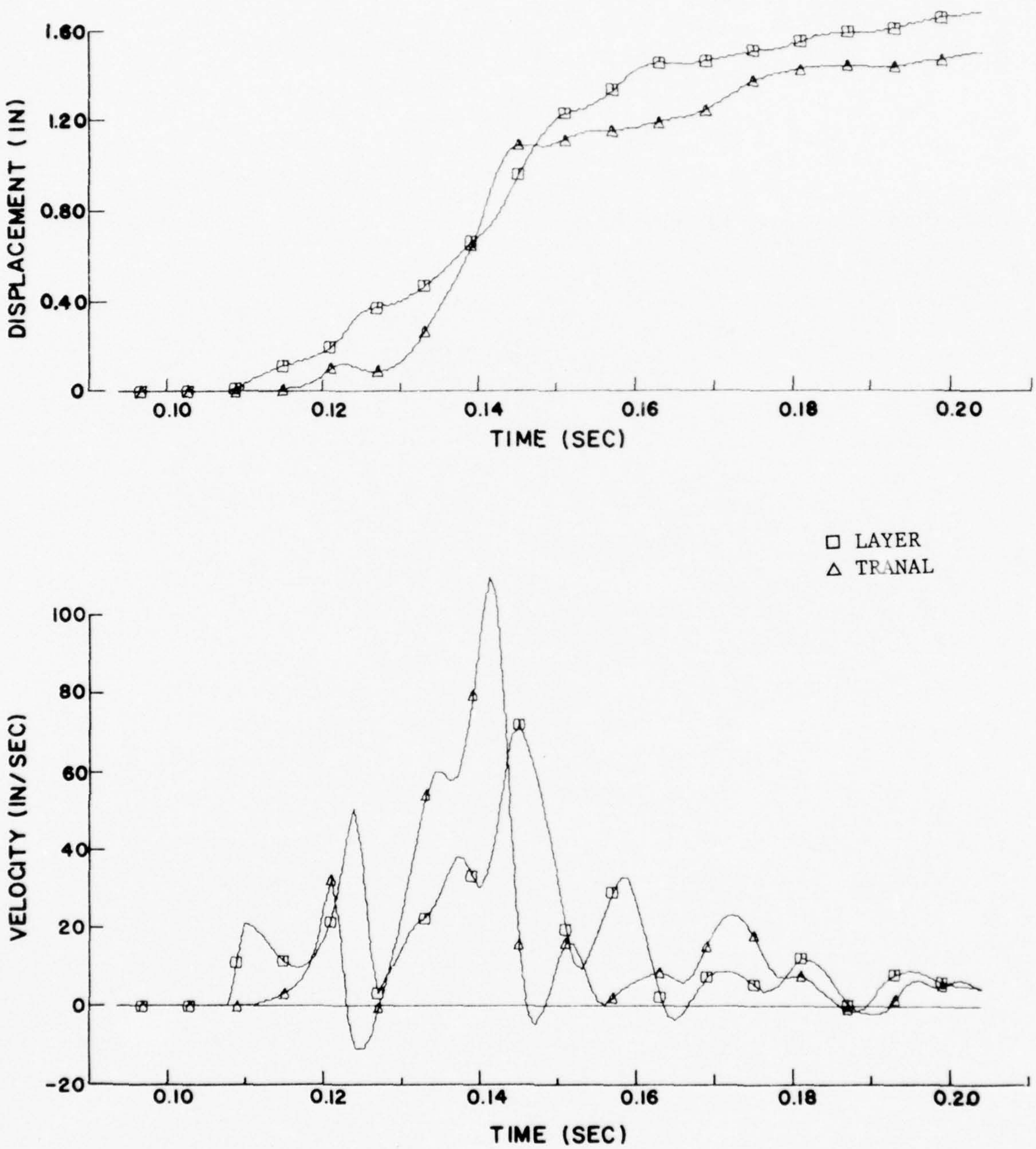


FIG. 7 PROBLEM P2 RADIAL RESPONSE AT RANGE = 1840 FT.
DEPTH = 2.9 FT.

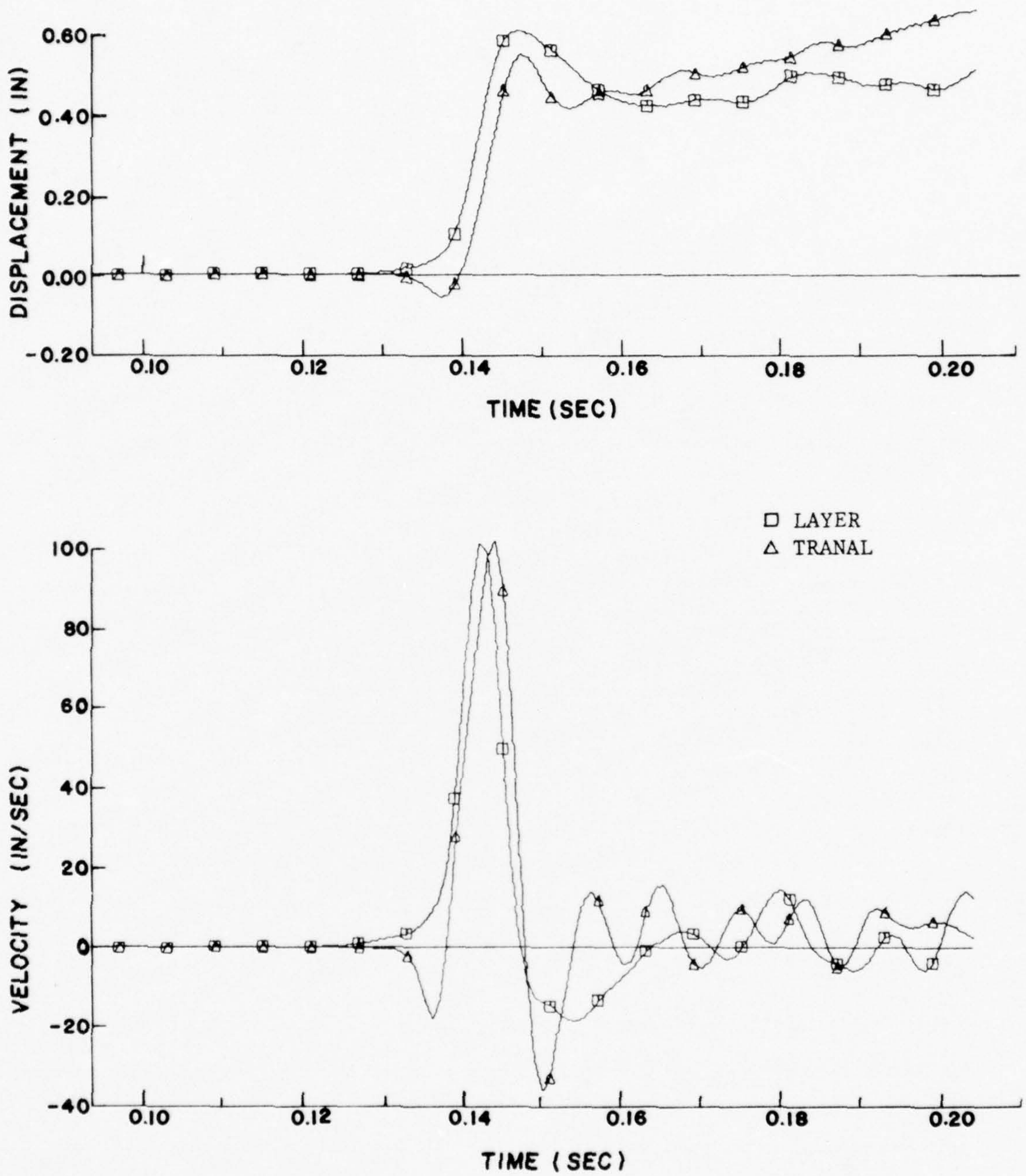
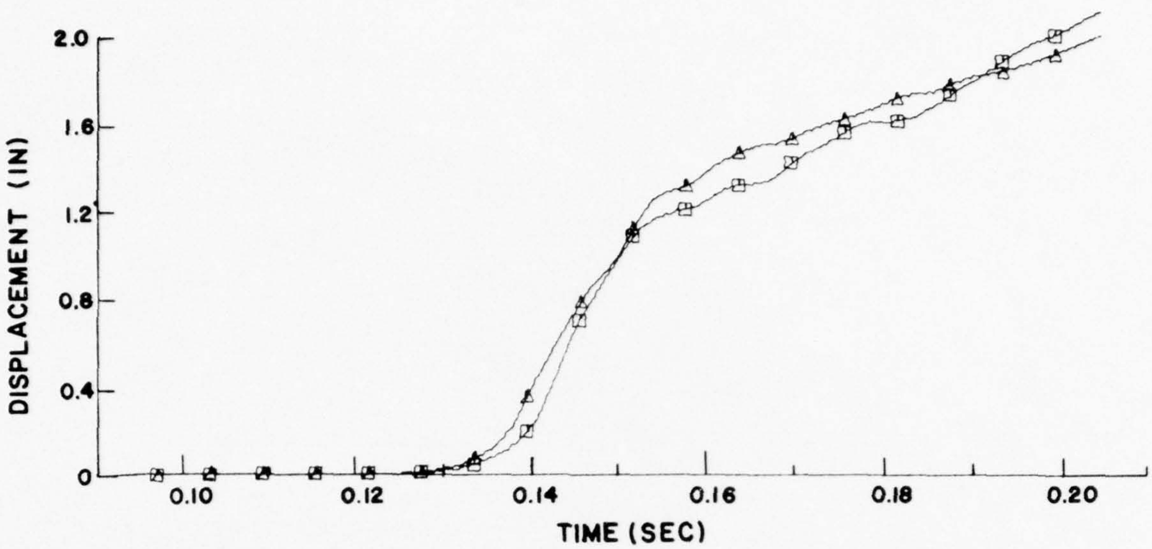


