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Paper 229

Development of a Computer Program for the Analysis and Design of Buried Pipelines

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Abstract

Buried pipelines essentially involve problems of soil-structure interaction that include several complex factors such as geometry, material properties, and boundary conditions. Complete, comprehensive and lengthy numerical analyses using the finite element methods were carried out in this research to calculate stresses and strains of buried pipes. Using the obtained results, regression equations were developed to predict the absolute maximum stress and diameter change of buried pipes. Personal computer software, using Visual Basic 6.0, was developed utilizing the results stated above. The results of the regression analysis were used to develop three modules, which contain subroutines or functions to perform tasks as follows: Design and Analysis of Straight Pipe, Design and Analysis of Horizontal or Vertical Bend, and Buckling Check.

Keywords: buried pipelines, regression, horizontal bend, vertical bend, homoscedasticity, normality.

1 Introduction

Analysis and design of buried pipelines are usually based on classical theories and semi-empirical methods. The confidence in these approaches is very limited and use of them could lead to a very conservative design, which could cause major increases in costs. One of such methods is the American Petroleum Institute (API) [1] recommended practice 1102 to design pipelines which are to be located under highways and railroad crossings. The most recent version of this practice, API RP 1102 [2], incorporated the knowledge gained from the latest research and experience in measuring the actual performance of buried pipes under dead and live loads as well as under internal pressure. A computer program for PCs, PC-PISCESL [3,4] (Personal Computer-Pipeline Soil Crossing Evaluation System Liquids) was developed by Cornell University for the Gas Research Institute to perform calculation of pipe stresses under highway and roadway crossings. PISCESL is based on the design methodology for uncased railroad and highway crossings embodied in API RP 1102. This design methodology relates to steel pipelines installed using trenchless construction methods, in particular auger boring, with a crossing that is perpendicular to the railroad or highway. Use of this program is limited to pipelines having a diameter of 2 to 42 in. and ratios of diameter to wall thickness within the range of D/t = 12.5 to 100. In addition, highway crossings can be analyzed only for backfill heights between 3 and 10 ft. Furthermore, the program does not handle vertical and horizontal pipe bends. Therefore, the major objective of this research is to develop software which can handle the major limitations that have been observed in the PC-PISCESL program. Also, the proposed software will consider the local soil conditions.

2 Numerical Analysis

In soil-structure interaction problems, it is difficult, if not impossible, to find exact theoretical answers (or the so-called "closed-form solutions") in many applications. The soil behaviour is variable, very complicated and highly nonlinear, and the interaction with buried structures such as pipes makes it even more complex. This has led to the utilization of computational methods. In particular, the finite element method (FEM) is the most powerful, general, and widely used tool among the different numerical techniques.

The use of any FEM requires inputting the characteristics of the various materials involved in the soil-pipeline system. The properties provided by the manufacturers were used for the steel pipes. The soil materials (bedding, backfill, and natural soils) were characterized using the following properties: soil classification (particle-size distribution and consistency limits), density-moisture relationship, relative density, strength properties (angle of internal friction and cohesion), the constitutive model parameters (elastic modulus and bulk modulus), and the hyperbolic model parameters. These properties were determined based on the finding of a series of extensive in-situ/field and laboratory tests conducted on soil samples representing various types of soils. These tests included: field density measurements by nuclear gauge, sieve analysis, hydrometer analysis, Atterberg limits determination, Proctor compaction test, relative density tests, triaxial compression tests, direct shear tests and hydrostatic compression tests. Three different types of soil were selected in this research, since they are the most predominant soils in the Eastern Province of Saudi Arabia, namely: sand, marl, and sabkha.

Four major FEM analysis programs were selected and used for the different soil types and loading conditions [5 - 10]. Culvert ANalysis and DEsign (CANDE) software was utilized for sand overburden and highway crossing analyses. Structural Medium Analysis Program-3 Dimensions (SMAP-3D) was selected for the vertically and horizontally bent buried pipes. It was also used for comparing and checking the results of CANDE, which is a two-dimensional program. Finite Element Modelling and Post-Processing (FEMAP) is the package employed for preand post-processing. Personal Computer-PIpeline Soil Crossing Evaluation System Liquids (PC-PISCESL) was used – within its applicability – to compare different results and to explore its limitations.

Complete, comprehensive and lengthy numerical analyses using the finite element method were carried out for the buried pipes. They included sand dunes, highway crossings, vertically and horizontally bent pipes, and pipe buckling.

