Allowable Differential Settlement of Oil Pipelines

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Abstract

The pipelines' allowable settlement has rarely been mentioned in design references and codes. The present paper studies the effects of differential settlement of pipeline bed on resulted forces and deformations and then determines the allowable differential settlement of pipelines in two conditions as follows: (i) heterogeneous soil bed (ii) adjacent to steel tanks. Numerical simulation of pipeline is used in order to accomplish the studies. The pipeline bed is idealized by Winkler springs and four-element standard viscoelastic Burger model. Also, the use of geosynthetic reinforcement is studied in heterogeneous soil beds and the effect of geosynthetics on decreasing the settlement has been investigated. The pipeline-tank joints in two cases of fixed and flexible joints are investigated and the results for two kinds of joints are compared.

Keywords: Allowable Differential Settlement, Burger Model, Fixed Joint, Flexible Joint, Geosynthetic.

1. INTRODUCTION

The values of allowable settlement of pipeline have rarely been discussed in pipeline design references and this subject challenged geotechnical and pipeline engineers. Discussions about allowable settlement of pipelines were propounded for pipelines constructed in permafrost zone and exposed to thaw differential settlement [1] & [2].

Also, investigations have been proposed about evaluation of deformations and generated forces of pipelines that have been exposed to settlement of soil bed [3] & [4].

Moreover, studies through analysis the deformations of pipeline due to settlement of other equipments were also thoroughly accomplished [5]. But the comprehensive study has not been made to determine the quantitative and qualitative values of allowable differential settlement of pipelines yet.

2. STATEMENT OF THE PROBLEM

There are various conditions to generate the differential settlement of pipeline. In proposed research, some prevalent states have been studied.

2.1. Pipeline Resting on Heterogeneous Soil Bed

Schematically, Figure 1 shows the pipeline and it's soil bed (Burger model). The pipeline passed from a loose bed. It's assumed that the intermediate loose bed is composed of soft clayey deposit and exposed to instantaneous settlement, primary consolidation and creep, due to applied loading. The ground foundation around loose clay bed is composed of dense granular soil that only is exposed to finite instantaneous settlement.

Respectively, the pipeline diameter and thickness are D and t. Loads that are applied on pipeline are the weight of steel materials, transitional oil media, soil surcharge over the pipeline and the pressure of internal fluid.

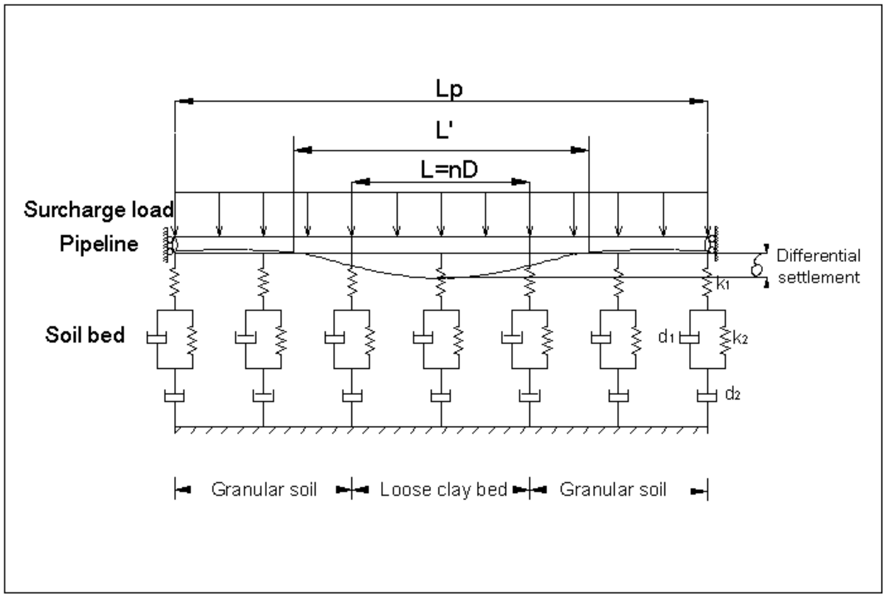


FIGURE 1: Schematic sketch of pipeline resting on heterogeneous bed.

2.2. The Use of Geosynthetic Reinforcement in Pipeline Bed

A geosynthetic layer with specified tensile strength is entered the model to decrease the differential settlement of pipeline resting on heterogeneous beds.

A dense sandy layer (by Winkler springs elements) is placed beneath the pipeline and over the heterogeneous bed and geosynthetic layer is lied at the interface of two soil layers in the model of geosynthetic-reinforced bed. Figure 2.

