RELIABILITY BASED DESIGN OF BURIED FLEXIBLE PIPES

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Introduction

Pipelines of large diameters are used for water supply, drainage sewers, and gaslines. Steel pipes are commonly used for such large diameters. These pipelines are considered as flexible for high D/t ratios of the order of 100 to 200 i.e., very small thickness. The design of flexible pipes is done considering internal and external loads, material and backfill characteristics. It is recognized that uncertainties cannot be avoided in the design and construction of buried soil structures (Watkins, 1999) and the role of uncertainties in specifying design limits such as factor of safety or tolerable deflection limits needs to be understood. To take care of the uncertainties, while the conventional methodology incorporates arbitrary factors of safety for deflection and buckling, it is important that these aspects of variability be incorporated in design. Reliability analysis plays a major role in considering the uncertainties influencing the design of underground flexible pipes. The purpose of this paper is to highlight some of these factors. The present study considers the uncertainties in load (coming from backfill) and the soil reaction modulus for two modes of failure 1) Deflection and 2) Buckling. In the following sections, difficulties with the conventional approaches are reviewed and the uncertainties in design of buries pipes are highlighted. Reliability analysis is performed for a typical buried pipe using point estimate method (Harr, 1987) and the probabilities of failure are evaluated.

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Difficulties with conventional factor of safety approach

The traditional factor of safety is defined as the ratio of ultimate resistance to the applied load. The loads and the resistance are considered deterministic and are represented by nominal or characteristic values. Some times, the factor of safety is either considered in terms of means of loads and resistance or maximum load and minimum resistance. The factor of safety under these circumstances needs to be more than unity or more, but still, there is a probability of failure under some combinations of loads and resistance.

U. S. Army Corps of Engineers (1999) suggest that reliability analysis is very useful in

1) Identifying the unsatisfactory performance events and estimate their probability of occurrence
2) Estimation of unsatisfactory performance events
3) Estimation of changes in probability and consequences associated with improvement and
4) Decision-making based on risk, cost and benefit to risk reduction.

Duncan (2000) presents applications of the above aspects and to geotechnical engineering. Watkins (1999) indicates the need for incorporation of the above aspects in pipeline engineering.

In practice, calculations of allowable deflection limit Δ_a use factor of safety concept. It is commonly defined as the ratio of allowable deflection (Δ_a) to actual deflection (Δ). In the case of flexible pipes, Δ_a is fixed at 5% with a factor of safety of 4.0, Moser (1990). Stephenson (1976) suggests that the deflection be normally limited to 2% to prevent damage of the pipes.

The evaluation of Δ is to assess whether the deflection remains safe under given conditions. In order to decide whether the pipe is safe in terms of deflection.

$\Delta > \Delta_a$	unsafe	not reliable
$\Delta < \Delta_a$	safe	reliable

Uncertainties

Earth load acting on buried flexible pipe is indispensable for the interpretation of the actual behavior on the ground and in the design. Moser (1990) reports a range of values of arching coefficient depending on the depth and width of buried structure as well as the soil type. The static load coming on the pipe is from the backfill soil in the ditch. The relative movement of soil on the side causes arching action, the pipe takes lesser load than what it actually supports. In the case of Marston's load equation and with Modified Iowa formula, The uncertainties depend on the compaction effort, modulus of native soil (E_n), and modulus of soil reaction, pipe stiffness and width of the trench. The modulus of soil reaction characterizes the stiffness of the soil backfill at the sides of the buried pipeline. Earlier studies on E′ have shown that the value of E′ varies with soil type, degree of compaction and depth of backfill. Since the soil modulus exhibits a dependence on confining pressure, it might be expected that E′ depends not only on soil type and density but on the depth of backfill as well. Watkins (1958) observed that E′ is a function of depth of soil on top of the pipe and pipe stiffness. According to Howard (1972), Duncan and Hartley (1987), E′ value is not a direct property of the soil and cannot be measured readily in the laboratory or field. Duncan and Hartley (1987) suggest that in spite of its empirical nature, E′ is conceptually similar to soil modulus and can be reasonably thought to behave in the same manner. In view of the inevitable variations in the values of E′, the value has to be used with appropriate care for estimating pipe deflections due to fill loads. It is important to assess realistically all factors that affect E′ and also use values that accurately represent stiffness of the backfill for design purpose. In view of the uncertainties in input parameters, predictions of deflection are made. Considerable differences between predicted and measured values are often reported and attributed to various features such as variation in embedment depth, in-situ soil properties and inadequacy of analytical models Petroff (1990)

