

## ANALYTICAL RECREATION OF A DENT PROFILE CONSIDERING VARIED SOIL, OPERATING, AND BOUNDARY CONDITIONS

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### ABSTRACT

This paper presents findings related to an analysis conducted on a dented section of a 36" X 0.344", X52 grade pipe. The objective of the study is to determine conditions that are necessary to create a particular dent shape. The finite element method is used to conduct this study assuming a plane strain elastic-plastic model. Soil interaction is modeled using spring elements placed horizontally and vertically at each node of the model. At the beginning of this study, two dent formation processes were considered to be likely candidates. One possible denting process assumes the dent was created during installation (before hydrotesting). The other process assumes that the pipe was damaged after several years of operation with pressure in the line. Results of this analysis suggest that the dent was formed while the pipe was pressurized and buried in normally consolidated soil.

Although this study addresses a pipe with specific geometry and boundary conditions, the methodology developed for this analysis can be applied to a variety of similar situations.

### INTRODUCTION

Although considerable research has been conducted over the past 20 years to improve the general understanding of the origin and effects of mechanical pipe damage, several concerns still exist. One area of concern are residual dents in buried pipelines and the loads and boundary conditions necessary to generate the residual dent profile. The activities in the forensic community provide the impetus for this type of research. Often buried pipeline ruptures occur as a result of prior pipeline damage that leads to fatigue failures as a result of normal pressure cycles. Accident examiners are often provided with a section of pipe that has a given dent profile and are asked to determine the process that developed the dent and the time at which the initial indentation occurred. To answer these questions the examiner must determine the initial dent depth, the level of rerounding, and the soil conditions that exist at the time of the indentation. The results of this study suggest that all of these factors play a role in evaluating pipeline fatigue factors that are a result of external dents.

This paper provides a description of the analysis procedure used to evaluate residual dents that often precipitate pipeline fatigue failures. This procedure also demonstrates the effect that individual parameters such as soil consolidation, initial dent depth, hydro test pressure, and operating internal pressure have on the residual dent profile.

The authors have conducted numerous analyses and experiments on the fatigue life of dented pipes. Some of this work has been published (see *References*). This research suggests that three parameters important to the evaluation of a denting process are

- 1) the shape of the intenter
- 2) the pressure magnitude and cycle history
- 3) the residual dent profile.

Without an understanding of these parameters, a postmortem evaluation of dented pipe fatigue failures is complicated. For the case studied in this paper, the residual dent profile was the only reliable evidence available. Therefore, a sensitivity study was undertaken to determine the indentation method and the load history.

**Figure 1** provides an isometric view of the finite element (FE) model used in this analysis. The model is composed of a single row of 180 shell elements (one element per degree) aligned in the circumferential direction. There are three symmetry planes associated with this model. Two planes act transverse to the pipe direction (3-direction) and one is aligned with the pipe longitudinal axis (1-direction). The latter permits only one-half of the pipe to be modeled. The transverse boundary conditions create a plane-strain formulation in which there is no variation in stress, strain, or displacement in the axial direction. This assumption is appropriate when considering indentation at the center of a long, uniform dent.

The general-purpose ABAQUS finite element program is used in this analysis. This program involves three types of non-linearity (material, geometric, and rigid contact), which is effectively handled by the ABAQUS program. The ABAQUS S4R5 shell element is used in this analysis. The S4R5 element is a four-noded isoparametric element with reduced integration.

The material model used in this analysis is based upon stress-strain data for X52 pipe obtained by the authors in other research efforts. **Figure 2** provides the true stress-strain curve employed in this analysis. The material model considered five stress-strain input pairs and isotropic hardening was assumed. The X52 pipeline considered in this analysis has an outer diameter of 36 inches and a wall thickness of 0.344 inches.