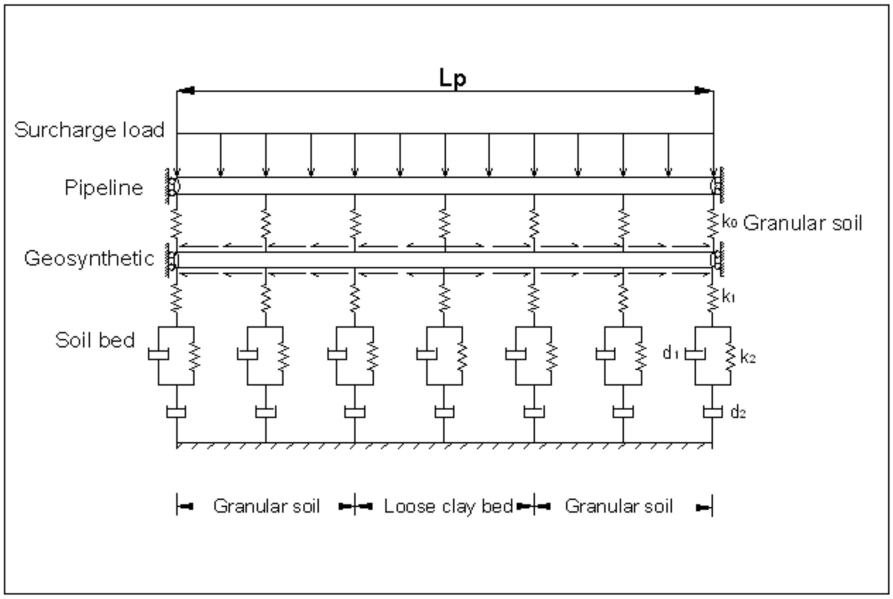


FIGURE 2: Schematic sketch of geosynthetic-reinforced bed beneath the pipeline.

2.3. Pipeline Adjacent to Tank

The schematic sketch of pipeline that is adjacent to tank is shown in Figure 3. This condition is very practical in oil industry.

The pipeline bed is idealized by Winkler spring elements. The distance of first sleeper beneath the pipeline from tank is specified as a function of pipe diameter (L_t=nD).

Two kinds of joints are used practically to attach the pipeline to the tanks: (i) fixed joint (ii) hinge or flexible joint. These kinds are compared in present paper. It's possible to rotate and move vertically at flexible joint whereas the rotations in all directions are restrained at fixed joint. Figure 4 shows an example of flexible joint used in a project in south of Iran.

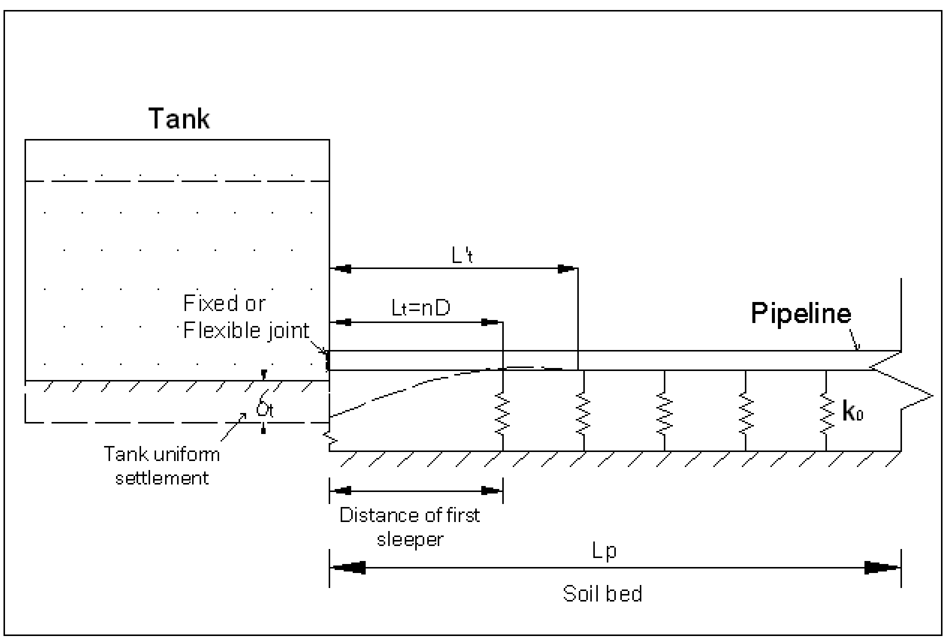


FIGURE 3: Schematic sketch of pipeline adjacent to a tank.

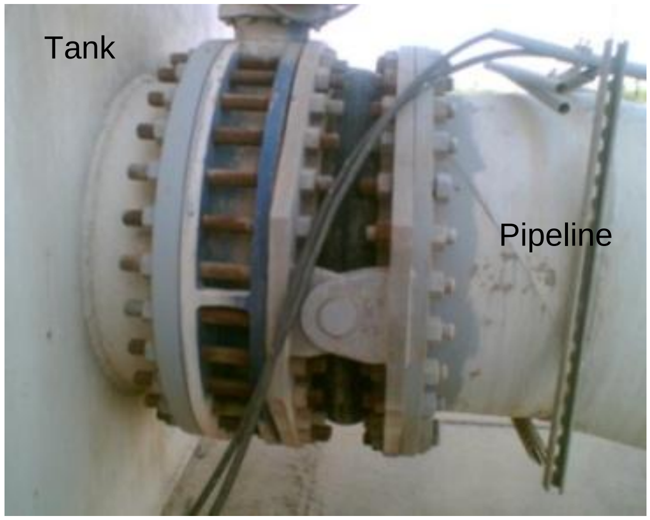


FIGURE 4: Pipeline-tank flexible joint.

