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Physical Security Division

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CRASH BARRIER ANALYSIS PROGRAM

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PREFACE

A major concern associated with the security of U.S. Department of State embassies and missions outside the continental United States is to protect facilities and compounds from vehicular intrusions. The first line of protection for a facility or compound is a barrier around the perimeter. This document, sponsored by the Department of State, Bureau of Diplomatic Security, Secure Technology Directorate, presents a description, operational instructions and technical background of the Crash Barrier Analysis Program. This program gives a reliable means of testing the strength of the barrier with out full scale crash testing.

Developed under the direction of Gerald E. Meyers, The Development of the Crash Barrier Analysis Program was prepared by Patricia K. Hammar and David Tyrell of the Transportation Systems Center. The authors would like to express their thanks to William Baron for the development of the AutoCAD portion of the program, Joan Schoengart and J. Christopher Dorsey for their work in developing and exercising the finite element models described in this report, Brandon Schwarz for his research on foundation behavior, and William T. Hathaway and Herbert Weinstock for their invaluable guidance throughout this entire project. In addition, the authors would like to thank Gerald E. Meyers for his exceptional direction and valuable insights into the needs of the Department of State.

METRIC / ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd) = 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2) = 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2) = 0.09 square meter (m^2)
1 square yard (sq yd, yd^2) = 0.8 square meter (m^2)
1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2)
1 acre = 0.4 hectares (he) = 4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gr)
1 pound (lb) = .45 kilogram (kg)
1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp) = 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (l)
1 pint (pt) = 0.47 liter (l)
1 quart (qt) = 0.96 liter (l)
1 gallon (gal) = 3.8 liters (l)
1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3) = 0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x - 32) (5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
1 square meter (m^2) = 1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2) = 0.4 square mile (sq mi, mi^2)
1 hectare (he) = 10,000 square meters (m^2) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gr) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg) = 1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml) = 0.03 fluid ounce (fl oz)
1 liter (l) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)
1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH-CENTIMETER LENGTH CONVERSION

INCHES: 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10

CENTIMETERS: 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 | 25.40

QUICK FAHRENHEIT-CELCIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and/or other conversion factors, see NBS Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50. SD Catalog No. C13 10 286.

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EXECUTIVE SUMMARY

The Transportation Systems Center has developed a computer program for analyzing the resistances of various stationary crash barrier designs to vehicle impact for the Department of State. This computer program is to be used as an aid in evaluating the suitability of alternate crash barrier designs for protecting different Department of State embassies. The program is developed for use on IBM Personal computers and compatibles so that it may be used 'on site' for evaluating crash barrier designs.

This report presents the analytical models of five different crash barrier designs and the analytical model of the proof vehicle which are implemented in the computer program. The five barrier designs for which analyses are presented are: a concrete wall barrier, a reinforced concrete wall barrier, a bollard barrier, an embedded jersey barrier, and a freestanding jersey barrier. The proof vehicle modeled is a Ford F600 truck loaded to a total weight of 15,000 pounds. The vehicle model is based upon measurements of vehicle deceleration in full-scale vehicle impact tests.

1. INTRODUCTION

This report presents the results of a study to develop a computer model to assist in analyzing the effects of vehicle attacks. The physical security program of the Department of State (DOS) has five tiers, the first of which is perimeter protection. Perimeter barriers are structures designed to protect an embassy by preventing an attacking vehicle from penetrating the embassy compound. The current designs are costly and there are also U.S. Diplomatic missions which can not use the current barrier designs. Each design change means the new barrier must undergo full-scale crash tests which are costly. The cost quickly escalates when a barrier does not pass the first test and must be redesigned and tested again.

The goal of this computer program is to evaluate the adequacy of potential barrier designs and thereby reduce full scale crash tests. Furthermore, this program should allow the DOS personnel to identify the necessary size of the barrier and to eliminate the need to excessively over build. It should also be capable of exploring variations of the barriers which may fit currently unmet needs. The fundamental approach to Embassy security is to develop the appropriate standards and enforce them throughout the world. One step in enforcing these standards is having a reliable and inexpensive means of testing barriers to establish if they are meeting the standards.

1.1 SCOPE

The computer model presented in this report analyzes the resistance of various crash barrier designs to vehicle impact. This program is to be used as an aid in evaluating the suitability of alternate crash barrier designs for protecting U.S. diplomatic missions. The program is developed for use on IBM personal computers and compatibles so that it may be used 'on site' for evaluating crash barrier designs.

Currently, the Crash Barrier Analysis Program can analyze the response of five different barrier configurations, a bollard barrier, a concrete wall barrier, a reinforced concrete wall, an embedded double jersey barrier with fill, and a freestanding double jersey barrier with fill.

With the exception of the free-standing double jersey with fill, each of these barrier types allows for a foundation to stabilize the barrier. Other barrier configurations could be added easily due to the modular approach of this model.

The user chooses the physical parameters of the barrier, such as height, depth, etc. A computer generated drawing is then shown of the barrier with these parameters and then the barrier design is analyzed by the model.

The impacting vehicle used in the analysis is a Ford F600 truck loaded to a total weight of 15,000 pounds. The vehicle impact speed is chosen by the user. The program determines the response of the barrier while the vehicle is in contact with the barrier.

The program determines the degree of damage, if any, from the vehicle impact. For both the simple concrete and reinforced concrete wall barriers the program considers yielding of the concrete as failure of the barrier, while for the bollard model the computer program considers first yield or plastic hinge of the steel pipe as failure of the barrier. The output of the computer program includes plots of forces acting on the barrier versus time, barrier displacement (at the point of vehicle impact) versus time, and vehicle speed and crush versus time.

The vehicle model used in the analysis allows for the vehicle to absorb some of the energy and is based upon measurements of vehicle deceleration in full scale vehicle impact tests. The resistance characteristics of the barriers are based upon analytical calculations. In order to provide a verification of the program further testing will be required with more complete barrier instrumentation.

1.2 BACKGROUND

The situation modelled in this report is a vehicle impacting a stationary barrier. Examples of Stationary barriers include freestanding jersey barrier, such as barriers used to separate lanes of traffic on the highway, and bollard or pipe barriers, the vertical embedded pipes used to protect the drive-up windows at banks or fast food restaurants. Figure 1 is a sketch of a vehicle about to hit a stationary barrier, in this case a concrete wall.

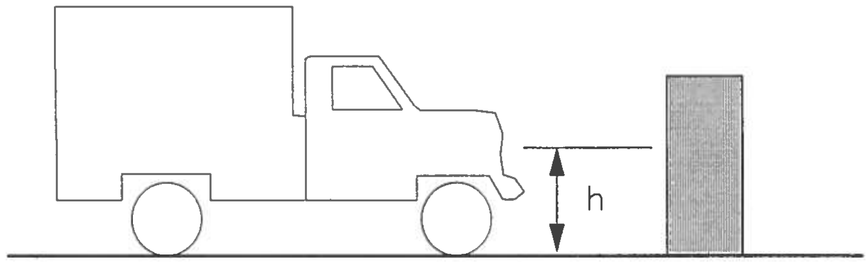

Figure 1. Sketch of a Vehicle Impact into a Stationary Barrier.

As part of the effort of evaluating crash barriers, the Department of State has conducted a series of full-scale crash tests of a FORD F600 proof vehicle crashed into a variety of barriers. Table 1 contains a summary of some of these barrier tests. In each test, a Ford F600 was loaded to a weight of approximately 15,000 lbs and run into the center of the barrier.

Table 1. Summary of Stationary Crash Barrier Tests

Test	Speed (mph)	Wall Construction	Outcome
SS-1 [1]	47.9	Reinforced concrete wall with brick facade	Wall collapsed, vehicle penetrated
DS-6 [2]	29.2	Reinforced concrete	Wall intact
DS-6a [3]	43.8	Reinforced concrete, same wall as DS-6	Cracks through wall, vehicle did not penetrate
DS-7 [4]	34.0	Reinforced concrete	Wall intact
DS-8 [5]	49.4	Concrete cinder blocks	Wall collapsed, vehicle penetrated
DS-9 [6]	50.2	Reinforced concrete	Wall intact, vehicle instrumentation failure after 50 milliseconds
DS-10 [7]	48.6	Steel pipe bollards	Bollards intact

The analysis done by the computer model will approximate the full scale tests by using a segment of barrier 40 feet long and the vehicle will strike the barrier perpendicularly in the center of the segment.

2 . OPERATION OF CRASH BARRIER ANALYSIS PROGRAM

2.1 SYSTEM REQUIREMENTS

There are two ways to run the Crash Barrier Analysis Program. It has been created to run with AutoCAD or without AutoCAD. AutoCAD is a licensed program and can not be released with the software. The AutoCAD version has a graphic interface and creates scaled drawings of the barriers, the stand alone version does not have the graphic interface. The following instructions will be split in two sections, one for the AutoCAD version and one for the stand alone version.

The Crash Barrier Analysis Program requires a IBM PC compatible or higher with at least 640K of RAM with CGA, EGA, VGA or Hercules Video Card. If the AutoCAD portion of the program is used you must have a Hercules, VGA or EGA video card, a mouse and a math coprocessor. The AutoCAD portion is designed to run with a mouse, although the mouse is not absolutely necessary, the program is much quicker and easier to use with a mouse.

The Crash Barrier Analysis Program comes on two disks. Disk 1 contains all the files necessary for the stand alone version of the program. Disk 2 contains the changes to the stand alone version and the changes to AutoCAD that allow the program to work with AutoCAD. Before using any program, the disks should be copied for a back up in case of an emergency.

If desired the Stand Alone version of the Crash Barrier Analysis Program can be run from a floppy. To do this the commands are:

(insert Floppy Disk 1 into drive a:)

a:	(this command moves you to drive a)
crash	(this command runs the program)

The menu will appear and you can begin the analysis.

2.2 STAND ALONE VERSION INSTALLATION

If you want to install the stand alone version of the program onto the hard drive (C:), when in drive C the commands are:

cd\	(this command moves you out of any directory)
Md crash	(this command makes the directory crash)
(insert the Floppy Disk 1 into drive a:)	
A:	(this command moves you to drive a:)
copy *.* C:\crash	(this command copies the files to drive C)

To run the program the commands are:

C:	(this command moves you back to drive C)
cd\crash	(this command moves you into the directory C:\CRASH)
crash	(this command runs the program)

The menu will appear and you can begin the analysis.

2.3 AUTOCAD VERSION INSTALLATION

Floppy Disk 2 contains the files necessary to use AutoCAD with the program, these files are contained in two directories, A:\ACAD and A:\CRASH. First, install AutoCAD on your machine. The Crash Barrier AutoCAD portion is set up for AutoCAD to be in C:\ACAD, if your AutoCAD is in a different directory it should be renamed acad or the batch files in the Crash Barrier Analysis Program must be changed. Next, install the stand alone version (disk 1) as directed above. At this point two subdirectories are present on your hard drive, CRASH and ACAD. We will next install some of the files on Disk 2 into the two directories. To install the AutoCAD portion of the program the commands are:

```
cd\acad              (this command moves you into the directory acad)
(insert Floppy Disk 2 into drive 'a')
copy a:\acad\*.*  (this command copies all the files from directory
                      a:\acad into directory c:\acad)
```

As stated before, the AutoCAD files must also be in this directory. The only files which come with the computer program are the files made in AutoCAD which are specific to the Crash Barrier Analysis Program.

The rest of the floppy disk should be copied into directory CRASH with the following commands:

```
cd\crash             (this command moves you into the directory crash)
(insert Floppy Disk 2 into drive 'a')
copy a:\crash\*.*    (this command copies all the files from directory
                     a:\crash into directory c:\crash)
```

The floppy disks are not needed thereafter, though they should be kept as a backup.

3. DESCRIPTION OF CRASH BARRIER ANALYSIS PROGRAM

The Crash Barrier Analysis Program is a combination of programs, combining a Fortran analysis program, a graphing program, and either AutoCAD or the nongraphic input program. These components each have their own menu and can be accessed from each menu with ease. When the program is run (crash is typed in the crash directory) the analysis menu appears.

The analysis menu, shown in Figure 2, allows the user 10 choices (the stand alone version of the software only allows the user 9 choices since creating input data files with AutoCAD is not an option). These choices are to enter the two input programs, analyze any of the five barrier types, view or print output, or quit the program.

```
Select the number corresponding to the analysis
        you would like to perform

        1.       Create Input Data Files (with Autocad)
        2        Create Input Data Files (without Autocad)
        3.       Bollard Barrier Analysis
        4.       Concrete Wall Analysis
        5.       Reinforced Concrete Analysis
        6.       Free Standing Jersey Barrier Analysis
        7.       Embedded Jersey Barrier Analysis
        8.       View Plots On Screen
        9.       Print Analysis Output and Plots
        10.      Quit
```

Figure 2. Analysis Menu

This is the only menu from which you are given the option of quitting the program. If you choose quit you will be back in DOS.

3.1 INPUT OPTIONS

If you choose to create data files you can enter barrier characteristics.

3.1.1 Drawing and Design Menu (AutoCAD)

The drawing and design menu is in AutoCAD and it leads the user through the design of a barrier. This menu is shown in Figure 3. The user has two paths through this menu, one is DESIGN where the user can choose the type of barrier to design, go through the design then DRAW which will have the computer draw the picture so that they can review their design. If the drawing is not desired the user can skip the DRAW portion. The other path is CHOOSE menu (Figure 4) where the barrier is chosen from small pictures of the barrier types, the barrier characteristics are input and then the barrier is immediately drawn.

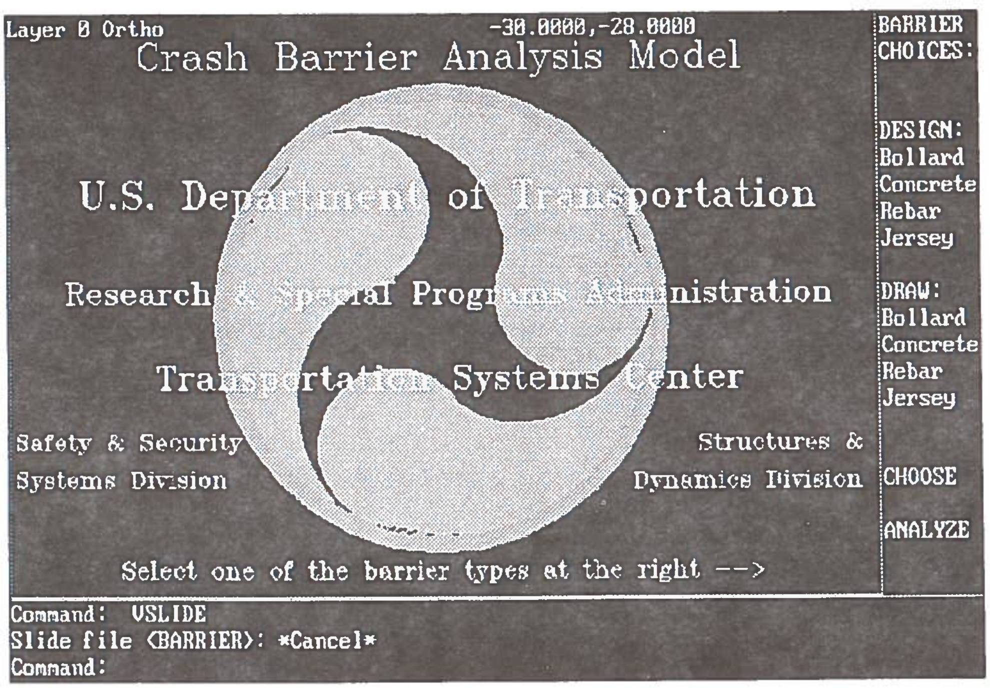

Figure 3. AutoCAD Menu

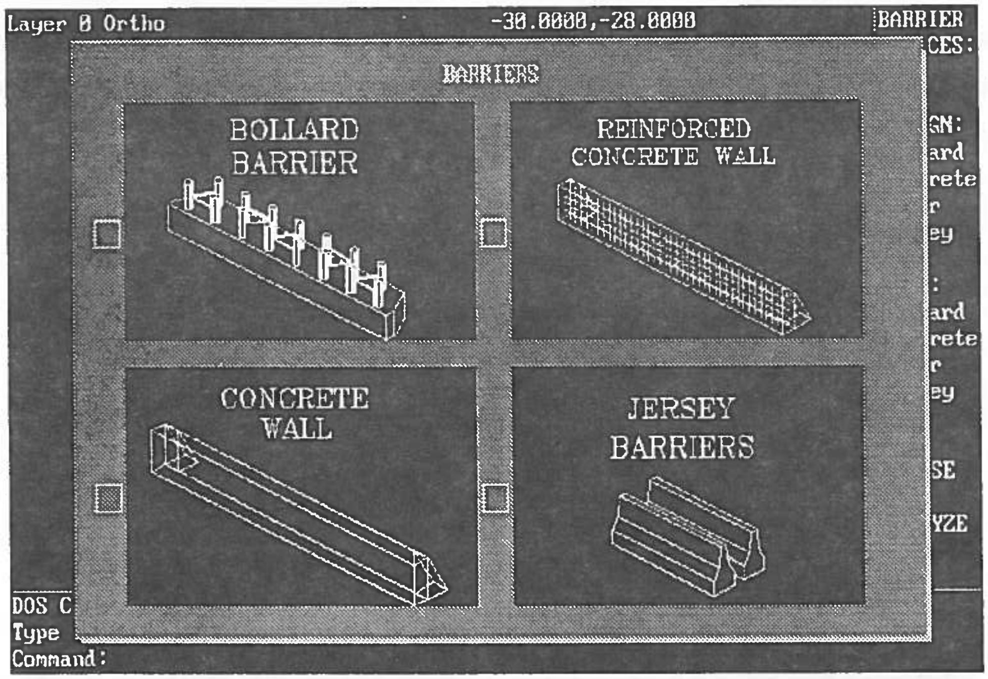

Figure 4. Choose Menu

For each barrier type, the dimensions of the barrier, the vehicle speed, and the soil type must be entered in addition to barrier specific questions. (The soil type is not required for the free standing jersey barrier.) The soil type options are:

1. Hard Clay
2. Dense Sand
3. Dense Sand and Gravel
4. DOS Backfill Specifications

The specifics about each soil type are found in Section 6.

3.1.1.1 Bollard

When DESIGN: Bollard is chosen you will see a picture of a bollard barrier as shown in Figure 5, Bollard Barrier. The computer will then query for the dimensions A - G as shown in Figure 5. All dimensions should be in inches. The dimensions are the width of the barrier (A), the height (B), the height of the bollards above the foundation (C) (the height must be at least 30 inches), the schedule size of the bollard (D) (the schedule sizes are 5, 6, 8, 10, and 12 inches), the distance between the bollards (E), the distance between the bollard rows (F), and the height of the support rods (G). In addition to these dimensions, the computer will query for whether the bollards are concrete filled.