3 Regression and Model Verification

In order to be able to handle the huge amount of generated data from the different finite element methods runs in the proposed software, regression equations were developed to predict the absolute maximum circumferential stress and diameter change of buried pipes. Regression equations were developed for pipes crossing both paved and non-paved highways and pipes which were subjected to sand overburden. Separate equations were developed to depict the effect of truck loads variations on the pipes crossing highways. The developed equations covered four types of native soils, namely: sand at low density, sand at high density, marl and sabkha. In addition, equations were developed to predict the ultimate temperature that the pipe can withstand in the presence of vertical or horizontal bends.

A comprehensive procedure was followed in developing and checking the different developed set of models. Due to the paper length restriction, only the development of regression equations for the effect of sand overburden on the four types of soils is discussed in this paper.

3.1 Selection of Design Variables

CANDE software was used to calculate the different stresses, in addition to the pipe diameter change for the four types of native soils included in the study. A total of 25 finite element simulations were performed, in which the sand overfill was varied from 1 to 60 ft for each soil type. In each of the finite element simulations, the one-foot depth of cover was activated in separate construction increment, which enabled getting the dead load stresses for depths of cover 1 to 60 ft in an increment of 1 ft from a single finite element simulation. The total number of analysis cases for each soil type was 1,500 cases. The outputs of the finite element runs were summarized in tabular forms that included the selected variables in addition to the calculated circumferential internal and external stresses at the crown, invert, and springline, the absolute maximum circumferential stress, and change in the diameter.

From the generated data, it was decided to build models to predict both the maximum circumferential absolute stress regardless of its position along the pipe and the change in the pipe's diameter for the four types of the underlying soils.

Linear multiple regression was used to build the relationships between the independent and the dependent variables. The independent variables (IV's) were the pipe's diameter, thickness of the pipe's wall, and depth of cover. The dependent variables (DV's) were the absolute maximum stress and the change in the pipe's diameter.

The general purpose of multiple regression was to study the relationship between several independent or predictor variables and a dependent or criterion variable and to build models that enable the prediction of the dependent variables from the values of the independent variables. The general form of the linear multiple regression model was:

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots\ldots + \beta_k x_k + \tilde{\varepsilon} \qquad (1)$$

where

Y = dependent variable

β_i = regression coefficient

x_i = independent variables

$\tilde{\varepsilon}$ = random error with mean equal zero and variance equal σ^2.

The least squares method, which aims at decreasing the error term, was used to predict the regression coefficients.

3.2 Selection of Cases for Model Validations

To test the validity of the developed models in predicting both the values of maximum absolute stress and diameter change, thirty-nine cases out of the 1500 cases for each soil were selected randomly. These runs were not used in developing the models, but were used in the generated models to test the accuracy of the models in predicting the dependent variables correctly.

3.3 Correlation Matrices of the Variables

To check the relationships between the variables used in the models, correlation matrices were obtained. Table 1 shows the correlation matrices for the variables used for all types of native soils. Correlation coefficients provide a normalized and scale-free measure of the association between two variables. The correlation coefficient value ranges between –1 and +1. A positive correlation coefficient indicates that the variables vary in the same direction, while a negative coefficient indicates that the variables vary in the opposite direction. Statistically independent variables have an expected correlation coefficient of zero.

In Table 1, the correlation matrices include both the dependent variables (DV) and the independent variables (IV). The following can be concluded from the generated correlation matrices:

- The native soil type does not affect the relation between the IV's, i.e., the correlation coefficients of the IV's don't change with the change in the type of native soil.
- There is a positive correlation between the pipe's diameter and the thickness of the pipe's wall (0.71938), i.e. the greater the value of the pipe's diameter the greater the thickness of the wall of the pipe.