FIG. 8 PROBLEM P2 - RADIAL RESPONSE AT RANGE = 1840 FT.
DEPTH = 20 FT.



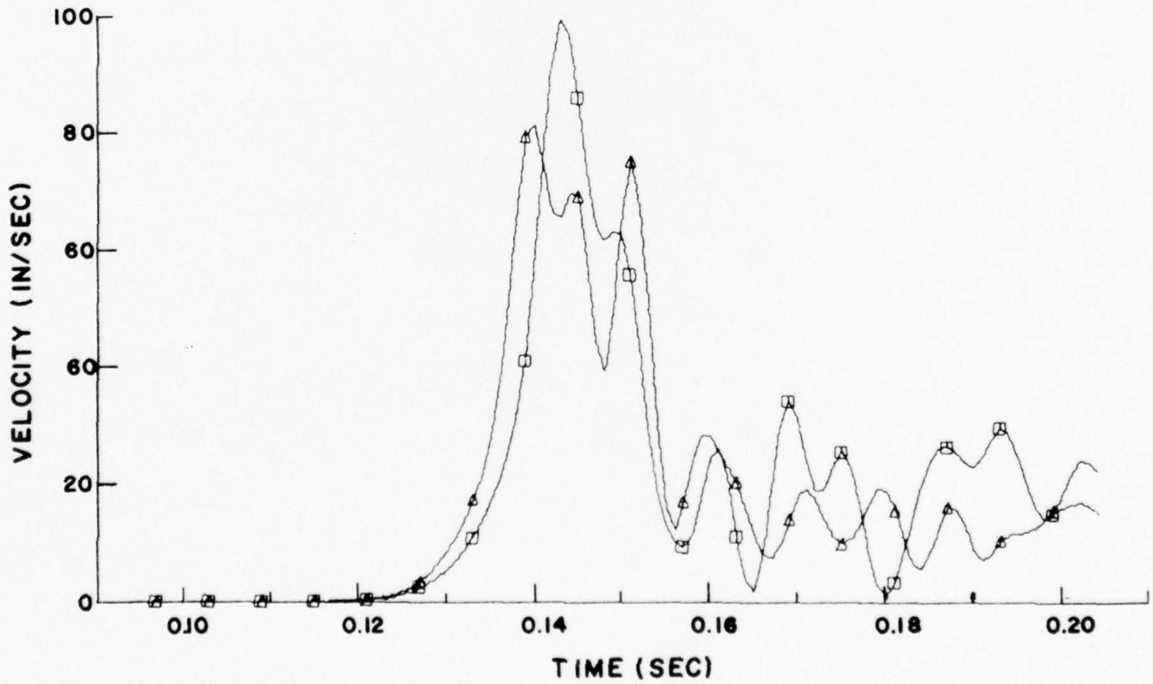


FIG. 9 PROBLEM P2 - VERTICAL RESPONSE AT RANGE = 1840 FT.
DEPTH = 30 FT.

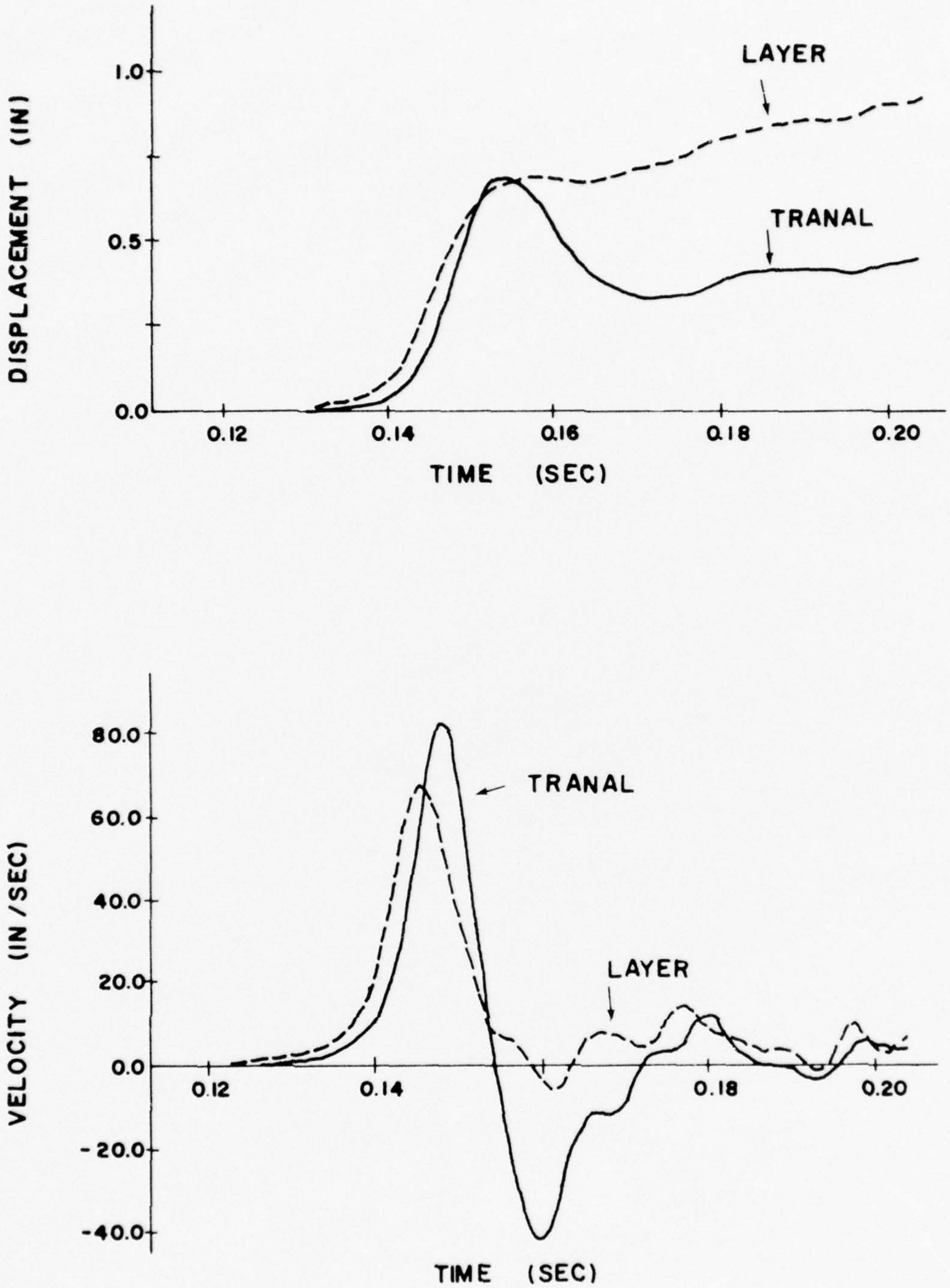


FIG. 10 PROBLEM P2 RADIAL RESPONSE AT RANGE = 1840 FT.
DEPTH = 40 FT.

load can then lead to noticeable changes in a potentially discontinuous quantity such as velocity (or stress). Displacements are generally better behaved as observed.