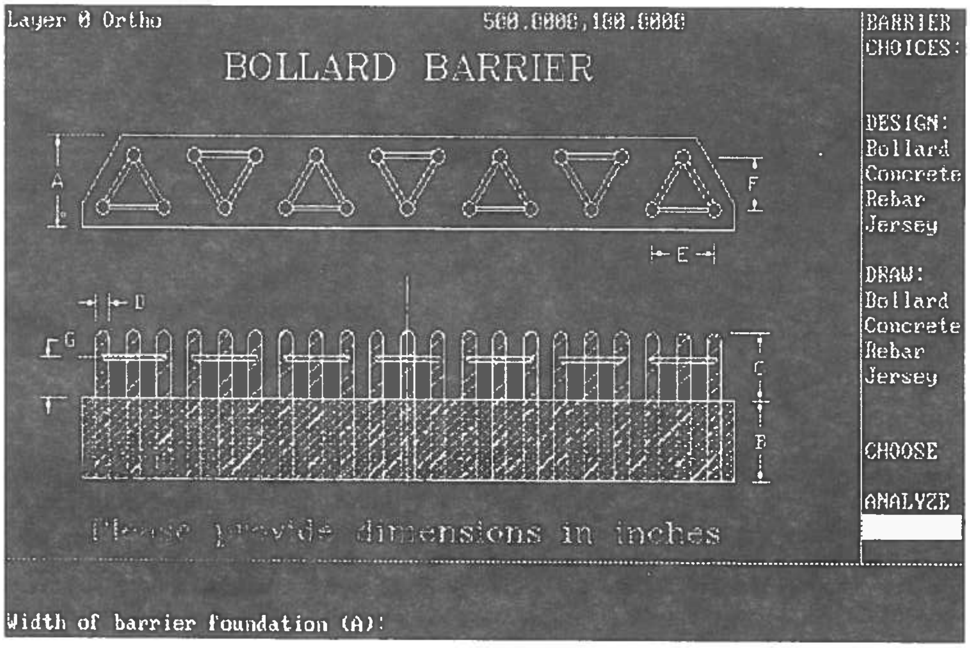

Figure 5. Bollard Barrier

When DRAW: Bollard is chosen the bollard barrier will be drawn with the dimensions given in DESIGN: Bollard. If no bollard has been designed, you can not draw a bollard barrier. An example is shown in Figure 6.

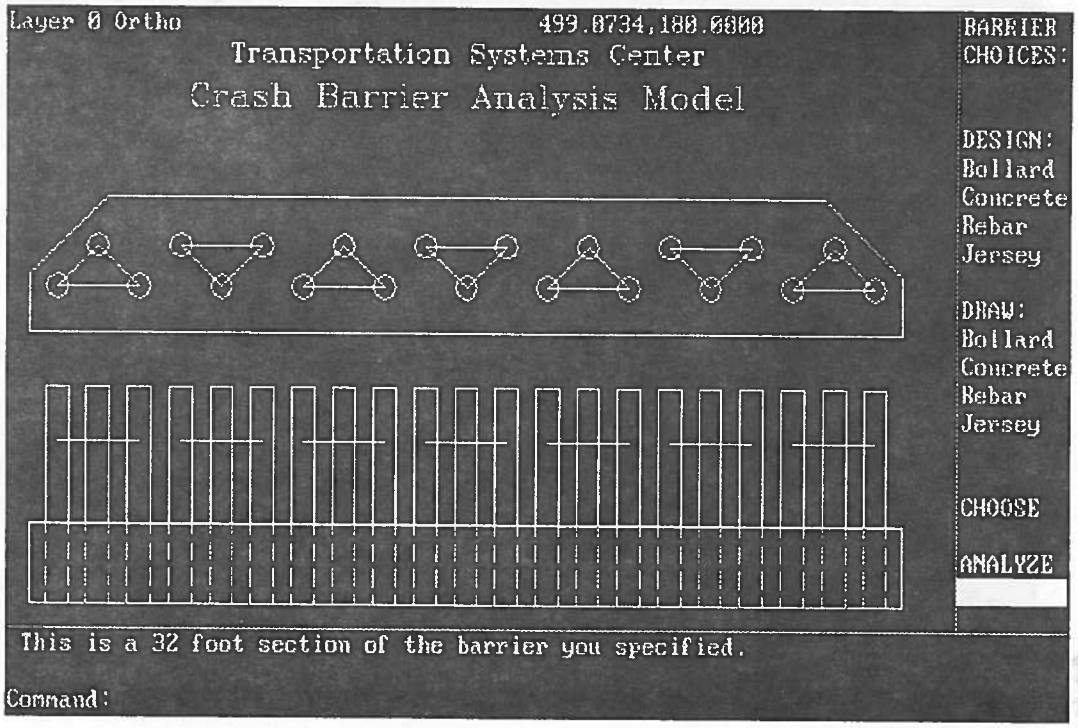

Figure 6. Custom Bollard Barrier

3.1.1.2 Concrete Wall

When DESIGN: Concrete is chosen you will see a picture of a concrete wall (inverted T) as shown in Figure 7, Concrete wall. The computer will then query for the dimensions A - E as shown in Figure 7. The dimensions are height of the wall above ground (A) (between 30 and 108 inches), the thickness of the wall (B) (between 12 and 36 inches), width of footing (C), depth of wall below ground (D), and height of wall foundation (E) (the sum of height of wall foundation & depth of wall below ground must be 24 inches).

When DRAW: Concrete is chosen the concrete wall will be drawn with the dimensions given in DESIGN: Concrete. If no concrete wall has been designed, you can not draw a concrete wall. An example is shown in Figure 8.

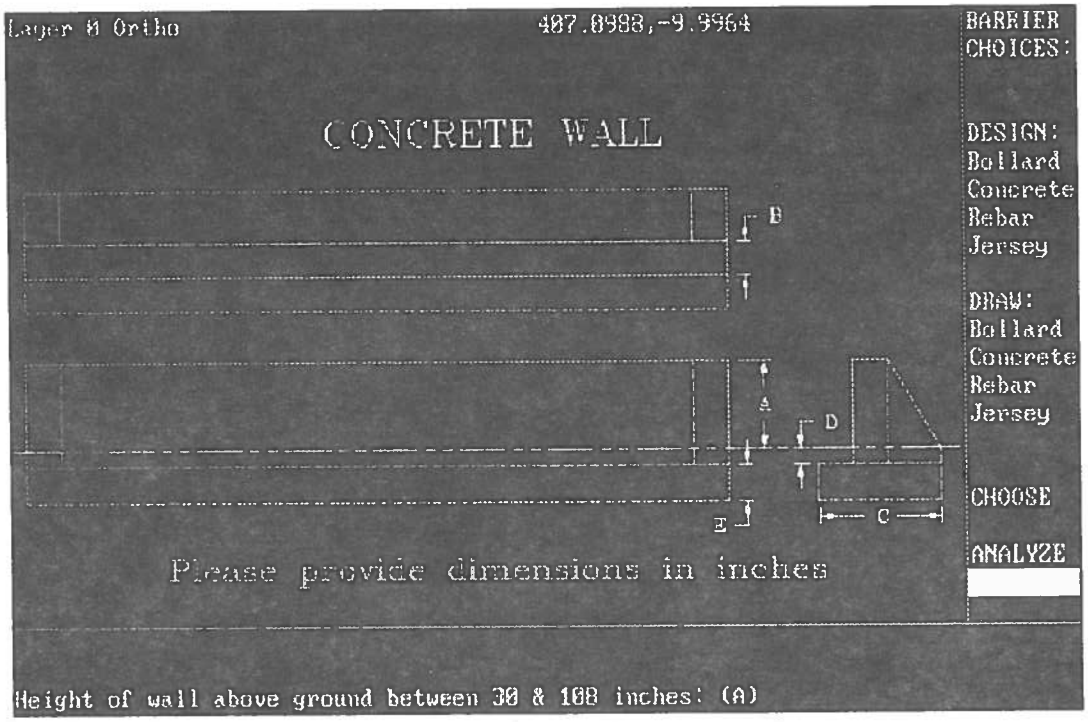

Figure 7. Concrete Wall

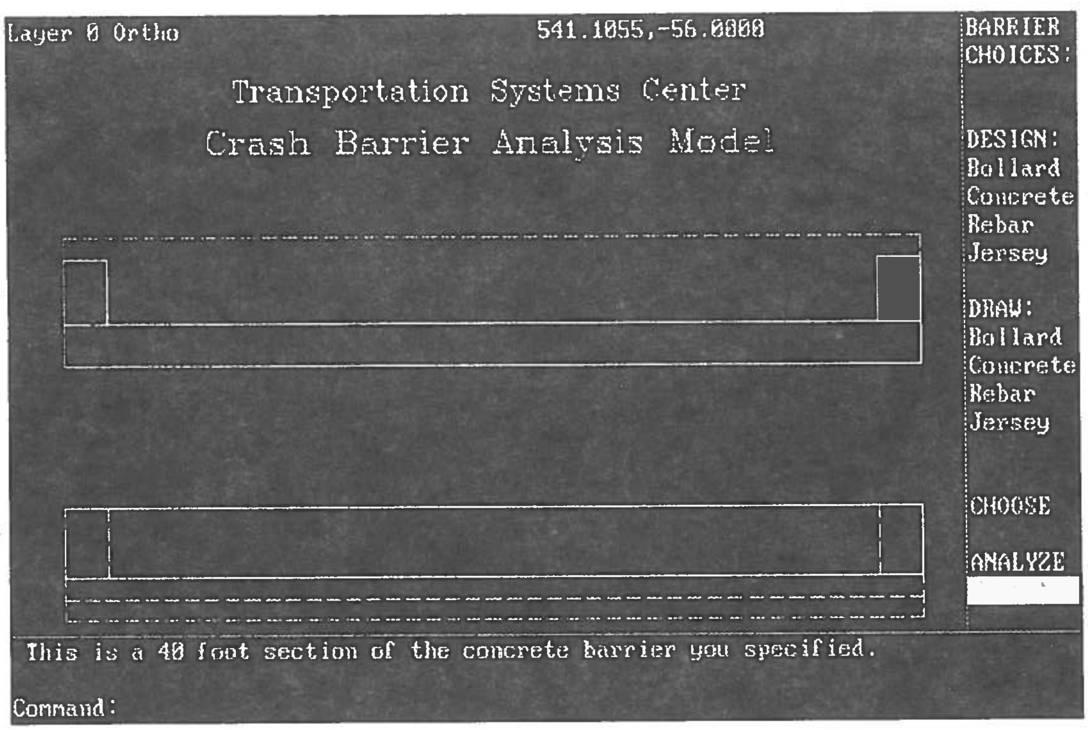

Figure 8. Custom Concrete Wall

3.1.1.3 Reinforced Concrete Wall

When DESIGN: Rebar is chosen you will see a picture of a reinforced concrete wall as shown in Figure 9 Reinforced Concrete wall. The computer will then query for the dimensions A - F as shown in Figure 9. The dimensions are height of the wall above ground (A) (between 30 and 108 inches), the thickness of the wall (B) (between 12 and 36 inches), spacing of Rebar (C) (6, 12, 18, or 24 inches), width of footing (D), depth of wall below ground (F), and height of wall foundation (E) (the sum of height of wall foundation & depth of wall below ground must be 24 inches). In addition to the dimensions the program queries for number of rebar selected (3 through 11) and the grade of rebar (40, 50, or 60). Information concerning this information is found in Section 7.3.

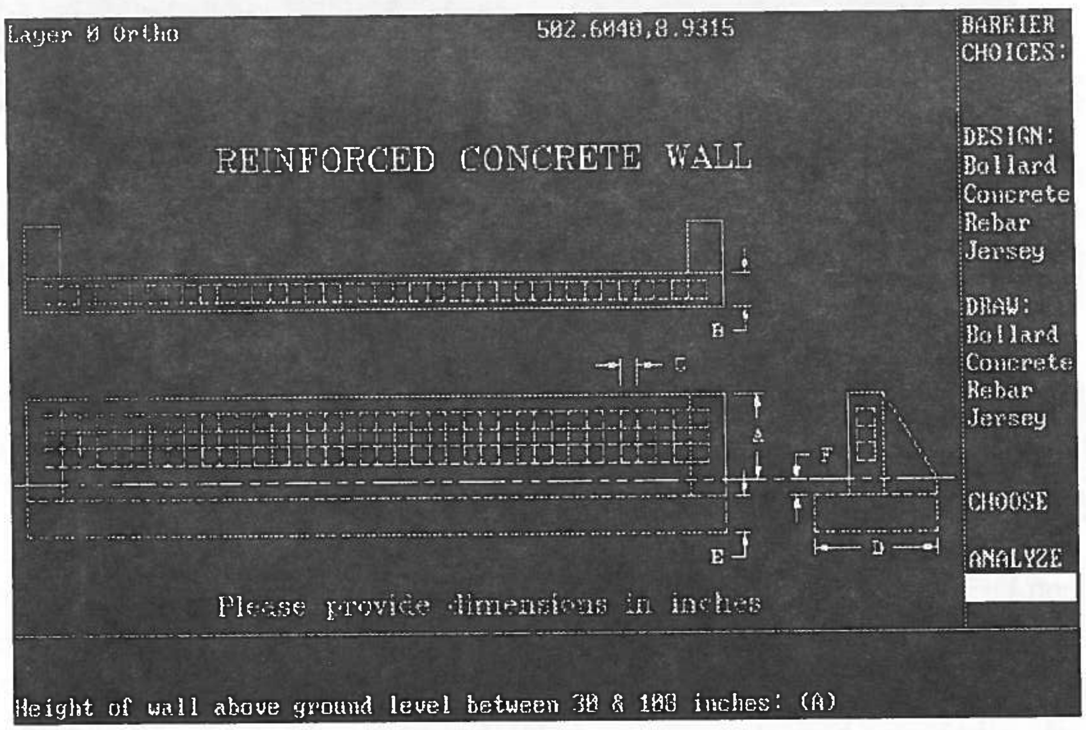

Figure 9. Reinforced Concrete Wall

When DRAW: Rebar is chosen the reinforced concrete wall will be drawn with the dimensions given in DESIGN: Rebar. If no reinforced concrete wall has been designed, you can not draw a reinforced concrete wall. An example is shown in Figure 10.

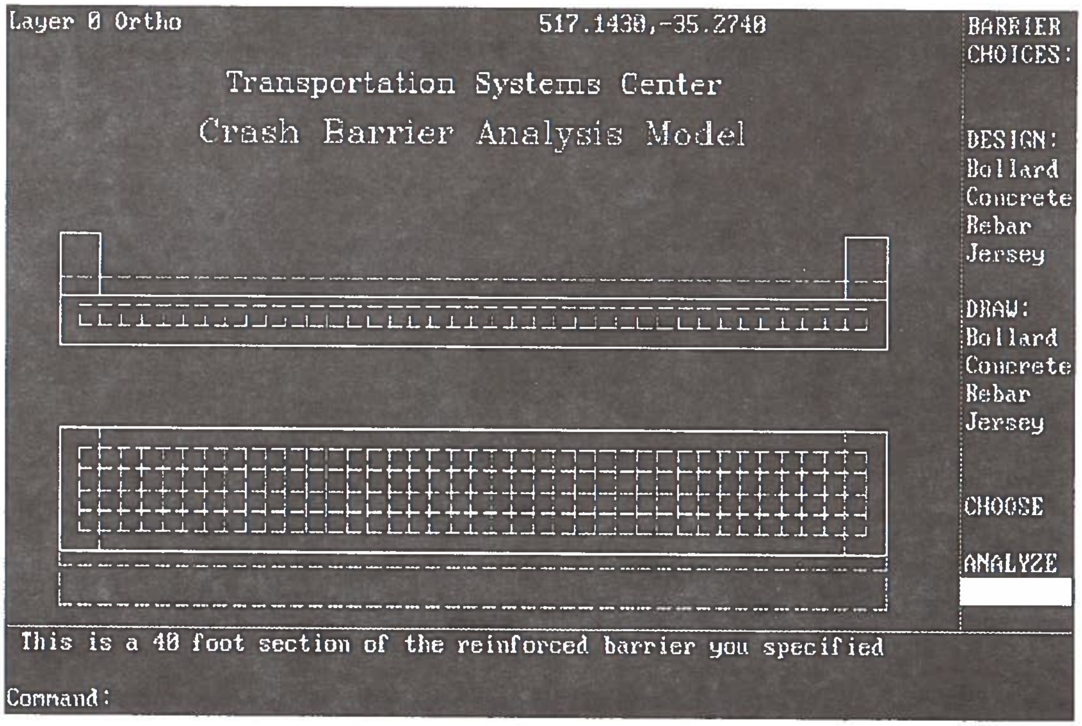

Figure 10. Custom Concrete Wall

3.1.1.4 Jersey Barrier

The Jersey Barrier in this model represent 2 commercially available jersey barriers with soil fill between them. The barriers are available commercially either flat for the free standing jersey barrier or with a 9 inch footing that must be embedded.

When DESIGN: Jersey is chosen the program will query whether the barrier is embedded (Y) or free standing (N). When N is chosen a picture of a free standing jersey barrier is shown as in Figure 11 Free Standing Jersey Barrier. The computer will then query for the spacing between barriers (A) as shown in Figure 11. In addition, the coefficient of friction must be entered (between .2 and .9 depending on the surface the barrier is placed on).

When Y is chosen, a picture of a embedded jersey barrier is shown as in Figure 12, Embedded Jersey Barrier. The computer will then query for the dimensions A - C as shown in Figure

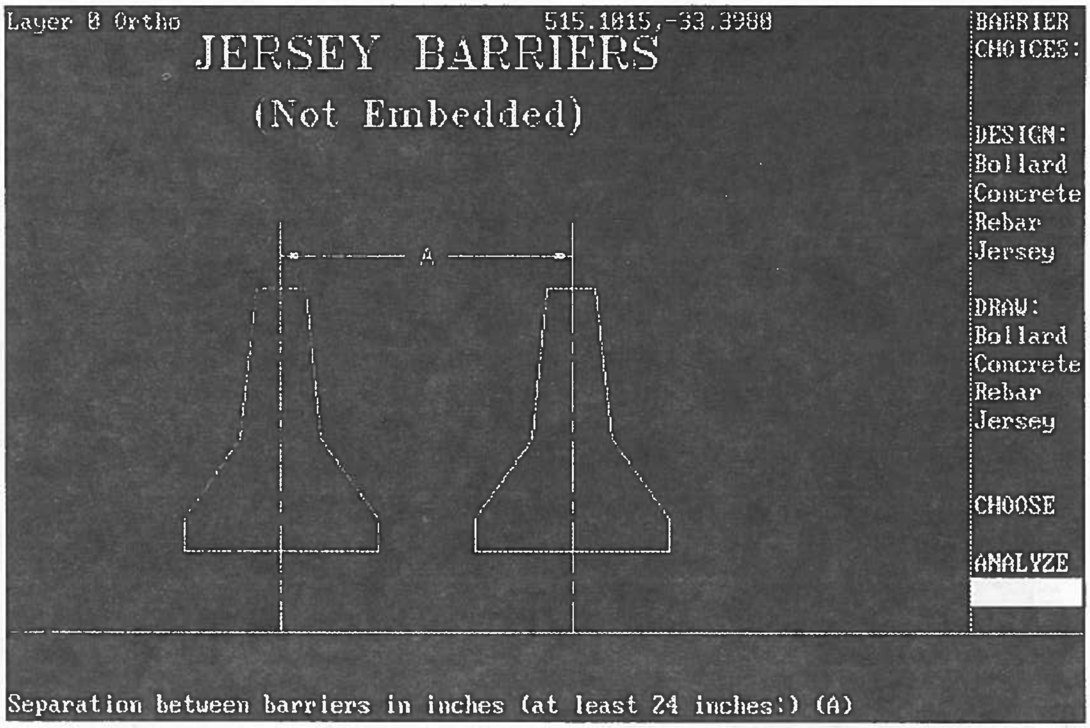

Figure 11. Free Standing Jersey Barrier

12. The dimensions are separation between barriers (A), width of footing (B), and depth of footing (C). In addition to these dimensions the program queries for the soil angle of shear resistance (between 15 and 45 degrees), for more information refer to Section 7.4.

When DRAW: Jersey is chosen the Jersey Barrier designed last, either embedded or freestanding, will be drawn with the dimensions given in Design: Jersey. If no Jersey Barrier has been designed, you can not draw a Jersey Barrier. An example is shown in Figure 13.