	Correlation Coefficient					
Soil Type	Variable \ Variable	Diameter	Thick-ness	Cover	Abs. Max. Stress	Diameter Change
Sand at low density	Diameter	1.00000	.71938	.00199	.22194	–.68579
	Thickness	.71938	1.00000	.00174	–.04953	–.13709
	Cover	.00199	.00174	1.00000	.89129	–.40315
	Abs. Max. Stress	.22194	–.04953	.89129	1.00000	–.71008
	Diameter Change	–.68579	–.13709	–.40315	–.71008	1.00000
Sand at high density	Diameter	1.00000	.71938	.00199	.00028	–.65433
	Thickness	.71938	1.00000	.00174	–.01104	–.18923
	Cover	.00199	.00174	1.00000	.98215	–.56203
	Abs. Max. Stress	.00028	–.01104	.98215	1.00000	–.56445
	Diameter Change	–.65433	–.18923	–.56203	–.56445	1.00000
Marl	Diameter	1.00000	.71938	.00199	.07369	–.64711
	Thickness	.71938	1.00000	.00174	–.06480	–.14144
	Cover	.00199	.00174	1.00000	.96104	–.51787
	Abs. Max. Stress	.07368	–.06480	.96104	1.00000	–.63364
	Diameter Change	–.64711	–.14144	–.51787	–.63364	1.00000
Sabkha	Diameter	1.00000	.71938	.00199	.02346	–.63555
	Thickness	.71938	1.00000	.00174	–.10872	–.11134
	Cover	.00199	.00174	1.00000	.95717	–.50623
	Abs. Max. Stress	.02346	–.10872	.95717	1.00000	–.59797
	Diameter Change	–.63555	–.11135	–.50623	–.59797	1.00000

Table 1: Correlation matrix for the used variables for all the soils for sand overburden

- Since the depth of cover was varied from 1 to 60 ft for all pipe diameters and pipe wall thicknesses, there is no correlation between the depth of cover and those two variables (0.00199 and 0.00174, respectively).
- There is a positive correlation between the pipe's diameter and the maximum absolute stress.
- The highest correlation coefficient between the pipe's diameter and the maximum absolute stress is for sand at low density (0.22194), then marl (0.07368), then sabkha (0.02346), followed by sand at high density (0.00028).
- As the density of sand increases, the correlation between the pipe's diameter and the maximum absolute stress is lost (the correlation coefficient reduced from 0.22194 to 0.00028 due to the increase in sand density).
- There is a negative correlation between the thickness of the pipe's wall and the maximum absolute stress.

- There is a strong positive correlation between the sand cover and the maximum absolute stress (correlation coefficient values range between 0.89129 and 0.98215 for the different native soils).
- The relation among all the IV's with a diameter change is negative and relatively strong.
- The pipe's diameter has the highest correlation coefficient with a diameter change (correlation coefficient values range between -0.63555 and -0.68579 for the different native soils).
- There is a negative, relatively strong correlation between the DV's.

3.4 Linearization of the Relationships

To view the shape of the relation between the IV's and the DV's, a data set from the data of the pipe overlying the sand at low density was selected and drawn in Figure 1. Figure 1 shows the effect of the pipe's diameter on the absolute maximum stress and on the amount of change in the pipe's diameter for a pipe having a wall thickness of 0.48 in. and a 10-ft depth of cover. It can be seen from this figure that the relationships between the IV's and DV's are not linear. To build linear models that relate the IV's and DV's, it was required to find ways and means to linearize the relationships between each of the IV's and each of the DV's. Numerous trial and error analyses were implemented to find the best method to linearize the relationships. Figure 2 shows the linearized relations between the IV's and the absolute maximum stress and change in the pipe's diameter. The square of the pipe diameter versus the square root of the absolute maximum stress and the exponential of the change in the pipe diameter were used to linearize their relationship. The same procedure was used to linearize the other variables.

3.5 Developed Equations

The linear multiple regression procedure, included in STATISTICA (Release 6.1) personal computer software, was used to generate the required prediction models that relate the IV's (pipe's diameter, pipe's wall thickness and height of cover) with the DV's (absolute maximum stress and change in diameter). Since more than one IV was used in each prediction model, a number of trials were performed to increase the goodness of fit (R^2) of the prediction equations by using different combinations of transformed independent and dependent variables. The models that have the highest R^2 values were selected. R^2 is an indication of the percent of variance in the dependent variable explained by the model. Table 2 shows the developed transformed prediction models for both the absolute maximum circumferential stress and the diameter change for all types of embedment soils. In addition, the coefficient of determination (R^2) and the significance levels of the models are shown in the table. R^2 values for the developed models are higher than 0.94. In addition, the confidence levels for all models are higher than 99.99%. A typical model fitting result and the analysis of variance for the prediction of the absolute maximum