3. NUMERICAL SIMULATION USED IN RESEARCH

A computer program had been written in ABAQUS [6] finite element software to carry out the studies.

3.1. Simulation of Soil Bed by Burger Model

Idealization of structures' beds by lumped parameter elements (spring elements) is considerable in previous investigations [7], but there are few references about the subject of Burger model used in soil beds [8].

This model idealizes primary and secondary (creep) consolidations as well as instantaneous settlement.

Each Burger model element is consisted of two spring elements with k_1 and k_2 stiffness coefficients and two dashpot elements with d_1 and d_2 viscous coefficients. The behavior of Burger element exposed to the force of F and resulted deflection of y that is stated as equation (1):[9]

$$y = \frac{F}{k_1} + \frac{F}{k_2}\left[1 - \exp\left(\frac{-k_2 t}{d_1}\right)\right] + \frac{Ft}{d_2} \qquad (1)$$

3.2. Pipeline Structure Model

The pipeline is idealized by three dimensional PIPE31 elements in present analyses and the pipe cross sections are selected according to the sections of API-5L-95 code [10] in order to use standard sections.

Respectively, the hoop stress (σ_h) and equivalent stress (σ_e) are defined as relations (2) and (3):[11]

$$\sigma_h = \frac{PD}{2t} \qquad (2)$$

$$\sigma_{eqv} = \sqrt{(\sigma_h^2 + \sigma_l^2 - \sigma_h \sigma_l + 3\tau^2)} \qquad (3)$$

Where P= internal pressure, D and t= diameter and thickness of pipeline respectively, σ_l= longitudinal stress and τ=shear stress of cross section. To study the effect of pipeline diameter, the ratio of diameter to thickness (D/t) is considered to be constant approximately in amount of 64.

3.3. Geosynthetic Model

To idealize geosynthetic layer, T3D2 tensile elements are used. To consider frictional strength of between the geosynthetic layer and granular soil (confinement effect) a distributed tensile force is applied over the geosynthetic layer as equation (4).

$$T_g = f\,\gamma_s\,H \qquad (\frac{kN}{m}) \qquad (4)$$

Where Tg= distributed tensile force, f= frictional coefficient (considered in amount of 1), γ_s= soil density (20 kN/m^3) and H=height of soil (1m).

4. THE EFFECTS OF VARIABLES

The effects of variables of Burger model on the values of settlement and resulted forces of pipeline were studied.

The stiffness coefficient of spring element as series in Burger model (and stiffness coefficient of Winkler model) is determined by the relation of subgrade reaction modulus according to the plate-load test [12].

The spring element of Burger model as it is series is used to model the instantaneous settlement of bed (relation 5):

$$k_1 = \frac{E}{D(1-\mu^2)} DL_i \qquad (\frac{N}{m}) \qquad (5)$$

Where D= plate width (pipe diameter), L_i=element length (0.01m), μ=Poisson's ratio of soil (0.5) and E=elasticity module of soil.

To vary the stiffness ratio of dense granular soil to intermediate loose clay soil (k_1(g)/k_1(c)) in heterogeneous soil bed showed the differential settlements have increased till k_1(g)/k_1(c)=25 and then varied negligibility.

Hence, in the present study the ratio of k_1(g)/k_1(c) is considered to be 25.

The studies have shown to select the coefficients of k_2, d_1 and d_2 as very large for around dense soil resulted in only instantaneous settlement.

These variables for intermediate loose clay soil were determined so that maximum long term settlement would be arised in various amounts of loose bed lengths.

In this way, minimum values are obtained for allowable settlement of pipelines on heterogeneous beds.

The studies have shown k_2=k_1/100 resulted in maximum long term settlement of pipeline. The variable of k_2 in equation (1) is used to model the primary consolidation settlement.

The primary consolidation values of bed due to various pipeline loads were obtained from used Burger model and Terzaghi relation as Figure 5.

