Sahel N. Abduljauwad

Hamdan N. Al-Ghamedy
e-mail: hghamdi@kfupm.edu.sa

Junaid A. Siddiqui

Ibrahim M. Asi

Naser A. Al-Shayea

Department of Civil Engineering,
King Fahd University of Petroleum and Minerals,
Dhahran 31261, Saudi Arabia

Stability of Vertically Bent Pipelines Buried in Sand

This paper discusses the stability of underground pipelines with preformed vertical bends buried in sandy soil. More specifically, the minimum cover height required to prevent the pipe from bowing under the action of forces due to temperature change and internal pressure is estimated. The variables considered include the pipe and soil materials, diameter, thickness, overburden height, bend radius, bend angle, internal pressure, fluid specific weight, and temperature variation. A comprehensive three-dimensional finite element analysis is carried out. The results are extracted from the output obtained. These results are put in a database which is used to develop general regression models to determine the relationships among the different variables. Different buckling modes are also considered. All of these results and models are entered into a computer software program for ready access. [DOI: 10.1115/1.1767858]

Introduction

Buried pipelines are very common in industry; they may carry water, gas, petroleum products, or other fluids. In certain situations, it is unavoidable, or at least more economical, to have vertical bends in cross-country pipelines. The behavior of such bent pipelines is quite different from straight ones, especially under temperature change. In order to make a comprehensive investigation and end up with solid conclusions and recommendations, several variables need to be considered in the study. They include the different soil properties and the parameters related to the pipe and the bend, such as pipe material properties, diameter, thickness, overburden height, bend radius, bend angle, internal pressure, fluid specific weight, and temperature variation.

In the literature, only a limited number of studies related to pipe bends have been carried out or discussed. Bends are mentioned in some standards/codes. The American Society of Mechanical Engineers Code ASME B31.4 [1] recognizes the flexural behavior of pipe bends by the use of what is termed a flexibility factor (k) and a stress intensification factor (i) in which simple beam theory is utilized. Karman [2] presented the first theoretical solution for smooth unrestrained bends, after which several studies were carried out, e.g., Vigness [3], Pardue and Vigness [4], Kafka and Dunn [5], Rodabaugh and George [6], and Findlay and Spence [7]. More recently, Thomson and Spence [8] presented some new analytical solutions. Thin shell theory was used by Whatham [9] who presented a solution without simplifying assumptions. Gresnight and van Foeken [10] presented an analytical model for the elastic/plastic design of pipe bends utilizing the minimum potential energy theory; in that model, the soil load that acts on a buried pipe bend was explicitly incorporated.

The finite element method was used by Natarajan and Blomfield [11], Ohtsubo and Watanabe [12], and Weiß et al. [13] to develop different design aids. Natarajan and Blomfield [11] examined several forms of end constraints for different parameters; it was concluded that the significance of the tangent depends on the ratio of the bend angle to the radius. Weiß et al. [13] demonstrated the use of the finite element method for the design of pipe bends with respect to fatigue strength and load carrying capacity.

In general, the proposed pipe bend elements can be broadly divided into two categories: beam-shell and shell-ring elements. Beam-shell elements are those in which shell type ovalization-deformation is superposed on a curved beam element. Hibett [14], Bathe and Almeida [15], and Mackenzie and Boyle [16] presented such a type. On the other hand, the shell-ring type of elements are wholly based on the thin shell theory. Ohtsubo and Watanabe [12] proposed such an element. De Melo and De Casto [17] presented a pipe element, derived from the arch bending theory, for the analysis of in-plane bending of curved pipes.

The restraint offered by soil against the movement of buried pipes, termed subgrade reaction, has been studied and modeled by many researchers. The first pioneer who introduced the concept of elastic subgrade reaction was Winkler [18], followed by Hetenyi [19]. Vesić [20] computed the uplift capacity of cylinders on the basis of the pressure required to expand a surface cavity. Audibert and Nyman [21] performed tests on the horizontal movement of pipes. There have also been some studies to quantify soil restraint against the oblique motion of pipelines such as that by Nyman [22] and Hsu [23]. Trautmann et al. [24,25] carried out an extensive laboratory study of the uplift and lateral movement of buried pipes. They compared the results with that of Vesić [20], Row and Davis [26], Ovesen [27], and Audibert and Nyman [21]. Dickin [28] and Poorooshasb et al. [29] carried out centrifuge model studies, while Hsu [30] studied velocity effects on the lateral soil restraint of pipelines. Utilizing the finite element method, Yin et al. [31], Altaee and Boivin [32], and Altaee et al. [33] performed some analyses of different soils. For restrained underground pipes, several other studies, such as that of Peng [34], Goodling [35], and Ng et al. [36], have been carried out. In the oil industry, Saudi Aramco, the biggest oil company in the world in terms of production, in its standard SAES-L-051 [37] specifies a simplified method for calculating the required soil cover over bent buried pipes using an "in house" computer program. It is based on the idealistic column buckling with distributed transverse loading, which represents the soil weight.

Description of the Problem and Need for the Research

Temperature variation and Poisson's effect due to internal pressure may cause significant longitudinal deformations in buried pipe bends. The earth pressure of the confining soil at the bend contributes in resisting the movement (It offers resistance to the moment.); thus, the strength of the soil is important to keep the buried pipe bend adequately restrained against excessive deformation. Methods based on classical theories have been, and are still being, used for such problems; however, they have proven to be inadequate in modeling the actual field behavior of the pipe-soil system. Numerical methods based on improved modeling techniques are occasionally used, but their application is limited for practical purposes due to the effort required in modeling the complex pipe-soil composite system. In particular, the finite element method (FEM) has proven to be capable of modeling buried pipe-

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lines satisfactorily; the major work on the subject has been summarized above. In this study, a very comprehensive investigation on the stability/soil cover requirement of vertically bent pipelines is carried out utilizing three-dimensional finite element analyses. Several variables including soil properties, pipe material properties, diameter, thickness, internal pressure, fluid specific weight, bend radius, bend angle, temperature variation, and overburden height are all considered. No such complete research has been done previously. The problem of buried pipeline bends is commonly encountered in the field, especially in the oil industry; thus, such a study is necessary in order to arrive at an optimum design which incorporates safety as well as economy.