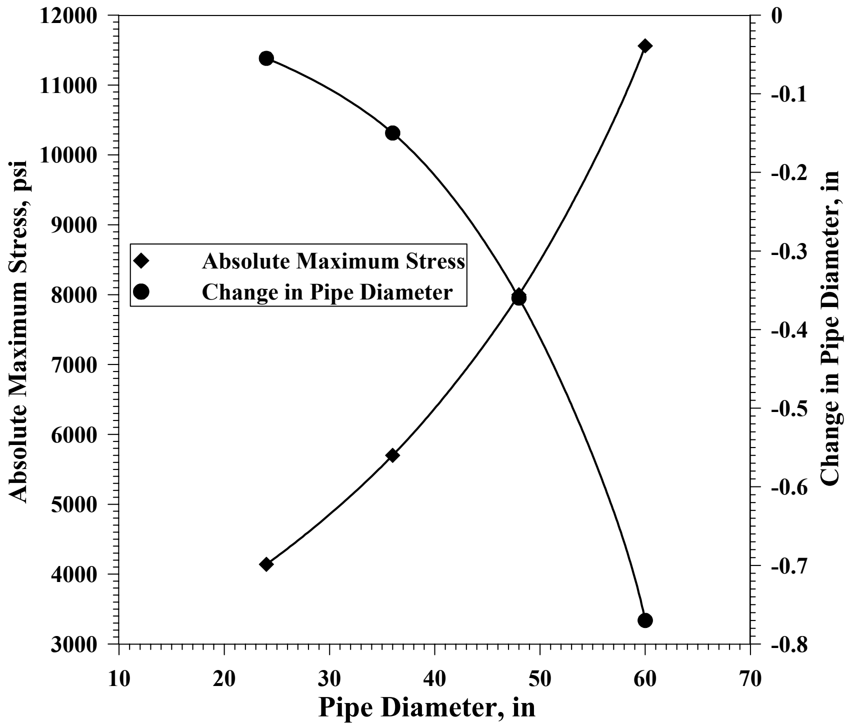

Figure 1: Relationship between pipe diameter and both absolute maximum stress and change in pipe diameter.

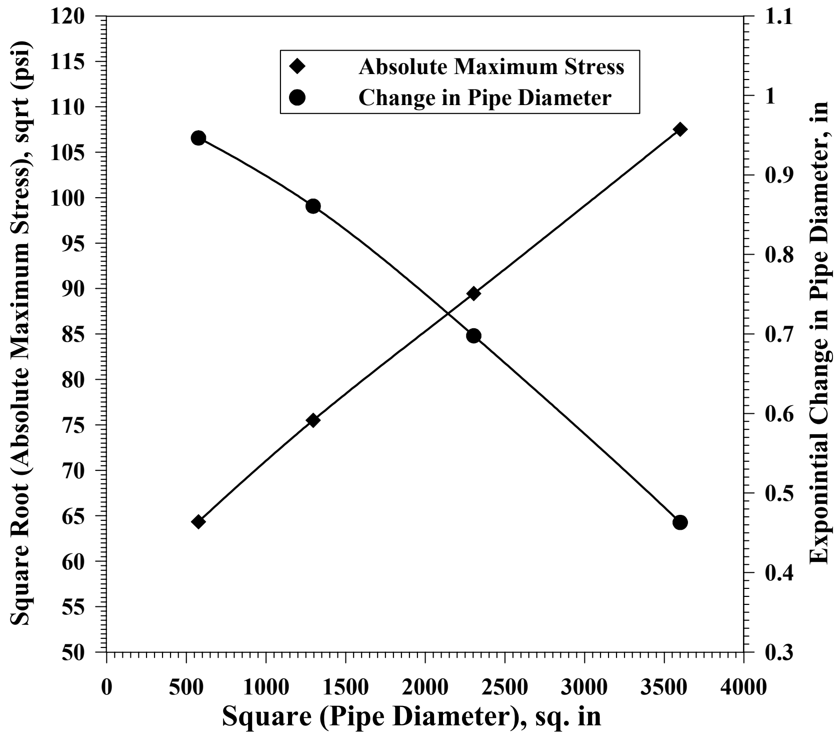

Figure 2: Linearization of the pipe diameter and absolute maximum stress and change in pipe diameter relationship.