To compare the settlements of Burger model with Terzaghi relation resulted in calibrated parameter of Burger model (k_2) that is stated as equation (6). This relation is used to determine the variable of k_2 for various diameters of pipelines. The settlements resulted from Burger model with calibrated variable of k_2 are in good agreement with settlements calculated by Terzaghi relation as it's shown Figure 5.

$$k_{2(D)} = \frac{D}{0.508} \times {k_1}/_{100} \quad (\frac{N}{m}) \qquad (6)$$

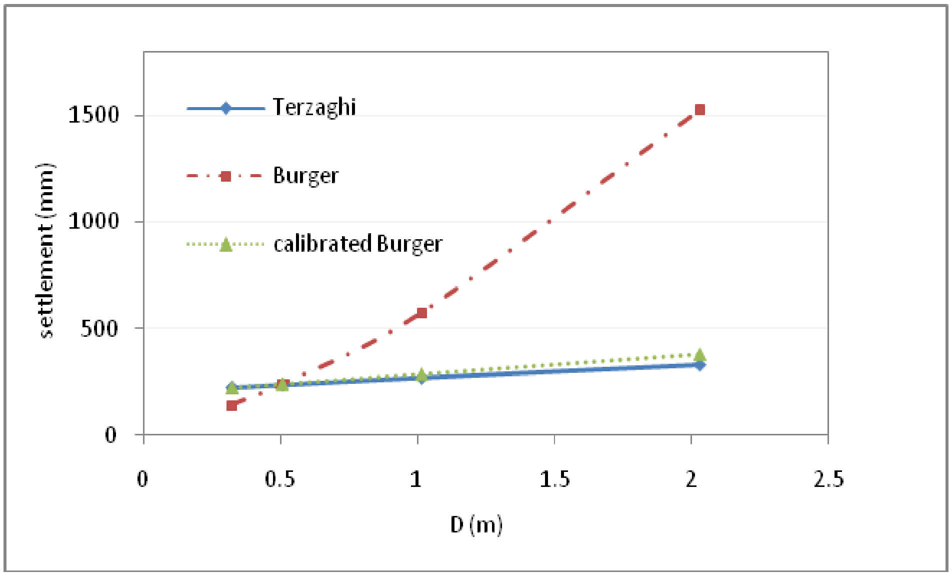


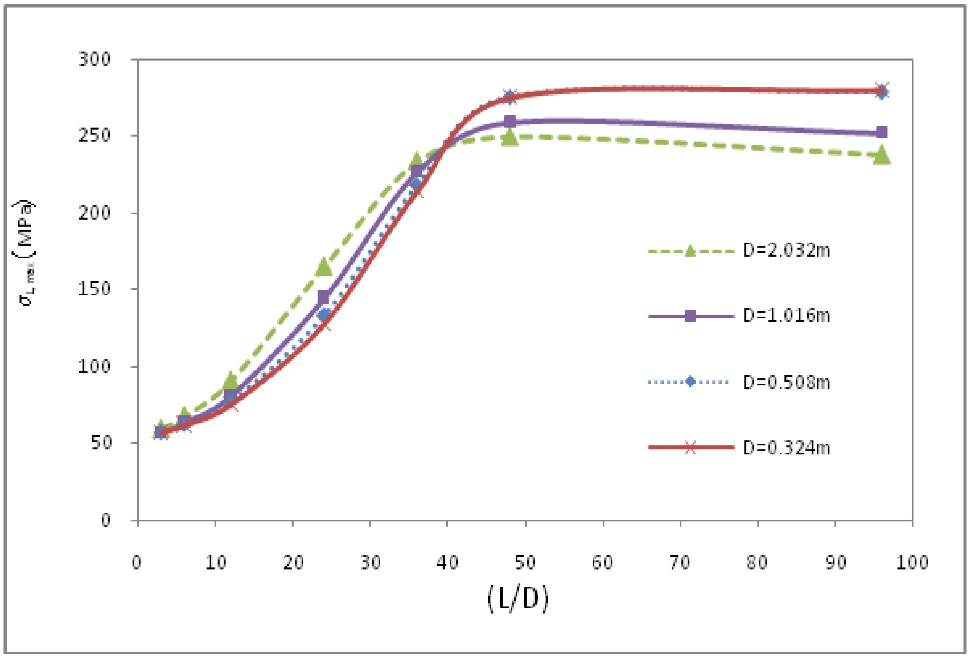
FIGURE 5: Comparison of settlement of Burger model with Terzaghi equation and correction of Burger model.

Also, parametric studies for various diameters of pipelines and length of loose clay bed have shown the ratio of (d_1/d_2) in Burger model is effective on time required for final settlement and consequently is effective on differential settlement values at analysis the time.