In this problem, the airblast shock front is traveling at about 7 ft/msec at the range of interest. The loading wave speed in the clay is less than 1 ft/msec which leads to a highly supersonic loading front in the clay. Thus radial motions are generally small (compared to the vertical) at the loading front and are affected substantially (percentage wise) by differences in phasing. After the loading front has reflected from the clay-shale interface, larger radial motions appear. However, by this time the coarse mesh coupled with the discontinuous behavior of the velocities has resulted in what appears to be a substantial error in the radial velocity. In fact, the difference noted in Fig. 7 of 35 in/sec between LAYER and TRANAL is only 10 per cent of the maximum velocity felt at that point in the vertical direction. In short, radial velocities will always appear unreliable in finite element and finite difference calculations of this type if they are viewed on an absolute scale. It is necessary instead to consider both components of the velocity in order to judge the results. With this point of view in mind, approximate values of maximum response for several depths are presented in Table II.

TABLE II. MAXIMUM RESPONSE WITH DEPTH
(during first 100 milliseconds)

Depth (Ft)	Displacements (in) Vertical	Displacements (in) Radial	Velocities (in/sec) Vertical	Velocities (in/sec) Radial
0	12	1.2	400	100
10	7	1.5	300	100
20	2	.6	100	100
30	2	.6	80	80
40	2	.6	80	80

The results in Table II are given with only one or two significant figures because of the above reasons. A few observations are in order however.

A vertical surface displacement of about 12 inches is quite reasonable for the highly hysteretic clay used. Maximum compaction at 600 psi is about 4 per cent. Since the clay layer is 20 ft. deep, the maximum displacement should be about 0.4 x 20 = .8 ft, or about 10 inches relative to the interface as observed.

The shale has very little hysteresis (see Fig. 1) and thus there should be little change with depth below 20 ft, as shown in Table II.

The shale has a wave speed of about 4.8 ft/msec. At this rate the loading front in the shale should be at about 45 degrees to the interface. Since the maximum velocity in the shale occurs at the loading front, the jump in vertical and radial velocities should be nearly equal below 20 ft, as shown in the table.

Problem P3

Selected motion and stress histories for problem P3 from TRANAL are shown in Figs. 11-20. It should be noted that, away from the structure, the motions for problem P3 are practically identical to those of problem P1, as they should be. Such comparisons have not been reproduced here since they would merely duplicate results in Figs. 5-10.

It should also be noted that certain conclusions are drawn here which are obtained by studying integrated quantities such as displacements and impulses. As discussed for problem P2, integrated quantities are more reliable due to the nature of wave propagation calculations of this type than are quantities such as maximum velocity or maximum stress. This is particularly true for a coarse grid calculation such as the one used here.

By looking at a point quite near the structure, it is possible to observe the similarity of the free-field motions (problems P1 and P2) to the results from problem P3. For example, Fig.12 shows a point two feet away from the top corner on the clay surface which should be compared with Fig. 5. In both cases, the displacement rises quickly but smoothly to a value of about 9 inches in less than 40 milliseconds and then rises slowly during the next 60 milliseconds to a maximum of about 10 inches or so. In essence then, the vertical motion of the clay surface is not significantly modified by the presence of the structure.