Research Methodology

In order to carry out the research and achieve its objectives, the following steps need to be executed:

1. Review the literature on the subject; this has been summarized above.
2. Select suitable software that is capable of modeling the system discussed above including a nonlinear/inelastic material model for soil behavior.
3. Set up and validate a three-dimensional FEM model that is capable of modeling a soil-vertical pipe bend system.
4. Carry out a complete analysis of the system for all possible combinations of the parameters that influence the behavior of vertical buried pipe bends.
5. Develop tables, graphs, and/or charts, which may be used as design aids, utilizing the results obtained by the FEM analyses to study the relationship between various variables. Similarly, regression models, which correlate the variables stated above, are to be formulated.

Material Models

Since it is always desirable, and most of the time required, to keep the working stress in the pipe below the yield strength, it is assumed that the pipe behavior will be within the linear elastic range and that the material of the pipe is steel. With regard to local soil, sand predominates, and it is always used as the trench backfill without compaction. Sand was thus considered in this study; therefore, the Mohr-Coulomb failure criterion was used. The steel properties (for different grades) are known, while the strength parameters of the local sand were determined experimentally by triaxial and direct shear tests. The angle of friction for the soil, ϕ, came out to be 35°, while the cohesion, c, was zero. An interface (joint) element was also used and will be discussed in the FEM model section.

Computer Program and Validation Checks

There are many FEM-based software packages available in the market. Among other factors, the availability, the need/nature of the problem at hand, and the cost should be considered when selecting a program for a study such as this. Accordingly, the Structure Medium Analysis Program (SMAP-3D) [38] was selected because it has special features which met our needs.

In order to validate the program and the models used, especially in the absence of previous studies (experimental and analytical) in the same field, several runs were carried out to study and compare individual structural phenomena. They included the load distribution or arching in the soil around the pipe, the soil resistance to the uplift movement of a straight pipe, and centrifuge modeling of buried bent pipes; details are given next.

To check the arching effect of flexible and rigid pipes, several problems were analyzed. The diameter chosen was 1219 mm (48 in.), while the elastic moduli and the thicknesses were 200 GPa (29,000 ksi) and 152 mm (6 in.) for the rigid material, representing steel, and 690 MPa (100 ksi) and 6.35 mm (0.25 in.) for the flexible material, which represents plastic. These were chosen in order to have distinct properties for the two different pipes. Cover depths of 762 mm (30 in.), 1067 mm (42 in.), 1524 mm (60 in.), and 2286 mm (90 in.) were selected. Compared with the formulas of Marston and Anderson [39], the *overall trend and behavior are similar*; however, more accurate results were expected using the FEM than with the formulas, due to their crude approximation and assumptions. Deformations as well as stress contours obtained were as expected for both types of pipes. Details can be obtained in Abduljauwad et al. [40,41].

In continuation of the validation process, the uplift movement of buried pipes was analyzed. The data used for the comparison and verification were taken from the Trautmann et al. [24] study in which full-scale laboratory tests were carried out. That investigation is widely recognized, and the use of its findings in design has been recommended in various publications such as ASME B31.1 [42] and CGL [43]. When the results of this study were compared with the experimental values, good agreement was obtained for small cover depths. As the cover depth increased, the FEM results started to deviate and became noticeably different for loose sand with the largest cover depth (52 in.). The same discrepancy was observed with other studies, e.g., [20,26]. Trautmann et al. [24] mentioned that a punching mechanism develops during the uplift of a deeply buried pipe in loose sand. They described the reason for this discrepancy as the inability of analytical models to account for the contractive behavior during shear; the high porosity of loose sand results in large volume change, and this effect was not taken into account by the analytical model. The original reference [24] can be referred to for more details. As stated in that study, the uncertainty in deeply buried pipes is higher than that of the shallow ones. Nevertheless, the results obtained here are better than those of the previously published work, which was cited above.

Since it was not feasible to carry out full-scale testing, centrifuge modeling was utilized to simulate field conditions. The main concept behind the centrifuge modeling is to amplify/scale the small model at hand by increasing the gravitational force by "*n*" times such that full scale testing is simulated. By doing so, the benefits of full scale testing are obtained, and, on the other hand, the disadvantages of normal laboratory experiments (small, idealized, etc.) and full scale testing (cost, time, etc.) are eliminated. The complete theory behind this is beyond the scope of the paper. For readers who are not familiar with centrifuge modeling concepts, many references on the subject, including [40], are available. The experiments were done using the centrifuge of the University of Colorado, Boulder, U.S.A. For the reason stated below, a 50.8 mm (2 in.) plastic pipe, with 1.93 MPa (280 psi) maximum pressure (ASTM D 1785), was used to prepare both 90° and 45° bends. The bends had an internal diameter of 50.8 mm (2 in.) and a thickness of 4.2 mm (0.165 in.). The model properties were selected to represent AP1 60 carbon steel pipe with 1218 mm (48 in.) outer diameter and 19 mm (0.76 in.) thickness using a scale factor of 20. The same setting was idealized by a three-dimensional FEM mesh for each bend. Reasonably good agreement between the centrifuge model measurements and the finite element predictions was observed. More details can be found in Abduljauwad et al. [40,41].