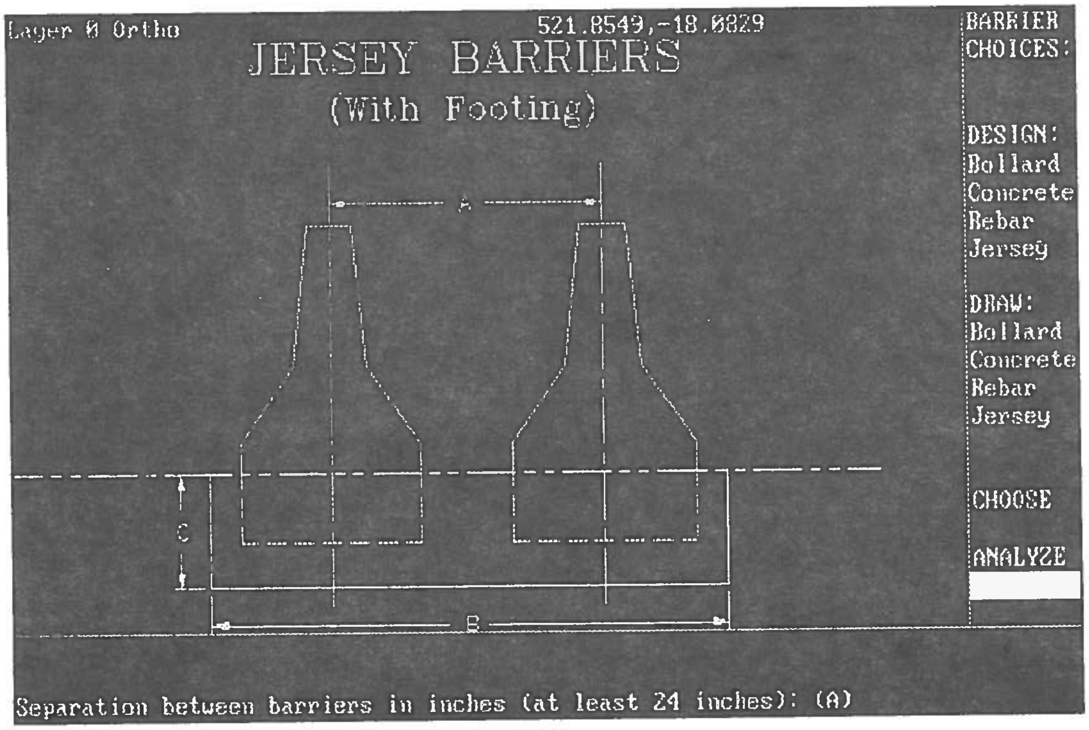

Figure 12. Embedded Jersey Barrier

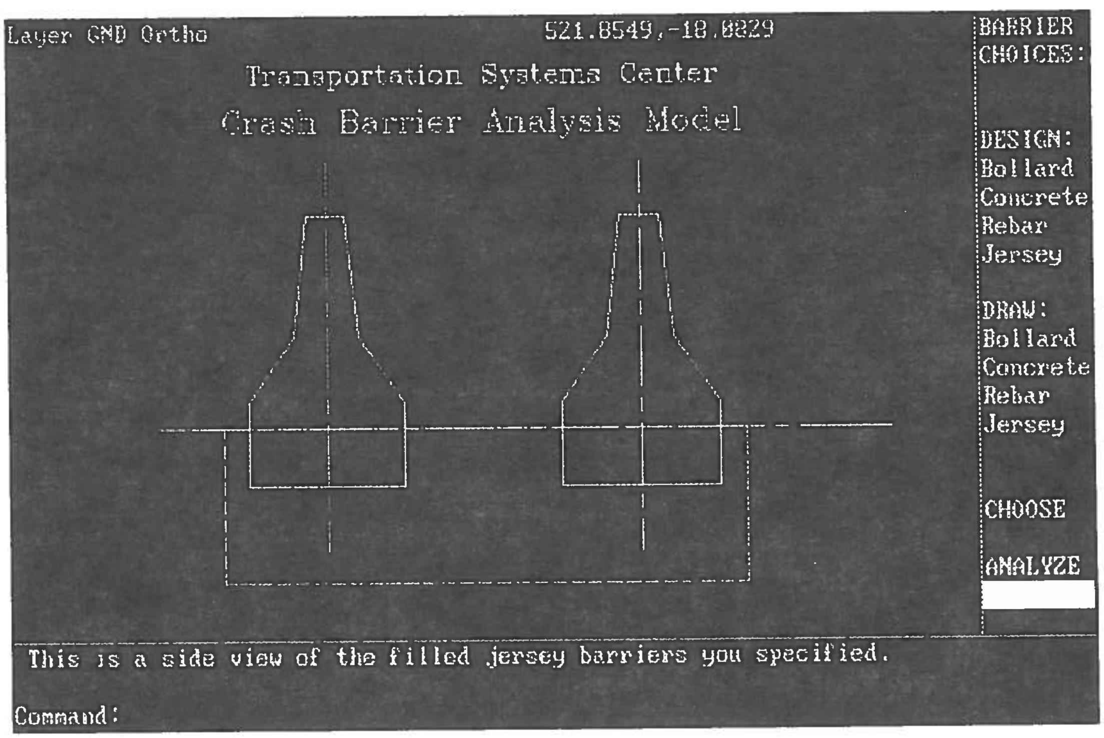

Figure 13. Custom Jersey Barrier

3.1.1.5 Analysis Menu

This choice should be made after the barrier is input. This choice will send you back to the analysis menu to choose your analysis option. This analysis options will be discussed below.

3.1.2 Alternate Input Menu

The alternate input menu allows the user to input the same material as the AutoCAD portion without the pictures of the barrier or the ability to draw and/or print the barriers designed. The alternate input menu is shown in Figure 14.

```
                         BARRIER SELECTION

                   <1>  BOLLARD BARRIER

                   <2>  CONCRETE BARRIER

                   <3>  REBAR BARRIER

                   <4>  FREE STANDING JERSEY BARRIER

                   <5>  EMBEDDED JERSEY BARRIER

                   <6>  ANALYSIS MENU

      PLEASE ENTER THE NUMBER OF THE BARRIER TO BE ANALYZED.
```

Figure 14. Alternate Input Menu

3.2 ANALYSIS OPTIONS

If you choose to analyze one of the barrier types, you will immediately get the analysis screen, shown in Figure 15, Analysis screen for Bollard Barrier, this screen is slightly different for each type of barrier but for each it gives the brief description of what the program does, the degree of freedom of the model, the force acting on the barrier, and the barrier characteristics.

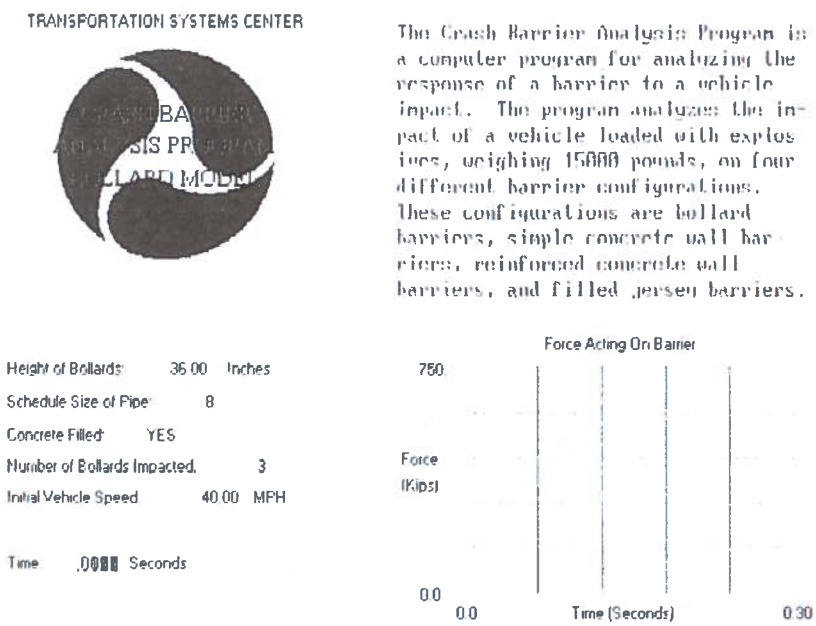

Figure 15. Analysis Screen

For the bollard the barrier characteristics given are the height of the bollards, schedule size of the bollard pipe, whether or not the pipes are concrete filled, the number of bollards which will be impacted by the vehicle and the initial speed of the vehicle. The number of bollards is computed by assuming the minimum number of bollards which can be impacted by an eight foot wide vehicle. Similar information is given for each barrier type on the analysis screen.

At the bottom, right hand side of the screen there will either be a graph which plots force acting on the barrier versus time or there will be a message about the maximum force acting on the barrier. When this is complete a message will appear that says to hit enter to continue.

3.3 OUTPUT OPTIONS

The output is different depending on which analysis is completed. If the two degree-of-freedom model is used the program creates an output report and 3 graphs. If the one degree-of-freedom model is used only the output report is created.

3.3.1 View Plots On Screen

View plots on screen can only be used when the two degree-of-freedom model was used. When chosen from the analysis menu, the Plotting Program menu appears (Figure 16). The three graphs created are force acting on barrier versus time, barrier displacement versus time, and vehicle displacement and velocity versus time.

*********** PLOTTING PROGRAM FOR CRASH BARRIER PROGRAM (CBMODEL) ***********

1) VIEW FORCE ACTING ON BARRIER - vs - TIME PLOT

2) VIEW BARRIER DISPLACEMENT - vs - TIME PLOT

3) VIEW (VEHICLE REACTION) DISP. & VEL. - vs - TIME PLOT

4) VIEW GRAPHS IN SUCCESSION

5) RETURN TO MAIN MENU

-----> PLEASE CHOOSE A NUMBER BETWEEN 1 AND 5 ----->.

Figure 16. Plotting Menu

3.3.2 Print Analysis Output and Plots

The print analysis output and plots option prints the output available for the analysis complete. An example of the analysis output is shown in Figure 17.

Crash Barrier Analysis Program *Date: February 8, 1991*
Transportation Systems Center *Time: 9:55*
US Department of Transportation

BOLLARD BARRIER ANALYSIS
Single Degree of Freedom Model

ANALYSIS RESULTS

Maximum Force Acting on Barrier: 285.611100 Kips
Steel Bollard Maximum Bending Stress: 294815.200000 psi

Maximum Barrier Rotation: 3.953173 Degrees
Maximum Barrier Displacement at Point of Impact: 3.326768 Inches

Number of Bollards Hit During Impact: 1
Barrier Weight: 24086.780000 lbs
Barrier Inertia: 10549.690000 in-lbs-seconds^2
Foundation Stiffness: 1.996251E+08 in-lbs/radian
Barrier/Foundation Natural Frequency: 21.893140 Hz

INPUT DATA

Barrier Data

Foundation Width: 24.000000 Inches
Foundation Depth: 24.000000 Inches
Bollard Height Above Ground Elevation: 24.000000 Inches
Bollard Lateral Spacing: 44.000000 Inches
Bollard (Extra Strong Pipe) Nominal Diameter: 8Inches
Bollards are NOT filled with concrete.
Soil Type: Dense Sand

Vehicle Data

Impact Speed: 44.000000 MPH
Vehicle Weight: 15000.050000 lbs
Vehicle Impact Stiffness: 3504.000000 lbs/Inch
Vehicle Rebound Stiffness: 28032.000000 lbs/Inch
Vehicle Impact Natural Frequency: 1.512080 Hz

- THE END -

Figure 17. Analysis Output

4. TECHNICAL APPROACH

The barrier and the vehicle act together as a system during the impact. The behavior during the impact is governed by the characteristics of the vehicle, the barrier, and the foundation of the barrier. The test data shows the vehicle is the softest member of the system, with vehicle crush in the range of 50 inches. The barrier is the stiffest member of the system with barrier bending deflections sufficiently small, making it difficult to measure [1-7]. Rigid body displacement of the barrier is small, about 1 inch at the soil elevation.

Based on observations of the test data, a model of a vehicle impacting a barrier is constructed. The model consists of a vehicle mass and spring, a rigid barrier mass, and a foundation spring. This model of a vehicle impacting a barrier is shown in Figure 18. This model is used to determine the force imparted on the barrier by the vehicle; however, the model is not sufficient for determining failure of the barrier. By assuming the barrier acts as a rigid body in relation to the vehicle, it has been implicitly assumed that the force imparted by the vehicle appears static to the barrier. The force calculated from the two degree-of-freedom model must be used in a structural analysis to determine if the barrier is structurally strong enough to survive the impact.

Figure 18. Sketch of Mass and Spring Colliding With a Second Mass and Spring

The small displacements of the barrier observed during the tests indicate that the barriers tested (which survived the tests) appear stationary to the vehicle during impact. There are two manners in which a rigid barrier can appear stationary to a vehicle during impact: through its own mass being sufficiently greater than the mass of the vehicle, or through the foundation being sufficiently stiffer than the vehicle. In both cases, the barrier must be structurally strong enough so that the vehicle cannot punch through the barrier.

The bounds of barrier massiveness and foundation stiffness is determined by taking some of the characteristics of the vehicle/barrier system to extremes. To investigate barrier massiveness, the foundation is assumed to offer no resistance and to investigate foundation stiffness, the barrier mass is assumed to be negligible.

4.1 BARRIER MASSIVENESS

The following analysis of a mass colliding with a second mass is done in order to evaluate how much greater the mass of the barrier must be than vehicle mass so that the barrier appears massive to the vehicle. Figure 19 contains a sketch of the model used in this analysis.

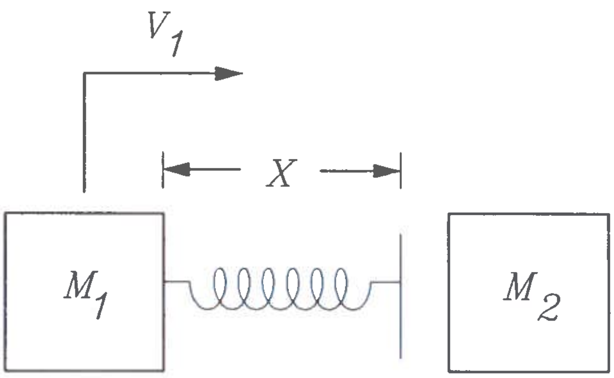

Figure 19. Sketch of a Mass Colliding With a Second Mass

From conservation of momentum,

$$m_1 V_1 = (m_1 + m_2) V_f \qquad (1)$$

From conservation of energy,

$$\frac{1}{2}m_1V_1^2=\frac{1}{2}(m_1+m_2)V_f^2+\frac{1}{2}KX^2 \tag{2}$$

Solving equations (1) and (2) for the displacement of the spring

$$X=\left(1+\frac{m_1}{m_2}\right)^{-1/2}\left(\frac{m_1}{K}\right)^{1/2}V_1 \tag{3}$$

If the barrier is assumed to be rigidly fixed to the ground and immovable, the estimated displacement of the spring would be

$$X_e=\left(\frac{m_1}{K}\right)^{1/2}V_1 \tag{4}$$

Normalizing the spring deflection of the two mass model by the spring deflection of the single mass/immovable barrier model leads to

$$\frac{X}{X_e}=\left(1+\frac{m_1}{m_2}\right)^{-1/2} \tag{5}$$

Figure 20 shows a graph of spring displacement as a function of barrier mass as described by Equation (5). This graph shows that when the barrier mass is equal to the vehicle mass the actual spring deflection will be 70% of the deflection estimated by assuming the barrier to be fixed. When the barrier is four times heavier than the vehicle, the actual spring deflection will be 90% of estimated spring deflection.

For barrier mass greater than about four times the vehicle mass, the barrier appears essentially immovable to the vehicle. For all barrier masses the spring deflection would be overestimated so that if the force acting on the barrier is the linear spring force, then for all barrier masses the force would be overestimated by assuming the barrier to be immovable. The spring force can be closely approximated by assuming the barrier to be immovable when the barrier is four or more times heavier than the vehicle.

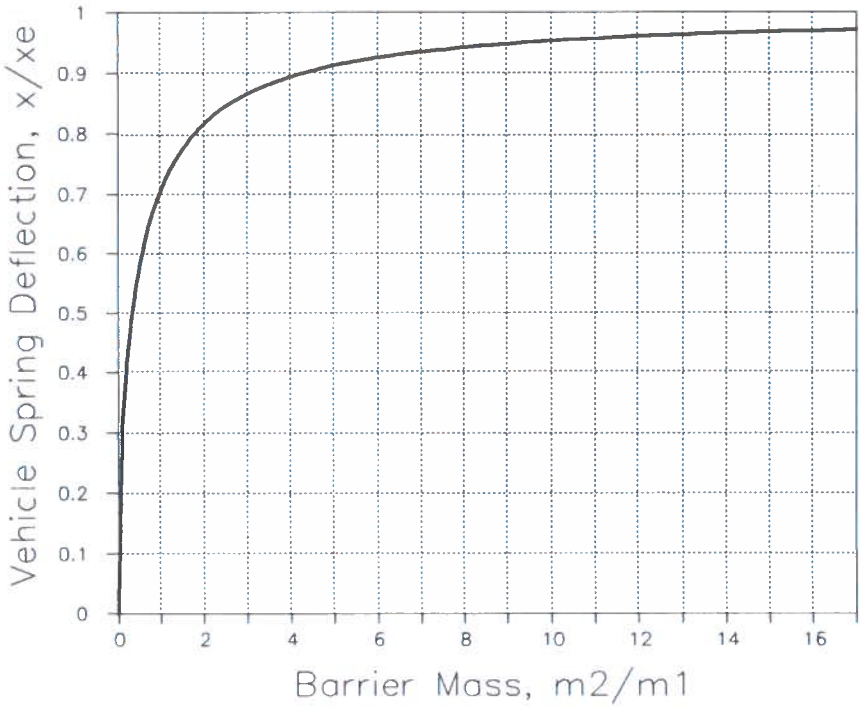

Figure 20. Plot of Spring Displacement vs. Barrier Mass

4.2 FOUNDATION STIFFNESS

A bounding analysis similar to the one presented for barrier massiveness is given below for foundation stiffness. In this analysis, the foundation is assumed to act as a spring and the barrier mass is assumed to be negligible. The model is then a mass with a spring hitting a second spring. The model used in this analysis is sketched in Figure 21.

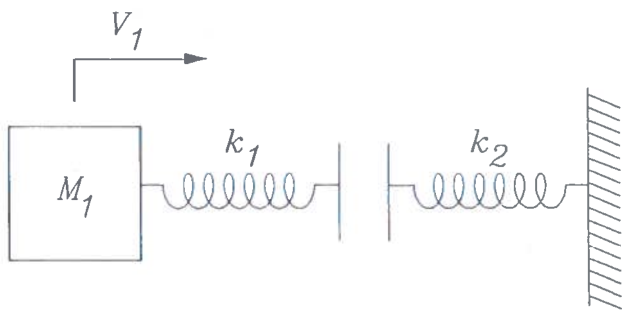

Figure 21. Sketch of Mass and Spring Colliding With a Second Spring

From conservation of energy,

$$\frac{1}{2}mV^2 = \frac{1}{2}\left(\frac{K_1K_2}{K_1+K_2}\right)(X_1+X_2)^2 \tag{6}$$

The force in each spring must be equal and opposite, so that

$$K_1X_1 = K_2X_2 \tag{7}$$

Solving for the deflection of the spring associated with the mass,

$$X_1 = \left(1+\frac{K_1}{K_2}\right)^{-1/2}\left(\frac{m}{K_1}\right)^{1/2}V \tag{8}$$

Normalizing the spring deflection of the two spring model to the spring deflection estimated for the immovable barrier, Equation (4),

$$\frac{X}{X_o} = \left(1+\frac{K_1}{K_2}\right)^{-1/2} \tag{9}$$

Figure 22 shows a graph of deflection of the spring associated with the mass as a function of foundation stiffness, which shows the same trend as the graph in Figure 20 of spring deflection as a function of barrier mass. If the barrier mass is negligible in comparison to the vehicle and the foundation stiffness is greater than four times the vehicle stiffness, then the barrier appears essentially immovable to the vehicle.