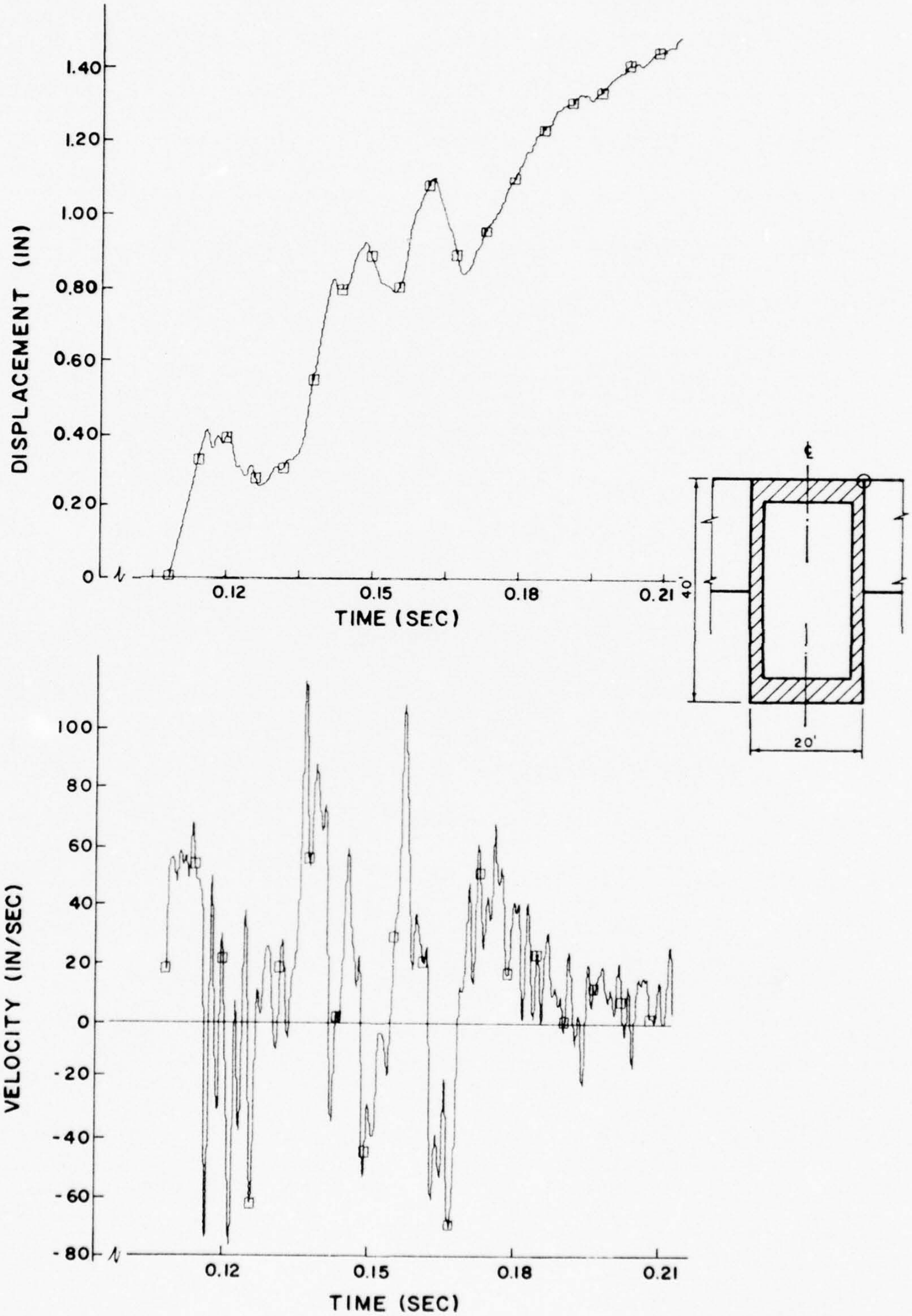


FIG. 11 PROBLEM P3 - VERTICAL RESPONSE, THE TOP CORNER OF STRUCTURE

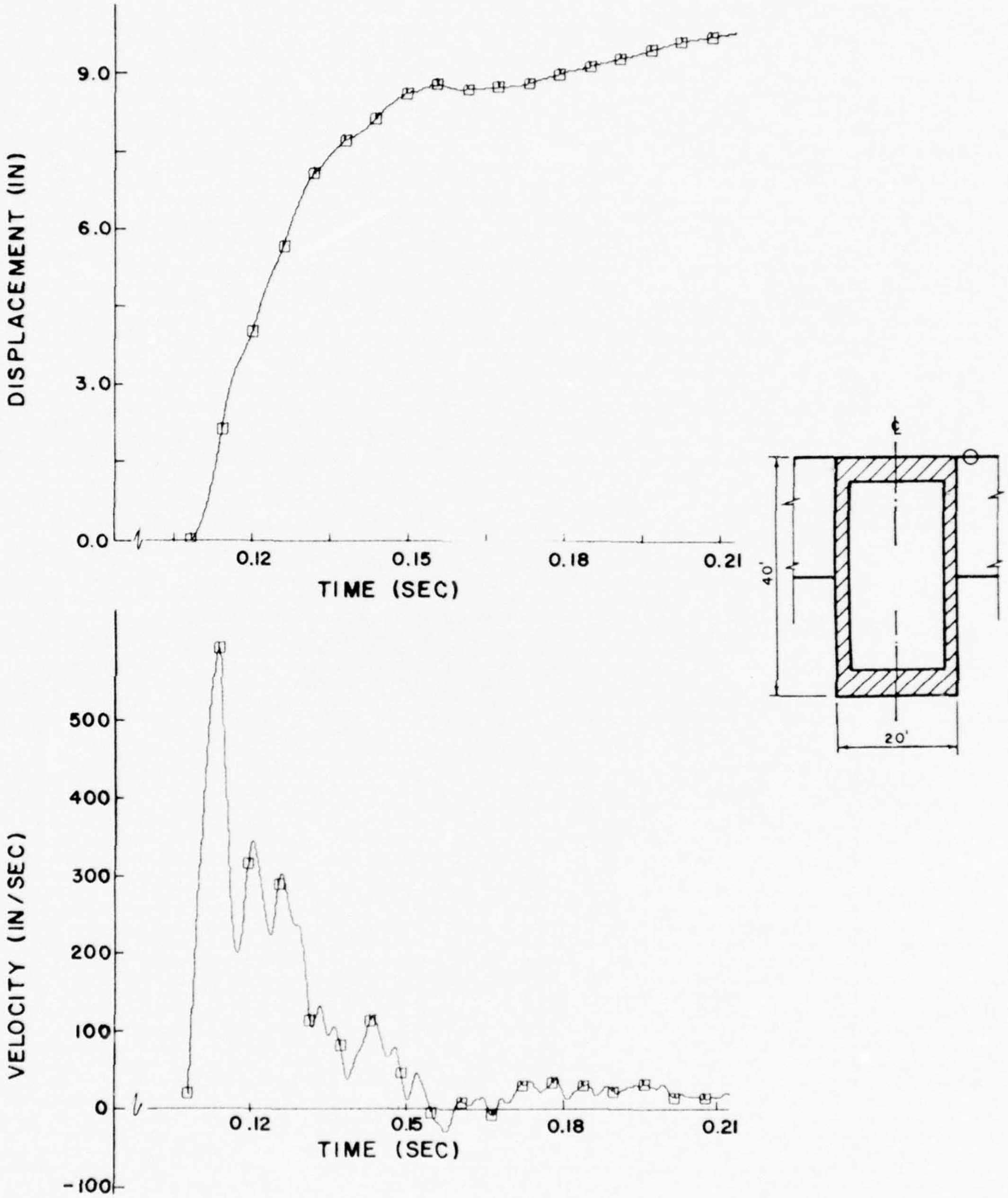


FIG. 12 PROBLEM P3 - VERTICAL RESPONSE 2 FT AWAY FROM TOP CORNER OF STRUCTURE