Problem description

Reliability analysis is performed for a flexible steel pipe of 1200mm and thickness 8mm with the following considerations that are relevant to the use of equations (1) and (2). The pipe is circular and buried in a ditch, diameter to thickness ratio of pipe (D/t) is 150. The material of the pipe is steel (E=210GPa). The back fill material is non-cohesive and homogenous with E′ of 4.83MPa for backfill soil and bedding constant of 0.10 are used.

$$\Delta = D_l \frac{KW_c r^3}{EI + 0.061E' r^3} \qquad (1)$$

Where, W_c, load coming on to the pipe (in lb/ft), D, external diameter of the pipe, D_l, deflection lag factor, E′, modulus of soil reaction, t, thickness of the pipe, H, height of fill above the top of the conduit, I, moment of inertia of pipe section ($t^3/12$), K, bedding constant, r, mean radius of the pipe (D-t)/2, Δ, vertical deflection of the pipe, Δ_a, allowable deflection.

Studies are carriedout for different lag factors 1.0 and 1.5 and for buried depths of 3.5m and 5.0m. Variation of load W_c and E′ are considered at ±30% from their nominal values. A similar study in case of buckling is carriedout.

The allowable buckling pressure is given by eq. 2 (AWWA-M45). The allowable deflection should be less than the internal vacuum pressure and load coming from the backfill soil. The load coming on the pipe here is taken not as the prism load but from the Marston's load calculations as load/unit area.

$$q_a = \frac{1}{FS}\left(32R_w B' E' \frac{EI}{D_m^3}\right)^{1/2} \quad (2)$$

$$q_{cr} = R_w W_c + P_v$$

All the equations are in FPS units, but the calculations were carried out in SI units. As per the buckling requirement the Probability of failure (P_f) is calculated as $P([q_{cr}\text{-}q_a]<0)$. In the above equations, $W_{c,}$ load coming on to the pipe (in psi), B′, dimensionless empirical coefficient for elastic support, B_d width of the trench, $D_{m,}$ mean diameter of the pipe, E, modulus of elasticity of the pipe material, E′, modulus of soil reaction, I, moment of inertia of pipe section ($t^3/12$), $R_{w,}$ water buoyancy factor, P_v, internal vacuum pressure, q_a, allowable buckling pressure, q_{cr}, critical buckling pressure.

Reliability Analysis

Reliability analysis is carriedout using point estimate method which, requires the knowledge of mean and coefficient of variation (or standard deviation) of each variable and the correlation coefficient between them (Harr, 1987; Christian and Baecher, 1999).

Coefficient of variation is a measure of reliability of central tendency. Correlation between different variables in a performance function has significant influence on the reliability. Theoretically, correlation coefficient varies from –1 to +1. In the present study, load coming on the pipe W_c and soil reaction modulus E' are the design variables and deflection Δ given by eq. (1) is the required performance function and ρ is the correlation coefficient between the random variables W_c and E'. In addition to the above the distributions of the variables are assumed as normal.

In the present case, soil load (W_c) represents the influence of soil type, and compaction conditions, are related to the soil modulus E′. As soil load increases, soil modulus increases indicating a positive correlation between them. The term W_c represents the field conditions and hence the correlation coefficient in the present study is varied from 0 to 0.75. Correlation coefficient zero indicates that the two variables are independent and the case is similar to the conventional practice where in the numerical values are considered as such without considering the inter relationship or interdependence between the variables. The probability of failure and reliability index are given by

$$P_f = P(\Delta < \Delta_a) \text{ or } P_f = P((q_a\text{-}q_{cr}) < 0)$$

$$\beta = \frac{X - \mu_\Delta}{\sigma_\Delta} \quad \text{or} \quad \beta = \frac{X - \mu_{(q_a - q_{cr})}}{\sigma_{(q_a - q_{cr})}}$$

Probability of failure or β-index a measure of risk and reliability. The failures can be categorized as poor, average or high based on these values (U S Army Corps of Engineers, 1999). It is inferred that higher the β value the better is the performance. Also lower the P_f value, better is the performance.