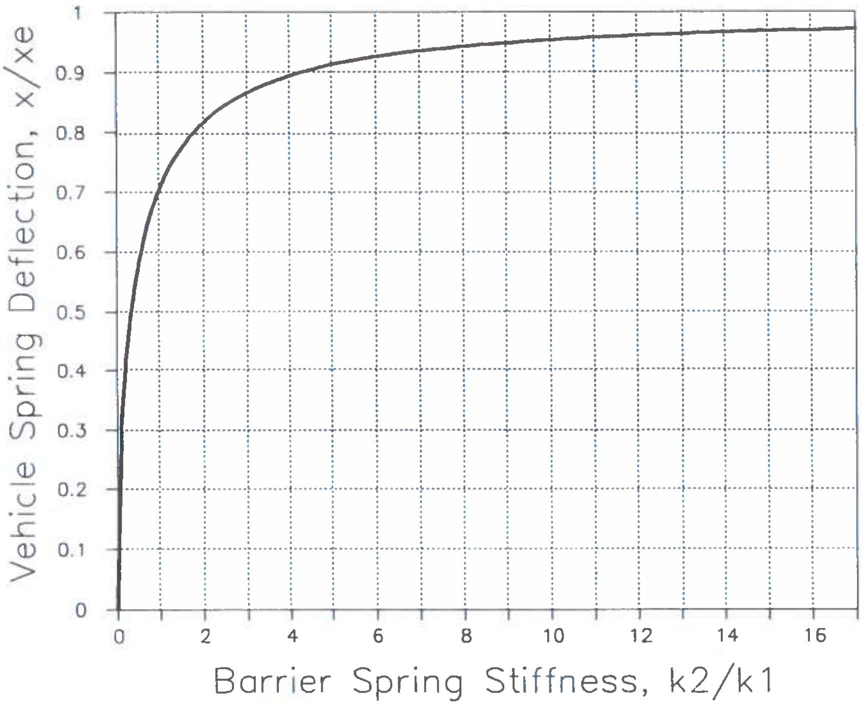

Figure 22. Plot of Vehicle Spring Displacement vs. Barrier Stiffness

4.3 DYNAMIC COUPLING BETWEEN VEHICLE AND BARRIER

The above analyses show that when the mass of the barrier is much greater than the mass of the vehicle and when the stiffness of the barrier is much greater than the stiffness of the vehicle, it is appropriate to model a vehicle impacting a barrier as a single degree-of-freedom system. However, some barriers use a combination of mass and foundation stiffness to stop the vehicle. In this section, the behavior of the entire system will be discussed which is made up of the vehicle and the barrier supported by its foundation.

The dynamic behavior of the barrier and the vehicle can be analyzed using the coupled equations of motion of the two degree-of-freedom model shown in Figure 18. The equations of motion are

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \begin{Bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{Bmatrix} + \begin{bmatrix} k_1 & -k_1 \\ -k_1 & k_1 + k_2 \end{bmatrix} \begin{Bmatrix} x_1 \\ x_2 \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \end{Bmatrix} \tag{10}$$

These equations are used to determine the range of barrier natural frequencies for which the barrier and vehicle will have significant dynamic coupling. The transient response of a two degree-of-freedom system has been analyzed in Reference [8]. Figure 23 shows a plot of vehicle spring displacement, which is X_1-X_2, normalized to the vehicle spring deflection estimated for the immovable barrier (Equation (4)) vs. the barrier natural frequency, normalized to the vehicle natural frequency. For plotting the data, the vehicle and barrier/foundation natural frequencies have been defined as $\omega_1 = \sqrt{\frac{K_1}{M_1}}, \omega_2 = \sqrt{\frac{K_2}{M_2}}$.

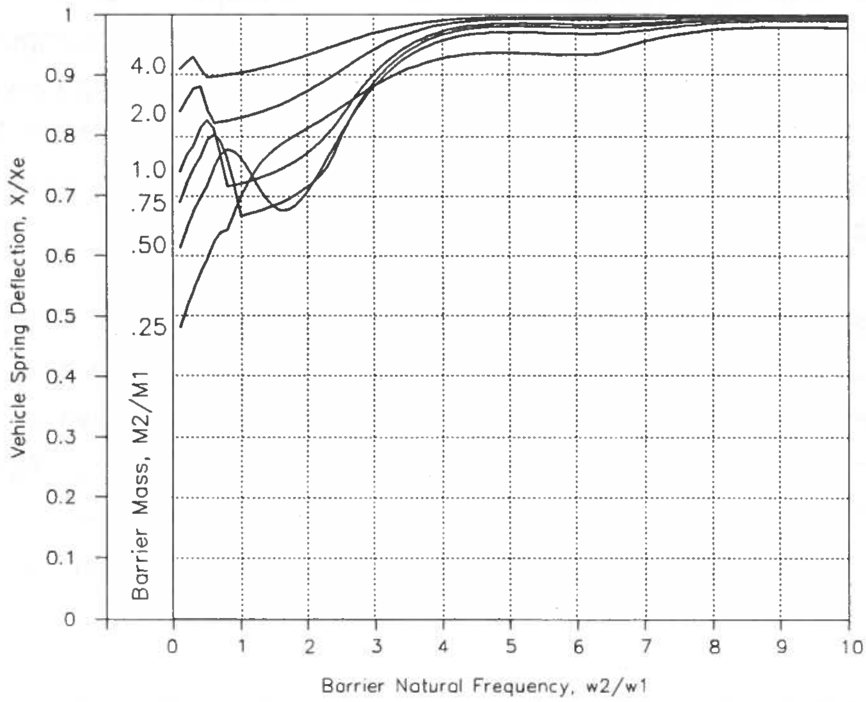

Figure 23. Plot of Vehicle Spring Displacement vs. Barrier Natural Frequency

The graph in Figure 23 shows that for barrier mass greater than four times the vehicle mass the barrier appears rigid to the vehicle and the vehicle spring displacement is 90% or more of the spring displacement that would be estimated from the immovable barrier analysis. The graph also shows that for barrier/foundation natural frequency greater than three times the vehicle natural frequency the barrier appears rigid to the vehicle, with the vehicle spring displacement 88% or more of the spring displacement that would be estimated from the immovable barrier analysis.

In cases when the barrier mass is less than four times the vehicle mass and the barrier/foundation natural frequency is less than three times the vehicle natural frequency there is dynamic coupling between the vehicle and the barrier supported by its foundation. In this region the two degree-of-freedom model, shown in Figure 18, must be used to determine the force imparted on the barrier by the vehicle during an impact.

4.4 BARRIER STRUCTURE

The above analyses of barrier mass, foundation stiffness, and dynamic coupling of the vehicle and the barrier on its foundation have all included the assumption that the barrier acts as a rigid mass. The results of dynamic coupling analysis imply that this assumption is valid for barriers with natural frequencies greater than three times the natural frequency of the vehicle. For all barriers to be analyzed with the models described in this report, the lowest natural frequency associated with the barrier must be at least three times greater than the natural frequency of the vehicle.

Some barrier designs will have a lowest natural frequency in the range of the vehicle and these barriers are expected to have a complex dynamic coupling with the vehicle. This type of barrier requires a multi-degree-of-freedom model for adequate analysis, with sufficient masses and springs to represent the dominant modes of dynamic response of the barrier. An example of this type of barrier is the steel guard rail used along most highways. This guard rail is designed to deform when it is hit, and the deformations of the guard rail can be of a similar size to the deformations of the impacting vehicle.

After determining the basic behavior of the vehicle/barrier system, the barrier must be analyzed to determine if it has the structural strength to survive the impact. For this structural analysis, the force applied to the barrier can be treated as static. A static analysis is conservative because the inertia of the barrier will help in absorbing the vehicle impact and any strain-rate effects, for the strain-rates associated with the vehicle crush characteristics, will tend to increase the strength of the barrier.

The exact structural analysis will depend upon the barrier type, for example, a concrete wall barrier would require a finite element analysis to determine the location of maximum stress.

This finite element analysis need only be done once because the concrete is a brittle material and behaves linearly until fracture and thus, to the point of fracture, the stress is proportional to the applied load. The details of the structural analyses are presented in Section 7 . BARRIER STRUCTURAL ANALYSIS.

5. VEHICLE ANALYSIS

A vehicle impact model of a loaded Ford F600 truck has been developed from test data. Data from three tests were used in developing the vehicle model. The three tests are Test DS-6, a 29-mph crash into a reinforced concrete wall 3 feet high and 1 1/2 feet deep, Test DS-6a, a 44-mph crash into the same barrier as Test DS-6, and Test DS-7, a 34-mph crash into a reinforced concrete wall 3 feet high and 1 3/4 feet deep. In each of the tests the barrier survived the impact and weighed more than five times the vehicle, and so acted as a stationary barrier. The vehicle model was developed in order to calculate the force imparted to the barrier by the vehicle for various impact speeds.

Figure 24 shows test data from three concrete wall barrier tests. Various accelerometers were mounted on the vehicle during the test. The acceleration plots shown in Figure 24 are from accelerometers which measured the longitudinal acceleration of the vehicle and were mounted on the left and right frame rails at approximately the midpoint of the vehicle wheelbase. The velocity and displacement data were calculated by integrating the acceleration data.

The high-frequency ringing which can be seen in the acceleration plot, is most likely due to a structural response of the accelerometer mountings [Reference 9]. Integration tends to smooth this ringing because the area under the ringing portion is small compared to the area under the fundamental vehicle acceleration curve.

The vehicle is modelled as a single mass with a nonlinear spring. The spring is piece-wise linear, with a crush stiffness and a rebound stiffness. Figure 25 shows a sketch of the vehicle impact model and its crush and rebound stiffness characteristics.

Impact Velocity

29.2 MPH　　34.0 MPH　　43.8 MPH

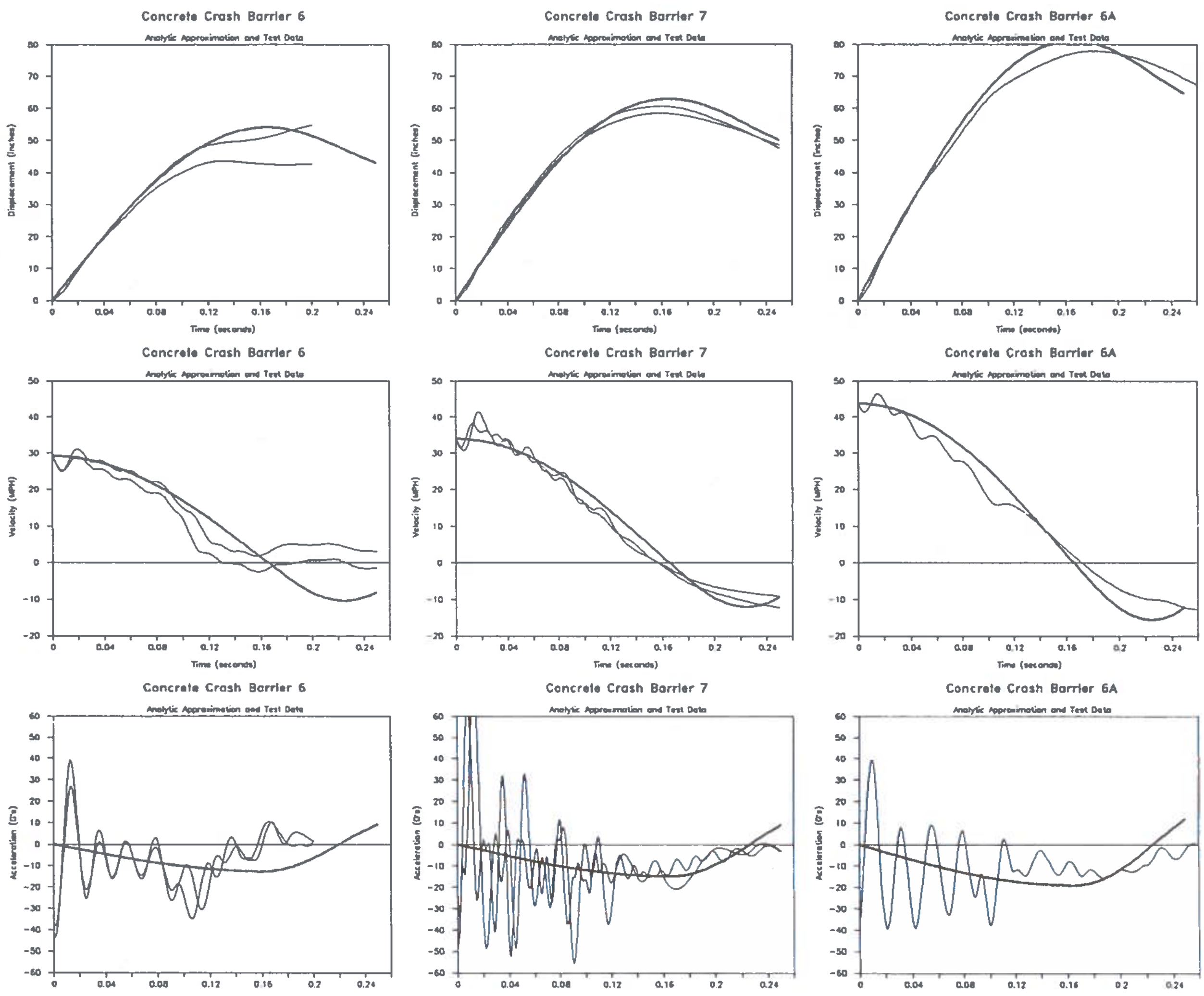

Figure 24. Acceleration, Velocity, and Displacement Plots, Analytic Approximation and Measured Data.

The stiffness parameters for the crush and the rebound equations of motion were determined by fitting data from the three tests. The parameters were chosen as a best fit to all three sets of test data.

The equation of motion when the vehicle is crushing (the spring in the model is compressing) is

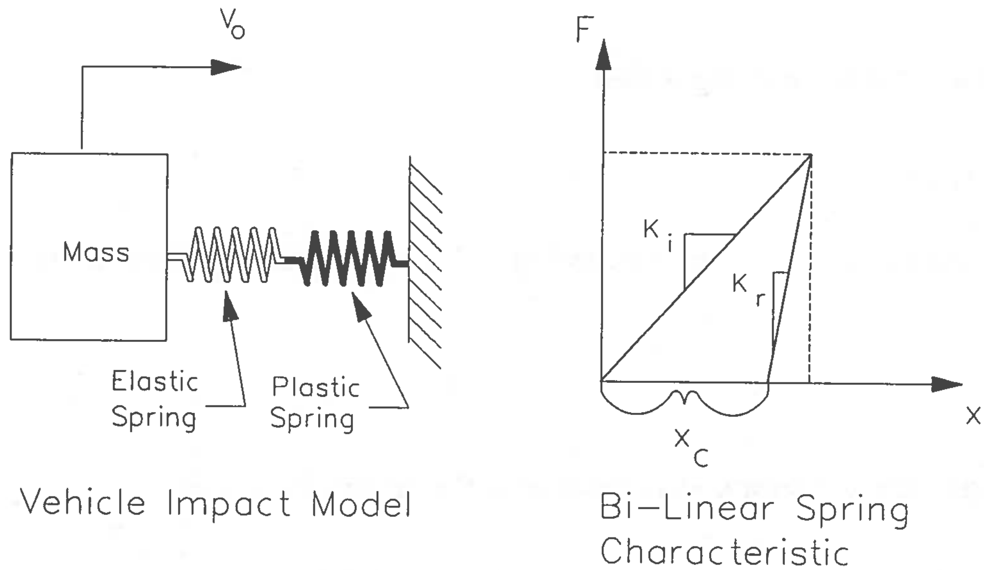

Figure 25. Vehicle Impact Model and Spring Characteristic.

$$m\ddot{x} + k_i x = 0 \tag{11}$$

The initial conditions at the instant just prior to impact are the impact velocity and the initial vehicle crush, which is zero .

The equation of motion when the vehicle is rebounding off the barrier is

$$m\ddot{x} + k_r(x - x_c) = 0 \tag{12}$$

$$m\ddot{x} + k_r x = k_r x_c \tag{13}$$

The initial conditions for this equation of motion are: the acceleration at the transition is continuous; the velocity at the transition is continuous and zero; and the displacement at the transition is continuous.

The natural frequency of the crush model is governed by the length of time it takes for the vehicle velocity to reach zero. The frequency which fits all three velocity curves well is

$$\omega_c = 9.5 radians/second \qquad f_i = 1.5 Hz \tag{14}$$

The stiffness of the crush spring is then

$$K_c = M\omega_c^2$$

If n is taken to be the ratio of the rebounding spring to the crushing spring, then

$$n = \frac{k_r}{k_c} \tag{15}$$

The rebound stiffness factor n was chosen to fit the displacement data.

Table 2 lists the vehicle model parameters for the Ford F600 truck.

Table 1. Vehicle Model Parameters

Loaded Ford F600 Truck	
Vehicle Mass	38.83 lb-s^2/in
Vehicle Stiffness	3772 lb/in
Rebound Stiffness Factor	8

The peak force predicted by this model will occur at peak crush, the transition point from the crush spring to the stiffer rebound spring. When the barrier is rigid in relation to the vehicle, the peak force is determined from the crush spring displacement at zero vehicle velocity. Figure 26 shows a plot of vehicle force as a function of speed in the case of the rigid barrier.

The vehicle model is useful for determining the force acting on the barrier and for extrapolating from the test data; however, the vehicle model is based on a limited amount of test data for one specific vehicle type. A comparison of the model to test data for a greater range of impact speeds would be useful, especially for impact speeds greater than 50 mph. This model may also be inappropriate for other impact vehicle types which are structurally different from the

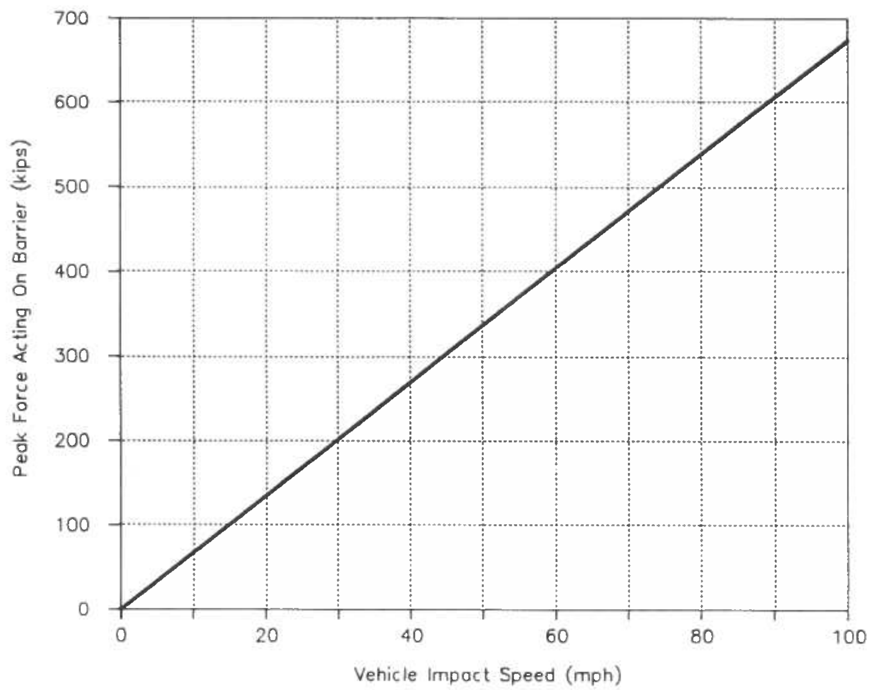

Figure 26. Force Acting on Barrier vs. Vehicle Impact Speed.