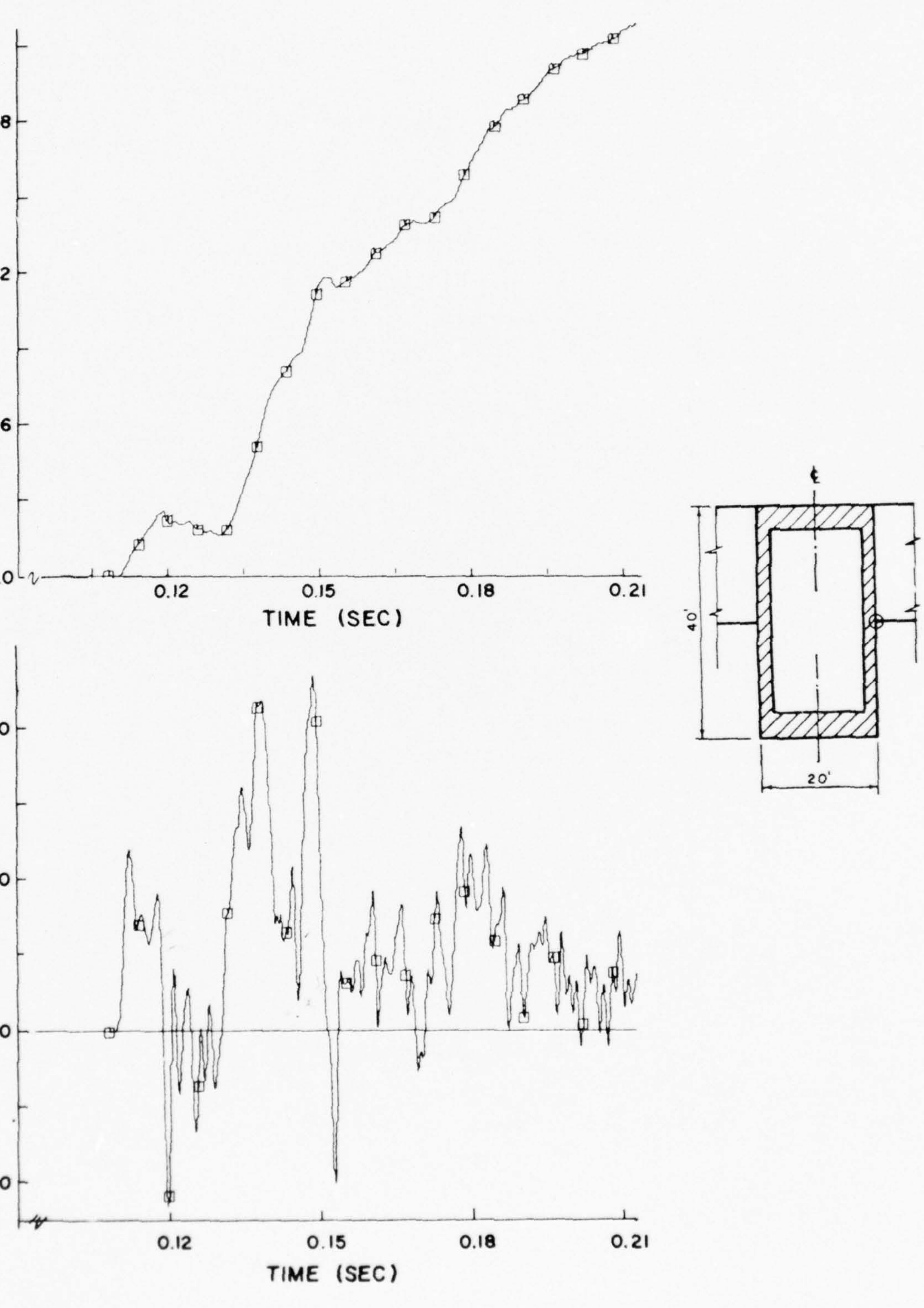


FIG. 13 PROBLEM P3 - VERTICAL RESPONSE AT THE CLAY-SHALE-CONCRETE INTERSECTION

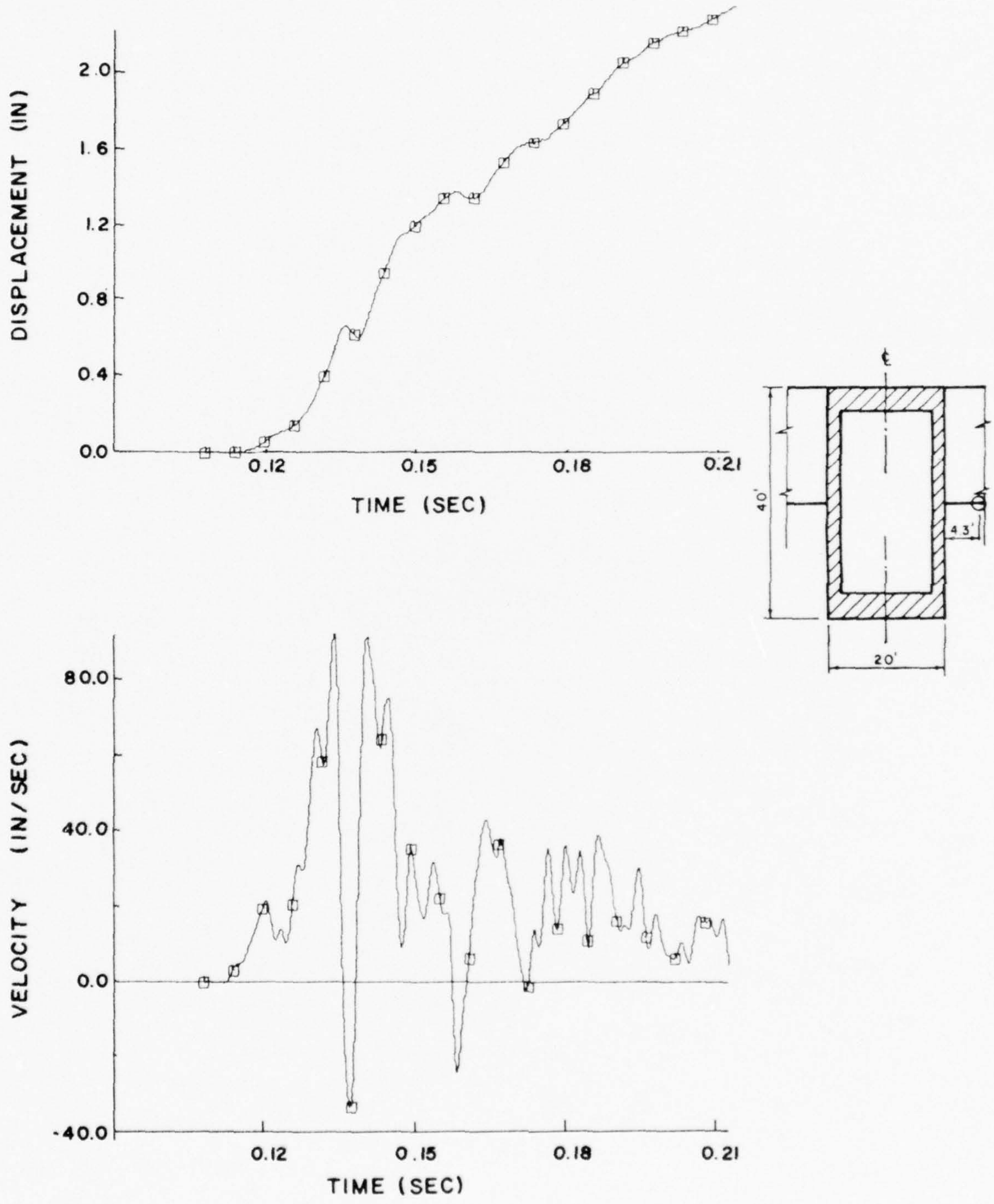


FIG. 14 PROBLEM P3 - VERTICAL RESPONSE AT THE CLAY-SHALE INTERFACE, 4.3 FT AWAY