Native Soil	Generated Model	R^2	Significance Level
Sand at low Density	Stress = $-4130.54 + 2.21 * (D)^2 - 7079.25 * (t)^2 + 2969.83 * (H_c)^{1/2}$	0.9697	0.000
	$\Delta D = ln\,[1.259 - 0.0145 * (D) + 0.533 * (t) - 0.0508 * (H_c)^{1/2}]$	0.9612	0.000
Sand at high Density	Stress = $-2822.30 + 0.060 * (D)^2 - 343.31 * (t)^2 + 2549.65 * (H_c)^{1/2}$	0.9786	0.000
	$\Delta D = ln\,[1.221 - 0.0095 * (D) + 0.3122 * (t) - 0.0498 * (H_c)^{1/2}]$	0.9406	0.000
Marl	Stress = $[26.081 + 0.438 * (D) - 26.211 * (t) + 16.835 * (H_c)^{1/2}]^2$	0.9734	0.000
	$\Delta D = ln\,[1.283 - 0.0138 * (D) + 0.4935 * (t) - 0.0643 * (H_c)^{1/2}]$	0.9502	0.000
Sabkha	Stress = $[33.815 + 0.4045 * (D) - 30.181 * (t) + 17.735 * (H_c)^{1/2}]^2$	0.9688	0.000
	$\Delta D = ln\,[1.270 - 0.0150 * (D) + 0.5626 * (t) - 0.0685 * (H_c)^{1/2}]$	0.9491	0.000

Stress = absolute maximum stress (psi) ΔD = change in the pipe's diameter (in.)
T = pipe's wall thickness (in.) D = pipe's diameter (in.) H_c = height of sand cover (ft)

Table 2: Generated models for the absolute maximum stress and diameter change for sand overburden

stresses for the pipe constructed on low density sand are shown in Table 3. In the model fitting results, the coefficients of all variables introduced in the model were given, in addition to their t-value statistics and significance levels. It is worth noting that all of the parameters used have a confidence level of 99.9%.

Figure 3 shows a typical plot of the predicted values versus the originally calculated values for the model of the absolute maximum stress for the pipe constructed on low density sand. The figure shows the distribution of the points around the 45° line. It can be noticed that all the calculated and predicted points are located around the 45° line with minor disturbance. This indicates the accuracy of the generated models in predicting the DV's.

3.6 Testing of Models

Sign Testing

Sign testing is performed to check if the variables' signs in the developed models are according to the expected relationships between the independent and dependent variables. The following is observed about the obtained signs in the developed models:

Model fitting results for absolute maximum stresses						
N=1461	BETA	St. Err. of BETA	B	St. Err. of B	t (1457)	p-level
Intercept			−4130.54	89.5424	−46.129	0.00
$(\text{Diameter})^2$	.467804	.005687	2.21	.0269	82.262	0.00
$(\text{Thickness})^2$	−.391523	.005687	−7079.25	102.8238	−68.848	0.00
$(\text{Cover})^{1/2}$	.903376	.004557	2969.83	14.9823	198.223	0.00

Analysis of variance					
Effect	Sums of Squares	Df	Mean Squares	$\boldsymbol{F}$	p-level
Regress.	491051E5	3	163683E5	15563.43	0.00
Residual	153236E4	1457	1051720.		
Total	506374E5				

Table 3: Model fitting results and analysis of variance for the prediction of the absolute maximum stresses for the pipe constructed on low density sand

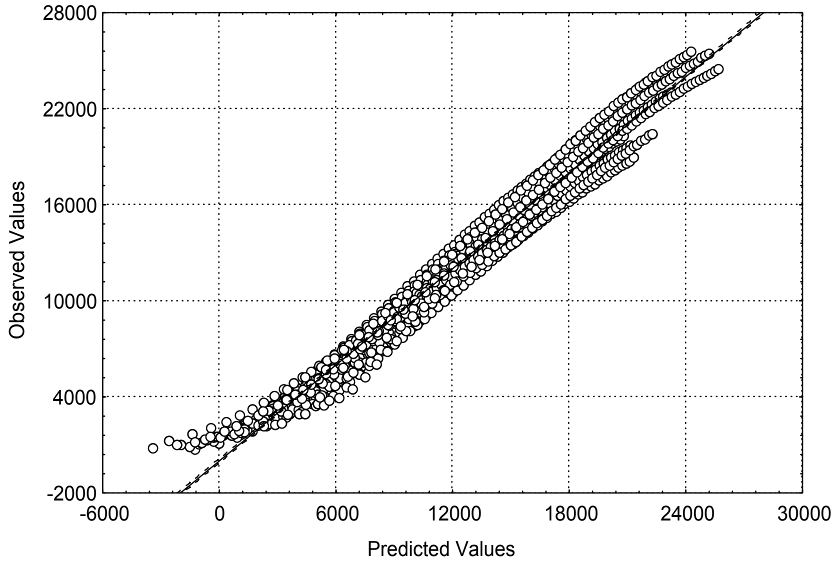

Figure 3: Plot of predicted versus calculated absolute maximum stresses for the pipe constructed on low density sand.