FEM Idealization and Analysis

Virtual Achor. The finite element analysis constituted the major and most demanding task in this work. Before elaborating on the three-dimensional behavior of buried bent pipes, some words about boundary conditions and pipe anchors are warranted. A typical buried pipe bend is shown in Fig. 1. When a straight pipe connected to a bend expands (or contracts) under temperature change and/or internal pressure, it causes the bend apex to move vertically, and this movement is resisted by the surrounding soil. The friction between the pipe and the soil restrains the longitudinal movement of the straight pipe relative to the soil. The maximum movement occurs at the end of the pipe where the bend is connected and starts to be reduced from there to a point beyond

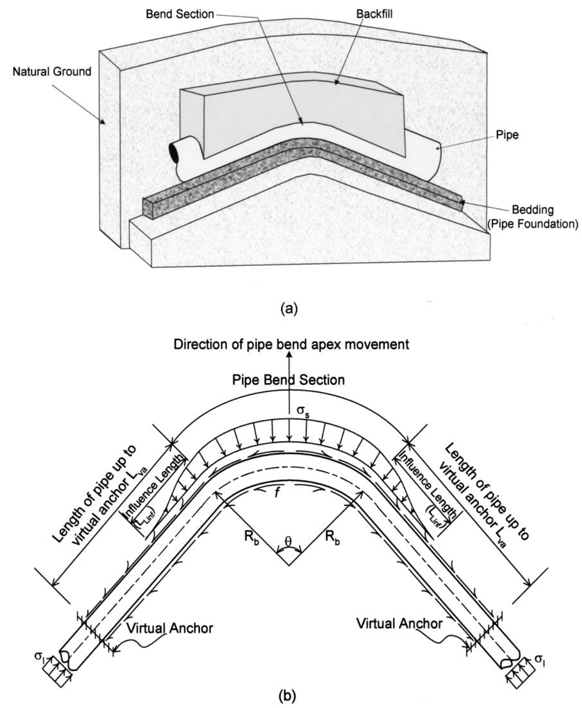

Fig. 1 Typical vertical buried pipe bend: (a) Perspective sectional view, (b) side view showing key parameters

which there is no movement of the pipe relative to the soil. This point is called the *virtual anchor*. The location of the virtual anchor is required to provide appropriate boundary conditions for the three-dimensional mesh of a buried pipe bend. The location of the virtual anchor is thus calculated using the method given in ASME B31.1 Appendix VII [42]. The following equation is used for calculating the virtual anchor location, L_{va}:

$$L_{va}=\Omega\left[\sqrt{1+\frac{2F_{\max}}{f\Omega}}-1\right] \tag{1}$$

where

- $\Omega=AE\beta/k$ is an effective length parameter
- $F_{\max}$ is the maximum axial force in pipe
- f is the unit soil friction force along the pipe
- A is the cross-sectional area of the pipe
- E is the modulus of elasticity of the pipe material
- β represents the pipe-soil system characteristics
- k is the soil modulus of the subgrade reaction

The value of the influence length $L_{\inf}$, which is the length at which the hyperbolic function in Hetenyi's equation [19] approaches unity, is calculated using the equation

$$L_{\inf}=\frac{3\pi}{4\beta} \tag{2}$$

The uplift movement of a vertical pipe bend is resisted by the overburden soil pressure σ_s (as shown in Fig. 1) and the shear strength of the soil τ_s, as illustrated in Fig. 2. In addition, the movement of a buried pipe is counteracted by the weight of the pipe and its contents. All of this is taken care of in the FEM idealization.

Mesh Generation. Since a soil system comprises a semi-infinite domain extending a large distance in the horizontal direction and downwards, one of the important aspects in making an FEM mesh is to truncate the mesh in the semi-infinite domain of

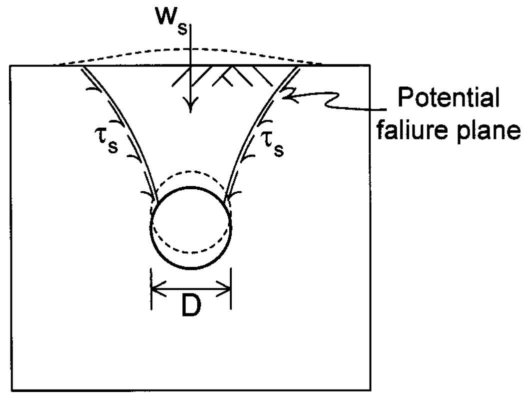

Fig. 2 Soil reaction against movement of buried vertical bend

the soil at a place where the geo-static condition exists. The limits used to truncate the mesh and specify the free field condition are shown in Fig. 3. These limits were conservatively established based on the recommendations in the literature (e.g., [26,33]) and utilizing the observation made during the two- and three-dimensional validation and trial runs using the SMAP [38] and CANDE [44] programs.

The task of generating the three-dimensional mesh of the buried pipe bend system for a given problem is accomplished utilizing the finite element modeling and postprocessing, FEMAP [45,46] program. The basic strategy used in FEMAP is to first generate a two-dimensional mesh along the pipe cross-section. The two-dimensional mesh is then extruded along the pipeline longitudinal axis to get the full three-dimensional mesh.

To model the system, continuum elements characterized by the Mohr-Coulomb failure criterion were used for the soil, shell elements were utilized to model the pipe, while joint elements were assumed to represent the pipe-soil interface. Since the thickness of the joint element occupies a region that is physically taken up by the soil, it is, therefore, desirable to keep its thickness as small as possible. However, it was found during the trial and validation runs that the solution did not converge if a very small value for the thickness of the joint element was used. Each of the validation runs was, therefore, solved a number of times by changing the value of the joint element thickness until a stable solution was obtained for the smallest possible value of the joint thickness. Thus, it was concluded that a suitable value for the joint element's thickness was $D/40$ where D is the outer diameter of the pipe. Apart from the thickness, the value of the joint element shear parameter, G, was also found out to be significant in achieving stable results because of the longitudinal movement of the pipe relative to the soil. Stable and converged results are obtained

