Journal of computer science and software applications
https://www.mfacademia.org/index.php/jcssa
ISSN:2377-0430
Vol. 5, No. 3, 2025

Stress Analysis and Safety Implications of Aviation Oil Pipelines Under Soil Piling: A Numerical Simulation Study

Arjun Sharma
University of Houston, Houston, USA
Arjun.Sharma2244@gmail.com

Abstract:

With the rapid development of the aviation oil industry, the safety of buried aviation oil pipelines under the influence of nearby soil piling has become a critical concern. This study investigates the stress response and deformation behavior of aviation oil pipelines subjected to soil piling through numerical simulation using ABAQUS software. The findings reveal that the maximum Mises stress in the pipeline increases significantly with decreasing soil pile distance and increasing pile height, exhibiting a near-linear relationship. Stress distribution patterns indicate that the middle section of the pipeline is most susceptible to damage, with stress symmetrically decreasing towards the ends. Results were validated against field tests, demonstrating the accuracy and applicability of the simulation approach in addressing engineering challenges. Preventive strategies are proposed to mitigate soil piling-induced stress and ensure the safe operation of aviation oil pipelines. This study provides valuable insights into the interaction between pipelines and surrounding soil, contributing to enhanced safety and reliability in pipeline management.

Keywords:

Soil Loading; Aviation Oil Pipeline; Finite Element Analysis.

1. Introduction

With the vigorous development of the global aviation oil industry, the demand for aviation oil pipeline transportation has shown a "blowout" growth. The impact of large slag yard, temporary stockyard, coal yard and filling of highway subgrade construction near the pipeline may cause stress impact due to soil stacking near the pipeline. Due to the unreasonable soil accumulation, the deformation or settlement of the soil around the buried aviation oil pipeline will be caused, and the pipeline will be squeezed, affecting and threatening the safety of the aviation oil pipeline. However, how to evaluate the impact of soil piling on the aviation oil pipeline, that is, how the stress of the pipeline changes under the effect of soil piling, what kind of deformation will occur, how much impact the deformation and stress changes of the pipeline have on its safety, and how to control the soil piling to ensure the safety of the oil and gas pipeline, are all the issues concerned by researchers and managers.

The pipeline was positioned in loose sand by foreign researcher Schupp[1], who then examined the correlation between the resistance produced during vertical displacement and the actual displacement. The data were then fitted to the formula for vertical and horizontal resistance to determine the stress during pipeline displacement. Anand[2] examined the resistance created when horizontal displacement occurred in a pipeline as part of a study on the effects of horizontal action between pipes and soil. Test results showed that the horizontal resistance of the pipeline was primarily positively correlated with the same displacement and gradually tended to a fixed value.

Using a centrifuge, Schaminee and Cheuka[3]et al. conducted research and tests and described the formula for calculating soil resistance based on the results of the tests. It was challenging for the calculation findings to be compatible with the currently used theoretical calculation methods due to variations in knowledge of the soil shear failure process. Taylor[5] used data to fit stress-displacement curves in a series of research studies on the impact of axial action between pipe and earth. Further axial loading tests were conducted by Lyons C G[6] to investigate the interaction of various soils and pipelines under the influence of their internal friction and cohesion. He highlighted the range of applications of the coulomb friction theory for stress interpretation of pipeline displacement in sand and soft clay and emphasized the importance of considering the impact of soil physical characteristics. For soft clay pipes, Brennodden[7] tested submerged pipelines, investigated the horizontal movement of pipes in loose sand, mild clay, and hard clay, and derived the comparison curve of pipeline resistance growth in various soils. By combining theoretical numerical simulation and experiments, Wu Yu[8] was able to analyze the pipe-soil interaction relationship of submarine pipelines. He then summarized the occurrence and variation rules of resistance of submarine pipelines when triaxial displacement occurs in their buried environment.

In terms of finite element research, Lyonsp[9] used finite element software to analyze the horizontal resistance of pipeline sliding in soft clay and noted that, without considering the reasons for the difference, the result of the simulated calculation was slightly larger than the empirical value when combined with the comparison data of actual experience. In order to construct a model of the fault, Xue[10] et al. used a combination of the discontinuous deformation analysis method and the finite element method. The results of the calculations demonstrate the effectiveness of the new modeling method in handling this particular type of complex deformation analysis.