- The diameter of the pipe: This is positively related to the absolute maximum stress, i.e. the higher the pipe's diameter, the higher will be the circumferential stresses.
- The thickness of the pipe's wall: This is negatively related to the absolute maximum stress, i.e. the higher the thickness of the pipe's wall, the lower will be the circumferential stresses.

- The depth of the pipe cover: This is positively related to the absolute maximum stress.
- The diameter of the pipe: This is positively related to the amount of change in the pipe's diameter. Although the sign in the developed model is negative, the higher the value of the diameter change (in negative) is, the higher will be the amount of deformation.
- The thickness of the pipe's wall: This is negatively related to the amount of change in the pipe's diameter.
- The depth of the pipe cover: This is positively related to the amount of change in the pipe's diameter.

The above-mentioned observations are all according to the expected relations between the IV's and DV's.

Homoscedasticity Testing

One of the main assumptions that must be satisfied when using the ordinary least squares method is that the errors should have a constant variance. This implies that there should be a scatter of errors around all points of the independent variables. This assumption is called homoscedasticity. To check for homoscedasticity of the variables used, plots of predicted values of DV against residuals (the difference between originally calculated and predicted values) will reveal any violation of this assumption [11]. The plots of predicted values versus residuals of estimation for one of the developed models is shown in Fig. 4. From this figure, it can be concluded that the homoscedasticity conditions are met for the developed model. Plots of predicted values versus residuals of estimation for the other DV's showed that the homoscedasticity conditions were met for all the developed models.

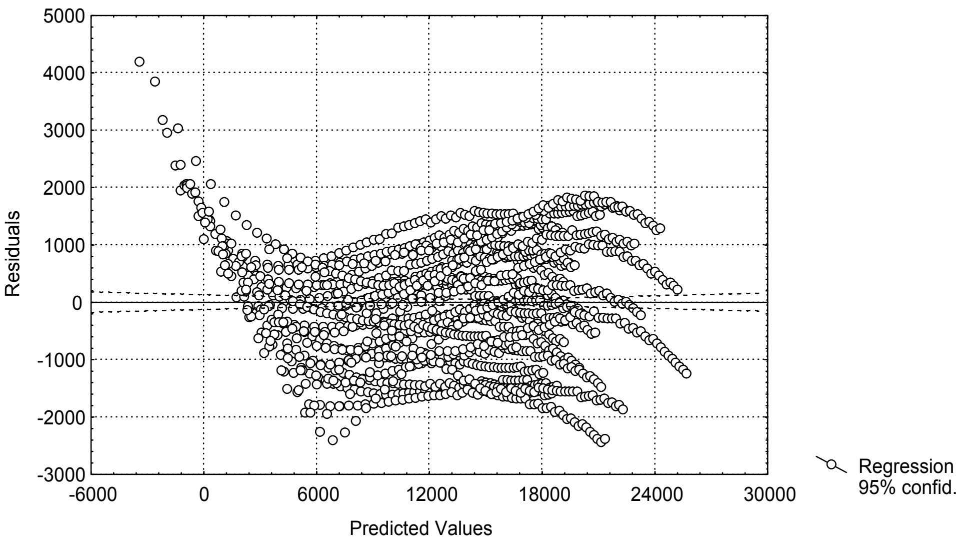

Figure 4: Predicted versus residuals of estimation for the prediction of the absolute maximum stresses for the pipe constructed on low density sand

Normality Testing

In multiple regression, normality is part of significance testing. Normal probability plots were drawn for the residuals to ensure that the errors are normally distributed. Figure 5 is the normal probability plot for the residuals of the developed model of the absolute maximum stresses for the pipe constructed on low density sand. From visual inspection of the normal line and the distribution of the points around the line, it appears that there is a normal distribution of the residuals. Therefore, the normality assumption of the error was met for the absolute maximum stresses for the pipe constructed on low density sand model. Normality testing was performed for all the other developed models, and the normality assumption of the error was met for all the models.