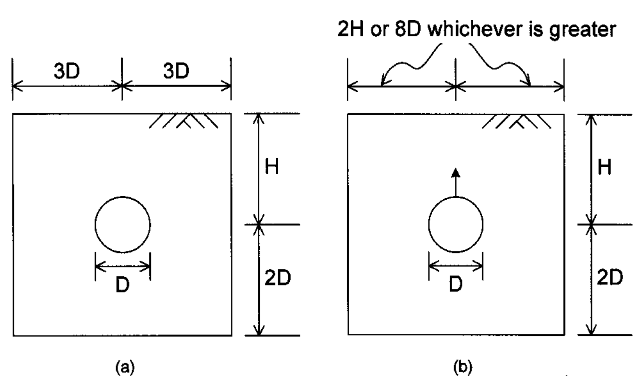

Fig. 3 Location of mesh boundaries: (a) limits for pipe under gravity loading; and (b) limits for pipe moving under uplift forces

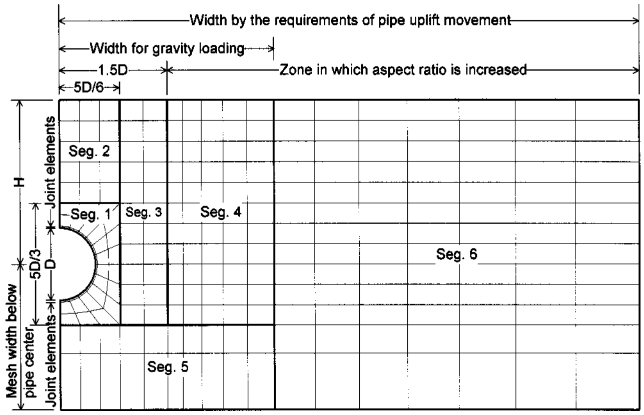

Fig. 4 Two-dimensional mesh made to extrude a three-dimensional vertical bend mesh

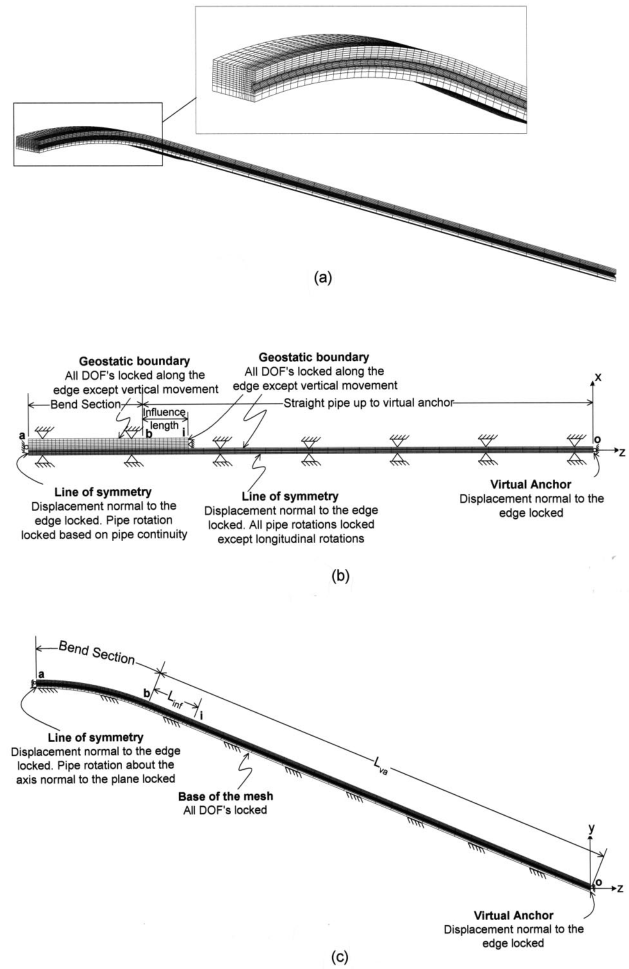

Fig. 5 Buried pipe vertical bend mesh (three-dimensional): (a) perspective view; (b) plan; and (c) side view

when the value of G does not exceed a certain limit. A value of 172 kPa (25 psi) emerged as the most appropriate for a cover depth of 305 mm (12 in) or more. A smaller value for G needs to be used in some cases where a very small cover depth is used.

A typical two-dimensional mesh, which is used to generate the three-dimensional mesh, is shown in Fig. 4 in which 24 shell elements are used to model the circle of the pipe; due to symmetry, only half of the domain is shown. The aspect ratio of the soil continuum elements is kept as close to 1 as possible within a width of 1.5D on each side of the pipe center. Beyond that width, the element aspect ratio is increased gradually up to the geo-static condition when it becomes 3, as a maximum. This scheme allows for satisfactory mesh density near the pipe while keeping the problem size relatively manageable. This conclusion was reached after many trial runs were carried out for different meshes, ranging from very fine with square or almost square elements to relatively coarse with rectangular/slender elements.

The extrusion of two-dimensional meshes to three-dimensional meshes is quite lengthy and geometrically complex, due to the nature of the problem and boundary conditions. However, a typical three-dimensional generated mesh is shown in Fig. 5 in which symmetry is taken advantage of so that only one quarter of the domain is considered with appropriate boundary conditions. Details can be found in Siddiqui [47].

Application of Loads

The loads considered in this investigation are gravity, which includes the weight of the soil and pipe and its contents, internal pressure, and temperature. When calculating the weight of fluid inside the pipe, the elevation of the vertical bend was taken into account at different nodes. Due to the nonlinearity of the problem, these loads were incremented, and within each increment iterations were performed until convergence of the solution was reached. After many numerical tests, 20 load steps were found to be the optimum for most runs.

Parametric Study

After the preliminary, but necessary, work presented above, a full and comprehensive parametric study was carried out. An extensive numerical analysis program, utilizing the FEM and considering all variables and factors of concern, was run, and large outputs and results were obtained. Only a brief description and sample results are presented here, and further explanations and presentation can be found in Abduljauwad et al. [40,41].

The parameters, along with their ranges, considered in this work are shown in Table 1. The values used for the FEM analysis were carefully selected within these ranges, with more emphasis on critical values and limits and intermediate points so that the results could be used to develop regression models which are general and reliable, as discussed later. The values of these parameters are varied within their limits, and various combinations were considered in order to obtain the effect of each of the parameters individually as well as the interaction among them.