Ford F600 truck, such as a front wheel drive automobile. Current front wheel drive automobiles tend to be subframe/unibody construction rather than the full ladder frame construction of trucks.

6. FOUNDATION ANALYSIS

An analysis is presented for determining the effective stiffness of the barrier footing and for determining footing failure. Footing failure occurs when the barrier simply rolls over and allows the vehicle to pass. The stiffness is necessary for determining the natural frequency of the barrier on its foundation. This natural frequency is required for analyzing the basic behavior of the barrier, as described in Section 4. TECHNICAL APPROACH. In addition, a foundation analysis is required for assessing the pressure distribution in the soil acting on the barrier. The pressure distribution is required in the structural analysis of the barrier.

In 1964, Douglas and Davis [Reference 10] analyzed the movement of footings, modelling the footing embedded in soil as a rigid plate embedded in a semi-infinite elastic medium. The analysis is based on Mindlin's equations for the displacements of a semi-infinite elastic medium due to a horizontal load applied at a point below the surface [11]. The results of the analysis include a set of influence coefficients for determining the rotation and displacement of the plate at the surface of the medium as a function of the horizontal force and moment applied at the surface. From Reference [10], the equations for horizontal displacement and rotation of the barrier are

$$\Theta = \left(\frac{M}{EBD^2}\right) I_{\Theta M} + \left(\frac{H}{EBD}\right) I_{\Theta H} \tag{16}$$

$$h = \left(\frac{M}{EBD}\right) I_{hM} + \left(\frac{H}{EB}\right) I_{hH} \tag{17}$$

Θ = Barrier rotation
h = Barrier displacement at soil elevation
M = Moment applied at the soil surface
H = Force applied at the soill surface, Kips
E = Modulus of Elasticity, KSF
B = Barrier length, Ft
D = Barrier footing depth, Ft
$I_{\Theta M}, I_{\Theta H}, I_{hM}, I_{hH}$ = Influence coefficients

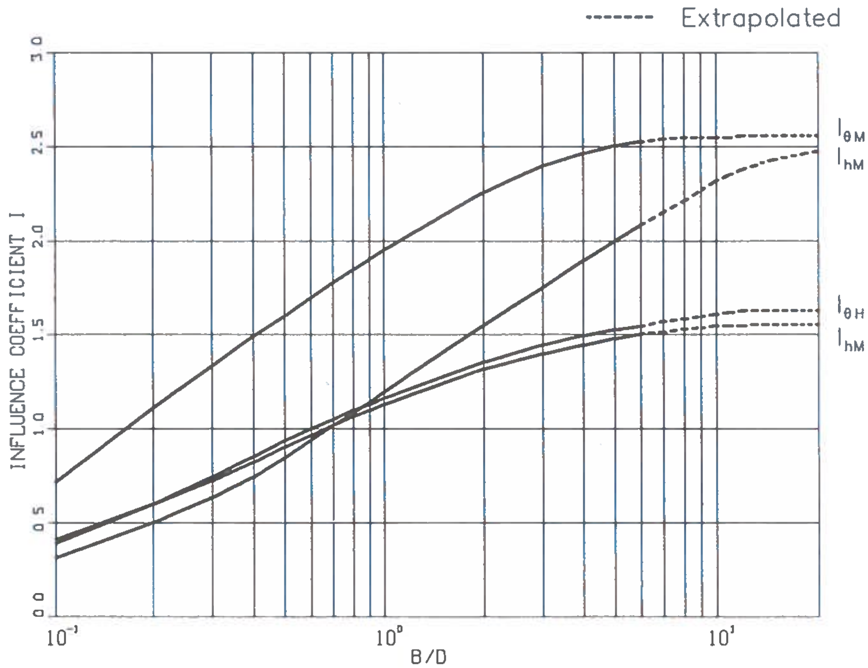

Figure 27. Influence Coefficients for the Rotation and Translation of a Rigid Plate Embedded in an Elastic Half-Space (Reference [10])

Figure 27 Shows a plot of the influence coefficients as a function of the plate breadth to depth ratio. The plot has been extrapolated from the data presented in Reference [10] in order to analyze long barriers with shallow footings.

The behavior of $I_{\theta M}$, $I_{\theta H}$, and I_{hM} appear asymptotic and can be extrapolated with reasonable confidence, however, it is more difficult to judge the behavior of I_{hH}. The behavior of I_{hH} may or may not be asymptotic and so it is extrapolated in a nearly straight line, which causes the predicted foundation stiffness to be less than the stiffness that would be calculated if I_{hH} was assumed to behave asymptotically.

Equations [16] and [17] require the elastic modulus of the soil. If the elastic modulus listed in most soil mechanics textbooks and handbooks (about 20 ksi is the measurement in the table for the type of soil used in the tests) is used in Equations [16] and [17], the resulting barrier displacements are smaller than values measured during State Department crash barrier tests. The soil elastic modulus is generally used to determine the reaction of the soil to a vertical load, not to a lateral load as is applied in the case of a barrier during impact. The elastic modulus of a soil is usually measured in a triaxial compression test, in which all surfaces of the soil are subject to the same pressure [Reference 12]. The soil has a free surface in the case of a barrier, and so the modulus measured in a triaxial compression test may not be appropriate for this analysis. Heuristically, it may be expected that a foundation would be softer laterally than vertically, because of the free surface on the soil that must react to the lateral force.

The elastic modulus for the soil used in the DS-6, DS-6a, DS-7, and DS-9 Tests is the average of the values calculated from the barrier angle measured during the tests. The modulus calculated is 4.4 ksi, which is 4.5 times less than the elastic modulus from Reference [13] of 20 ksi. In order to extend the analysis to other soil types, with different elastic moduli, the elastic modulus of the other soil types measured by a triaxial test are reduced by a factor of 4.5.

Table 2 shows the predicted barrier rotation and displacement using the elastic half-space analysis and Table 3 shows the scaled modulus of the soil, and the barrier rotation and displacement observed during four of the Department of State crash barrier tests. The horizontal displacement of the barrier at the top of the barrier above the center of impact was estimated from videotapes of the tests, while the rotation of the barrier was measured with gyroscopes during the test. Gyroscopes were placed on the east and west end of each barrier. The elastic half-space analysis shows reasonable agreement with the variation of the barrier displacement with foundation size and vehicle impact speed.

The elastic moduli for a range of soils is shown in Table 3. The most firm soil is the Department of State backfill specification soil and the softest soil is hard clay. The horizontal modulus is scaled from the vertical modulus.

Table 2. Comparison of Measured Barrier Displacements and Analysis Predictions

Barrier Test	Vehicle Impact Speed (mph)	Force Acting on Barrier (kips)	Maximum Barrier Rigid Body Rotation (degrees)		Maximum Horizontal Displacement at top of barrier at center of impact (inches)	
			Test	Analysis	Test	Analysis
DS-6	29.2	187.	0.60*	.61	~0.75	.71
DS-7	34.0	218.	0.47**	.35	< 0.5	.53
DS-6A	43.8	280.	0.88*	.91	~0.75	1.06
DS-9	50.2	321.	0.55**	.79	~1.5	1.01

* From west-end gyro only. East-end gyro results do not agree with barrier displacement recorded on videotape.

** Average of east- and west-end gyro results.

Table 3. Assumed Soil Characteristics

Soil Type	Vertical Modulus (psi) (reference [13])	Horizontal Modulus (psi)
Hard Clay	1000	220
Dense Sand	7000	1540
Dense Sand and Gravel	15000	3300
D.S. Backfill Specification	20000	4400

This model of soil behavior is based upon the assumption that the soil behaves as a linear elastic half-space. Other models, based upon different assumptions, have been proposed, and a review of some different soil models, including the Winkler and Pasternak soil models, is presented in Reference [14].

Accurate test data is required to validate the model. Appropriate data may be obtained from a test where a horizontal load is applied statically to a barrier and the displacement of the barrier is measured. Such a test may be less expensive and provide more data than a test in which a vehicle is crashed into a barrier.

6.1 FOUNDATION FAILURE

At some point, with sufficient load and a sufficiently structurally strong barrier, the foundation may be expected to fail allowing the barrier to roll over. The elastic half space analysis can predict the barrier displacement but it does not predict when the foundation may be expected to fail. The conditions under which the foundation may fail are best evaluated by testing. The tests that have already been conducted show that if the barrier displacement is less than 0.9 degrees than the foundation will survive, however one may intuitively expect the foundation to survive even greater displacements. Without an experimentally determined criteria for foundation failure, it is recommended that the barrier displacement due to foundation compliance be subjectively evaluated.

6.2 FOUNDATION STIFFNESS

The following discussion describes how to determine the foundation stiffness and barrier natural frequency from the horizontal displacement and rotation equations. The moment acting at the surface is

$$M = H\,l \qquad (18)$$

H is the horizontal force acting at the center of impact and l is the height of the center of impact above ground level. The angular rotation of the barrier is then

$$\Theta = H\left[\left(\frac{l}{E\,B\,D^{2}}\right)I_{\theta M} + \left(\frac{1}{E\,B\,D}\right)I_{\theta H}\right] \qquad (19)$$

The moment applied to the spring is $H(l + r_{e})$ so that the rotational stiffness of the barrier is then

$$K_\theta = \frac{l + r_e}{\left[\left(\frac{l}{EBD^2}\right) I_{\theta M} + \left(\frac{1}{EBD}\right) I_{\theta H}\right]} \tag{20}$$

The above equation shows that the foundation stiffness depends upon the soil elastic modulus, the barrier width, and the barrier depth.

In order to calculate the natural frequency, the center of rotation must be calculated so that the polar moment of inertia of the barrier can be determined. The effective radius of rotation, r_e, is the horizontal displacement at the surface divided by the rotation of the barrier.

$$r_e = \frac{\Theta}{h} \tag{21}$$

$$r_e = \frac{\left[\frac{l}{D} I_{hM} + I_{hH}\right]}{\left[\frac{l}{D^2} I_{\theta M} + \frac{1}{D} I_{\theta H}\right]}$$

The natural frequency of the barrier on its foundation is the square root of the rotational stiffness divided by the barrier polar moment of inertia about the center of rotation. The polar moment of inertia will be different for each barrier type. The range of natural frequencies for the different barrier types is discussed in the structural analysis section for each barrier.

6.3 FOUNDATION PRESSURE DISTRIBUTION

In order to structurally analyze a barrier all the forces acting on the barrier must be known. The forces acting on the barrier are the force imparted by the impacting vehicle and the reaction pressure in the soil surrounding the foundation required to keep the barrier in equilibrium. The force imparted to the barrier by the vehicle is discussed in Section 5 . VEHICLE ANALYSIS. This section discusses the reaction pressure in the soil surrounding the footing.

There is no single generally accepted method for analyzing soil pressure distributions which develop to support a horizontal load through a foundation. The soil pressure distribution which arises from the linear elastic half-space analysis in Reference [10] is shown in Figure 28a. This analysis predicts the end effects at the left and right edges of the barrier are neglected because the barrier is long and the edge effects are therefore presumed to be small. The difficulty with this pressure distribution is that high pressures are predicted at the surface, which is not intuitively appropriate for a free soil surface condition. Others have proposed pressure distributions assuming that no pressure is taken by the soil at the surface. Such a pressure distribution is shown in Figure 28b. This is the pressure distribution used in Reference [15], which is attributed to Seiler [16].

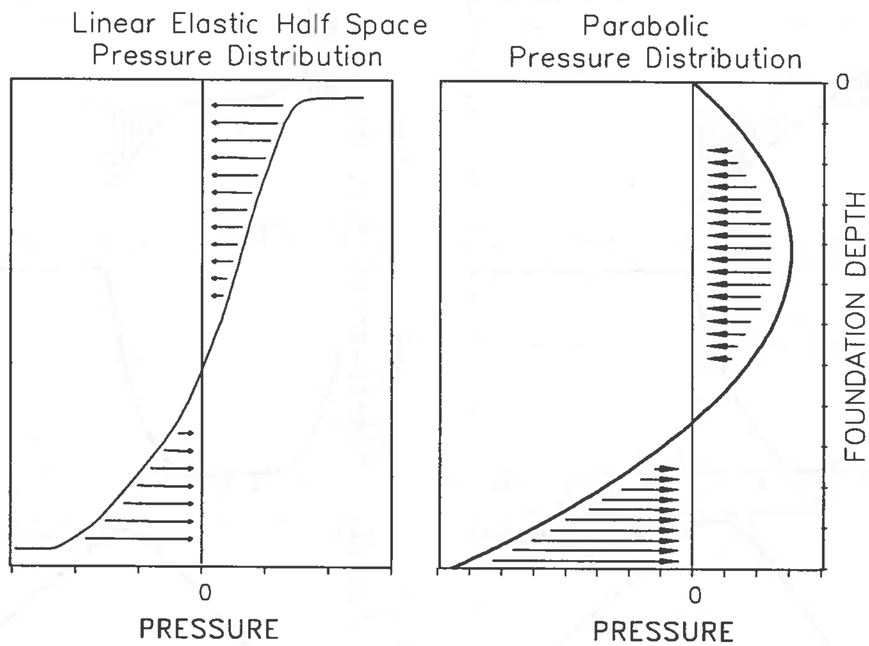

Figure 28. a & b Linear Elastic Halfspace and Parabolic Footing Pressure Distribution

The maximum stresses in a barrier with a foundation are expected to be bending stresses. The maximum stresses will then arise owing to the maximum moment. The pressure distributions shown in Figures 28a and 28b represent reasonable bounds for the possible pressure distributions developed in the soil around a footing when the barrier is hit. The effect of these different pressure distributions on the maximum moment carried through the barrier is investigated in order to determine their effect on the maximum moment, and hence, their effect on the maximum stresses.

In Reference [10], the pressure distribution is described for only a limited range of circumstances. The pressure distribution is therefore approximated, first as a linear pressure distribution, and then as a cubic distribution. Figure 29 shows a beam type analysis for a 2-foot deep foundation, with the force distribution and the shear and moment distributions that arise owing to the force distribution. In both circumstances the maximum moment is only slightly higher, less than 5%, than the maximum moment that would be calculated assuming a cantilever end condition.

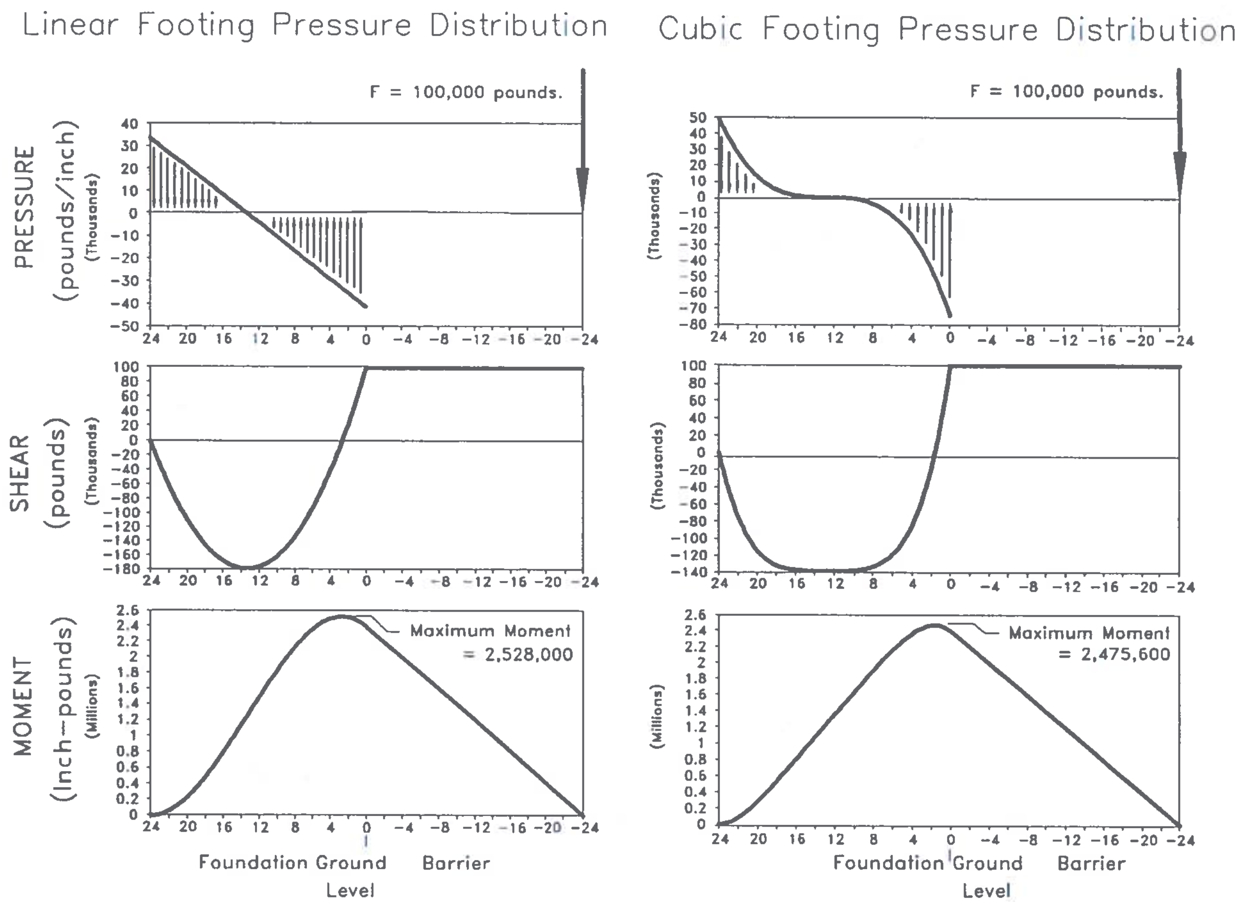

Figure 29. Linear and Cubic Footing Pressure Distribution Analysis.

The foundation soil pressure for the parabolic distribution is shown in Figure 30. Along with the shear and moment distribution. The maximum moment for a 2-foot deep foundation is 15% greater than the maximum moment that would be calculated assuming a cantilever end condition. As the footing depth increases, the maximum moment comes closer to the maximum moment calculated for the cantilever end condition.

Parabolic Footing Pressure Distribution

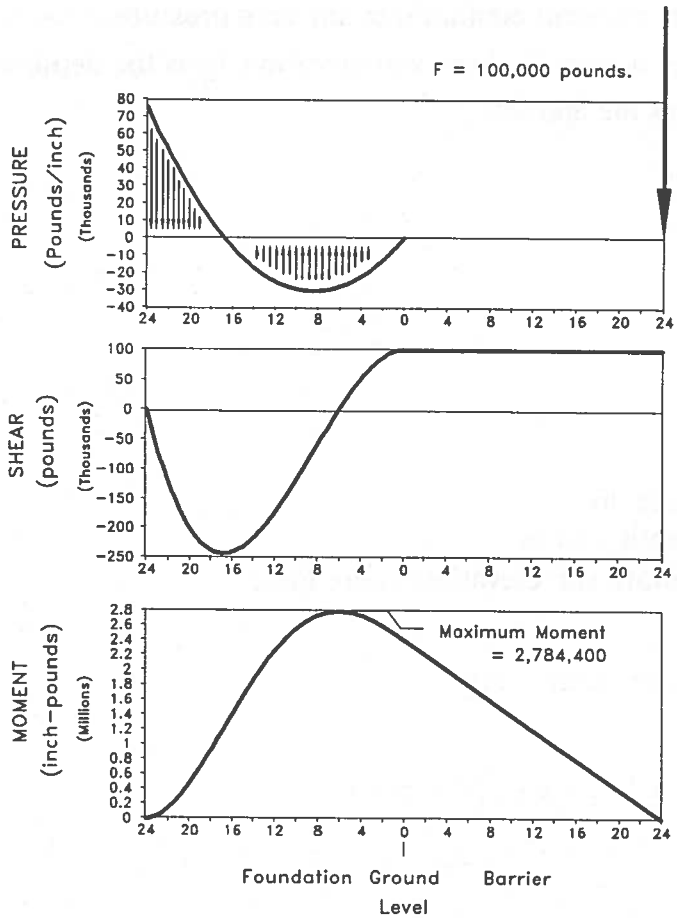

Figure 30. Parabolic Footing Pressure Distribution Analysis

The results of the above analysis suggest that a factor of safety may be used in a stress analysis of the barrier which uses a cantilever end condition, owing to the uncertainty in the foundation soil pressure distribution. The factor of safety is based on the parabolic pressure distribution analysis, which causes the greatest moment of the three soil pressure distributions analyzed.