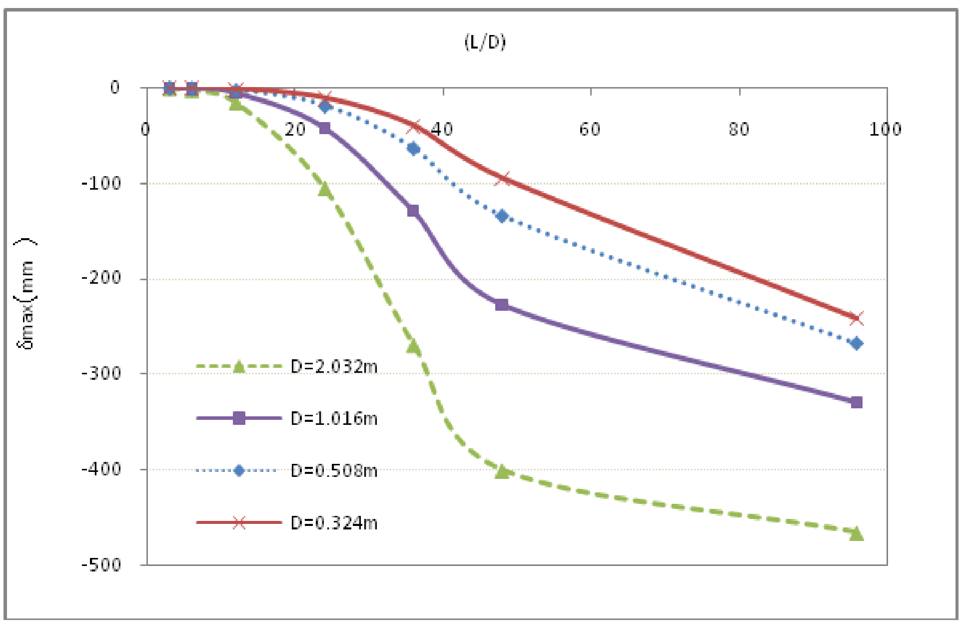
The d_1 and d_2 are viscous variables of Burger model that correlate to the time dependent variables of soil settlement.

Numerous studies about effects of variables of pipeline settlement were accomplished. Maximum values of differential settlement (δ_{max}), longitudinal stress resulted from settlement ($\sigma_{L,max}$), equivalent stress ($\sigma_{e,max}$), longitudinal strain ($\varepsilon_{L,max}$) and bending moment (M_{max}) were determined for various loose bed length (L) and pipeline diameter (D).

The Figures 6 show the variation of (δ_{max}) and ($\sigma_{L,max}$) with (L/D) for various diameters of pipeline.



(a)



(b)

FIGURE 6: Variation of (a) max longitudinal stress and (b) max differential settlement with the ratio of loose bed length to pipeline diameter.

Also, maximum values of stress-strain and bending moment due to varied settlement of tank (δ_t) were obtained for fixed and flexible joints of pipelines and various sleeper distances (L_t).

The Figure 7 shows the effect of sleeper distance on longitudinal stresses of a pipeline with fixed joint. To increase the sleeper distance results in less stresses-strains.

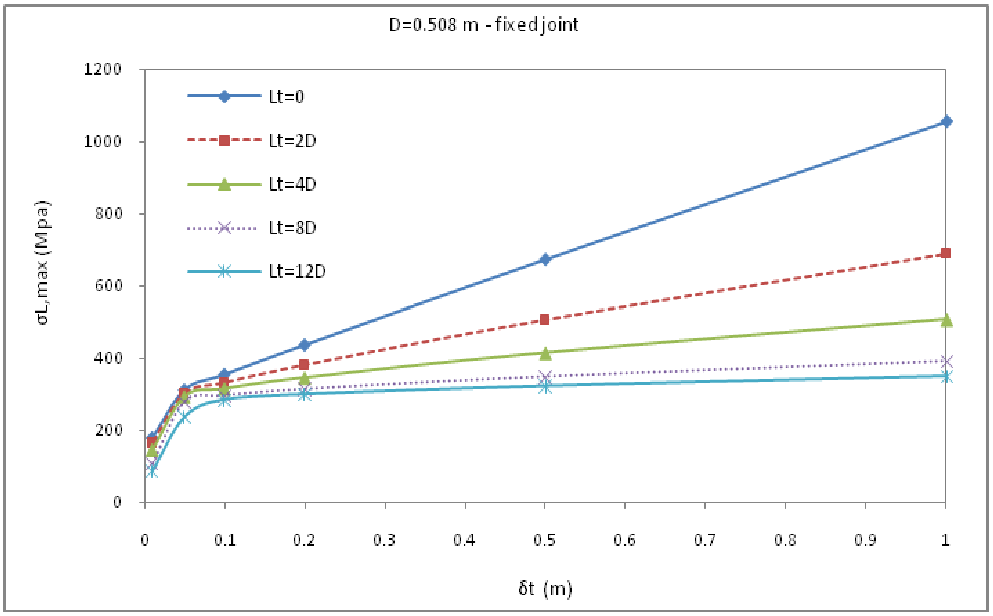


FIGURE 7: Effect of sleeper distance on max longitudinal stress with tank settlement (δt).

The other studies show the use of geosynthetic reinforcement causes to decrease the settlement of pipeline bed and resulted forces as it's shown Figure 8.