In order to study the influence of pipeline force based on nonlinear pipe-soil interaction, Liu [11]employed ANSYS finite element analysis software and obtained specific results. In order to offer a reference design basis for pipeline seismic resistance, Yue [12] studied the interaction between underground pipes and soil using the finite element program ABAQUS and compared her findings with the results of laboratory tests. The effectiveness of the model was demonstrated by Zhang [13]who used the finite element program ABAQUS to examine the tube-soil interaction of the pipeline under the influence of nearby underground tunnel excavation. He then compared the calculation results of the analytical solution formula of pipeline stress under the conditions. Yang [15]focused on the impact of different parameters on pipeline stress under static loads when simulating and analyzing the influence of pipeline stress under both dynamic and static loads. In order to investigate the criterion of lateral instability of undersea pipeline under tube-soil interaction, Ren [16] employed ABAQUS analysis software.

With the help of ABAQUS software and the numerical simulation method, this study will examine the stress around an aviation oil pipeline caused by a soil pile, examine how the pipeline is affected by action, examine the factors that affect how the soil occupies the pipeline, suggest preventive measures, and put those suggestions into practice. This study provide crucial guidance for reducing soil piling-related damage mishaps to aviation oil pipelines and guaranteeing their safe and reliable operation.

2. Finite Element Model

2.1 Foundation Soil Model

The soil is considered to be an isotropic uniform continuum with a foundation soil dimension of 30m×20m×18m. The two types of geotechnical materials that are most frequently used in geotechnical calculations are clay with cohesion and sand with little or no cohesion. The most popular Drucker-Prager and Mohr-Coulomb models in ABAQUS are constitutive models. Because the Drucker-Prager model in software can fully ignore the influence of cohesion, it can be utilized for sandy materials to get superior convergence. Both models are optional in the aforementioned convergence calculation for clay materials. As a result, the enlarged linear Drucker-Prager constitutive model is used for the soil mass. In Fig 1, the yield surface is displayed. The purpose of model is as follows:

$$F = t - p\tan\beta - d = 0$$

$$t = \frac{q}{2}\left[1 + \frac{1}{k} - \left(1 - \frac{1}{k}\right)\left(\frac{r}{1}\right)^3\right]$$

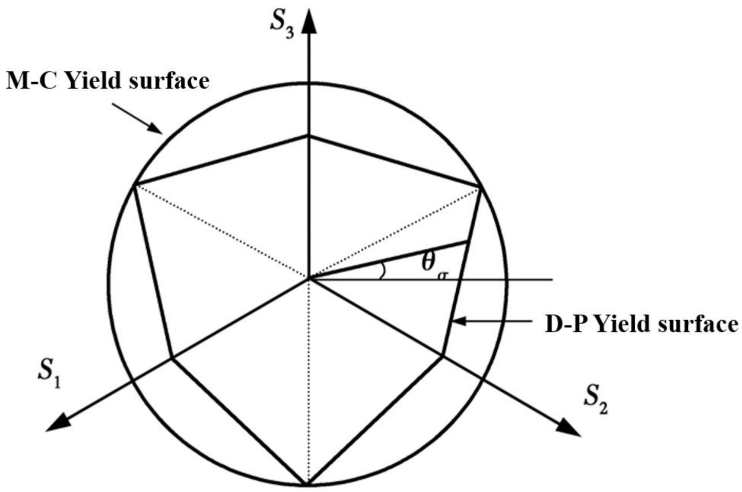

Fig 1. D-P Yield Trajectory Diagram

The soil property is common clay, and the soil parameters are shown in Table 1 and 2.