The pressure distribution which causes the greatest moment is parabolic. In equation form, taking p to be the pressure and x to be the depth into the ground, the pressure distribution is written

$$p(x) = q_0(x - x_0)^2 + q_1 \tag{22}$$

This equation has three unknowns, q_o, q_1, and x_o. The three conditions that must be satisfied are: force equilibrium, moment equilibrium, and zero pressure at the soil surface. Taking l_h as the height of center of impact above soil elevation, l_d as the depth of the barrier beneath soil elevation, and F as the applied force

$$x_0 = \frac{\left(\frac{1}{4}l_d^2 + \frac{1}{3}l_d l_h\right)}{\left(\frac{2}{3}l_d + l_h\right)} \tag{23}$$

$$q_0 = \frac{-F}{\frac{1}{3}l_d^3 - l_d^2 x_0}$$

$$q_1 = \frac{F}{\frac{l_d^3}{3x_0^2} + \frac{l_d^2}{x_0}}$$

F = Applied force, lbs
l_d = Footing depth, inches
l_h = Distance above soil elevation where force is applied, feet

The shear force and the moment are

$$V(x) = q_0\left[\frac{x^3}{3} - x^2 x_0 + x x_0^2\right] + q_1 x + F \tag{24}$$

$$M(x) = q_0\left[\frac{x^4}{12} - \frac{x^3 x_0}{3} + \frac{x^2 x_0^2}{2}\right] + \frac{q_1 x^2}{2} + F x + F l_h$$

x = Distance down from soil elevation
$V(x)$ = Shear distribution
$M(x)$ = Force distribution

In order to evaluate the maximum moment, the location of the maximum moment must be determined. Recognizing that the maximum moment occurs when the shear force is zero, the location of the maximum moment is determined by setting the shear force to zero and substituting for q_o and q_1. These steps lead to

$$0 = \frac{1}{3}(x^3 - l_d^3) - x_0(x^2 - l_d^2) \tag{25}$$

The above equation has three roots, one of which is at $x=l_d$. The equation is simplified somewhat by dividing through by $(x - l_d)$

$$0 = x^2 + (l_d - 3x_0)x + (l_d - 3x_0)l_d \tag{26}$$

x is determined using the quadratic equation, noting that the solution of interest occurs between 0 and l_d. The height of the center of impact stays at 25.3 inches above ground level because the impacting vehicle is assumed to be the Ford F600 truck. The moment equation are normalized to the cantilevered end condition moment of Fl_h and solved. The result is plotted in Figure 31. The maximum moment for a 1-foot deep foundation with a parabolic footing pressure distribution is 6% above the maximum moment calculated for a cantilever end condition. The maximum moment for a 4-foot deep foundation is 36% above the maximum moment calculated for a cantilever end condition.

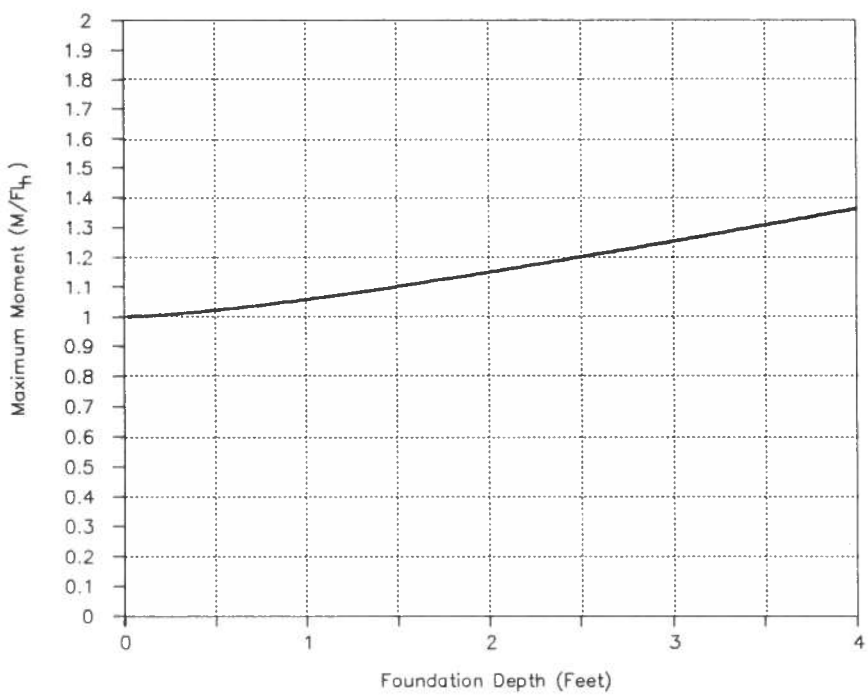

Figure 31. Increase in Moment with Foundation Depth Owing to Parabolic Footing Pressure Distribution.

A better description of the soil pressure acting on the barrier may allow less conservativeness in the analysis, however the factor of safety suggested by the preceding analysis is relatively small, in the range of 6% to 36% increase in the maximum moment calculated for a cantilevered end condition.

7. BARRIER STRUCTURAL ANALYSIS

The following sections detail the structural analyses for five different barrier designs; a solid concrete wall, a reinforced concrete wall, a bollard barrier, an embedded jersey barrier design, and a freestanding jersey barrier design. The objective of these analyses is to determine when the barrier structurally fails and allows a vehicle to pass.

7.1 BOLLARD BARRIER ANALYSIS

This barrier consists of rows of bollards embedded in a concrete footing. Figure 32 shows a sketch of the DS-10 bollard barrier design, which is an example of a bollard barrier. This barrier is analyzed for the failure of the bollard in its footing. The bollards may be filled with concrete.

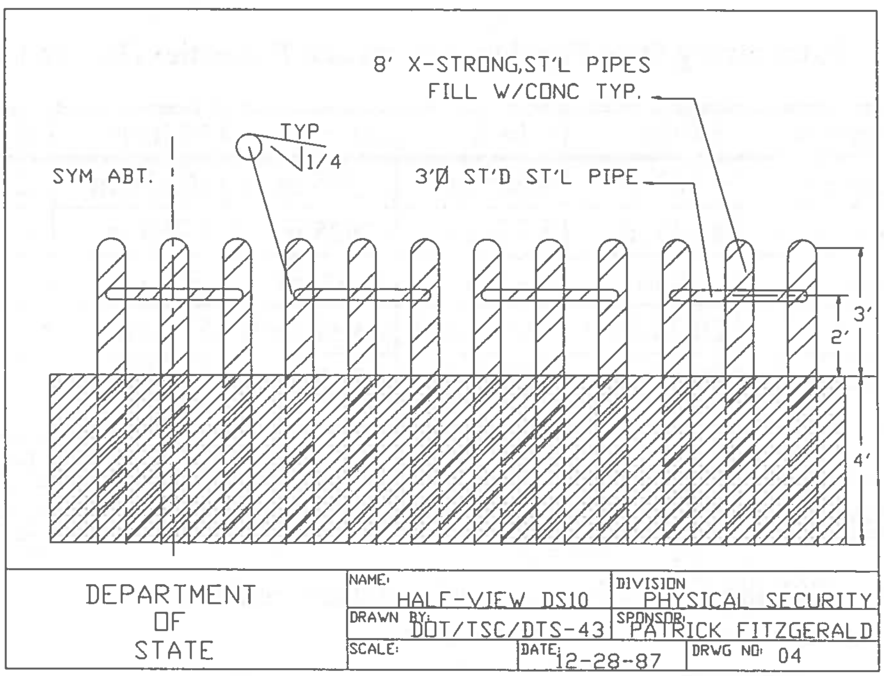

Figure 32. Sketch of a DS-10 Bollard Barrier Design.

The natural frequency of a barrier on its foundation is determined by first calculating the stiffness of the foundation and then the polar moment of inertia. The calculation of the foundation stiffness is described in Section 6.2 FOUNDATION STIFFNESS. The polar moment of inertia for a bollard barrier is

$$I_{xx} = \frac{1}{12}M_1 D^2 + M_1\left(r_e - \frac{D}{2}\right)^2 + \frac{1}{3}M_2 Z^2 + M_2(r_e)^2 \qquad (27)$$

where
Z is the height of the bollards above ground elevation
D is the depth of the foundation below ground elevation
r_e is the effective radius of rotation (defined in 6.2 FOUNDATION STIFFNESS)
M_1 is the mass of the foundation
M_2 is the mass of the bollards

The dimensions and properties for the (bollard) pipe sizes considered in the analysis here are listed in Table 4.

Table 4. Extra Strong Steel Pipe Dimensions and Properties (Reference [19])

Nominal Diameter	5 Inch	6 Inch	8 Inch	10 Inch	12 Inch
Outside Diameter	5.563 in	6.625 in	8.625 in	10.750 in	12.750 in
Inside Diameter	4.813 in	5.761 in	7.625 in	9.750 in	11.750 in
Wall Thickness	.375 in	.432 in	0.500 in	.500 in	.500 in
Weight	20.78 lb/ft	28.57 lb/ft	43.39 lb/ft	54.74 lb/ft	65.42 lb/ft
Area Moment of Inertia	20.67 in^4	40.49in^4	105.7 in^4	211.9 in^4	361.5 in^4
Area	6.112 in^2	8.405 in^2	12.76 in^2	16.10 in^2	19.24 in^2
Radius of Gyration	1.84 in	2.20 in	2.88 in	3.63 in	4.34 in

From Reference [20], the natural frequency of a cantilevered beam is

$$\omega_n = (\beta_n l)^2 \sqrt{EI/ml^4} \qquad (28)$$

where
$(\beta_1 l)^2 = 3.5160$
E is the elastic modulus

I is the area moment of inertia of the beam
m is the mass per unit length
l is the length of the beam

The above equation applies to a beam that is made from a homogeneous material, and the concrete filled bollard is *not* homogeneous. The natural frequency of a concrete filled bollard is expected to between the natural frequency of the beam made from steel pipe and the natural frequency of the beam made from concrete. The lowest natural frequency of the concrete is 6.7 Hz and for the steel is 22.6 Hz, both natural frequencies are associated with a nine foot long schedule 5 pipe. A first estimate of the lowest natural frequency of the bollard with concrete fill is made by using the combined mass of the steel and concrete with the stiffness of the steel, neglecting the stiffness of the concrete. This estimate provides a lower bound to the natural frequency by underestimating the stiffness. The combined natural frequency is estimated as 12.9 Hz. This natural frequency is more than three times greater than the vehicle natural frequency of 1.5 Hz, which implies that the bollards appear rigid to the vehicle during the impact.

The highest stress that occurs in the bollard is the bending stress. The bending stress for a beam is

$$\sigma = \frac{Mc}{I} \tag{29}$$

where
M is the moment
c is the maximum distance from the neutral axis of the beam
I is the area moment of inertia of the beam

The maximum moment for a cantilevered beam, such as the bollard, occurs at the base. The maximum moment is therefore equal to the peak impact force times the distance of the center of impact above ground elevation. For multiple bollards, the impact force is assumed to be shared equally among all the bollards hit during the impact.

For a concrete filled bollard, the force is resisted by both the concrete and the steel. The load distribution is determined using the displacement compatibility of the concrete and the steel. The displacement of a cantilevered beam at the location of the applied load is

$$y = \frac{F l^3}{3EI} \tag{30}$$

where
F is the applied load
l is the distance from cantilevered end to the applied load
E is the elastic modulus of the material
I is the area moment of inertia of the beam

The elastic modulus and the area moment of inertia are different for each of the materials. Setting the displacement of the steel equal to the displacement of the concrete leads to the following apportionment of the load

$$F_c = \frac{F}{\left(1 + \left(\frac{E_s I_s}{E_c I_c}\right)\right)} \tag{31}$$

$$F_s = \frac{F}{\left(1 + \left(\frac{E_c I_c}{E_s I_s}\right)\right)}$$

The concrete is assumed to yield if the resulting tension stress from bending exceeds the tension strength of the concrete. The tension strength of concrete is set to 500 psi in the program. If the concrete yields, the steel takes the entire applied load.

This analysis neglects the possibility of the bollard ripping out of the concrete footing.

7.2 CONCRETE WALL ANALYSIS

The barrier analyzed in this section is a concrete wall with a foundation. The barrier sketched in Figure 33 is an example of such a barrier. The expected failure mode for this barrier design is a failure owing to tensile bending stresses.

The ranges of barrier height above soil elevation, footing depth, barrier width, and barrier length considered in this analysis are shown in Table 5.

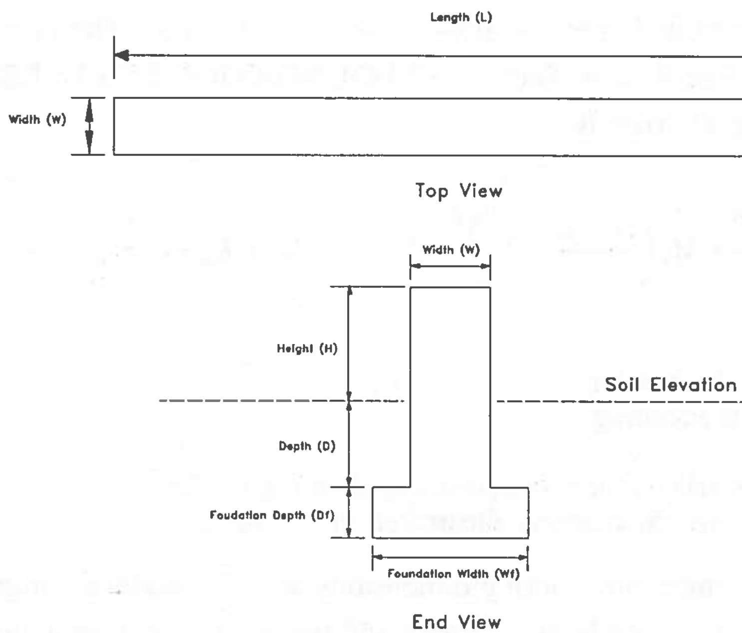

Figure 33. Sketch of Concrete Wall Barrier

Table 5. Wall and Reinforced Wall Range of Dimensions

Dimension	Minimum	Maximum
Barrier Height, H	2.5 feet	9 feet
Barrier Width, W	1 foot	3 feet
Barrier Depth*, D	0 feet	6 feet
Footing Width, W_f	0 feet	6 feet
Footing Depth*, D_f	0 feet	6 feet

* the barrier length/(barrier depth + footing depth) ratio is limited to 20 by the foundation analysis, which means that the sum of the barrier depth and footing depth must be at least 2 feet. The barrier length is assumed to be 40 feet.

The natural frequency of a barrier on its foundation is determined by first calculating the stiffness of the foundation and then the polar moment of inertia. The calculation of the foundation stiffness is described in Section 6.2 FOUNDATION STIFFNESS. The polar moment of inertia for this barrier is

$$I_{xx} = \frac{M_b (H+D)^2}{12} + M_b \left(\frac{H-D}{2} + R_e \right)^2 + M_f D_f^2 + M_f \left(R_e - D - \frac{D_f}{2} \right)^2 \qquad (32)$$

where

M_b is the mass of the barrier
M_f is the mass of the footing
R_e is the
H, W, D are the barrier dimensions, illustrated in Figure 32
W_f, D_f are the barrier dimensions, illustrated in Figure 32

The ranges of barrier dimensions, footing dimensions, and the material properties denote ranges for the barrier mass, foundation stiffness and barrier/foundation natural frequency, and these ranges are shown for the plain concrete wall in Table 6.

The lowest concrete wall barrier free vibration natural frequency for the range of concrete wall barriers is more than three times greater than the vehicle impact natural frequency. This ratio of frequencies indicates that the barrier acts as a rigid body during the impact, as discussed in Section 4.3 DYNAMIC COUPLING BETWEEN VEHICLE AND BARRIER. The range of barrier/foundation natural frequencies, however, overlaps the region where the two degree-of-freedom model must be used to estimate the force, and overlaps the region where the single degree-of-freedom model is used to estimate the force. In either case, a structural analysis of the barrier is done using the peak impact force calculated from the one or two degree-of-freedom model, as appropriate.

The barrier is structurally analyzed using a finite element model. The model has a cantilevered end condition. The force imparted by the vehicle on the barrier is assumed to be an even-pressure force which acts on the surface at the barrier on an area and height equivalent to the vehicle bumper area and height. This assumption is made because the focus of the analysis is on the failure of the barrier to restrain the vehicle. This analysis neglects local

Table 6. Concrete Wall Mass, Stiffness, and Natural Frequency Ranges

Parameter	Minimum	Barrier Dimensions	Maximum	Barrier Dimensions
Barrier Weight	27,000 lbs.	barrier 2.5 feet high 1 feet wide 2 feet deep footing 0 feet wide 0 feet deep	486,000 lbs.	barrier 9 feet high 3 feet wide 6 feet deep footing 6 feet wide 6 feet deep
Foundation Stiffness	$5.7x10^8$ in-lbs/rad	barrier 2 feet deep footing 0 feet deep	$3.1x10^{10}$ in-lbs/rad	barrier 6 feet deep footing 6 feet deep
Barrier/Foundation Natural Frequency	.5 hz	barrier 9 feet high 3 feet wide 2 feet deep footing 0 feet wide 0 feet deep Soil: Hard Clay	17.4 hz	barrier 2.5 feet high 1 foot wide 6 feet deep footing 0 feet wide 0 feet deep Soil: D.S. Backfill
Barrier Free Vibration Natural Frequency, First Mode	1,592 Hz	barrier 9 feet high 1 foot wide	17,755 Hz	barrier 2.5 feet high 3 feet wide

surface spalling in the area of the vehicle impact force. The area of impact is centered in the length of the barrier. Figure 34 shows a sketch of the model. The following paragraphs present results of the analysis conducted with the finite element model.

Failure of the barrier occurs when the tensile stresses exceed the maximum value for concrete. The maximum tensile stresses predicted using this model are the bending stresses at the ground elevation, beneath the area of impact. The analysis in Section 6.3 FOUNDATION PRESSURE DISTRIBUTION indicates that the maximum stresses in the actual barrier will be slightly higher - in the range of 15% higher depending on the foundation depth - than the stresses calculated assuming a cantilevered end condition. It also indicates that the maximum stresses will occur below ground elevation.