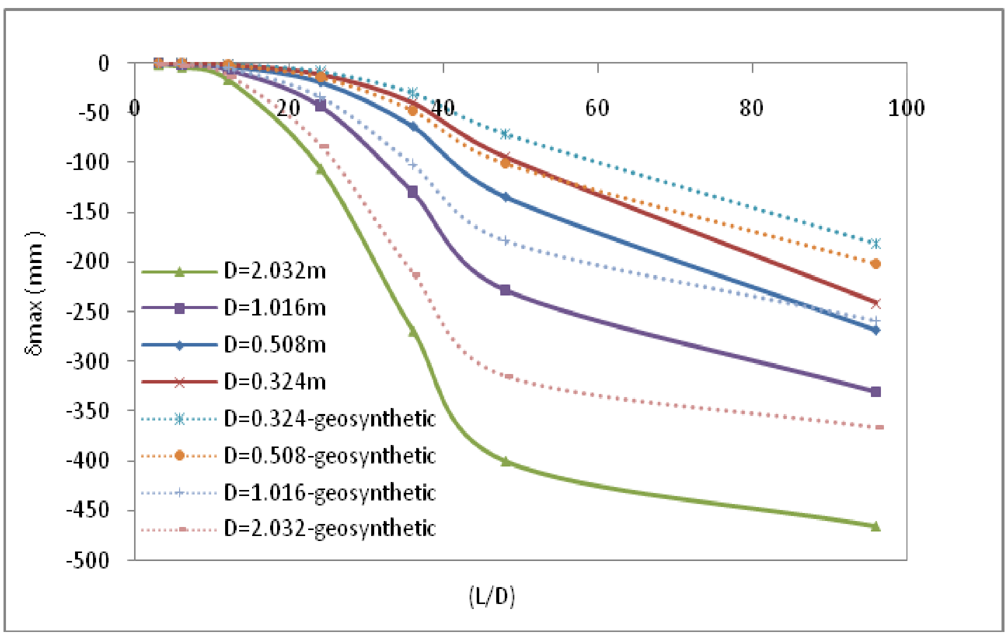


FIGURE 8: The effects of geosynthetic layer on differential settlement of pipeline with the ratio of loose bed length to pipeline diameter (L/D).

5. DISCUSSION ABOUT ALLOWABLE SETTLEMENT OF PIPELINES

5.1. The Criteria for Limiting the Settlement

The present paper aim is to suggest allowable differential settlement of pipelines. To limit the settlement, various criteria can be used. Stress and strain are two main criteria for limiting the pipeline settlement. Historically, most of the codes of pipelines have been used the allowable stress-based design methods to design the pipelines against applied forces. In half of the '90 ies limit state design methods entered the pipeline design codes. In this way, to define failure states of pipelines has provided the possibility of more efficient and economic designs. The limit state design methods use limited strains and bending moments moreover the limited stresses.

(i). Allowable stress method:
For this method in present research the design factors were used from ABS2000 code [13]. Respectively, this code limits the hoop stresses, longitudinal and equivalent stresses to 72%, 80% and 90% specified minimum yield stress (SMYS).

(ii). Bending moment capacity method:
The bending moments of pipeline were controlled by this method. Maximum allowable bending moment of pipeline ($M_{Allowable}$) is determined according to the proposed relation of reference [14].

(iii). Allowable strain method:
The critical compression strain of pipeline materials (ε_c^{crit}) would be estimated by using empirical equation according to CSA-Z662 code [15]. The limit state of plastic failure of welds is initiated from the cracks of weld surface due to tensile strains. Many of codes consider the value of 2% as allowable tensile strain [16].

As settlement increases, the mentioned criteria would happen respectively as it can be seen in Figure 9.