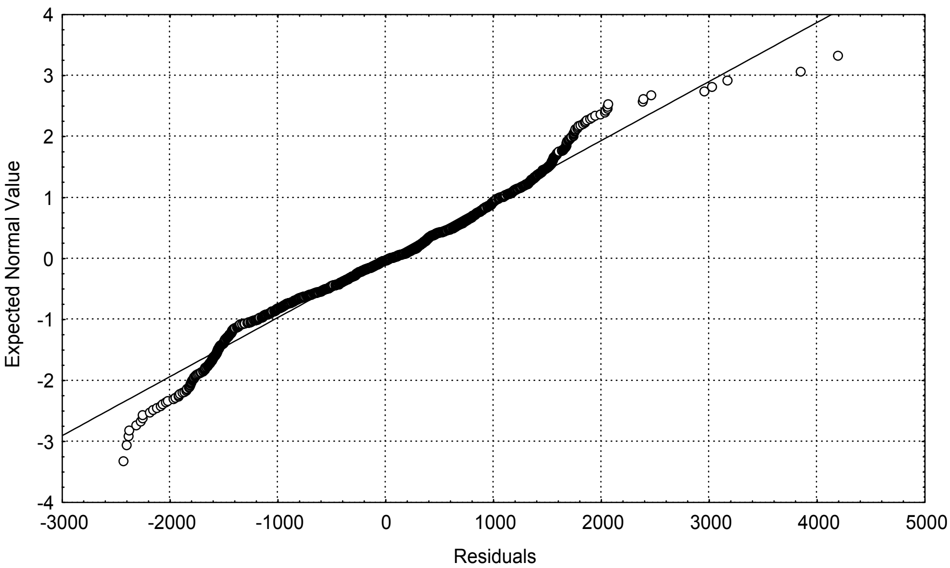

Figure 5: Normal probability plot for the prediction of the absolute maximum stresses for the pipe constructed on low density sand

Model Validation

As stated previously, thirty-nine cases for each type of embedment soil were selected randomly for validation of the developed models. Developed equations were used to calculate the absolute maximum circumferential stress and the diameter change for the different embedment soils for the validation data. Montgomery and Peck [11] suggested a procedure for validation testing by fitting the validation data for the developed models and calculating the coefficient of determination (R^2) for the newly fitted data, then comparing this value with the R^2 of the model with the original data. This test was performed for the developed models. Table 4 shows the coefficient of determination for both the original and validation data; in addition, it shows the accuracy of the developed models in predicting both the absolute maximum stresses and the diameter change for all types of soils that was considered in the study. It can be noticed that R^2 values of the validation data and original data are very close.

		R^2	
Type of Embedment Soil	Variable	Original Data	Validation Data
Sand at low density	Abs. Max. Stress	0.9697	0.9689
	Diameter Change	0.9612	0.9747
Sand at high density	Abs. Max. Stress	0.9786	0.9747
	Diameter Change	0.9406	0.9410
Marl	Abs. Max. Stress	0.9734	0.9669
	Diameter Change	0.9502	0.9554
Sabkha	Abs. Max. Stress	0.9688	0.9625
	Diameter Change	0.9491	0.9597

Table 4: Coefficient of determination for both original and validation data for sand overburden case.

4 Development of the Pc-Software

The ADBP software which is an abbreviation of Analysis and Design of Buried Pipelines was developed using Visual Basic 6.0. The generated regression equations were programmed to either design or analyse different pipe conditions.

Therefore, the developed software has two main categories of options: Analysis and Design. The analysis part has the following four sub-options:

i) Sand Overburden (calculation of actual pipe stresses and deflection)
ii) Sand Overburden (calculation of allowable maximum sand height)
iii) Highway Crossing Pipeline (calculation of pipe stresses and deflection)
iv) Vertical and Horizontal Bends (maximum allowable temperature change).

The design part gives the recommended pipe wall thickness for the following three sub-options:

i) Sand Overburden
ii) Highway Crossing Pipeline
iii) Vertical and Horizontal Bends (required cover height)

Upon selecting one of the options, the program will display the appropriate screen for the user to input the data and receive the answers. The input/output screens have a menu to run the problem (calculate), to report the problem, to print the screen, to exit the program when the user is done, and to go back to the welcome screen to solve another kind of problem. The program is also equipped with a detailed help menu. Program screens start with suggested default values that are assigned to the input parameters. Through drop menus, the user changes the default values according to the problem requirements.

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