To define the capacity of the buried pipe vertical bend due to temperature changes (in addition to gravity loads and internal pressure), two criteria are possible. The first one, termed by the authors as the ultimate temperature method (UTM) defines the point when the soil above the pipe is on the verge of shear failure. This means that the pipe would have moved "some distance" up before failure, which implies that the soil would have "flowed" beneath the pipe. This action is regarded as completely undesirable by some oil companies, including Saudi Aramco; thus, it is not presented here even though it is more economical. The second method, named by the authors as the installation condition method (ICM), requires that the upward movement of the bend under the combined applied loads is restricted to the installation condition, which is defined as the state of the trench before the pipe is laid. After the installation of the pipe, the whole system settles down under the weight of the pipe and soil cover. Therefore, according to the ICM, the allowed upward movement of the bend apex is equal to the settlement caused by the weight of the soil cover and pipe *before* applying the loads. Care has to be taken in the FEM analysis regarding the total settlement. The contribution from the mesh *below* the pipe under its own weight (before laying the pipe and filling the trench) should be subtracted from the total settlement of the pipe bend extrados apex in order to get the allowed

Table 1 Range of parameters considered in the study

Factor	Minimum	Maximum	Comments
Pipe outer diameter, D	305 mm (12 in.)	1524 mm (60 in.)	This range is common in the oil industry
Height of overburden from surface to pipe crown, H_c	As required	As required	This is usually the needed variable
Pipe bend radius, R_b	15.2 m (50 ft)	213.4 m (700 ft)	This range is common in the oil industry
Pipe bend angle, θ	1°	20°	This range is common in the oil industry
Diameter/thickness ratio, D/t	50	150	This range is common in the oil industry
Internal pressure, p	0	*	* The maximum the pipe can carry before reaching the maximum allowable stress
Specific gravity of pipe content, G_f	0	1	0 (Gas), 0.56 (LPG), 0.86 (Crude Oil), 1 (Water)
Temperature change, ΔT	0	66.7°C (120°F)	This range is common in the oil industry
Pipe allowable stress	*	*	* Any grade of steel with an appropriate safety factor
Safety factor	*	*	* As specified by the used code/standard . . . etc.
Modulus of soil reaction, E'	*	*	* Appropriate value for the local soil (for buckling check)
Winkler spring coefficient, k_0	*	*	* Appropriate value for the local soil (for buckling check)

uplift movement according to this method. Due to space limitation, details of the two methods cannot be fully presented here; e.g., see Siddiqui [47].

The results obtained by the FEM analysis, which are of concern here, are best summarized in a tabular form. Since the list is very long, only a partial list of the results is presented in Table 2. They have been extracted from the huge output of the three-dimensional analyses which took several months to run on the latest Pentium processor. Generally, each single run took several hours to complete. As sample representatives, some of the results are presented graphically in Figs. 6 to 8.

Buckling of Buried Pipes

Since buckling of pipes can occur, it needs to be checked, along with the analysis above; it could be critical, especially in large diameter-small thickness pipes. The buckling of shell-type structures is quite involved, while the buckling of buried and relatively flexible pipes is even more complicated. There are many buckling modes and ‘‘exact’’ theories do not exist for some of them. Due to this, certain theories with specific assumptions and limitations, supported with some experimental results, if available, are utilized in the current study. Without elaboration, the following buckling modes are considered:

1. Buckling of cylindrical shells under the action of uniform axial compression (axial buckling by warping) (Timoshenko and Gere [48], Antaki [49], Ellinas [50], and Watashi and Iwata [51]).
2. Buckling of cylindrical shells under the action of uniform external pressure (ring buckling) (Farshad [52], Timoshenko and Gere [48], Antaki [49], AWWA C150 [53], and Moore and Booker [54,55]).
3. Pure bending buckling (winkling due to longitudinal bending) (Farshad [52], Antaki [49], Murray [56], Chiou and Chi [57], Hobbs [58,59], Taylor and Gan [60,61,62], Reddy [63], and Stephens [64]).
4. Lateral beam/shell buckling (beam-column/shell) (Antaki [49], Yun and Kyriakides [65,66], Deutsch and Weston [67], Shaw and Bomba [68] Choiu and Chi [69], and Zhou and Murray [70]).
5. Buckling of buried initially-bent pipes (Croll [71], Allan [72], and Raoof and Maschner [73]).
6. Buckling due to the combined effect of the stress components (API RP 1102 [74], Farshad [52], and German Code DIN 18800 Part 4 in Jullien [75]).

These checks were carried out utilizing the results obtained from the FEM analysis. This was done by a comprehensive computer program written for this project. If any of the buckling modes occurs, then a message is given indicating the mode of buckling, meaning that there is *instability*; i.e., the stability of the system cannot be maintained. This leads to problem redesign (especially pipe thickness), then analysis, and then check.

Regression Models

The design variables used in developing the regression equations to predict the ultimate temperature, as the dependent variable, that the pipe can withstand in the presence of a vertical pipe bend are pipe diameter, pipe thickness (or D/t ratio), depth of cover, radius and angle of bend, internal pressure, and specific gravity of the transported material. These are the variables which were varied in the finite element runs to generate a database. As an alternative, the cover height can be made the dependent variable.

To check the relationships among the variables used in the development of the regression model, first a correlation matrix is obtained. Second, on a further study of the trend of the data, different groups of such data are created according to the behavior of the buried pipe bend.