Table 1: Soil parameters

Yield stress	0.17	0.65	0.75	0.8	0.85
Absolute plastic strain	0	0.035	0.051	0.073	0.092

Table 2: Hardening parameters of D-P model

Modulus of elasticity (MPa)	Poisson's ratio	Density($kg \cdot m^{-3}$)	Angle of friction (°)	Flow stress ratio
20	0.4	1870	37	1

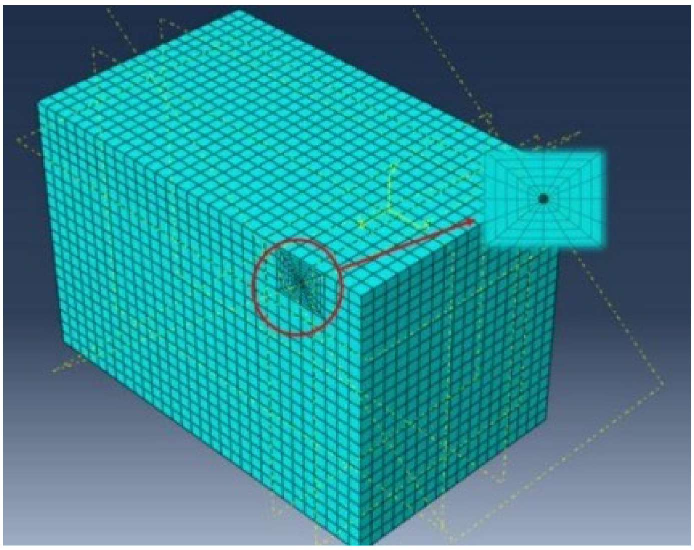

Fig 2. Foundation Soil Model Diagram

The pipe served as the main plane when the model was meshing in the meshing module. In order to prevent the nodes of the main plane from entering the slave plane, the mesh size of the pipe was bigger than the mesh size of the surrounding soil. The grid surrounding the pipeline was improved using the C3D8R element to guarantee the fidelity. The soil grid diagram is displayed in Fig 2.

2.2 Tube-soil Coupling Model

The beam model of elastic foundation that was previously introduced is primarily employed in analytical analysis, and literature also uses finite element models to calculate elastic foundations[4]. It is challenging to obtain the forces in all directions around the pipeline using such a model, which can only retrieve the force and strain characteristics along the pipeline. The ground source model and nonlinear contact surface model in the ABAQUS software are better at simulating the interaction between underground pipes and dirt. In this work, an inelastic foundation model is used. The user can specify the constitutive relationship using the user subroutine UMAT in ABAQUS, which offers a number of material constitutive models that can be chosen in accordance with the specified models.

There are normal and tangential lines of action between the pipe and the ground, and surface contact is chosen for pipe-soil interaction. Normal contact is a firm contact, allowing for an unrestricted transition pressure between the contact surfaces. The friction coefficient is directly correlated with the kind of soil, humidity, and anticorrosive coating on the pipeline surface. Tangential contact follows the conventional Coulomb friction model. The real measurement should be used to determine the friction coefficient. As demonstrated in Table 3, the value can be determined without actual data by consulting the literature. The value in this article is 0.5.

Table 3: Tube-soil friction coefficient

Soil type	Coefficient of friction
clay	0.25-0.6
Silty clay	0.25-0.55
Sandy soil	0.40-0.70

2.3 Loads and Boundary Conditions

The principal loads supported by the pipeline under the influence of soil loads are as follows: dead weight of the pipeline, medium pressure, internal pressure of the pipeline, dead weight of the overlying soil, interaction force of the pipeline, etc., which are set in the load options in the appropriate places. The upper surface is left as a free surface, and the load of soil pile is applied to the foundation soil as a surface load. The soil pile is 6m by 4m in size and is situated just above the pipeline. The soil pile heights of 1.5m, 2m, and 2.5m are corresponding to load sizes of 0.02748 MPa, 0.03664 MPa, and 0.0480 MPa, respectively.

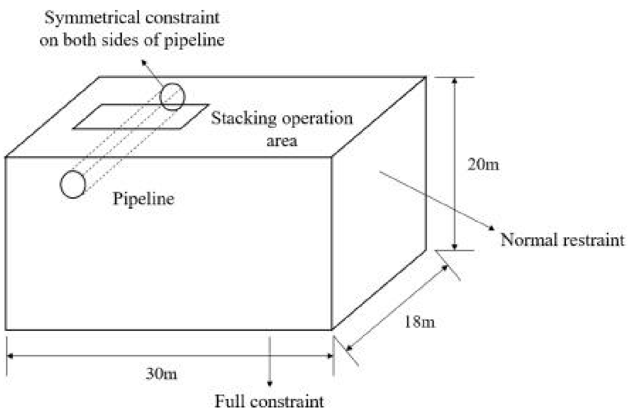

Fig 3. Schematic Diagram of Model Boundary

3. Analysis of Influencing Factors

The axis closest to the load on the belly of the pipeline was chosen as the research object in order to make it easier to examine variations in Mises stress, horizontal displacement, and vertical displacement along the pipeline axis of various influencing factors. Other parameters don't change when the selection parameter does.