It is clear that an adequate model of the pipe is critical to the dent analysis. However, adequate modeling of the restraint associated with the surrounding soil is equally important. Spring elements are attached to the

nodes of selected pipe shell elements within the model to represent the soil stiffness. These spring elements simulate soil resistance to pipe deformation. Two orthogonal sets of springs are attached to each node of the model. Vertical springs are used to provide restraint on the bottom half of the pipe, whereas horizontal springs act on the side of the pipe. The stiffness of both the horizontal and vertical springs vary with circumferential position. Based upon experience of the authors, a normally consolidated soil at a depth of 6 feet possesses maximum horizontal and vertical spring stiffnesses of 500 lb/in per linear inch of pipe. As expected, lower levels of consolidation provide lower levels of stiffness. In the *Results* section, information is presented relating soil stiffness variation to the behavior of the pipeline and associated dent.

To effectively evaluate the important problem parameters listed above, it is necessary to define a load step sequence that will be used in the finite element analysis. The following load step sequence is used in all but a few of the cases analyzed in this study,

1. Application of internal pressure to pipe
2. Dent to a target initial depth (*initial* dent depth)
3. Remove the indenter from the pipe surface
4. Apply hydrotest pressure
5. Remove internal pressure (*residual* dent depth)
6. Compare FE data to actual profile.

Some variations in the above steps existed in order to address specific issues.

The iterative procedure involves increasing the initial dent depth until the desired residual dent depth is obtained. This process is critical to insuring that the model accurately depicts the pipeline dent depth and profile. As will be shown in later sections, modifications were made to variables other than the initial dent depth. These variables included soil stiffness, stiffness variation circumferentially, pressure at the time of denting and hydro test pressure.

As previously discussed, the focus of this paper is a particular case study. The objective of this particular study is to determine the load sequence, the initial dent depth, and soil confinement that will result in a residual dent profile that matches a measured dent profile. A significant number of cases are evaluated to determine a specific combination of model and load parameters (load sequence, soil stiffness, hydro test pressure, etc.) that provides a good comparison between the calculated and measured residual dent profile.

## RESULTS

Results are presented which illustrate variables that have the greatest impact on the residual dent profile. As stated previously, parameters are varied in a logical manner until a match between calculated and measured residual dent profiles is obtained. The following variables were deemed the most critical in achieving the final results:

- ◆ Internal pressure during denting
- ◆ Hydrostatic test pressure
- ◆ Soil stiffness and circumferential variation
- ◆ Indenter diameter
- ◆ Dent depth.

Whereas soil stiffness and indenter diameter have the greatest impact on the calculated residual dent profile, the internal pressure, both at the time

Although the preceding results provide useful insights, several questions

of denting and during hydrotesting, has the greatest impact on the residual dent depth.

**Figure 3** provides a digitized representation of the measured residual dent profile. Also included in **Fig. 3** is a plot of the undeformed pipe cross section. **Table 1** provides a complete listing of the load cases considered in this analyses. A total of 19 load cases with varying values for indenter diameter, indentation pressure, hydro pressure, soil spring stiffness, and soil spring stiffness distribution are listed.

### Establishing Residual Dent Depth

For this particular case study, we are interested in determining which of two possible load sequences can generate the residual dent profile that was measured. As stated previously, two potential load histories are considered in this study. These load histories are listed below.

1. The dent was created during installation of the pipeline, prior to hydrotesting
2. The dent was created during an excavation operation with the pipeline under pressure.

The initial objective is to determine the level of indentation required to develop a residual dent depth of 0.34 inches. Various dent depths and soil conditions are considered as illustrated in **Table 1** for Load Cases 1 through 6. Without knowing the source of the indentation, a cylindrical indenter with a 1 inch radius was initially used.

A total of 42 different soil/dent depth combinations are considered in Load Cases 1 through 6. **Figure 4** provides a plot of these results. The results presented in this figure suggest that excessively stiff soils act to limit the magnitude of the residual dent. This behavior is due to the spring-back associated with the relatively stiff soil confinement. A residual dent of 0.34 inches is only obtained when the following conditions exist.