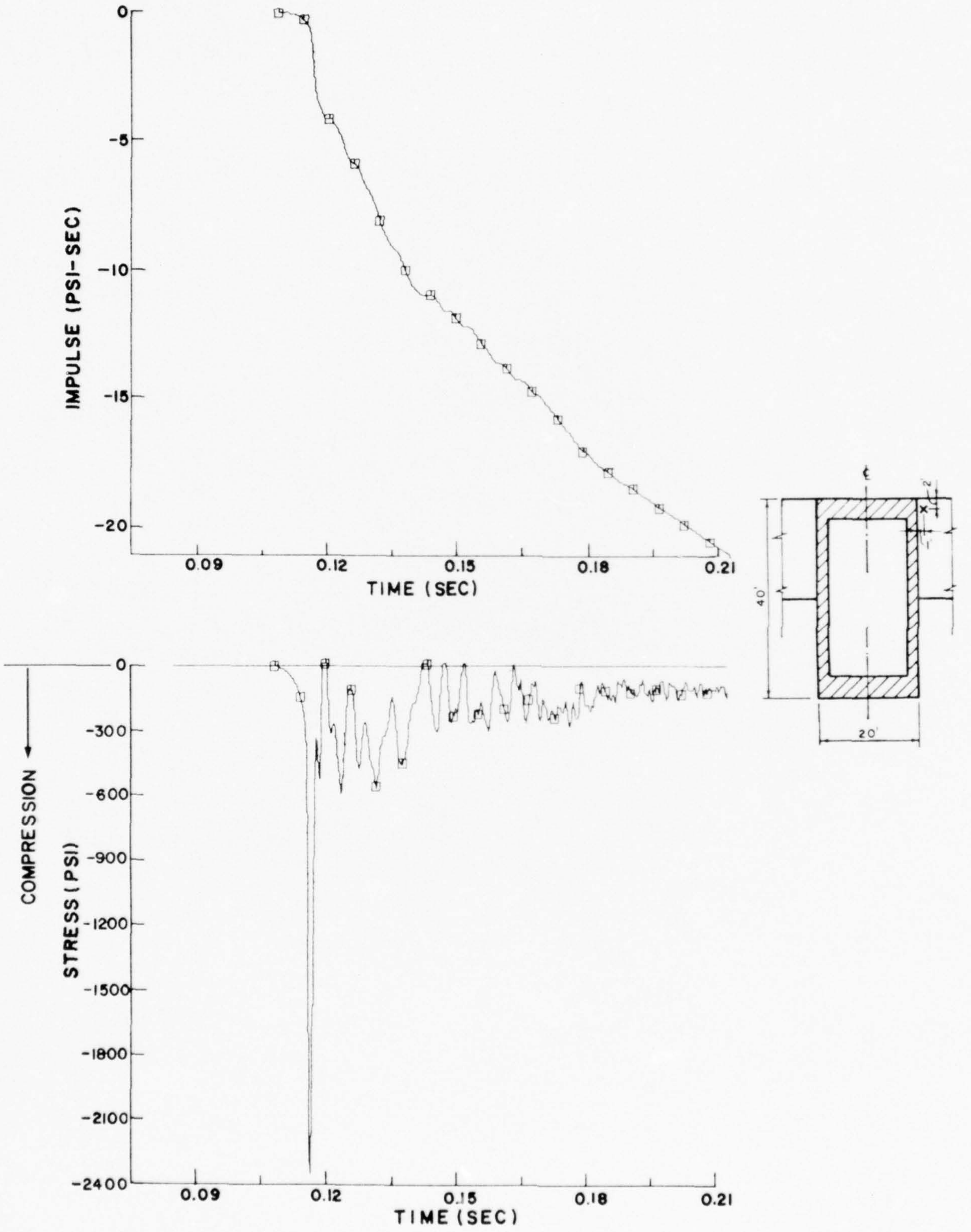


FIG. 15 PROBLEM P3 - VERTICAL STRESS AND IMPULSE NEAR TOP CORNER OF STRUCTURE, 1 FT AWAY

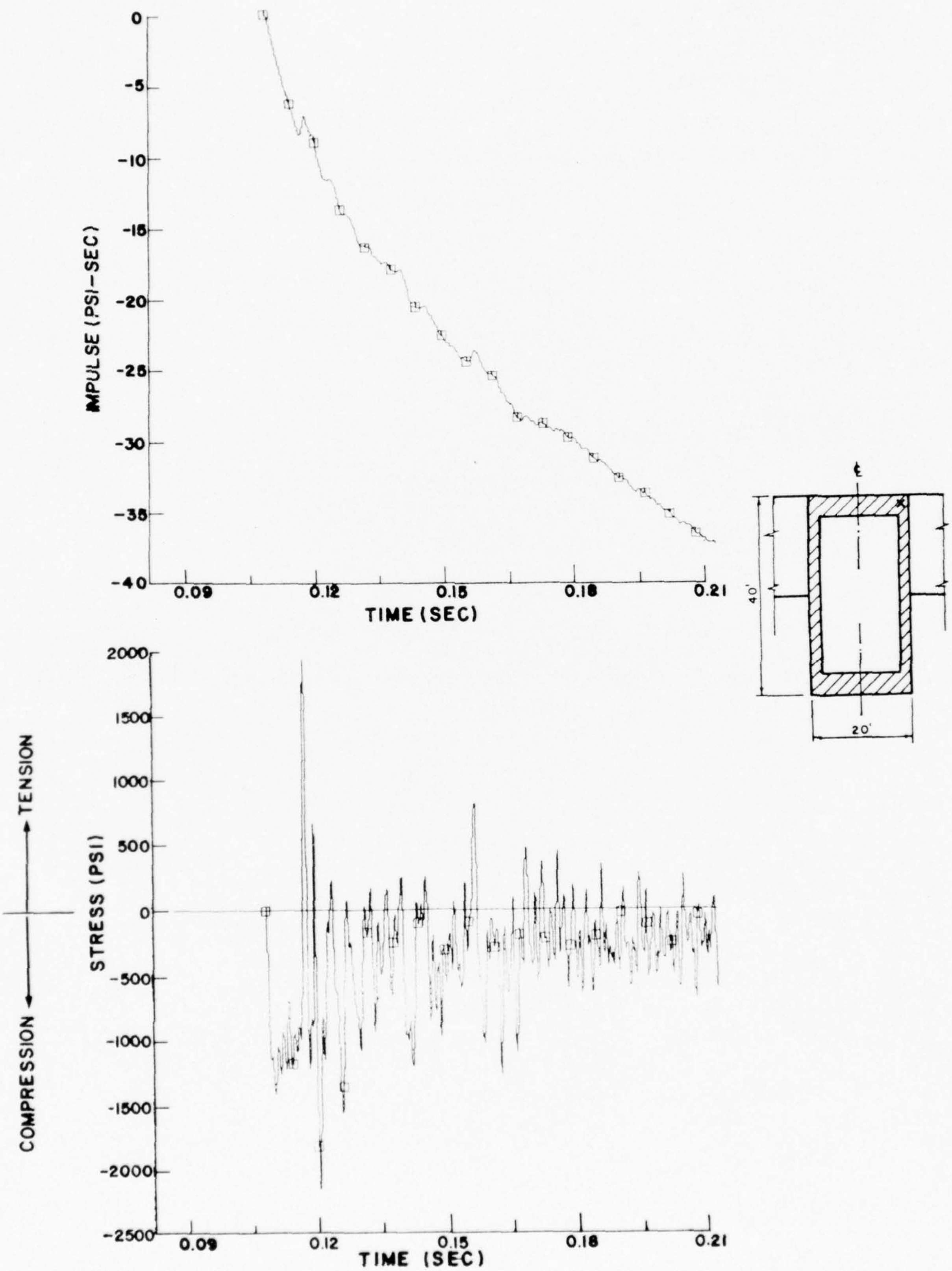


FIG. 16 PROBLEM P3 - VERTICAL STRESS AND IMPULSE IN TOP CORNER OF STRUCTURE