3.1 Influence of Soil Pile Distance on Aviation Fuel Pipeline

In this investigation, the load distance steadily decreases from 5m to 5m, 2.5m, 1.25m, and 0m (right above the pipeline) as we examine how the load distance affects the pipeline.

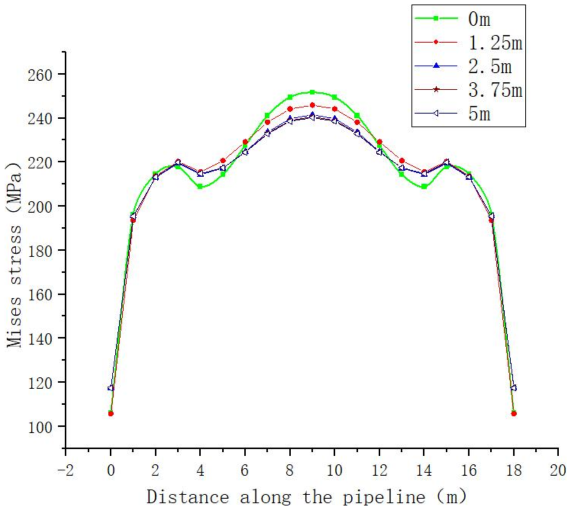

Fig 4. Mises Stress at The Top of The Pipeline Under Different Load Distances

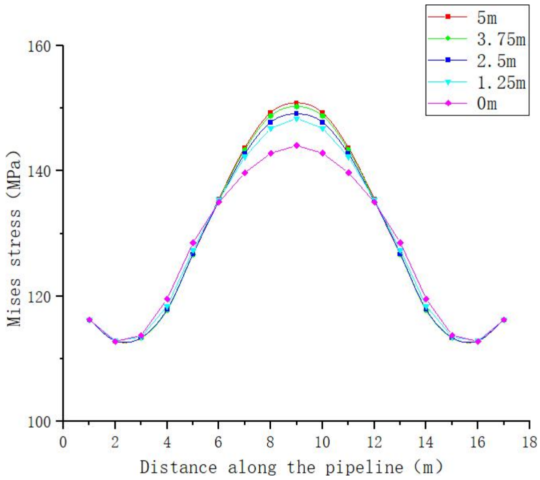

Fig 5. Mises Stress at The Bottom of The Pipeline Under Different Load Distances

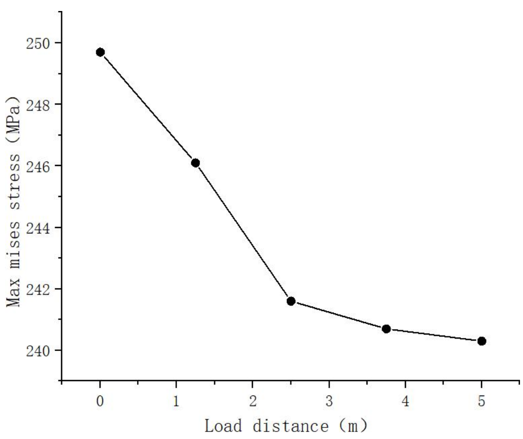

Fig 6. Maximum Pipeline Stress Under Different Load Distance Conditions

Fig 4- Fig 6, obtained by computing the effects of various load distances on the gas pipeline, show that the Mises stress in the pipeline is symmetrically distributed and follows the same change rule. The Mises stress reaches its maximum value in the middle of the pipeline and gradually decreases to both ends. The Mises stress becomes more frequent as the load carrier approaches the gas pipeline. When the load distance is between 0 and 2.5 meters, the Mises load clearly affects the pipeline, but when the load distance exceeds 2.5 meters, the Mises load has no discernible effects.