- ◆ No soil, saddle only (120° support angle)
- ◆ Vertical springs with  $k = 62.5$  lb/in/in, no horizontal springs
- ◆ Vertical springs with cosine variation ( $k_{max} = 62.5$  lb/in/in), no horizontal springs.

All data plotted in **Fig. 4** correspond to indentations made with 480 psi internal pressure and a hydrotest of 900 psi. This load sequence corresponds to the indentation of a pressurized pipeline. The data plotted in **Fig. 4** also assume that a hydro test pressure is applied to the pipe subsequent to the application of the dent. To obtain a residual dent depth of 0.34 inches, the initial indentation ranged from 11 percent of the pipe diameter (for the saddle only case) to 25 percent of the pipe diameter (for the no horizontal spring case). In spite of the success in achieving the desired residual dent depth, the 1" diameter indenter failed to generate a dent profile that is similar to the measured dent profile. The measured profile has greater curvature near the maximum dent depth than the calculated residual dent profile. Therefore, the investigation was extended in an attempt to eliminate discrepancies between the measured and calculated residual dent profiles. The size of the indenter is likely to have an effect on the residual dent profile, therefore, effects of the indenter diameter is addressed in the following section.

still remain,

- ◆ What indenter diameter or geometry is required to map the desired dent profile?
- ◆ How will the increased diameter change the response of the pipe and its reaction with the surrounding soil (e.g. will a more stiff soil configuration be required)?
- ◆ Could the dent have been created with no soil around the line?

#### **Establishing Parameters for the Dent Profile**

The next round of analyses address the effect that a larger indenter diameter has on the calculated residual dent profile. As will be shown, this series of models did not produce the final dent configuration, but it did serve to direct the program in the areas of soil stiffness and whether the dent could have been installed without internal pressure in the line.

**Figure 5** provides the results of simulations conducted with larger indenters. An indenter with a 6 inch diameter is modeled with a soil stiffness of 500 lb/in/in. Results are presented for a load case with internal pressure at the time of denting and another without internal pressure. As illustrated in **Fig. 5**, the relatively linear nature of the unpressurized residual dent profile suggests that the pipe was probably dented while fully pressurized. While a steeper slope can be obtained without pressure in the line, this can only occur with an extremely deep initial dent which not produce the desired residual dent depth of 0.34 inches (would be more on the order of 1 inch).

Another significant observation from the results provided in **Fig. 5** is the reasonable agreement between the calculated and measured residual dent profiles. These results suggest that a 6" indenter acting on a pressurized pipeline surrounded by a constant 500 lb/in/in soil stiffness produces respectable results. In light of these results, a final round of analyses attempts to fine-tune the calculated residual dent profile by adjusting the indenter diameter and the soil stiffness distribution.

#### **Finalizing the Dent Depth, Dent Profile and Pressure Conditions**

The results of the final series of simulations are provided in **Fig. 6**. The parameters used to generate the curves presented are specified in **Table 1** Load Cases 19. Note that hydro pressure is not applied to any of the cases represented in **Fig. 6**. It is apparent that three of the curves presented in **Fig. 6** do not match well with the measured residual dent profile. Each of these three curves are the result of simulations that do not include lateral soil support. Two of the 5 calculated curves shown in this figure match reasonably well with the measured dent profile. Of these two curves, the one that matches the best is the one that is generated assuming that the indentation occurs with pressure in the pipeline. The other curve represents the case in which the indentation is done with no pressure in the pipeline. A more complete description of the parameters used for the two curves that result in the best match between the measured and calculated residual dent profiles are:

- ◆ No hydro, 4% initial dent with P=480 psi, 135° soil springs ( $k_{max}=500$  lb/in/in)
- ◆ No hydro, 3% initial dent with P=0 psi, 135° soil springs ( $k_{max}=500$  lb/in/in).