Results and Discussion

Results for two buried depths and lag factors of 1.0 and 1.5 in the case of deflection and for factors of safety of 1.0 and 2.5 in the case of buckling are obtained and discussed in the following sections.

The variation of coefficient of variation of input parameters vs output parameters for individual variables and correlated variables in the case of deflection is shown in Fig.1(a) and 1(b). It can be seen that when only W_c or E' alone is varied, the coresponding variations in deflection are the same in the case of Wc and marginally less in the case of soil reaction modulus. These variations are due to the direct relation of load in the case of W_c and inverse relation for E'. When both W_c and E' have the same magnitude of variation and the correlation between W_c and E' is considered, the results are shown in Fig.1(b). It can be observed that, corresponding to lesser correlation coeffients (0.00 and 0.25), variations in deflection are more than variation in input parameters. For correlation coefficients of 0.50 and 0.75, variations in deflection are equal or less than the input variations suggesting that correlation coefficient is likely to be an important variable in estimation of reliability of burried pipes. This is relfected in the plot of probability of failure vs. coefficient of variation of deflection in percent for four cases of different depths and lag factors are shown in Figs. 2(a), 2(b), 2(c) and 2(d). In Fig. 2(a), the probabilities of failure are low for lesser coefficients of variation and increase upto a value of 0.21 for zero correlation. It can also be observed that when correlation cofficient is considered, probability of failure decreases considerably and at the same time, the range of variation is less. On the otherhand, when the lag factor is increased to 1.50, the expected values are more than the allowable deflection limit (2%), indicating very high probabilities of failure as shown in Fig.2(b). It is observed that for lesser coefficients of variation the failure probabilities are high and decrease for higher coefficients of variation. Similar observations have been made by Griffiths and Fenton (2000) in the assessment of probablity of failure, when the factor of safety is less than unity. The above sections highlight the need for consideration of correlation cofficient as well as focus on the need for guidelines on the deflection lag factor for evaluation of proability of failure of buried pipes.

In Figs.2(c) and 2(d), similar trends for 5.0m buried depth and 1.00 and 1.50 lag factors. It is clearly seen that the probabilities of failure for Wc and E' are the extreme boundaries and the probabilities of failure lie in between, when correlation between Wc and E′ is considered. It is also observed that for increased correlation coefficient and decrease in coefficient of variation, the variations of the probabilities of failures deflection are also low.

Similar studies were carried out for different depths (3.5m and 5.0m) and a factors of safety 1.0 and 2.5 to estimate the probablity of failure by buckling. Probabilities of failure (P_f) are calculated by deducting the allowable buckling pressure from the buckling requirement $P([(R_w W_c + P_v) - q_a] < 0)$. Submergence effect is not considered ($R_w = 1$). In the present study, W_c is taken as Marston's load per unit unit area in ML^{-2} dimensions, instead of taking W_c as prism load ($\gamma H/144$) which gives conservative values.
Plots for input and output coefficients of variation in Fig. 3(a) and 3(b) show that the coefficient of variation of the performance function is siginificantly less than the input parameter variation except for the case of zero correlation between Wc and E′. Similar results were observed for factor of safety of 2.5. The probabilities of failure of buckling are presented in Figs.4(a) and 4(b) for 5.0m deep and a factor of safety of 1.0. The probabilities of failure range from approximately 10^{-15} to 0.003 for FS=1.0 and for FS=2.5 the P_f values range from approximately 10^{-15} to 0.04.

Conclusions

The paper presents the reliability analysis of deflection of buried flexible pipes. The results show that there is a need to consider variations of basic variables and the correlations for estimation of reliability of buried pipes. The probability of failure by buckling in the present case is quite low and at the same the probabilities of failure in deflection are dependent on deflection lag factor. Significant differences in failure probabilities due of consideration of different factors of safety were not observed.