3.2 Influence of Soil Pile Height on Aviation Oil Pipeline

The load distance is set as being directly above the pipeline for examining how the load height affects the pipeline. The load heights used in this analysis are primarily 5m, 3.5m, 3m, 2.5m, 2m, and 1.5m.

It can be seen from Fig 7–Fig 9 that the calculation of the effects of various load heights on gas pipelines shows that the variation rule of Mises stress at the top of the pipeline under various load heights is consistent with that under various load distances, the stress in the middle of the pipeline is the highest and gradually decreases to both ends, and the Mises stress increases with the increase of load height. As the load height grew and the Mises stress at the bottom increased, the stress near the load boundary increased while the stress in the middle of the pipeline declined. As the load height grew, there was an approximately linear increase in the maximum stress of the pipeline. The aforementioned graph demonstrates how the load height significantly affects the stress.

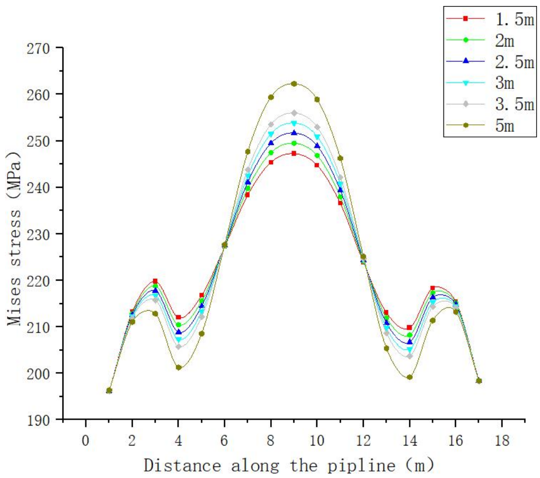

Fig 7. Mises Stress at The Top of The Pipeline Under Different Load Heights

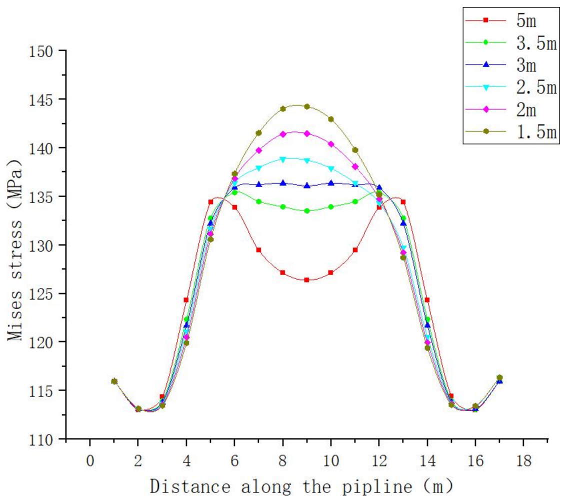

Fig 8. Mises Stress at The Bottom of The Pipeline Under Different Load Heights

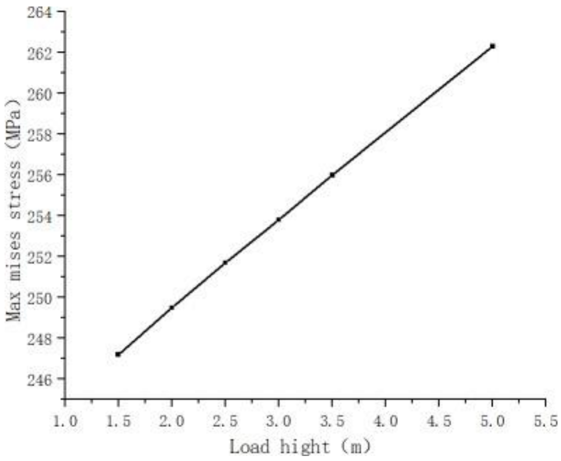

Fig 9. Maximum Pipe Stress Under Different Load Heights

4. Conclusion

In this study, the influence of aviation oil pipeline on soil piling was investigated, and the following conclusions were reached after utilizing the ABAQUS program to measure the stress under the situation of soil piling around the pipeline:

(1) It is discovered that the change in the maximum stress of the pipeline under the soil pile distance and soil pile height is essentially consistent with the field test based on the coupling of pipe-soil load simulation calculation. The accuracy satisfies engineering field standards, and it has some applicability in resolving the issue of soil pile height and distance on the dynamic stress of pipeline.