In summary, the following loading and boundary conditions were necessary to produce the desired profile,

- ◆ 36" diameter indenter
- ◆ Initial indentation of 4% the pipe diameter
- ◆ Internal pressure of 480 psi at time of denting
- ◆ No hydrostatic test pressure

- ◆ Cosine variation in stiffness, 135° circumferential distribution
- ◆ Maximum soil stiffness of 500 lb/in/in.

Load cases 14 through 18 of **Table 1** assume the same loading conditions as shown above, but with differing indenter diameters. The results of these models indicated that the 36 inch diameter indenter best represented the experimental profile. It should be noted that this diameter is similar to the width of a typical backhoe excavation bucket.

#### **COMMENTS AND CONCLUSIONS**

As mentioned previously, the objective of this study is to determine the conditions that are required to produce the measured residual dented pipe profile. Through trial and error, using a variety of different boundary conditions, a set of parameters have been identified that result in a calculated residual dent profile that is similar to the measured dent profile. However, due to the limited scope of this study, we have not proved that the best solution obtained through this analysis is the only solution. In fact, it will be difficult to prove uniqueness with a numerical approach such as the one described here. However, it is clear that important parameters for this type of analysis include: indenter size, internal pressure during indentation, as well as soil confinement magnitude and distribution. Furthermore, a hydro test that occurs after indentation can have a significant effect on the residual dent profile. For the particular case study under investigation, it is reasonably clear that the dent in question was created after the line was installed and the hydro test completed.

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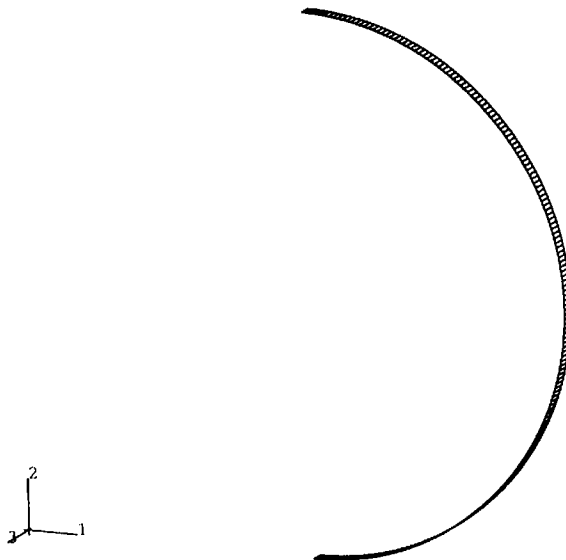
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**Table 1 Listing of Major Models Considered in Soil Analyses**

Load	Indenter Diameter	Indentation	Hydro Pressure	Maximum Spring	Stiffness
1	1	480	990	$k_x = k_y = 500$	Constant
2	1	480	990	$k_x = k_y = 250$	Constant
3	1	480	990	$k_x = k_y = 62.5$	Constant
4	1	480	990	Saddle, no soil	N/A
5	1	480	990	$k_x = 0, k_y = 62.5$	Cosine
6	1	480	990	$k_x = 0, k_y = 62.5$	Constant
7	6	480	990	$k_x = k_y = 500$	Constant
8	6	0	990	$k_x = k_y = 500$	Constant
9	6	480	990	$k_x = 0, k_y = 500$	Cosine
10	6	0	990	$k_x = 0, k_y = 500$	Cosine
11	6	480	990	$k_x = 0.5k_y, k_y = 500$	Cosine
12	36	480	990	$k_x = k_y = 500$	Constant
13	12	480	990	$k_x = k_y = 500$	Constant
14	6	480	0	$k_x = k_y = 500$	Cosine (135° horiz.)
15	12	480	0	$k_x = k_y = 500$	Cosine (135° horiz.)
16	15	480	0	$k_x = k_y = 500$	Cosine (135° horiz.)
17	21	480	0	$k_x = k_y = 500$	Cosine (135° horiz.)
18	25	480	0	$k_x = k_y = 500$	Cosine (135° horiz.)
19	36	480	0	$k_x = k_y = 500$	Cosine (135° horiz.)