A regression analysis was performed utilizing the software package STATISTICA (release 6.1). The resulting regression models for the different groups of data are shown in Table 3. The results of the finite element analysis were utilized to develop the correlation coefficients of the models. The coefficient of determination, R^2, and the significance levels of the generated models are

Table 2 Maximum temperature change

S. No.	D mm (in)	H_c mm (in)	R_b m (ft)	θ (Deg)	D/t	p kPa (psi)	G_f	Maximum temperature change °C (°F)
1	300 (12)	1750 (70)	15 (50)	20	50	1034 (150)	0	30.14 (54.26)
2	600 (24)	900 (36)	15 (50)	20	50	1034 (150)	0	12.72 (22.89)
3	600 (24)	1500 (60)	15 (50)	20	50	1034 (150)	0	20.34 (36.61)
4	1050 (42)	900 (36)	15 (50)	20	50	1034 (150)	0	13.91 (25.04)
5	1050 (42)	1500 (60)	15 (50)	20	50	1034 (150)	0	20.71 (37.27)
6	1500 (60)	900 (36)	15 (50)	20	50	1034 (150)	0	15.68 (28.22)
7	300 (12)	300 (12)	90 (300)	20	50	1034 (150)	0	22.77 (40.99)
8	300 (12)	750 (30)	90 (300)	20	50	1034 (150)	0	61.75 (111.15)
9	600 (24)	750 (30)	90 (300)	20	50	1034 (150)	0	32.3 (58.14)
10	600 (24)	425 (17)	210 (700)	20	50	1034 (150)	0	39.52 (71.13)
11	600 (24)	525 (21)	210 (700)	20	50	1034 (150)	0	47.78 (86.01)
12	1500 (60)	1500 (60)	15 (50)	15	50	1034 (150)	0	25.48 (45.86)
13	300 (12)	300 (12)	90 (300)	15	50	1034 (150)	0	22.49 (40.48)
14	1050 (42)	750 (30)	210 (700)	15	50	1034 (150)	0	42.68 (76.82)
15	1050 (42)	900 (36)	210 (700)	15	50	1034 (150)	0	50.09 (90.16)
16	1050 (42)	1050 (42)	90 (300)	8	50	1034 (150)	0	31.8 (57.24)
17	1050 (42)	1500 (60)	90 (300)	8	50	1034 (150)	0	45.24 (81.43)
18	1500 (60)	900 (36)	90 (300)	8	50	1034 (150)	0	26.77 (48.19)
19	1500 (60)	1050 (42)	90 (300)	8	50	1034 (150)	0	30.54 (54.98)
20	1500 (60)	1500 (60)	90 (300)	8	50	1034 (150)	0	41.63 (74.93)
21	300 (12)	250 (10)	210 (700)	8	50	1034 (150)	0	35.71 (64.27)
22	300 (12)	375 (15)	210 (700)	8	50	1034 (150)	0	54.23 (97.61)
23	600 (24)	900 (36)	15 (50)	20	100	1034 (150)	0	19.33 (34.8)
24	600 (24)	1500 (60)	15 (50)	20	100	1034 (150)	0	33.32 (59.97)
25	1050 (42)	900 (36)	15 (50)	20	100	1034 (150)	0	20.1 (36.18)
26	1500 (60)	1500 (60)	15 (50)	20	100	1034 (150)	0	32.99 (59.39)
27	600 (24)	375 (15)	90 (300)	20	100	1034 (150)	0	30.81 (55.45)
28	600 (24)	600 (24)	90 (300)	20	100	1034 (150)	0	46.54 (83.77)
29	1500 (60)	300 (12)	210 (700)	20	100	1034 (150)	0	29.07 (52.32)
30	1500 (60)	450 (18)	210 (700)	20	100	1034 (150)	0	39.08 (70.35)
31	1050 (42)	600 (24)	90 (300)	18	100	1034 (150)	0	28.11 (50.59)
32	1050 (42)	900 (36)	90 (300)	15	100	1034 (150)	0	40.24 (72.44)
33	1500 (60)	600 (24)	210 (700)	15	100	1034 (150)	0	44.45 (80.01)
34	1050 (42)	600 (24)	90(300)	11	100	1034 (150)	0	27.09(48.77)
35	600 (24)	750 (30)	15 (50)	8	100	1034 (150)	0	29 (52.2)
36	1050 (42)	600 (24)	210 (700)	8	100	1034 (150)	0	51.57 (92.83)
37	1500 (60)	600 (24)	210 (700)	8	100	1034 (150)	0	40.09 (72.16)
38	1500 (60)	900 (36)	210 (700)	8	100	1034 (150)	0	59 (106.2)
39	600 (24)	900 (36)	15 (50)	20	150	1034 (150)	0	24.66 (44.39)
40	600 (24)	1050 (42)	15 (50)	20	150	1034 (150)	0	29.52 (53.14)
41	1050 (42)	900 (36)	15 (50)	20	150	1034 (150)	0	23.92 (43.06)
42	600 (24)	375 (15)	90 (300)	15	150	1034 (150)	0	34.79 (62.63)
43	600 (24)	450 (18)	90 (300)	15	150	1034 (150)	0	42.26 (76.06)
44	1050 (42)	600 (24)	90 (300)	15	150	1034 (150)	0	35.26 (63.47)
45	1500 (60)	450 (18)	210 (700)	15	150	1034 (150)	0	41.29 (74.33)
46	1050 (42)	600 (24)	90 (300)	11	150	1034 (150)	0	35.63 (64.13)
47	600 (24)	600 (24)	15 (50)	8	150	1034 (150)	0	28.29 (50.93)
48	1050 (42)	700 (28)	15 (50)	8	150	1034 (150)	0	35.66 (64.19)
49	1500 (60)	700 (28)	15 (50)	8	150	1034 (150)	0	38.67 (69.6)
50	1500 (60)	375 (15)	210 (700)	8	150	1034 (150)	0	31.24 (56.23)
51	1500 (60)	450 (18)	210 (700)	8	150	1034 (150)	0	36.06 (64.91)
52	1500 (60)	900 (36)	210 (700)	20	50	4309 (625)	0	34.53 (62.15)
53	600 (24)	1050 (42)	90 (300)	15	50	4309 (625)	0	36.07 (64.92)
54	1500 (60)	900 (36)	15 (50)	8	50	4309 (625)	0	19.8 (35.64)
55	1500 (60)	600 (24)	15 (50)	8	100	4309 (625)	0	13.89 (25)
56	1500 (60)	600 (24)	210 (700)	20	150	4309 (625)	0	59.82 (107.67)
57	300 (12)	1750 (70)	15 (50)	20	50	5516 (800)	0	21.74 (39.14)
58	300 (12)	3500 (140)	15 (50)	20	50	5516 (800)	0	51.97 (93.55)
59	300 (12)	750 (30)	90 (300)	15	50	5516 (800)	0	48.98 (88.17)
60	1500 (60)	900 (36)	210 (700)	20	50	7584 (1100)	0	29.26 (52.67)
61	1050 (42)	600 (24)	90 (300)	20	150	7584 (1100)	0	20.87 (37.56)
62	1500 (60)	750 (30)	210 (700)	20	150	7584 (1100)	0	51.55 (92.79)
63	525 (21)	450 (18)	198 (660)	10	85	689 (100)	0	62.16 (111.89)
64	1050 (42)	500 (20)	202.5 (675)	19	115	1379 (200)	0	50.87 (91.56)
65	1375 (55)	2000 (80)	30 (100)	18	75	5516 (800)	0	27.04 (48.67)
66	675 (27)	500 (20)	113.4 (378)	19	90	1586 (230)	0	39.97 (71.95)
67	450 (18)	1750 (70)	30 (100)	18	75	1551 (225)	0	51 (91.8)
68	650 (26)	2000 (80)	30 (100)	18	75	1551 (225)	0	46.35 (83.43)
69	900 (36)	1750 (70)	30 (100)	18	75	1551 (225)	0	35.64 (64.15)
70	1250 (50)	2000 (80)	30 (100)	18	75	3447 (500)	0	33.41 (60.13)
71	650 (26)	2000 (80)	30 (100)	18	75	2413 (350)	0	43.92 (79.06)
72	450 (18)	250 (10)	190.5 (635)	16	135	2068 (300)	0	36.12 (65.02)
73	1200 (48)	1750 (70)	30 (100)	18	75	3103 (450)	1	31.14 (56.06)
74	1500 (60)	900 (36)	210 (700)	20	50	1034 (150)	1	46.25 (83.25)
75	1500 (60)	900 (36)	15 (50)	8	50	1034 (150)	1	31.12 (56.01)
76	1500 (60)	450 (18)	210 (700)	20	100	1034 (150)	1	50.03 (90.05)
77	1500 (60)	450 (18)	15 (50)	8	100	1034 (150)	1	30.52 (54.94)
78	1500 (60)	900 (36)	90 (300)	8	100	1034 (150)	1	48.36 (87.05)
79	600 (24)	300 (12)	210 (700)	20	150	4309 (625)	1	24.7 (44.46)
80	1050 (42)	60 (24)	90 (300)	18	150	4309 (625)	1	39.95 (71.91)

