Published by Avanti Publishers

Global Journal of Earth Science and Engineering

ISSN (online): 2409-5710

Examining the effect of Debris Flow on Oil and Gas Pipelines Using Numerical Analysis

Zahiraniza Mustaffa, Mohammed A.M. Al-Bared*, Nursyahira Habeeb and Mudassir A. Khan

Department of Civil and Environmental Engineering, Universiti Teknologi PETRONAS, Seri Iskandar, 32610 Perak, Malaysia

ARTICLE INFO

Article Type: Research Article

Keywords:
Shear failure
Wall thickness
Impact of debris flow
Finite element modeling
Pipeline in east Malaysia

Timeline:
Received: July 05, 2022
Accepted: August 20, 2022
Published: September 07, 2022

Citation: Mustaffa Z, Al-Bared MAM, Habeeb N, Khan MA. Examining the effect of Debris Flow on Oil and Gas Pipelines Using Numerical Analysis. Glob J Earth Sci Eng. 2022; 9: 74-87.

DOI: https://doi.org/10.15377/2409-5710.2022.09.6

ABSTRACT

This article examines the impact of debris flow on semi-exposed pipelines to determine the plastic deformation and stresses by considering pipe-debris flow interaction. A 3-D finite element approach was adopted to study the mechanical behavior of pipelines subjected to debris flow. Integration of pipeline property (thickness) with debris flow intensity (impact pressure and angle) was also considered in a finite element numerical model for semi-exposed. The analysis showed that the impact angle between 35° and 75° with an impact pressure of 200 kPa and 250 kPa significantly affected the stability and integrity of the pipeline. There was a slight impact of wall thickness on the stability of the pipeline due to the passive soil resistance. Maximum plastic deformation of 124 mm was encountered in the case of 35° impact angle, which was 3% more than the deformation observed at 20° impact angle.

Moreover, large distribution of von mises stresses was observed, as 1390 Mpa, 1450 Mpa, 1440 Mpa, and 1440 Mpa for impact angles of 20°, 35°, 75°, and 90° in the impacted zone of the pipeline in each set of analysis. Shear failure of the pipeline was observed during the analysis as von misses' stresses were more than the yield stress (520 Mpa) of the pipeline. The developed model in this study can be utilized for further research and will be a basis for designing pipelines crossing through mountainous regions.

*Corresponding Author
Email: albared2009@yahoo.com
Tel: +(60) 176571475

1. Introduction

Service pipelines transporting oil and gas cross variable physiographical terrain, including mountainous ranges, upland plateaus, highly uneven topography, and several geological conditions. This method of construction/ installation usually decreases the entire cost of the projects, reduces the possibility of urban damages, and minimizes the bends in the path of pipelines [1]. However, intensive rainfall and the instability of rock and soil slopes contribute to exposing the buried pipelines to rockfall, sliding, soil slope failure, landslides, and debris flow hazards within time [2-6]. This will lead to corrosion defects on the exposed pipeline, significantly affecting its durability [7,8]. Besides, the action of earthquakes and the seismic vibrations severely affect the mechanical behavior of the pipelines [9,10]. During the installation/construction, pipelines will either be buried in soil within a certain depth or exposed to the ground, depending on the project's cost, distance and requirements. Pipelines that are constructed within unstable soil regions and debris flow potential occurrence zones are frequently subjected to the active loading of soil slide or debris flow hazards [11]. Quantification of active loading and deformation within the pipelines loaded by unstable/problematic soil is always considered a challenge for researchers and scholars worldwide [12]. In this context, significant research has been published on measuring the magnitude of loading impacted on the pipelines by the slide mass and its impact angle [5,13-16]. For instance, an investigation of the large deformation of pipelines impacted by rockfall in Chongqing in 2005 [17] by debris flow [18] was performed numerically. In addition, Yuan et al. [19] developed an analytical model for quantification of large deformation impacted by debris flow at different angles by dividing the pipeline into four segments. The load-deformation (P-y) equations resulted from the combined effects of the impact width, angle, and soil resistance. Further, Wu and Li [5] also claimed that velocity, impact angle, and corrosion effect significantly influenced the mechanical behavior of the semi-exposed pipeline, while the exposed length of the pipeline did not have that much influence.