**General Notes**

1. Use of the 1" diameter indenter was to establish a residual dent depth resembling the prototype
2. The larger indenter diameters were used to reproduce the exact dent profile found in the prototype
3. Load cases using the indentation pressure of 480 psi simulate dent installation with pressure in the line
4. Load cases with the indentation pressure of 0 psi simulate the dent installation before hydrotesting
5. Variation in soil stiffness were used to get a representation of the possible soil combinations
6. Of all the soil combinations considered, those for load cases 14 through 19 produced the most accurate results



**Fig. 1 Plain Strain Finite Element Mesh**

### STRESS-STRAIN CURVE USED AS INPUT FOR THE FINITE ELEMENT MODEL

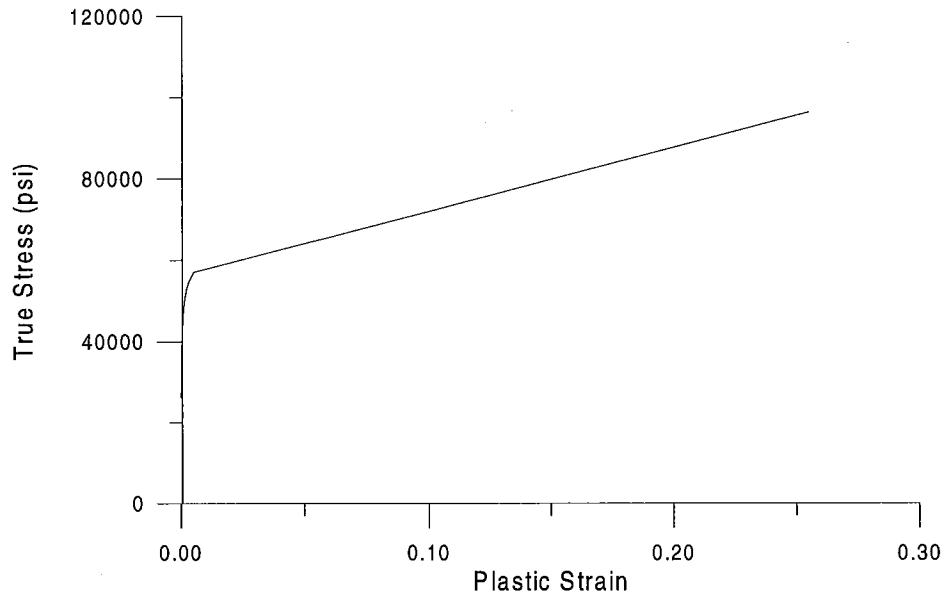


Fig. 2 Stress-strain Curve used as Input for Finite Element Model

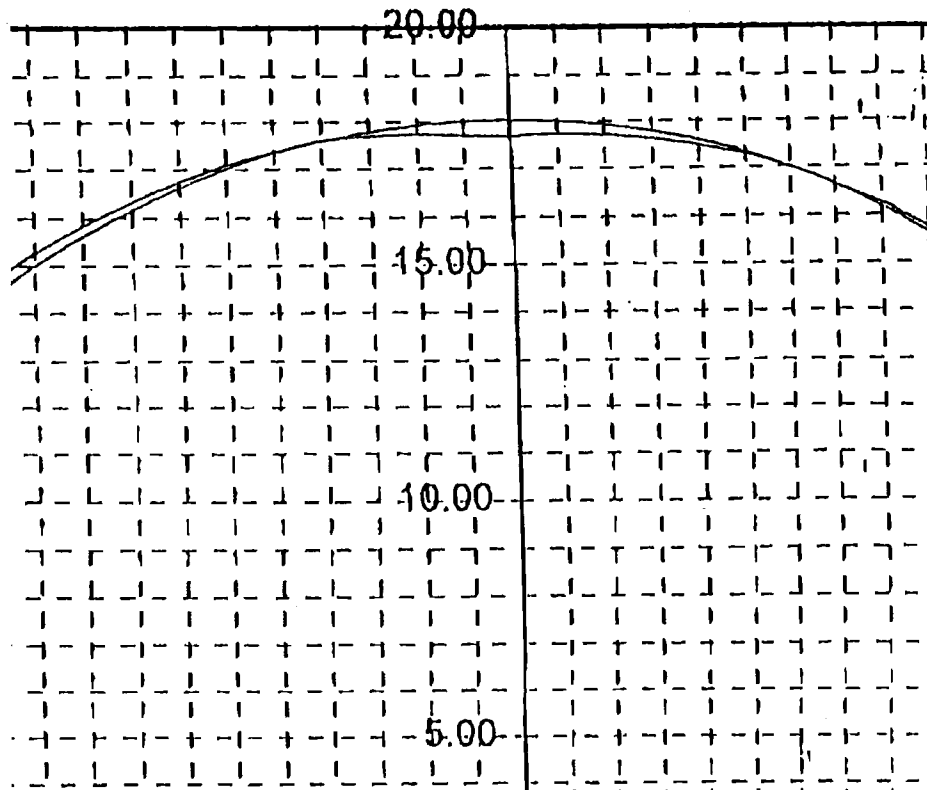
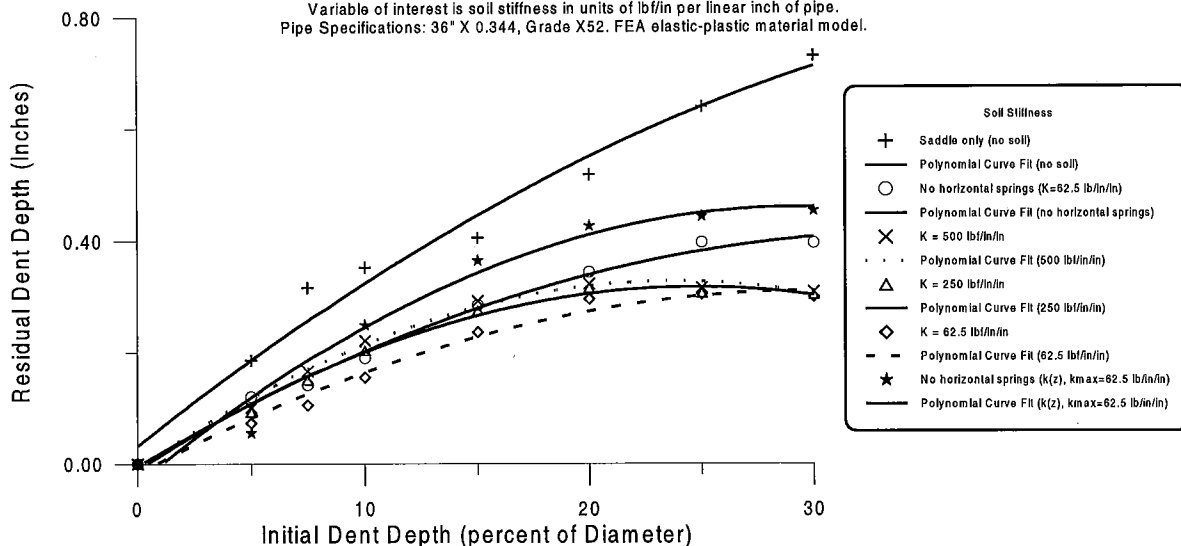