Table 2 (*Continued*)

S. No.	D mm (in)	H_c mm (in)	R_b m (ft)	θ (Deg)	D/t	p kPa (psi)	G_f	Maximum temperature change °C (°F)
81	1050 (42)	375 (15)	210 (700)	15	150	4309 (625)	1	45.97 (82.75)
82	1050 (42)	450 (18)	210 (700)	15	100	7584 (1100)	1	32.01 (57.62)
83	1500 (60)	900 (36)	90 (300)	8	100	7584 (1100)	1	24.41 (43.93)
84	600 (24)	450 (18)	90 (300)	15	150	7584 (1100)	1	36.82 (66.28)

also presented in that table. The R^2 values for all developed models are higher than 0.88. Moreover, the confidence levels for all models are higher than 99.99%. Two forms of equations are presented. One is used to calculate the maximum allowable temperature change, ΔT, as a function of the other variables. The second form is to determine the required (minimum) cover height, H_c, needed for specific values of the other variables. The first form is suitable for checking existing problems/applications, while the second one is appropriate for the actual design (at the beginning). For values falling between two groups, interpolation is utilized; this is done automatically in the computer program written for this purpose. In addition, or as an alternative, figures and charts can be plotted utilizing the data generated. However, this is a lengthy process and is not presented here.

The results of entire research program discussed above were programmed into a computer code. The result is a user-friendly software package called ''Analysis and Design of Buried Pipelines'' (ADBP) which is capable of making all necessary checks, analysis, and design (Abduljauwad et al. [76,77]). It is worth mentioning that the original database used and the analyses carried out were in FPS/U.S. customary units as shown in the table; thus, the coefficients and the variables in the models must be in such units. The conversion factors from these units to the SI units are written at the bottom of the table; however, such conversion factors are programmed in the computer so that the user can select the SI units, and the program automatically converts the SI units into the appropriate units at the beginning of the analysis and at the end to show the results in the standard SI units. The SI units' user does not ''feel'' it. The authors thought that this is the easiest/best way of doing it for two main reasons. First, it is not worth changing all the units in the database, regression analysis, etc. since the program accepts either of the two systems of units and make the appropriate conversion without the user's interference. Second, some societies/associations/individuals still use the U.S. Customary units, or at least they allow their usage.