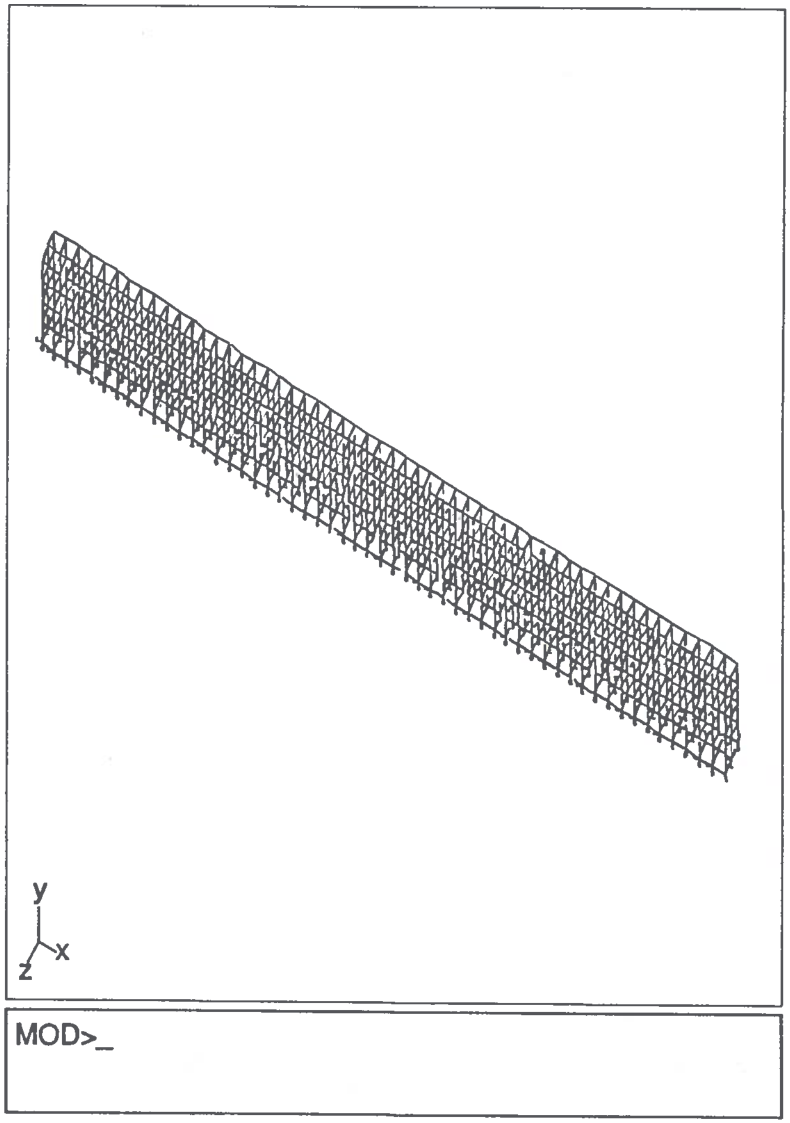

Figure 34. Sketch of Barrier Wall Model

The results of the finite element analysis are used to develop a relationship between the net force applied to the barrier and the maximum tensile stress. The concrete is modelled as a brittle material, i.e., the stress is linearly proportional to the strain up to the point of material failure. Because the material is linear elastic, the stress is proportional to the net force applied to the barrier. A net force of 100 kips was applied to the barrier in the finite element analysis and the location of the maximum tensile stress in the model was determined. This maximum stress is scaled to the applied force and the scaled stress is used to determine the maximum stress in the barrier for different applied forces. The maximum stress is then adjusted according to the factor of safety and is then compared to the ultimate tensile strength of the material.

Figure 35 shows the influence of barrier length on the maximum tensile bending stress on a barrier with an 18 inch width. This stress is maximum at the base of the barrier beneath the area of impact. The graph in the figure shows that as the barrier length increases, the maximum tensile stress decreases. However, for barrier lengths greater than 15 feet, additional barrier length does not appreciably decrease the maximum tensile stress. This fact was used to decrease the size of the finite element models used to investigate the effect of barrier width on the maximum bending stress.

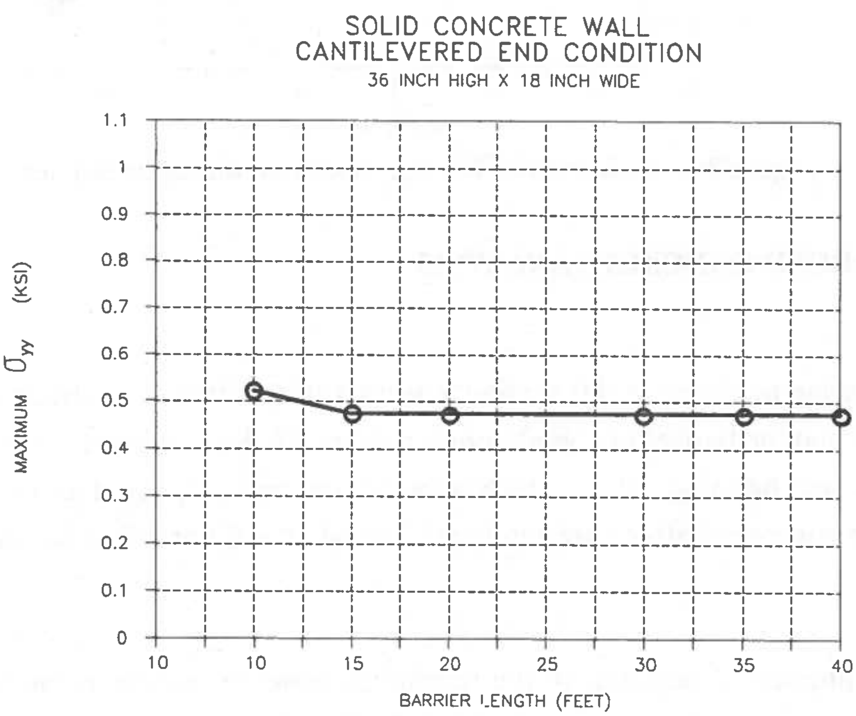

Figure 35. Influence of Barrier Length on Stress in Barrier

Figure 36 shows the results of the investigation of the influence of barrier width on the maximum bending stress. The figure shows that increasing barrier width decreases the maximum tensile stress exponentially. The data shown in the Figure 36 is normalized to a stress per unit force and is used in the solid wall computer program.

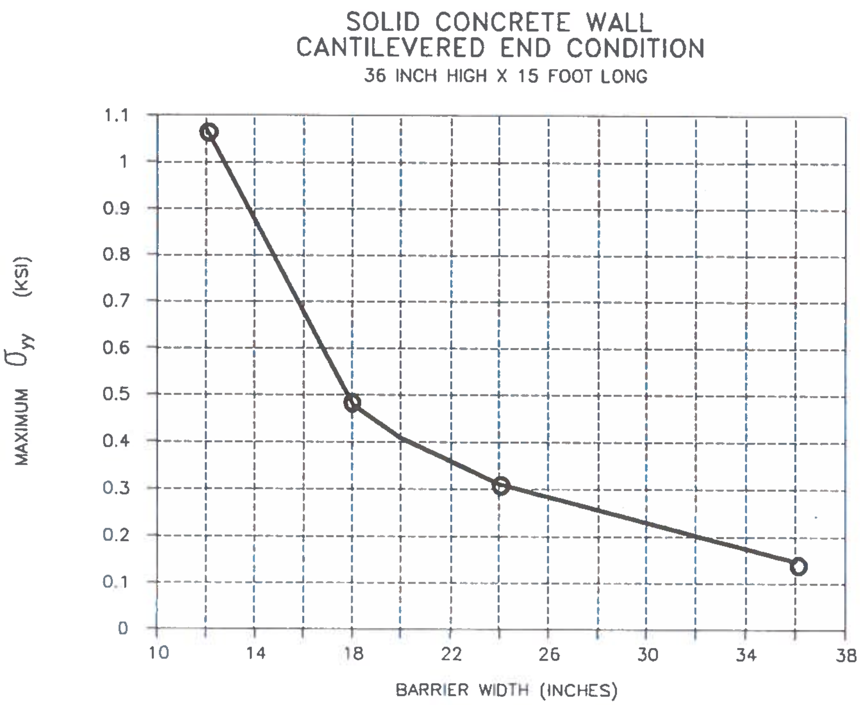

Figure 36. Influence of Barrier Width on Stress in Barrier

7.3 REINFORCED CONCRETE ANALYSIS

The barrier design analyzed in this section is similar to the barrier analyzed in the previous section except that the barrier analyzed here is reinforced. Reinforcement is generally added to concrete to limit bending failure, which is the failure mode expected for the solid concrete barrier. If the concrete wall is adequately reinforced, it will not fail in bending but will fail in shear.

The range of physical dimensions of the reinforced concrete barrier is the same as for the solid concrete barrier, which is shown in Table 5. The ranges of mass, stiffness, and natural frequencies for the reinforced wall are different from the ranges for the solid concrete wall. These ranges for the reinforced wall are shown in Table 7.

The principle difference between the two barriers is the reinforcement. The reinforcement is assumed to be evenly spaced in all three directions. The range of rebar sizes considered is shown in Table 8. and the range of reinforcement grades is shown in Table 9.

Table 7. Reinforced Concrete Wall Mass, Stiffness, and Natural Frequency Ranges.

Parameter	Minimum	Barrier Dimensions	Maximum	Barrier Dimensions
Barrier Weight	27,750 lbs.	barrier 2.5 feet high 1 foot wide 2 feet deep footing 0 feet wide 0 feet deep	494,860 lbs.	barrier 9 feet high 3 feet wide 6 feet deep footing 6 feet wide 6 feet deep
Foundation Stiffness	5.7×10^{8} in-lbs/rad	barrier 2 feet deep footing 2 feet deep	3.1×10^{10} in-lbs/rad	barrier 2 feet deep footing 2 feet deep
Barrier/Foundation Natural Frequency	.5 hz	barrier 9 feet high 3 feet wide 2 feet deep footing 0 feet wide 0 feet deep soil: Hard Clay	17.2 hz	barrier 2.5 feet high 1 foot wide 6 feet deep footing 0 feet wide 0 feet deep Soil: D.S. Backfill

Table 8. Reinforcement Bar Sizes.

Bar Number	Nominal Diameter (inches)	Cross Sectional Area (inches^2)
3	0.375	0.11
4	0.500	0.20
5	0.625	0.31
6	0.750	0.44
7	0.875	0.60
8	1.000	0.79
9	1.128	1.00
10	1.270	1.27
11	1.410	2.56

Table 9. Reinforcement Bar Grades and Strengths.

Grade	Yield Strength (psi)	Ultimate Tensile Strength (psi)
40	$40x10^3$	$70x10^3$
50	$50x10^3$	$80x10^3$
60	$60x10^3$	$90x10^3$

The addition of steel reinforcement is expected to raise the free vibration natural frequency of the reinforced concrete barrier above the frequency of the solid concrete barrier, for the same size barrier, because the reinforcement adds more stiffness than mass to the barrier. Therefore, the lowest free vibration natural frequency of the reinforced concrete wall will be greater than 1,592 Hz, which is the lowest free vibration natural frequency associated with the solid concrete wall for the barrier sizes under consideration. The natural frequencies associated with the barrier free vibration are more than three times greater than the vehicle natural frequency of 1.5 Hz, and so the barrier is treated as rigid.

Like the solid concrete wall, the natural frequencies associated with the reinforced concrete wall on its foundation can be less than three times the vehicle natural frequency. Therefore, a structural analysis of the barrier is done using the peak impact force calculated from the one or two degree-of-freedom model. The one degree-of-freedom model is used when the barrier foundation natural frequency is greater than three times the vehicle natural frequency. The two degree-of-freedom model is used when it is less than three times the vehicle natural frequency.

Similar to the solid concrete barrier, the natural frequency of the reinforced concrete barrier on its foundation is determined by first calculating the stiffness of the foundation and then the polar moment of inertia. The moment of inertia of the reinforced barrier is calculated using Equation (27), which is the same equation as for the solid concrete barrier. The difference between the two barriers in calculating the polar moment of inertia is in the mass of the barrier. The reinforced barrier includes the mass of the reinforcement, which increases the total mass and the inertia of the reinforced barrier over the mass of the solid concrete barrier.

Reinforced concrete walls are analyzed for two structural failure modes. The first mode is failure owing to the maximum bending stress and the second mode is a failure owing to the punching shear. In the following analyses, the concrete is assumed to take the compression load while the steel reinforcement takes the tension load.

Beam bending failure is analyzed by using the maximum moment at the base determined from the finite element analysis for the homogeneous concrete wall. The moment used in this analysis is the moment beneath the center of impact multiplied by the foundation factor of safety (described in section 5.3) and is expressed as a moment per unit length (this is the moment per length of the barrier).

The American Concrete Institute (ACI) Code [17] requires that a structural concrete section be reinforced in such a manner that if it fails, it is the steel reinforcement that fails rather than the concrete. This is because the failure mode associated with steel is a plastic failure and the failure mode associated with the concrete is a brittle failure. Brittle failures of concrete can be precipitous while plastic failures of steel tend to be slower. In the case of a reinforced concrete barrier, it makes little difference if the failure is associated with the concrete or the steel, however reinforcement above that required for balanced failure of the wall (a failure in which both the concrete and reinforcement fail simultaneously) is not necessary and will not increase the strength of the wall appreciably. In the case of an overreinforced wall, the concrete will fail and the reinforcement will bend out of the way. The reinforcement ratio is calculated and compared to the balanced reinforcement ratio. From Reference [18], the balanced reinforcement ratio is

$$\rho_b = \frac{A_{sb}}{bd} = \frac{0.85\beta_1 f'_c}{f_y} \frac{87,000}{87,000 + f_y} \qquad (33)$$

where

A_{sb} is the area of steel (in.^{3})
d is the distance from the compression surface to the centroid of the tension steel (in.)
b is the length of the concrete section (in.)
f'_c is the compressive strength of the concrete (psi)
f_y is the yield strength of the steel reinforcement (psi)

β_1 is coefficient which relates the depth of the strength-design stress block to the distance from the compression surface to the neutral axis. This coefficient is based upon test results [18]. The expression for this coefficient is

$$\beta_1 = .85 - .05(f'_c - 4) \qquad (34)$$

$$.85 \geq \beta_1 >= .65$$

The compressive strength of concrete, f'_c, must be expressed in kips/inch^2 in the above equation.

The maximum moment the barrier can sustain is then calculated. From Reference [18] the maximum moment a concrete section, with a reinforcement ratio less than or equal to the balanced reinforcement ratio, can sustain is

$$\frac{M_n}{b} = f'_c d^2 q(1 - 0.59q) \qquad (35)$$

where

$\frac{M_n}{b}$ is the moment per unit length of the barrier
d is the distance from the compression surface to the centroid of the tension steel
f'_c is the compressive strength of the concrete
q is the tension reinforcement index, $q = \rho \frac{f_y}{f'_c}$

The equation for the reinforcement ratio (33) and equation for the maximum moment the barrier can sustain (35) both include the term *d*, which is the distance from the compression surface to the centroid of the tension steel. Figure 37 shows a sketch of a reinforced concrete section, which illustrates some of the parameters associated with the section. In addition to *d*, these parameters also include *y*, which is the distance of the neutral axis from the compression surface, and *d'*, which is defined as the distance of the compression steel from the neutral axis. Because a change in the location of the neutral axis affects the location of the centroid of the compression steel, a balance between *y* and *d* must be reached. This balance is reached by iterating among the moment equation, which balances the moment taken by the tension steel and the moment taken by the compression concrete and the compression steel, and the equations which describe the locations of *d* and *d'*. Summing moments about the neutral axis leads to

$$y \cdot b \cdot \left(\frac{y}{2}\right) + 2nA'_s d' = nA_s(d-y) \tag{36}$$

where

n is the ratio of the modulus of steel to the modulus of concrete
A_S is the area of the tension steel
A'_S is the area of the compression steel

The equations which describe the locations of the steel centroids are

$$d = y + \frac{1}{J}\sum_{j=1}^{J}\delta_j \tag{37}$$

$$d' = \frac{1}{K}\sum_{k=1}^{K}\delta'_j \tag{38}$$

where

J is the number of rows of reinforcement in tension
K is the number of rows of reinforcement in compression

Any reinforcement that is centered on the neutral axis is neglected in the calculation of the centroids.

The maximum punching shear force a reinforced section can sustain is from Reference [18],

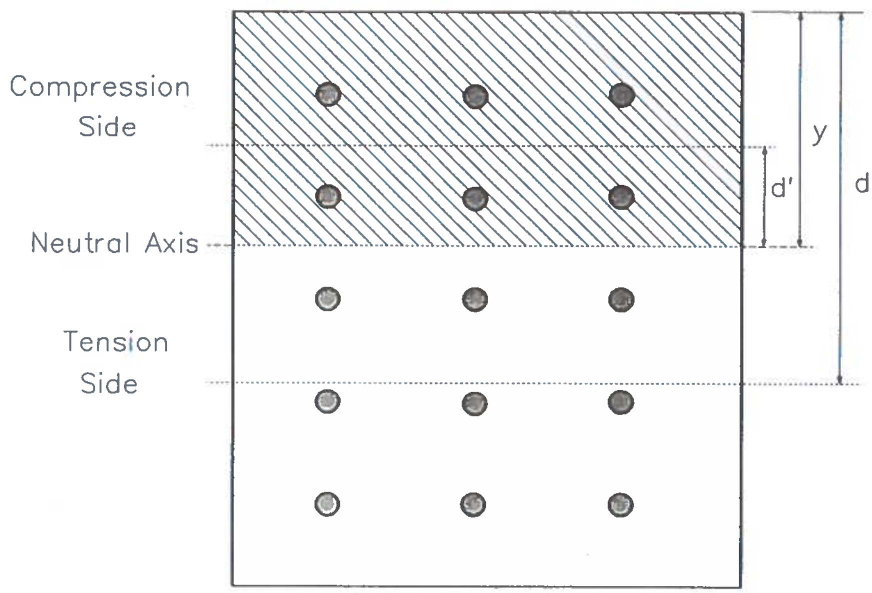

Figure 37. Sketch of a Reinforced Cross Section.

$$V_u \leq \phi(V_s + V_c) \tag{39}$$

where
V_u is the maximum shear force applied to the barrier
V_s is the maximum shear force that can be supported by the steel
V_u is the maximum shear force that can be supported by the concrete
ϕ is a reduction factor, which is equal to 0.85

For the steel, the maximum shear force that can be carried through the assumed crack is

$$V_s = A_v f_y n \tag{40}$$

where
A_v is the cross-sectional area of a steel reinforcement bar
f_y is the yield strength of the steel
n is the number of steel reinforcement bars crossing the crack

The above equation requires the number of reinforcement bars crossing the crack. This number is calculated from the reinforcement spacing, the length of the crack, and the projection of the crack. The projection of the crack is assumed to be d/2. Figure 38 shows the dimensions of the crack. The length of the crack is taken to be the shorter of Crack 1 and Crack 2 in the drawing.

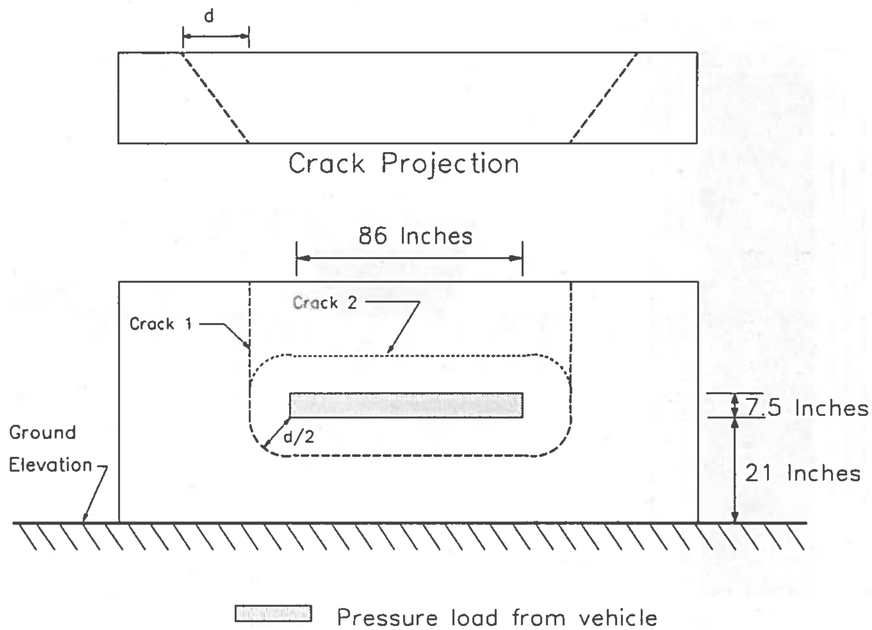

Figure 38. Assumed Shear Crack Dimensions

The punching shear force that the concrete can sustain is calculated using the ACI empirical formula,

$$V_c = 2\sqrt{f'_c}\, b_0 d \tag{41}$$

where

b_o is the length of the crack
d is the distance from the compression surface to the centroid of the tension steel
f'_c is the compression strength of the concrete

The bending analysis has been extended from the ACI code for beam design. The punching shear analysis is taken from the ACI code for a concentrated load applied to a slab.