Fig. 3 Digitized Plot of the Actual Dented Region of the Pipeline

## RESIDUAL DENT DEPTH AS A FUNCTION OF INITIAL DENT DEPTH AND SOIL STIFFNESS

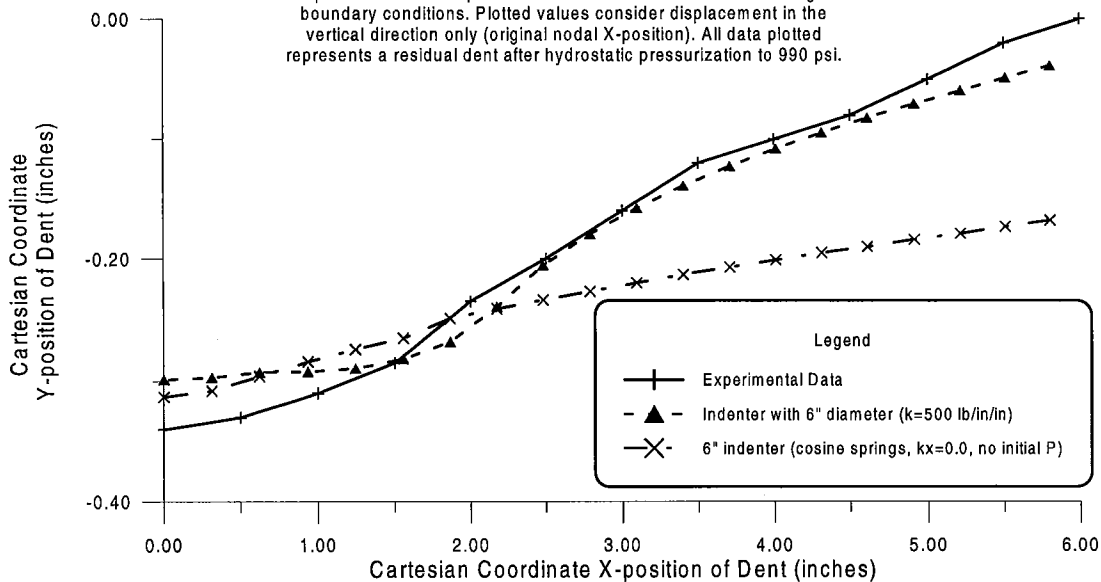
Results based upon ABAQUS finite element plain strain models. Shell elements used to model pipe and soil modeled with spring elements. Variable of interest is soil stiffness in units of lb/in per linear inch of pipe. Pipe Specifications: 36" X 0.344, Grade X52. FEA elastic-plastic material model.



**Fig. 4 Residual Dent Depth as a Function of Initial Dent Depth and Soil Stiffness**

## DENT CONTOUR AS A FUNCTION OF LOADING AND BOUNDARY CONDITIONS

Data presented based upon finite element results for varied loading and boundary conditions. Plotted values consider displacement in the vertical direction only (original nodal X-position). All data plotted represents a residual dent after hydrostatic pressurization to 990 psi.