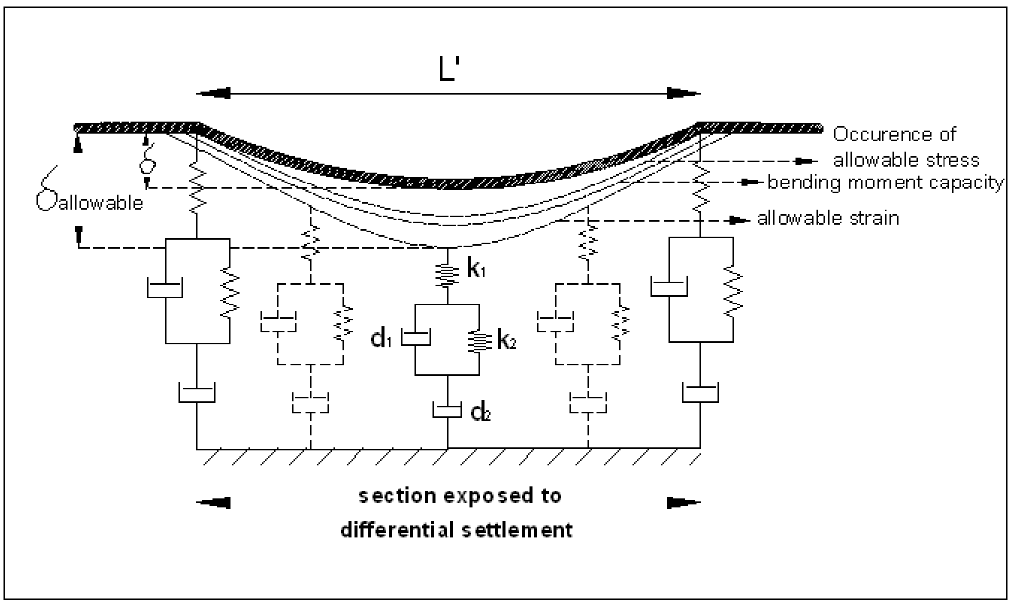


FIGURE 9: Determination of allowable differential settlement of pipeline.

5.2. The Allowable Differential Settlement of Pipelines on Heterogeneous Soil Bed
After many analyses, allowable differential settlement of pipeline is estimated by comparing the resulted forces and stress-strain surface due to settlement with allowable limits (Section 5.1).
The values of allowable differential settlement on the basis of used methods are summarized as Table1.

As an example, for determining the allowable differential settlement with the allowable longitudinal stress method, the length of loose bed is increased till the longitudinal stresses of pipeline due to settlement reach to allowable limit and then the maximum differential settlement corresponding to allowable longitudinal stress is considered as allowable differential settlement of pipeline($\delta_{allowable}$).

The analyses were accomplished for some pipelines with various diameters and it observed the allowable differential settlements of pipelines that were 0.09D by using the allowable longitudinal stress method, Figure 6.

The results were determined for D/t=64 but overestimately, these are acceptable for D/t<64.

Relative conditions	Control method	Allowable differential settlement ($\delta_{allowable}$)
Conservative	Allowable equivalent stress	0.08D
	Allowable longitudinal stress	0.09D
Moderate	Bending moment capacity	0.12D
Most economic	Allowable compression strain	0.8D

TABLE 1: Allowable differential settlements of pipelines resting on heterogeneous soil beds.

Respectively, the allowable settlement values of 0.08D, 0.09D, 0.12D and 0.8D, are obtained in loose bed lengths of 29D, 31D, 35D and 105D. If the length of loose bed is less than mentioned values, then the pipeline settlement is less than allowable amount in any soil conditions.

If the loose bed length is more than them, the above table values are accepted as minimum allowable differential settlements.

It should be accounted for the variables of Burger model were determined so that the maximum settlements of bed were resulted. If the soil bed conditions are improved then allowable limits of moment/stress-strain would happen in larger loose bed lengths and more values of differential settlement than above values would resulted.

A designer engineer by using the Table 1 can determine allowable settlements of a pipeline according to pipeline diameter and length of loose bed.

5.3. The Allowable Differential Settlement of Pipelines Adjacent to Tanks

To determine the allowable settlement, various analyses were accomplished and the results were accumulated.

Respect to the flexibility of pipelines, the distance of tank from the first pipeline sleeper has many effects on controlling the settlement values. Hence the allowable differential settlements of pipelines at joint location, are determined as it can be seen in Table 2, according to pipeline diameter, distance of first sleeper from the tank and the kind of joint.

Relative conditions	Control method	Distance of first pipeline sleeper from tank (Lt)	Joint kind	Allowable differential settlement ($\delta_{t,allowable}$)	Joint kind	Allowable differential settlement ($\delta_{t,allowable}$)
Conservative	Allowable equivalent stress	0	Fixed	0.015D	Flexible	0.068D
		8D	Fixed	0.030D	Flexible	0.141D
Moderate	Bending moment capacity	0	Fixed	0.029D	Flexible	0.085D
		8D	Fixed	0.09D	Flexible	0.300D
Most economic	Allowable compression strain	0	Fixed	0.034D	Flexible	0.160D
		8D	Fixed	0.107D	Flexible	0.380D
	Allowable tensile strain	0	Fixed	0.059D	Flexible	0.283D
		8D	Fixed	0.175D	Flexible	0.783D

Table 2: Allowable differential settlements of pipelines adjacent to tanks.

As it could have been seen from Figure 10, used design method on the basis of considered relative conditions has effective effect on allowable differential settlements of pipeline ($\delta_{t,allowable}$/D) adjacent to tank.