(2) The Mises stress in the gas pipeline was symmetrically distributed and altered in the same way under different load distances. The Mises stress was highest in the middle of the pipeline, where pipeline damage was most likely to occur. The Mises stress on the gas pipeline steadily increases as the load carrier gets closer to the pipeline, and when the weight reaches 0–2.5m, there is a noticeable impact on the load.

(3) The stress in the middle of the pipeline was the highest and gradually dropped to both ends in the changing law of Mises stress at the top of the pipeline under various load heights. The Mises stress at the bottom of the pipeline grew as the Mises stress increased, and the changing law of the Mises stress at the bottom of the pipeline dropped as the load height climbed. The maximum stress of the pipeline grows with an increase in the height of the pile of soil, which is nearly linear, as the tension near the load boundary increases. The stress is significantly influenced by the height of pile.

References

[1] Schupp J, W Byrne B, Eacott, N C, etc., Pipeline unburial behaviour in loose land, 25th International Conference on Offshore Mechanics and Arctic Engineering, Hamburg, Germany, 2006,92542:1-12.

[2] Anand S. and Agarwal, S.L, Field and laboratory studies for evaluating submarine pipeline frictional resistance, Transactions of ASME, Journal of Energy Resources Technology, 1981, 103, 250-254.

[3] Bransby M.F, Newson T.A, Brunning P. The upheaval capacity of pipelines in jetted clay backfills [J]. International Journal of Offshore and Polar Engineering.2002,12(4):280-287.

[4] Palmer, White, Baumgard. Uplift resistance of buried submarine pipelines: Comparison between centrifuge modeling and full-scaletests[J]. Geotechnique.2003,53(10):877-883.

[5] Taylor, Richardson and Gan. On submarine pipeline frictional characteristics in the presence of buckling, Proc. International Symposium on Offshore Mechanics and Arctic Engineering, ASME, Dallas. Texas 1985: 508-515.

[6] Lyons C G. Soil Resistance to Lateral Sliding of Marine Pipelines[A]. roceedings of Fifth Annual Offshore Technology Conference[C], 1973, OTC1876:479-484.

[7] Brennodden, Sveggen, Wagner. Ful-scale pipe-soil interaction tests, In: Proceedings of the 18th offshore technology conference, Houston,1986,5338,434-440.

[8] Lyons C G, Soil resistance to lateral sliding of marine pipelines,5th Offshore Technology Conference, 1973, 1876 (2):479-484.

[9] Wu Y F. Study on Pipe-soil Interaction of Buried Marine Pipelines [D]. Tianjin University, 2009.

[10] Xue N, Li H J, Sun G J. Discontinuous Deformation Analysis on Pipe-Soil Contact of Buried Pipeline due to Fault [J],2013,34(02): 324-330.DOI: 10.15959/j.cnki.0254-0053.2013.02.014.

[11] Liu C G, Ke G M. Analysis for seismic response of buried pipeline in liquefied soil [J]. World Earthquake Engineering,2010,26(01):125-130.

[12] Yue Q X, Wu H Y, Li J. Analysis of dynamic interaction between pipe and soil [J]. Earthquake Engineering and Engineering Vibration, 2007(03): 132-136. DOI: 10.13197/j.eeev.2007.03.022.

[13] Zhang K Y, Wang Y, Ai Y B. Analytical solution to interaction between pipelines and soils under arbitrary loads [J]. Chinese Journal of Geotechnical Engineering,2010,32(08):1189-1193.

[14] Jing L, Wang S, Du X L. Buckling response analysis of buried pipelines subjected to the site soil settlement [J]. World Earthquake Engineering,2011,27(02):142-147.

[15] Yang J T. Research on longitudinal Mechanical Characteristics of Pipelines Buried in Soft Soil Under Vertical Loads [D]. Zhejiang University,2006.

[16] Ren Y R, Liu Y B, Gu X Y. Using ABAQUS software to deal with the problem of contact surface in pipe-soil interaction [J]. Mechanics in Engineering,2004(06):43-45.

[17] Ren Y R, Liu Y B, Gu X Y. Analysis of pipe/soil interaction on elastic-plastic seabed [J]. engineering mechanics, 2004(02):84-87+83.