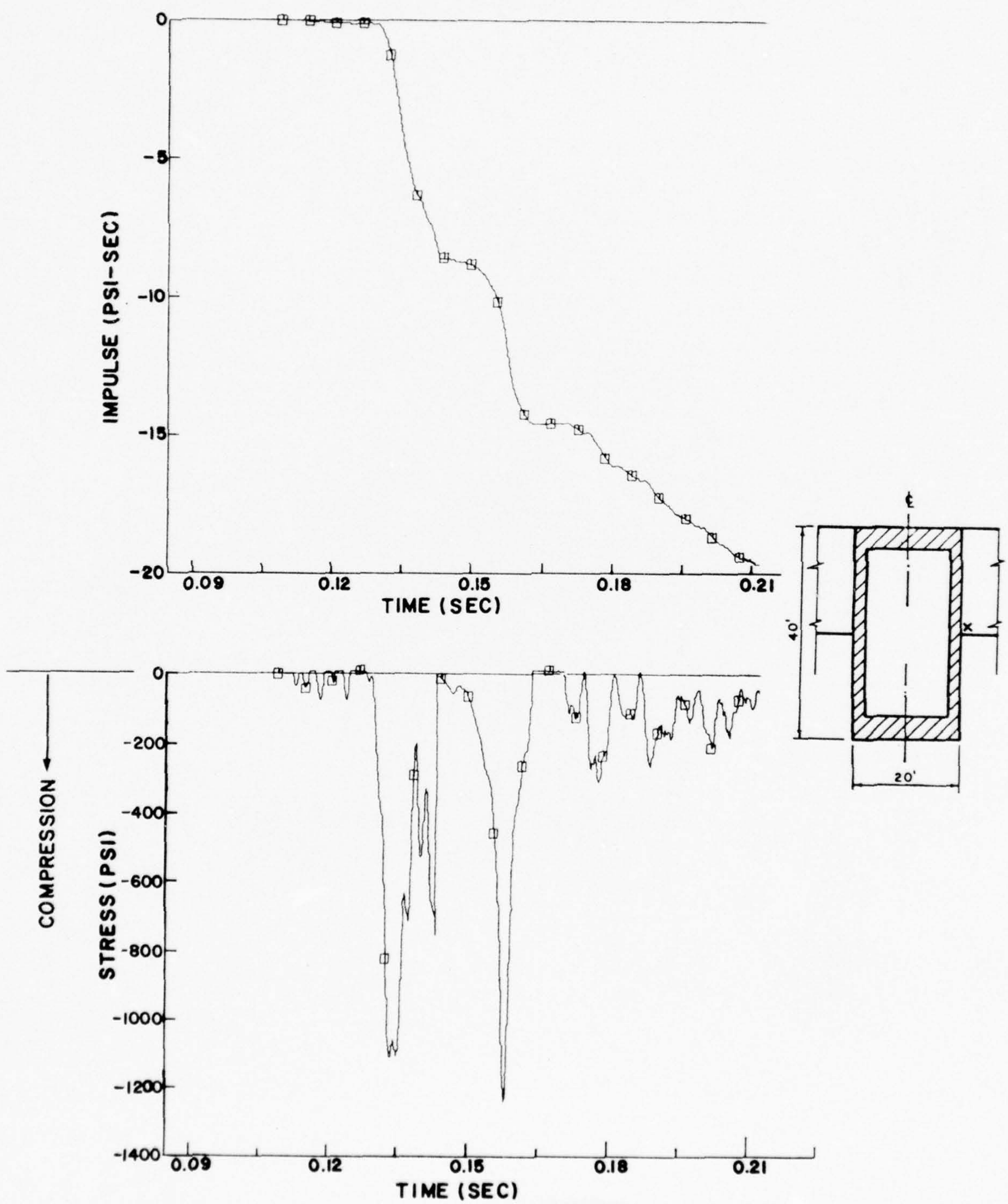


FIG. 17 PROBLEM P3 — VERTICAL STRESS AND IMPULSE 2 FT. ABOVE CLAY SHALE INTERFACE, 1 FT AWAY

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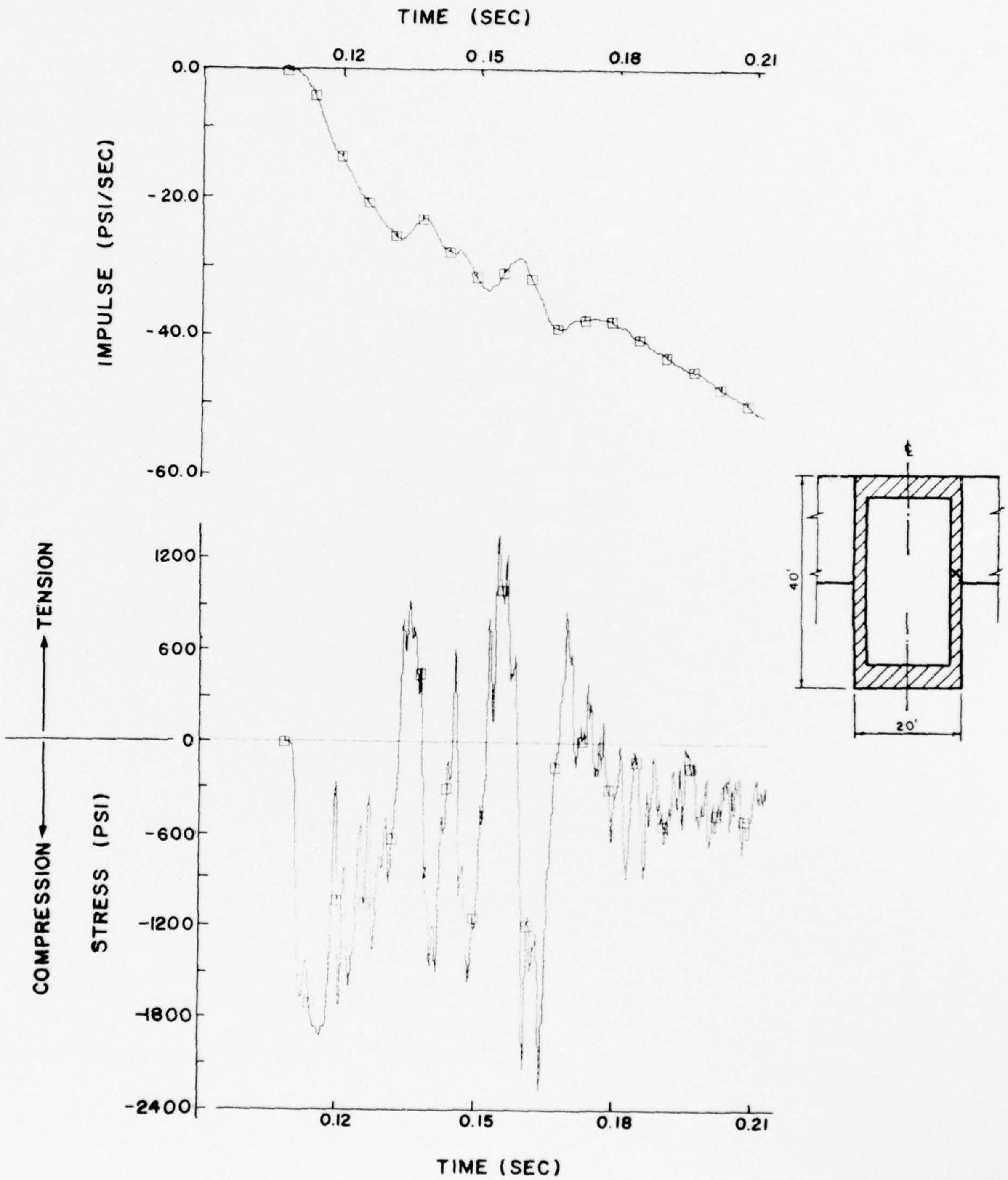