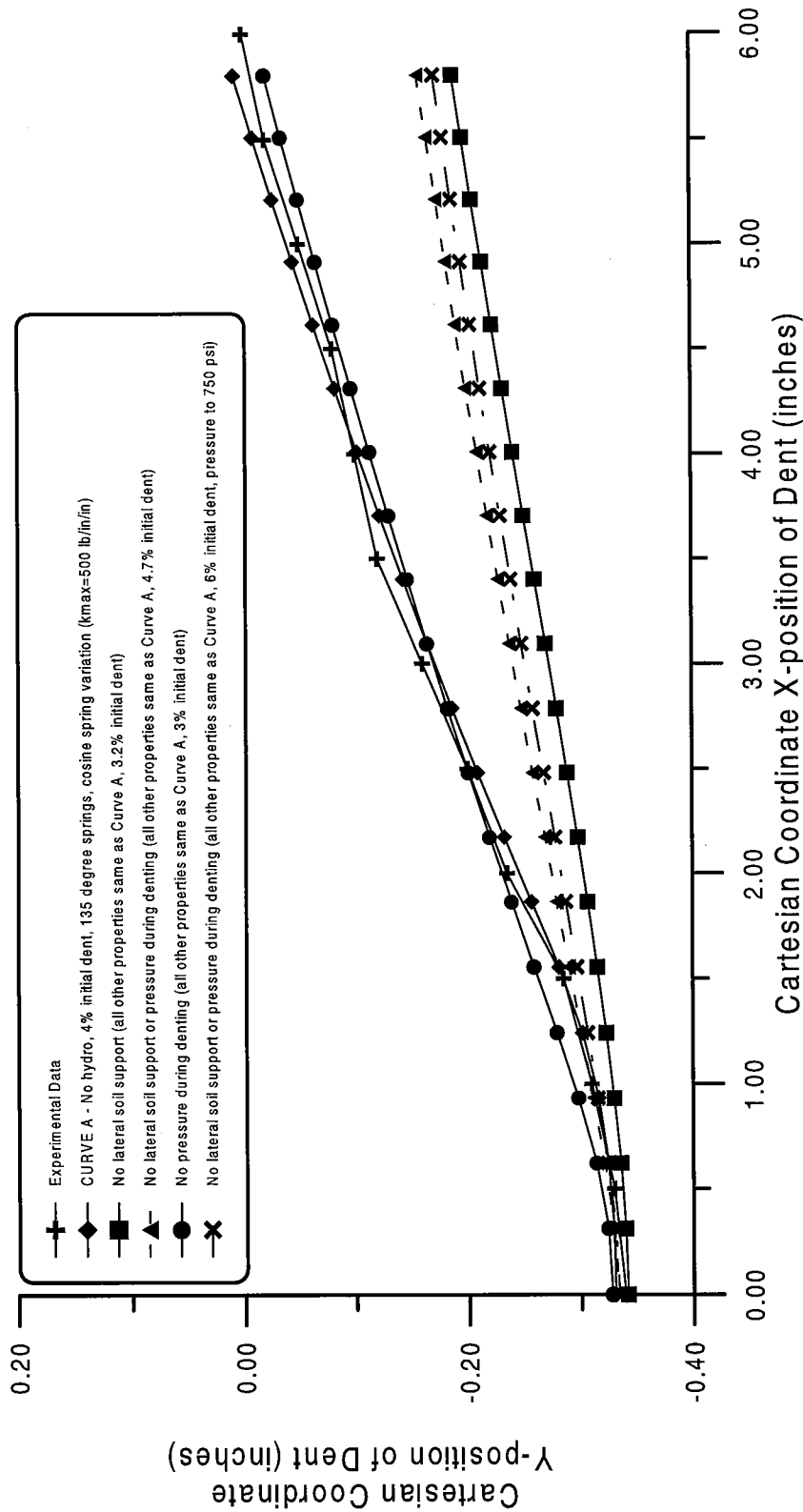


Notes:  
 1. Data plotted for k=500 lb/in/in had an indentation pressure of 480 psi  
 2. Data plotted for k(y) had a maximum soil stiffness of 62.5 lb/in/in on bottom of pipe and minimum of 0 psi at spring-line (unless otherwise noted). No internal pressure present during installation of dent for this model.

**Fig. 5 Dent Contour as a Function of Loading and Boundary Conditions for a 6" Indenter**

# DENT CONTOUR AS A FUNCTION OF LOADING AND BOUNDARY CONDITIONS FOR A 36" INDENTER

Data presented based upon finite element results for varied loading and boundary conditions. Plotted values consider displacement in the vertical direction only (original nodal X-position). Indenter has a 36" diameter.



- Notes:
1. Data plotted for  $k_y$  &  $k_x$  had a maximum soil stiffness of 500 lb/in/in considering a cosine variation of stiffness in both the X and Y directions (135 degree distribution).
  2. All samples pressurized to 480 psi during and after denting unless otherwise noted.

Fig. 6 Dent Contour as a Function of Loading and Boundary Conditions for a 36" Indenter