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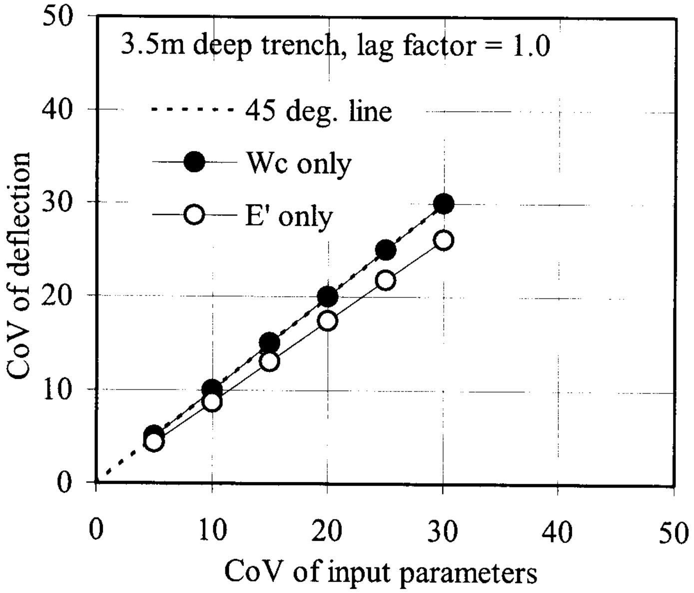

Figure 1a CoVof Ouput Deflection vs. CoV of input parameters (without correlation)

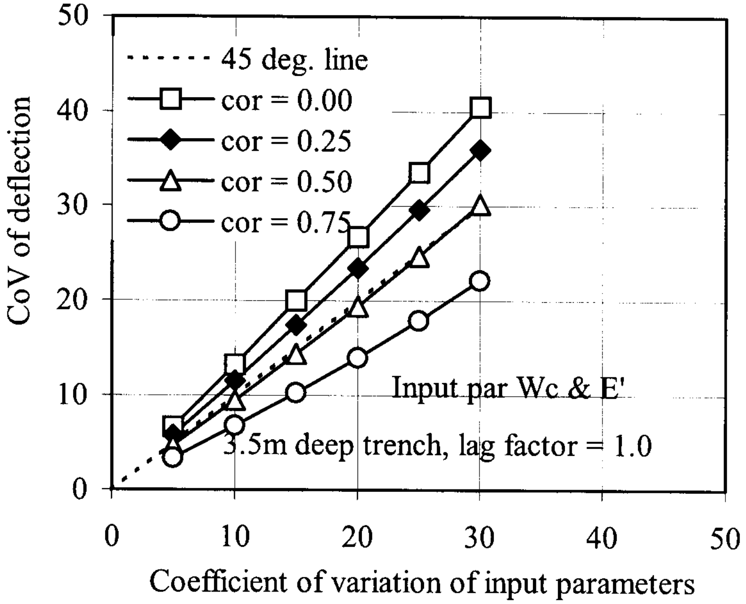

Figure 1b CoV of Ouput Deflection vs. CoV of input parameters ((with correlation)

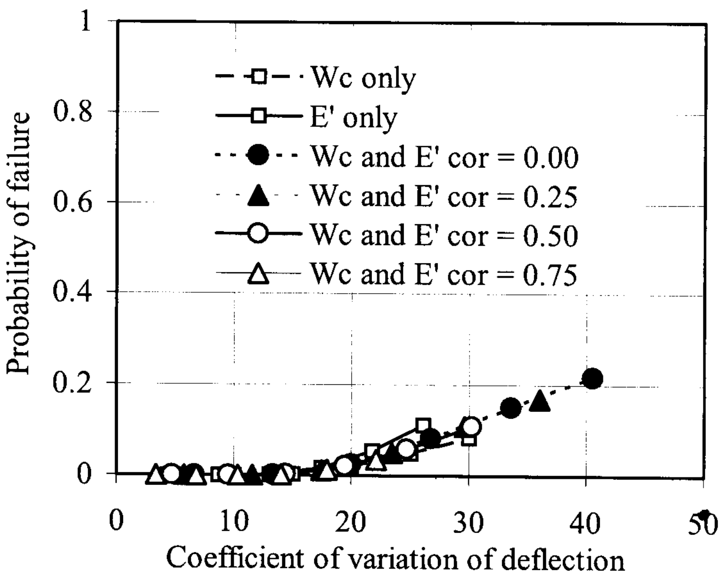

Figure 2a Probabilty of failure vs. Cofficient of variation of deflection (3.5m deep, 1.0 lag factor)