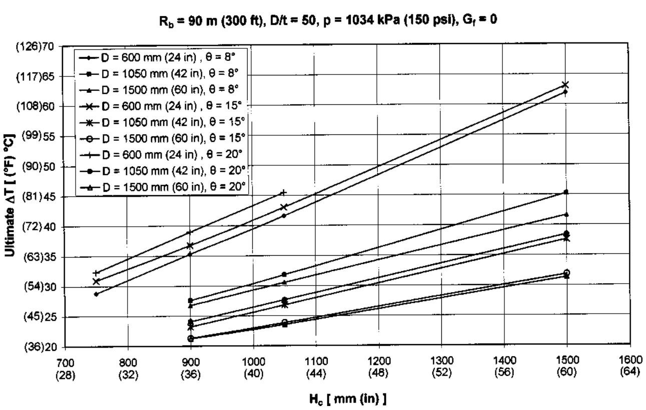

Fig. 6 Effect of cover height

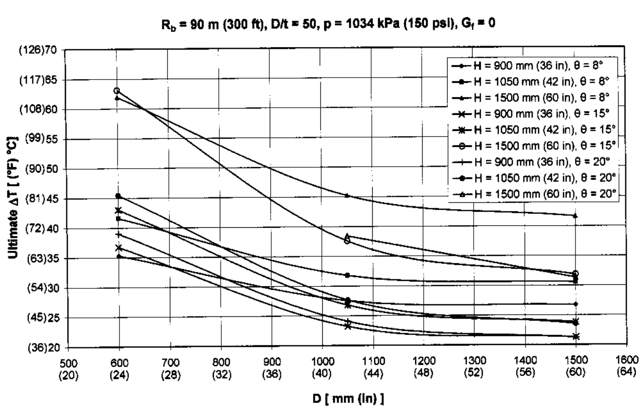

Fig. 7 Effect of pipe diameter

Summary and Conclusions

The stability and cover height requirements for buried pipelines with vertical bends were investigated. Based on preliminary trial tests and laboratory experiments, comprehensive finite element analyses were carried out, and the required data were obtained. These results were utilized to develop regression equations considering different variables including pipe and soil properties, diameter, thickness, overburden height, bend radius, bend angle, internal pressure, fluid specific weight, and temperature variation. The developed models gave good estimates for the required cover height needed to prevent the pipe from bowing. Moreover, the suggested models are easy to understand and apply by practicing engineers.

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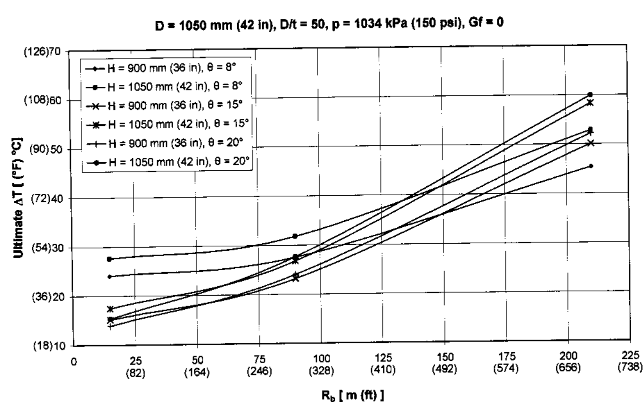

Fig. 8 Effect of bend radius

Table 3 Generated models for the ultimate change in temperature and depth of cover for pipes with vertical bends

Bend Radius (ft)	Pipe Diameter (in.)	Generated Model	R^2	Significance level
50	All	$\Delta T = 71.5294 + 0.2184\ D/t + 0.9088\ H_c - 28.6915*\ln(\theta) - 0.0496\ p + 19.2352\ G_f$ $H_c = -1/0.9088*(-\Delta T + 71.5294 + 0.2184 *D/t - 28.6915*\ln(\theta) - 0.0496*\ p + 19.2352*G_f)$	0.8877	0.000
300	24	$\Delta T = 32.3662 - 188.241\ 0t + 2.6496\ H_c + 11.7831\ \ln(\theta) - 0.0306\ p + 12.6470\ G_f$ $H_c = 1/2.6496*(\Delta T - 32.3662 + 188.241 *t - 11.7831*\ln(\theta) + 0.0306*\ p - 12.647 *G_f)$	0.8837	0.000
300	42	$\Delta T = 1/(0.0191 + 0.0223\ t - 0.0004\ H_c - 0.0148(1/\theta) + 1.02\ *E-5*\ p - 0.0076\ G_f)$ $H_c = 1/0.0004*(-1/\Delta T + 0.0191 + 0.0223\ *t - 0.0148*(1/\theta) + 0.0000102\ *p - 0.0076 *G_f)$	0.9067	0.000
300	60	$\Delta T = \exp(3.6872 - 0.5906\ \ln(t) + 0.0216 H_c - 0.2022\ \ln(\theta) - 9.49\ *E-4*p + 0.4650\ G_f)$ $H_c = -1/0.0216*(-\ln(\Delta T) + 3.6872 - 0.5906 *\ln(t) - 0.2022*\ln(\theta) - 0.000949 *p + 0.465*\ G_f)$	0.9323	0.000
700	24	$\Delta T = \exp(3.0677 - 0.5615\ \ln(t) + 0.0676\ H_c + 0.1169\ \ln(\theta) - 4.85*E-3*p + 0.8480\ G_f)$ $H_c = -1/0.0676*(-\ln(\Delta T) + 3.0677 - 0.5615*\ln(t) + 0.1169*\ln(\theta) - 0.00485\ *p + 0.848*\ G_f)$	0.9453	0.000
700	42	$\Delta T = -20.9612 - 29.7225\ \ln(t) + 2.2437\ H_c + 11.3463\ \ln(\theta) - 0.0280\ p + 12.4599\ G_f$ $H_c = -1/2.2437*(-\Delta T - 20.9612 - 29.7225* \ln(t) + 11.3463*\ln(\theta) - 0.028\ *p + 12.4599\ *G_f)$	0.9064	0.000
700	60	$\Delta T = 41.1284 - 66.1520\ t + 2.0727\ H_c + 10.8649\ \ln(\theta) - 0.0123\ p + 33.8879\ G_f$ $H_c = -1/2.0727*(-\Delta T + 41.1284 - 66.152\ *t + 10.8649*\ln(\theta) - 0.0123\ *p + 33.8879*\ G_f)$	0.8894	0.000

ΔT=ultimate change in temperature, °F
θ=angle of bend, °
t=pipe wall thickness, in
p=internal pressure, psi
H_c=depth of cover, in
G_f=carried material specific gravity
To convert from °F to °C: $\Delta T(°C) = [\Delta T(°F)]\ 5/9$
To convert from in. to mm: H_c (mm)=[H_c (in.)]25.4

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