7.4 EMBEDDED JERSEY BARRIER MODEL

Figure 39 shows a sketch a barrier comprised of two rows of embedded jersey barriers with soil fill. Figure 40 shows a detailed sketch of an individual jersey barrier which is meant to be embedded nine inches into a footing.

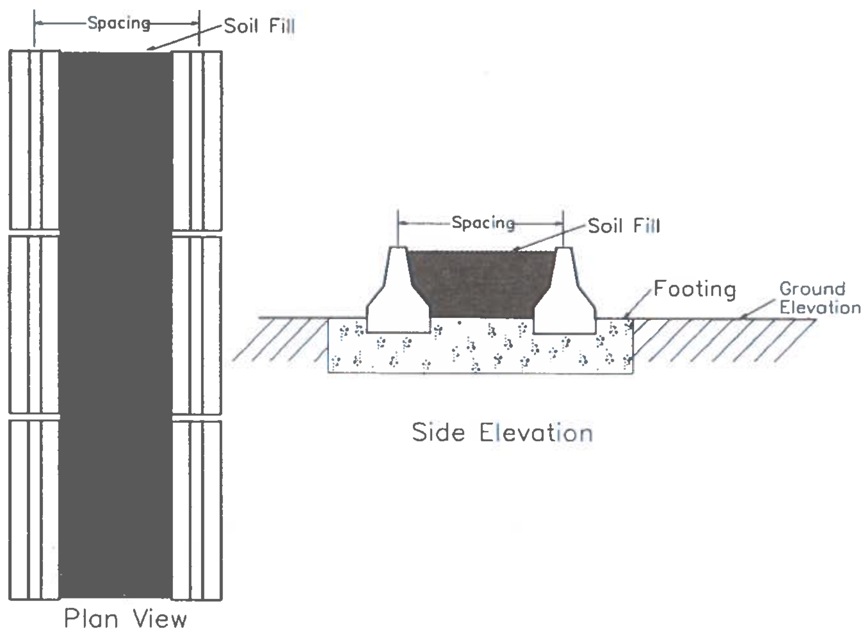

Figure 39. Sketch of a Soil Filled Embedded Jersey Barrier Segment

The barrier spacing, and hence the amount of fill between the barriers, is variable in the analysis, however the design of the individual jersey barriers is fixed to the design shown in Figure 39. The range of barrier centerline-to-centerline spacing is from two feet (where the base of the two barriers are in contact) to ten feet. The density of the soil fill between the barriers is 120 lbs/ft^3. The range of the fill soil modulus of elasticity is the same as that for the foundation analysis. As in the foundation analysis, the soil foundation modulus of elasticity is reduced by a factor of 4.5 because the soil fill has a free surface.

In the event of a vehicle impact in which the barrier fails, the vehicle will break through the outer jersey barrier first, then plow through the soil, and finally break through the inner jersey barrier. This barrier is structurally analyzed using three models. The first is a model of the outer row of jersey barriers, the second is a model of the soil fill, and the third is a model of the inner jersey barrier.

The inner and outer jersey barriers are analyzed in a similar fashion to the solid concrete wall. That is, the maximum force applied to the barrier during the impact is determined using a one or two degree-of-freedom model (described in Section 4) and this maximum force is then used in a structural analysis.

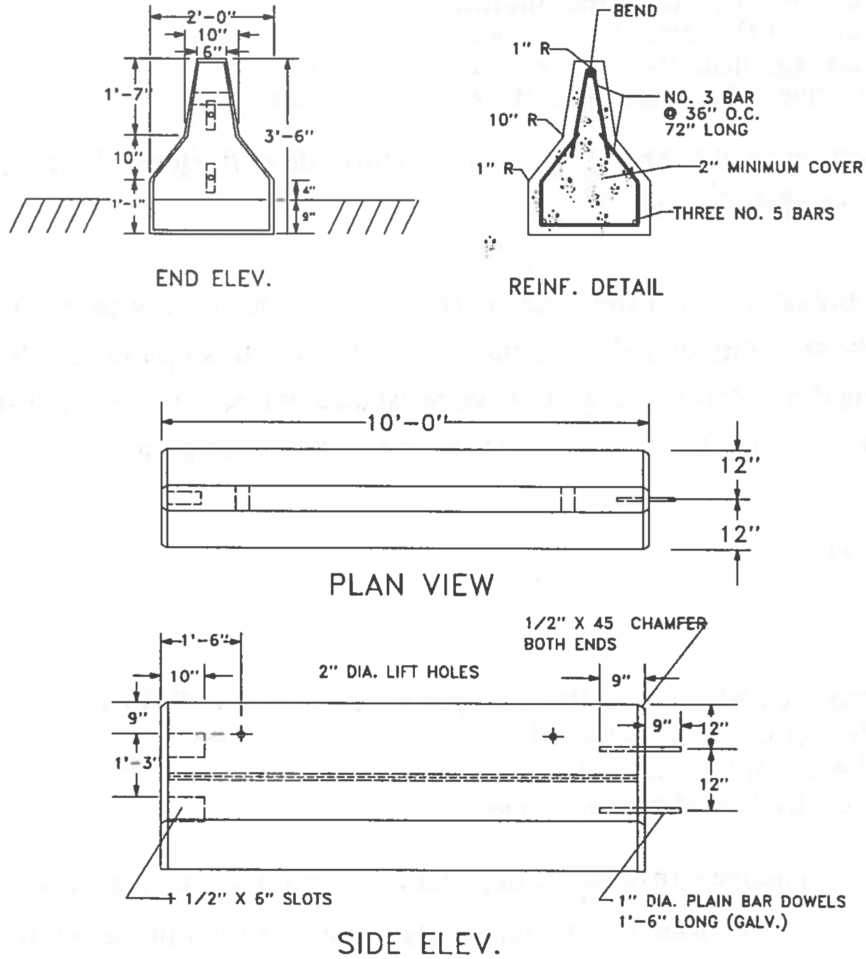

Figure 40. Sketch of an Individual Embedded Jersey Barrier.

The natural frequency of a barrier on its foundation is determined by first calculating the stiffness of the foundation and then the polar moment of inertia. The calculation of the foundation stiffness is described in Section 6.2 FOUNDATION STIFFNESS. The polar moment of inertia for this barrier is

$$I_{xx} = \qquad (42)$$

The outer barrier is structurally analyzed using a finite element model, in a similar fashion to the solid concrete wall. The barrier has a cantilevered end condition. In addition, the soil fill is modelled as a set of linear springs which supports the rear side of the barrier. The stiffness of the springs is calculated from EA/nL, where

E is the elastic modulus of the soil fill,
A is the area of the jersey which is supported by the soil fill
L is the average distance between the two barriers
n is the number of springs supporting the jersey barrier.

A spring supports each of the nodes on the back (fill) side of the jersey barrier, except for the nodes at the base of the barrier.

If the vehicle breaks through the outer barrier, it then must plow through the soil. The resistance of the soil is modelled as a constant force acting to stop the vehicle. This force is calculated using the equation for the passive resistance of a retaining wall. From Reference [21], the equation for the passive resistance acting on a retaining wall is

$$P_p = \frac{1}{2}\gamma H^2 K_p \tag{43}$$

where
P is the passive resistance of the wall, per linear foot of wall (lbs/ft)
γ is the density of the soil (lbs/ft^3)
H is the height of the wall (ft)
K_p is the coefficient of passive stress

The coefficient of passive stress, K_p, is dependent upon the angle of shearing resistance , ϕ. From Reference [21], the following equations describes the relation between the coefficient of passive stress and the angle of shearing resistance for level backfill as used in the model.

$$K_p = \frac{1 + \sin\phi}{1 - \sin\phi} \tag{44}$$

After breaking through the outer barrier and then plowing through the soil, the vehicle will then impact the inner barrier. The inner barrier is analyzed using a finite element model with cantilevered end condition.

In both finite element models, the inner and outer barrier models, the reinforcement is neglected. This is done because a model which included the reinforcement would have exceeded the capabilities of the finite element analysis package, COSMOSM/M. This is a conservative approximation as the amount of reinforcement is low and is expected to only contribute a small amount to the strength.

The results of the finite element analyses of the inner and outer jersey barriers indicate that both will fail owing to the bending stress at the change in cross-section which is 14 inches above ground level. The results of the finite element analyses are shown in Figure 41.

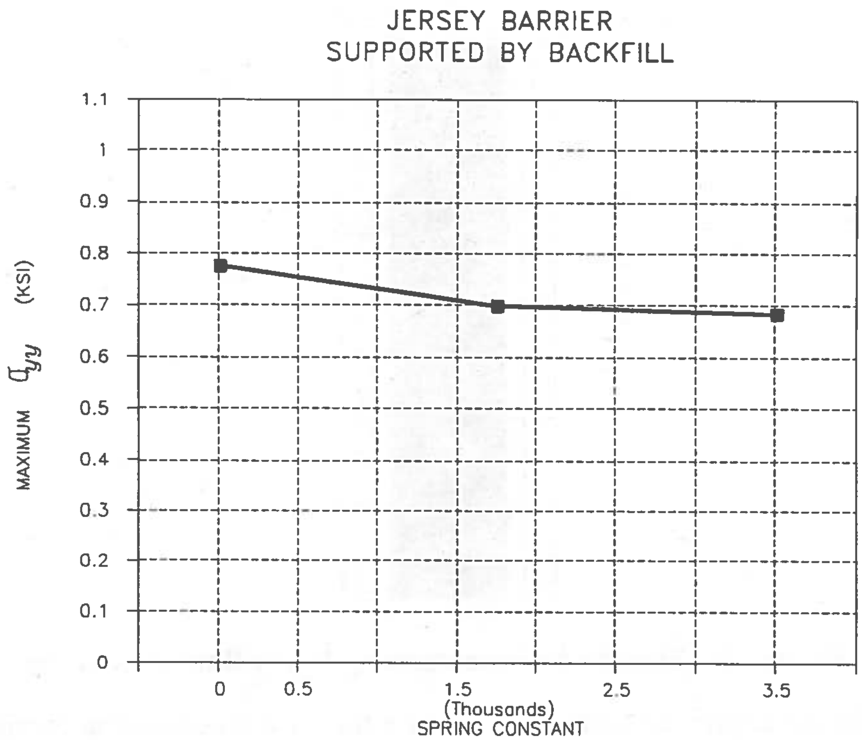

Figure 41. Influence of Backfill on Embedded Jersey Barrier Maximum Bending Stress

7.5 FREESTANDING JERSEY BARRIER ANALYSIS

Figure 42 is a sketch of a barrier made up of freestanding jersey barriers. It is comprised of two rows of barriers with soil fill in between. Because this barrier configuration has no foundation, the barrier acts to stop the vehicle through its own massiveness. Figure 43 shows a detailed sketch of an individual jersey barrier.

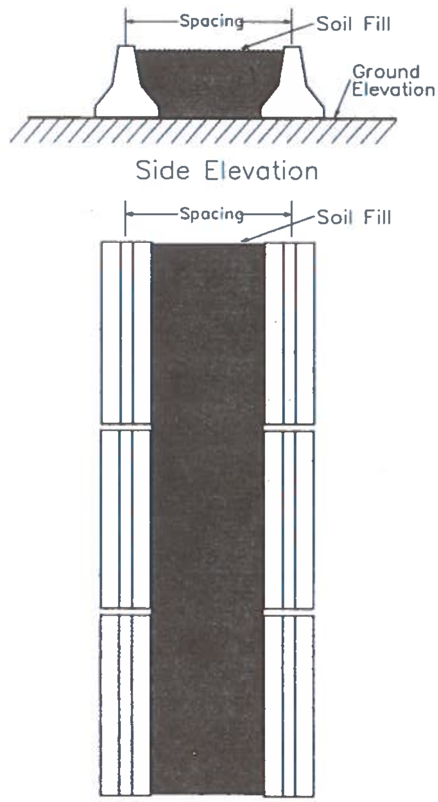

Figure 42. Sketch of a FreeStanding Jersey Barrier Segment

Figure 44 shows the analytical model of a vehicle hitting a freestanding barrier. During an impact the vehicle is resisted by the mass of two barrier segments and the soil fill in between, and by the friction force between the barrier and the ground. The weight of an individual segment is 4.2 kips. The density of the soil is 120 lbs/ft^3. The friction force is assumed to be proportional to the total weight of the two barrier segments and the soil fill between them. The coefficient of friction is input by the user.

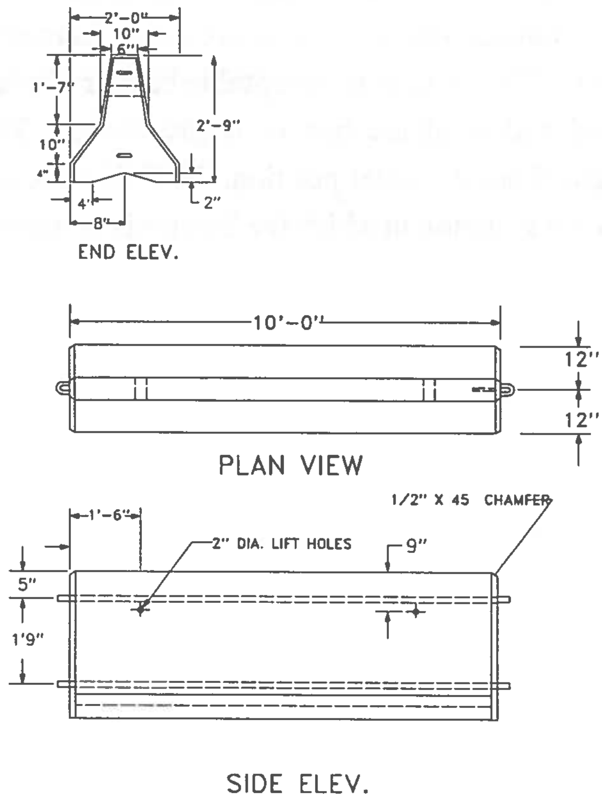

Figure 43. Sketch of an Individual Free Standing Jersey Barrier

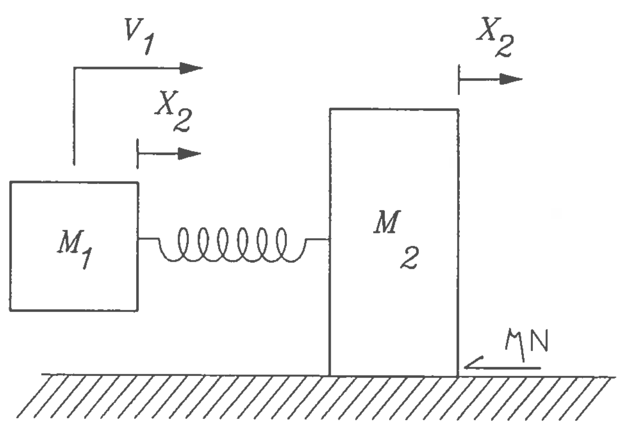

Figure 44. Sketch of a Free Standing Jersey Barrier Model

The equations of motion which describe this system are

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \begin{Bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{Bmatrix} + \begin{bmatrix} k_1 & -k_1 \\ -k_1 & k_1 \end{bmatrix} \begin{Bmatrix} x_1 \\ x_2 \end{Bmatrix} = \begin{Bmatrix} 0 \\ -\mu N \end{Bmatrix} \tag{45}$$

What constitutes failure for this type of barrier depends upon the circumstances in which the barrier is used. This type of barrier will generally move unless its mass is considerably greater than the mass of the vehicle. The amount of acceptable barrier displacement will depend on where the barrier is used and what the barrier is protecting. This model predicts the displacement of the barrier from its initial position. This displacement must be evaluated with an understanding of the situation in which the barrier is being used.

8 . SUMMARY AND RECOMMENDATIONS

8.1 SUMMARY

The Crash Barrier Analysis Program presented in this report is a quick and accurate tool to find the theoretical results of the impact of a 15,000 lb vehicle with a variety of wall configurations. No computer program can take into account the myriad parameters of a full scale crash test but through matching theoretical analysis with data from full scale tests this model incorporates the constant fluctuations from theory which the test data shows.

In summary, the Crash Barrier Analysis Program is a powerful tool to analyze bollard barriers, concrete walls, reinforced concrete walls, and jersey barriers. The programs goals were the following:

Use full scale crash test data and theory to develop an analysis tool for Department of State's most widely used passive barriers

Provide a User friendly analysis tool which could be used on an intermittent basis on a readily available personal computer

Provide a presentation output which can be used to show management the results of analysis

Provide a design tool for quick estimates of analysis results due to routine design changes

The benefits for the Department of State are the following:

The ability to judge between conservative building and overbuilding

Quick (5 minutes from design through analysis) analysis of barriers even for infrequent users

An extension of the costly full scale crash tests to an everyday tool

Program portability for use in the field when necessary

Although this program was developed for Department of State, the problem of choosing efficient barriers is growing for many agencies in the federal government. This program is a beginning in everyone gaining access to the modelling technology and has potential to be enlarged to fit many needs.

8.2 RECOMMENDATIONS

The immediate goals of the Crash Barrier Analysis Program have been met, now, the future must be considered. The Crash Barrier Analysis Program is a stepping stone to the future analysis programs. The first and most important recommendation is to complete full scale crash testing for validation of the model. The test data available and the instrumentation of those tests is minimal. The analyses of barrier behavior during an impact are based upon analytical calculations which relied heavily upon the data from the previous tests. In order to provide information on the limitations of the analyses, further testing is required with more complete barrier instrumentation. Some specifics which could be accomplished through testing are:

To develop criteria for declaring foundation failure

To review foundation analysis based on elastic half-space for adequacy for soil

To review definition of pressure distribution acting on footing for conservatism in the analysis

To see how conservative inertia effects will make quasi-static analyses

In addition to validation, the Crash Barrier Analysis Program must develop to include the current needs of the industry. The modular methods employed allow additional features to be easily added to the analysis program.

To include automobiles as a second test vehicle, or other weight vehicles.

This would allow the user to choose the vehicle most like their threat. Most of the data necessary for this addition exists in Department of Transportation research. The data would need to be reviewed, analyzed and added to the program.

To include an analysis of curbs and their effect on the impact.

This would allow the user to specify the height of curb and distance from the barrier. The curb would change the height of impact and would result in very different loading on the barrier.

Include angle impact

This would allow the user to specify the angle of impact. The angle of impact would change the loading on the barrier

Include other barrier types

This would increase the number of barrier types covered by the model. The barrier would need to be reviewed for scaling effects and analysis would be completed based on the barrier type.

Include material choices

This would allow the user to the materials used in the barriers. Most easily applied to the AutoCAD version, where the user could specify the type of steel, type of concrete, or use default values for each material in the barrier.

Include a cost module

This module would be used with the material choices above or a default material list. This would allow a user to specify the quantity of barrier necessary and to compute changes in cost due to changes in material, thickness, foundation excavation required, etc.

Incorporate other barrier models

This would incorporate more extensive and less user friendly models as an option for the structural engineer. This would allow new barrier types to be modelled.

These changes would permit the model to better fulfill the demands of the growing threat of explosive laden vehicles to federal agency's facilities.

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