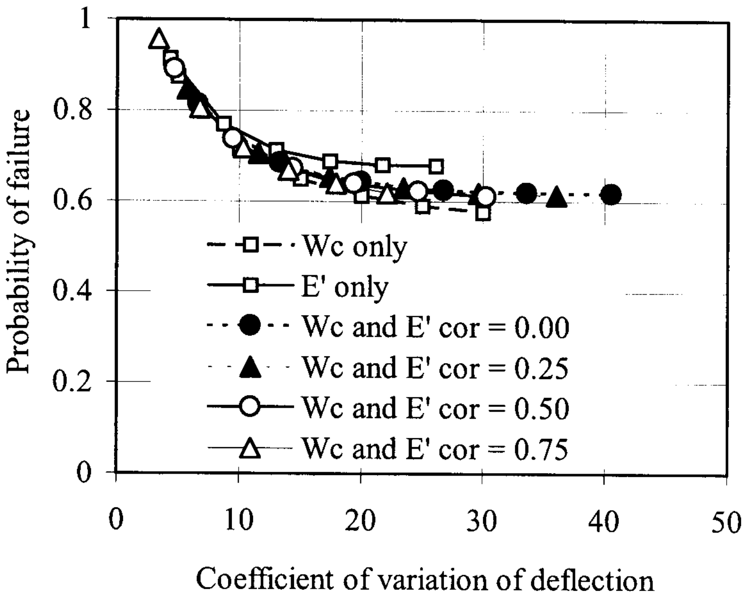

Figure 2b Probabilty of failure vs. Cofficient of variation of deflection (3.5m deep, 1.5 lag factor)

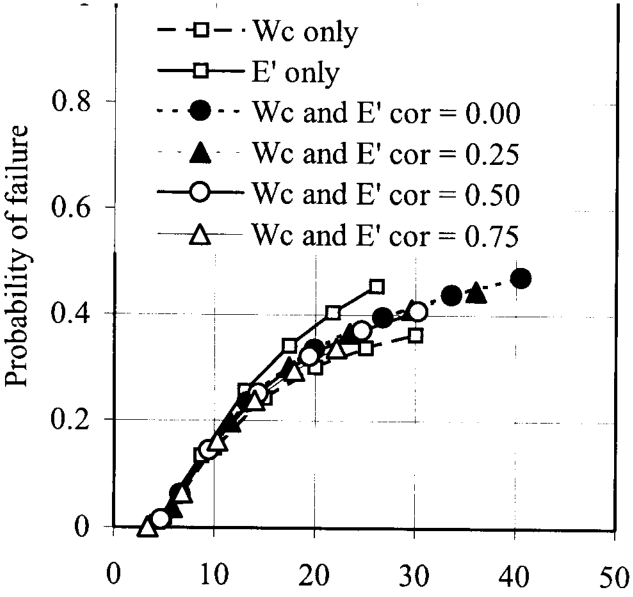

Figure 3a Probabilty of failure vs. Cofficient of variation of deflection (5m deep, 1.0 lag factor)

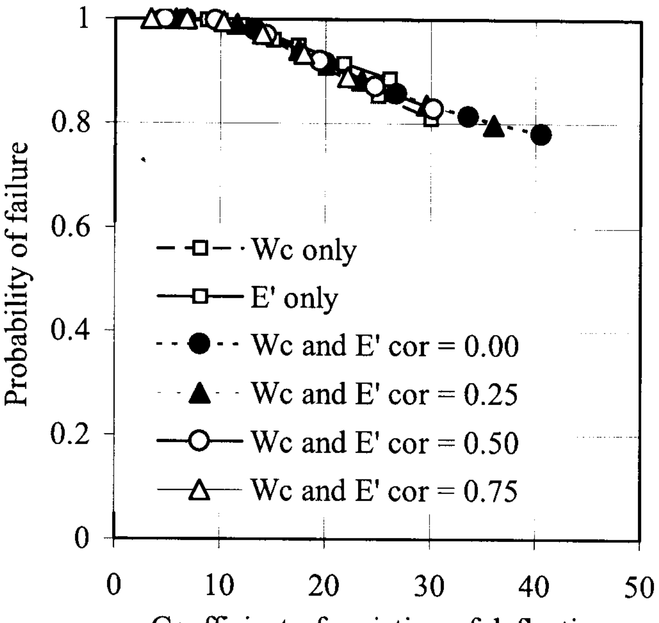

Figure 3b Probabilty of failure vs. Cofficient of variation of deflection (5m deep, 1.5 lag factor)