FIG. 18 PROBLEM P3 - VERTICAL STRESS AND IMPULSE IN SIDE WALL OF STRUCTURE

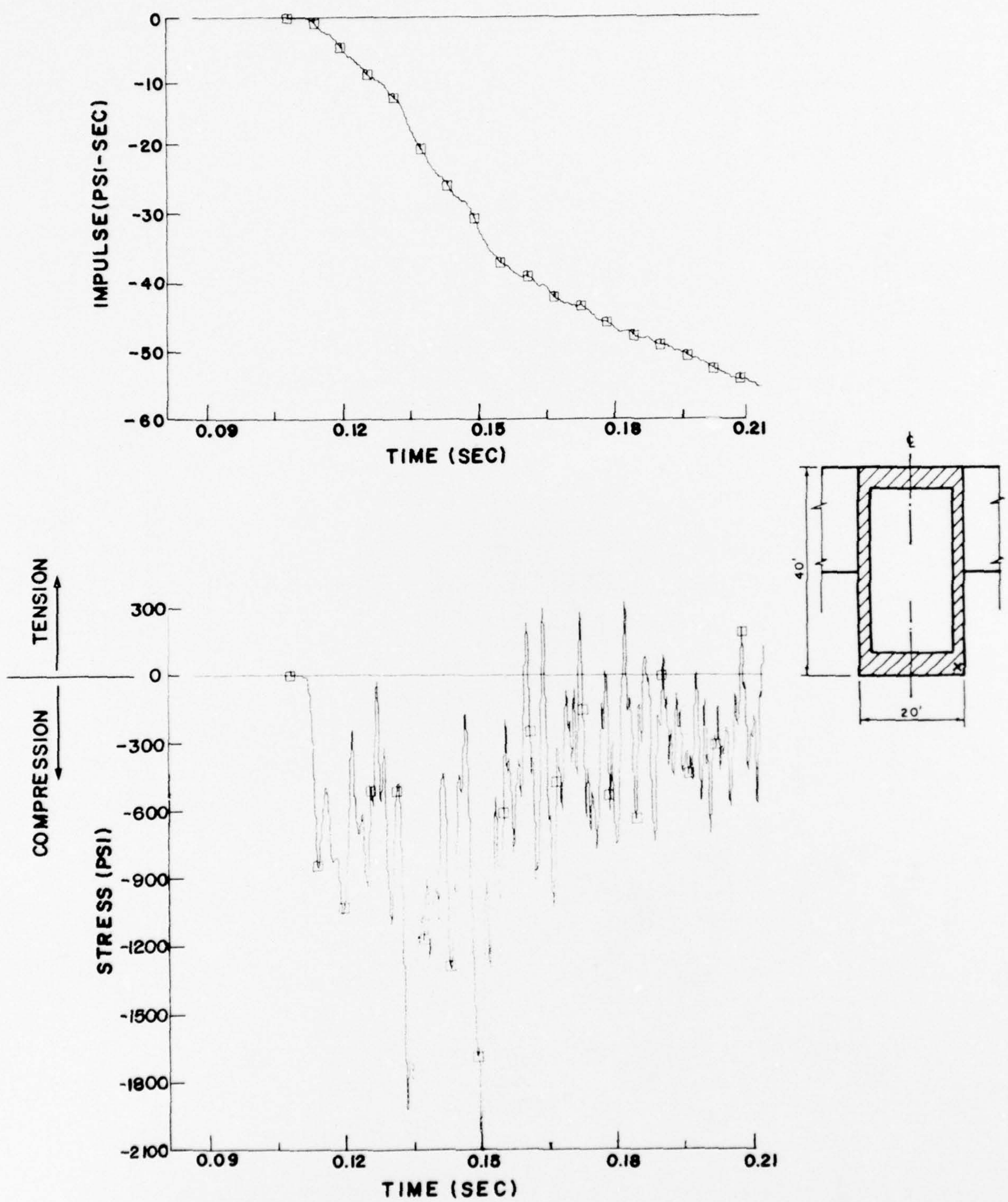

FIG.19 PROBLEM P3 - VERTICAL STRESS AND IMPULSE IN BOTTOM CORNER OF STRUCTURE

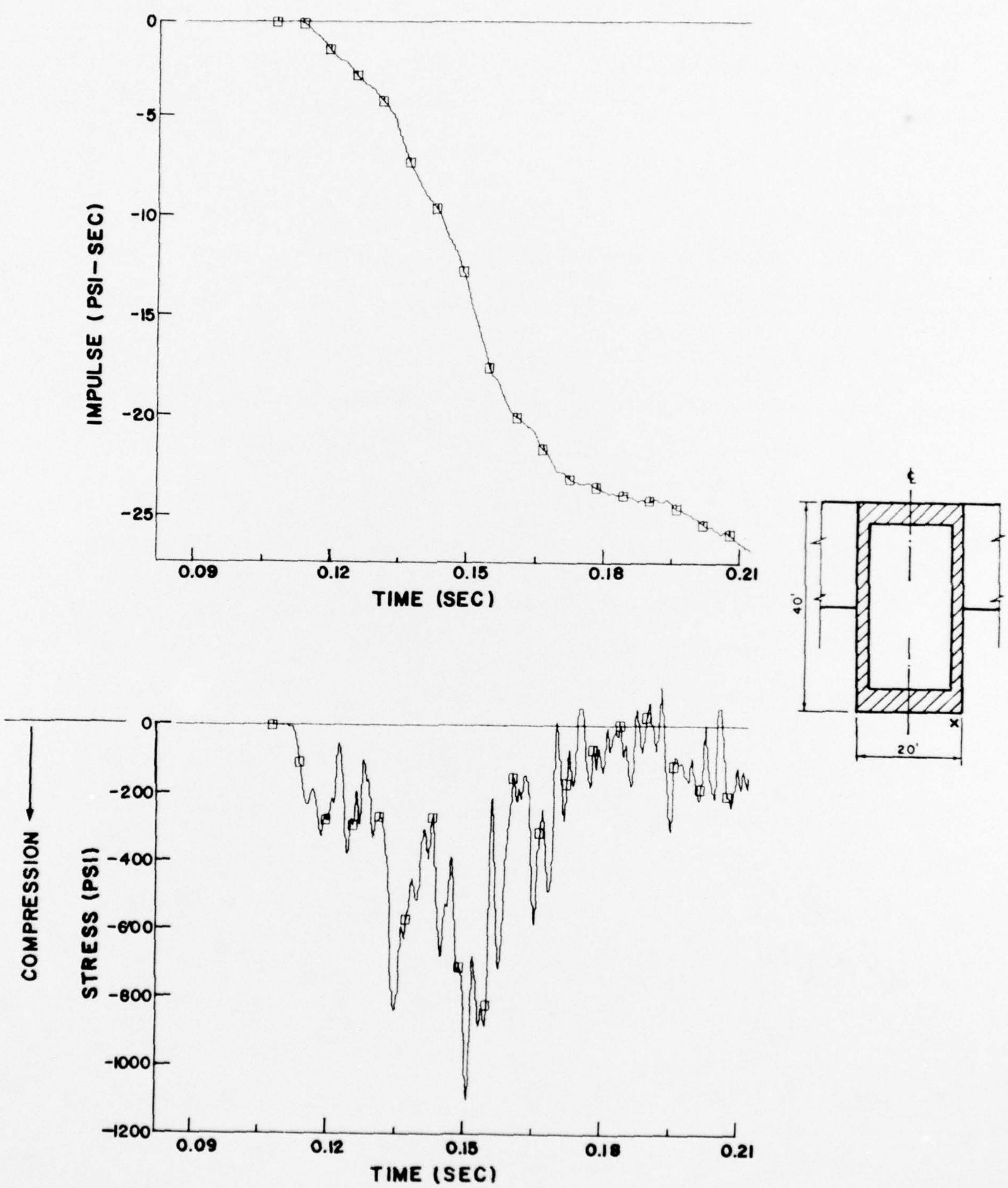

FIG. 20 PROBLEM P3 VERTICAL STRESS AND IMPULSE 2 FT BELOW BOTTOM CORNER OF STRUCTURE

On the other hand, the motion of the structure itself is quite different from the surrounding clay at the surface. As can be seen in Fig. 11, the top corner of the structure deflects rapidly about 0.4 inches, reverses slightly about 0.1 inches, further deflects quickly to about 0.9 inches, oscillates twice at roughly this level with an amplitude of about 0.1 inches and then deflects to a maximum displacement of about 1.6 inches. The oscillatory motion has a period of about 16 milliseconds. Since the dilatational wave speed of the concrete is about 10 ft/msec and its height is 40 ft., this period is just the time required for a wave to travel four times the height of the concrete. Four times is the correct number needed for a wave front to reflect (i) from the bottom, (ii) then the top, (iii) again the bottom and finally (iv) the top so that the velocities and stresses are both back in phase with the original wave front.

Again, by looking at a point about 4 ft. from the side wall of the structure, it is a simple matter to observe the similarity of the free-field motion and the results of problem P3. In particular, Fig. 14 should be compared with Fig. 9. In both cases the displacement rises to a value of about 1.4 inches in 30 milliseconds and then rises more slowly during the next 60 milliseconds to a peak of about 2.2 inches. Maximum velocities of about 100 in/sec occur in each case. Naturally, high frequency motions are affected as can be seen by comparing the velocity waveforms. However, judging from the displacements, the free-field is not significantly altered by the structure.

The maximum vertical impulse imparted to the surface during the first 100 milliseconds is about 22 psi-secs (calculated from the Brode simple fit, Ref. [5]). Figure 15 shows that the maximum impulse in the clay at a point near the top corner of the structure is about 21 psi-secs. Figure 17 shows a similar value of 20 psi-secs at a depth of 18 ft in the clay at a point next to the concrete wall. This indicates that the impulse imparted to the surface is conducted vertically through the clay to the interface without significant modification. On the other hand, the concrete structure has maximum impulse values in the wall of 52 and 54 psi-secs, as shown in Figs. 18 and 20. This is due to the fact that the load applied over the entire surface of the structure must be conducted down the relatively thin walls since the cylinder is hollow. In fact, the ratio of the wall impulse, I_w, to the surface impulse, I_s, should have the same value as the ratio of the top surface area of the structure to the wall area through which the vertical stress is conducted; that is,

$$\frac{I_w}{I_s} \approx \frac{A_s}{A_w} = \frac{10^2}{10^2-8^2} = 2.77$$

Since I_s is about 22 psi-sec, the value of I_w should be about 61 psi-secs. The fact that the peak is somewhat less in Figs. 18 and 20 probably reflects the fact that some impulse is transmitted to the surrounding soil (although not much).

Maximum stress values, while somewhat unreliable in this calculation, were always less than 2,400 psi in the concrete walls and, except for short durations (a few milliseconds), maximum stresses in the side walls were less than 2,000 psi which is much less than the assumed compressive strength (6,000 psi) of the concrete. This indicates that the walls of the structure will not fail in compression from a load of the type used in problem P3.

The largest observed stress anywhere in the structure was less than 6,000 psi and occurred in the middle of the top for about one millisecond. The calculations for the top are not particularly reliable though since only one element was used through the roof and a great deal of bending and shear behavior was evident. Additional study would be required to resolve the question of whether or not the top could fail under the assumed loading. Tensile failure in the Structure, assumed to be 667 psi in mean pressure, was observed occassionally but only for short durations and thus did not appear to be important in this problem.

Thus, the picture that emerges from problem P3 when problems P1 and P2 are considered is that (i) the structure and the surrounding soil interact very little and (ii) the side walls of the structure can survive the type of loading prescribed for problem P3. Only the survival of the top of the structure is in doubt and this question can be studied more economically by other methods. If a rapidly expanding load is prescribed, as in problem P2, then additional modes of behavior (two and three dimensional effects) can lead to additional interaction phenomena.

However, it appears highly unlikely that the walls of this structure will fail from a loading of this type during the first 100 milliseconds (which is probably the most critical period).

V SUMMARY AND CONCLUDING REMARKS

Vulnerability problems of interest to SAMSO require the simulation of soil-structure interaction effects due to nearby explosions. The SAMSO-TRW test problems have been used to check out various features of the TRANAL code and many of the capabilities required for such studies have been demonstrated.

For two of the test problems, TRANAL and LAYER results were compared and the differences can be understood in terms of code details such as surface pressure phasing and approximation techniques (finite element and finite difference).

The third problem, which involves an embedded hollow cylinder, is studied and it is concluded that, for the prescribed loading, (i) the structure and surrounding soil interact very little and (ii) the side walls of the structure will survive. However, these conclusions are based on a simple two dimensional, axisymmetric problem. In order to understand the vulnerability problem more fully, it is necessary to examine a three dimensional problem with a more realistic structural model and site profile.

Studies of the HARD PAN I-3 event are now under way (under SAMSO contract) in order to study a full 3-D case. In order to reduce this problem to manageable proportions, the soil-island method, Ref. [7], is being used with soil-island boundary motions produced from the LAYER code.

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