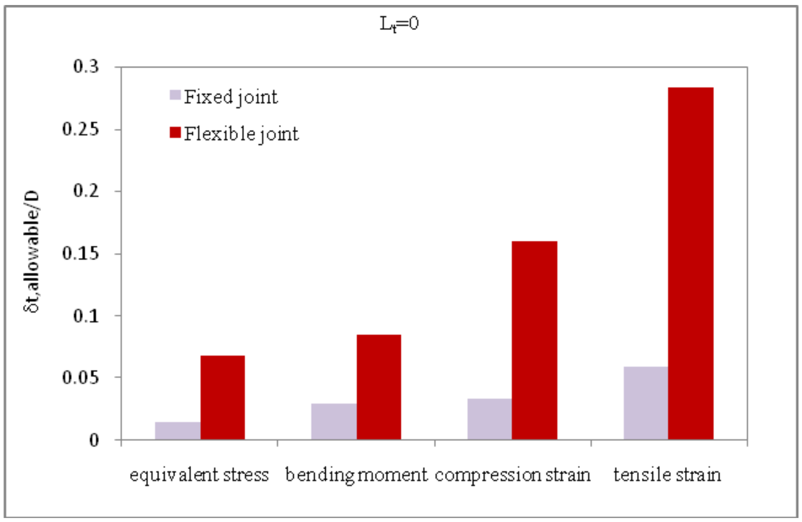


FIGURE 10: The effect of used design method on allowable differential settlement of pipeline adjacent to tank.

The diagrams of Figure 11, show the effect of distance of the first sleeper beneath the pipeline (as L_t/D) on allowable settlement values of pipeline at joint location ($\delta_{t,allowable}$/D).

The similar results have been obtained for other design methods. Also the effects of using the flexible joints on distributing the resulted forces and increasing the values of allowable settlement, are observed from Figures 10 and 11.

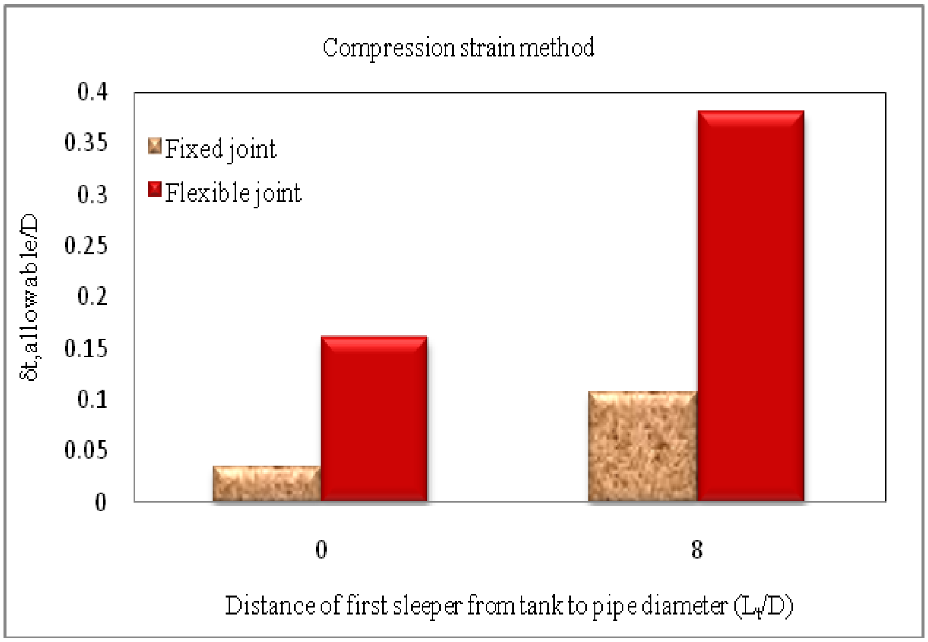


FIGURE 11: The effect of sleeper distance on allowable differential settlement of pipeline adjacent to tank.

6. CONCLUSIONS

The paper results are stated as follows:

1. The allowable differential settlements of pipelines are proposed as Table 1 and Table 2. These tables are useful for geotechnical designer engineers to decide about the values of allowable settlement in a project.

2. According to Figure 8, using of geosynthetic layer is effective on decreasing the settlement values and resulted forces of pipelines. This effect has been more observed in loose bed length of about L=24D. Also, beneficial effects of geosynthetic are observed for smaller diameters of pipelines.

3. As the distance of first sleeper from tank (L_t) increases, the values of resulted forces of pipeline from settlement decrease considerably.

4. Using of flexible joint and placement of first sleeper in distance of (L_t=8D), causes a considerable increasing of allowable differential settlement of pipeline.

5. The ratio of loose bed length to pipe diameter (L/D) is effective on the value of differential settlement. As the ratio of (L/D) increases the values of differential settlement and resulted forces of pipeline increase, too.

6. In the same ratio of loose bed length to diameter (L/D), increasing of pipeline diameter will increase the differential settlement of pipeline.

7. For pipeline adjacent to tank, the resulted forces and stresses-strains increase as the tank settlement (δ_t) increases. Also, by decreasing the pipeline diameter (D) in the same settlement of tank, the resulted forces and stress-strain values increase.

Proposal allowable settlements as indicated in Table 1 and 2 could be considered as the main achievements of this paper.

The above mentioned conclusions could be used by designer engineers to determine allowable settlement and also to understand the governing parameters.

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