Nowadays, the traditional design methods of pipelines that include only the stress-based criteria are considered not enough to adopt the current needs in this industry. Recently, oil and gas pipelines have been constructed in large diameters for very long distances, operating under high pressures and passing through difficult environments subjected to sudden and frequent geohazards. Hence, a more reliable, efficient, and economical pipeline design is required [20]. The design of the pipelines should consider the deflection and deformation to overcome the pipe buckling and rupture [21]. Bing et al. [22] examined the strain-based design for oil and gas pipelines subjected to landslide events. ABAQUS was used to analyze strain caused by the action of landslide. The results showed that the pipelines were primarily subjected to tensile stresses and strain along the central axis when the action of the landslide was perpendicular to the pipe.

Moreover, Gao et al. [23] conducted a study on the concepts of strain-based pipeline design. It was found that the strain-based design is composed of the strain limits of compressive and tensile strains. Meanwhile, among the aspects that influence the strain-based design are the properties of steel pipe, strain aging, girth welding, and its non-destructive test performance. The strain-based design for oil and gas pipelines comprises of determination of the longitudinal and compressive strains that can be achieved by considering soil-pipe interaction in finite element analysis.

Furthermore, previously published literature [24-26] and many oil and gas companies such as Transredes oil and gas pipeline, Bolivia [22] Pacific northern gas pipeline in British Columbia, Canada [27], and most recently Sabah and Sarawak gas pipeline, Malaysia [28] conducted an in-depth investigation in the failure of pipelines. The latter suggested a detailed investigation of pipeline failure due to the impact of debris flow by considering the relevant parameters of wall thickness and impact angle. Integrating the pipeline parameters with debris flow impact pressure and angle may provide a broad spectrum of failure patterns of pipelines in the mountainous region, which have not been extensively discussed in the literature. Furthermore, to the authors' best knowledge, very limited literature investigated the strain-based design for the oil and gas pipelines. Hence, this study aims to analyze the debris flow impact by considering variable wall thickness, impact pressure and impact angle on semi-exposed pipeline using finite element method (ABAQUS). The deformation, stress and strain were analyzed and discussed under the effect of variable impact pressures, wall thicknesses impact angles. The outcome of this study may provide the basis for pipeline strain-based design subjected to the action of debris flow.

2. Materials and Methods

2.1. Materials

The material of the pipeline that was considered for the analysis in this study was made of API 5L X70 steel type. This type was used in the gas pipelines located in Sabah and Sarawak [29]. The physical and mechanical properties of the pipeline are shown in Table **1**.

Table 1: Physical and mechanical properties of the studied pipeline.

Material	D (mm)	T (mm)	(Kg/m^3)	E (GPa)	μ	σ_y (MPa)	σ_t (MPa)
API 5L X70	920	14,16,20	8050	210	0.3	520	565

The studied pipeline was investigated using different thicknesses, as shown in Table **1**, for better analysis results. The soil placed around the pipeline was identified as silty clayey soil with a density of 1500 kg/m^3. This soil applied lateral resistance to the pipeline against the deformation due to the impact of the debris flow. The coefficient of lateral resistance for the soil and pipeline was chosen as 0.4 for the analysis [30]. The impact pressure of the debris flow was varied and set as 150 kPa, 200 kPa, and 250 kPa as per the relevant literature [3,6,31,32].

The ideal stress-strain relationship was considered to exhibit the elastic and plastic zones of the tested pipeline. In this analysis, the elastic zone was expressed using the elastic constitutive model by utilizing the yield stress and Poisson's ratio. Besides, von mises stress was also employed as yield stress to meet the failure criteria. Hence, equivalent von mises stress was set lower than the yield stress for all the pipeline nodes, as shown in Eqs. 1 and 2 below.

$$\sigma_{eq} < \sigma_y \tag{1}$$

$$\text{Von mises stress } (\sigma_{eq}) = \sqrt{\frac{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_1-\sigma_3)^2}{2}} \tag{2}$$

Where σ_1, σ_2, and σ_3 are the principal stresses in major, intermediate and minor plane, respectively.

2.2. Finite Element Modelling

ABAQUS 2017, which can be described as a finite element solver for failure analysis of semi-exposed pipelines, was utilized in this study. The analysis and modeling of the pipeline were performed by varying the geomechanical properties, such as the impact of debris flow, the impact angle, and the wall thickness, as shown in Table **2**.

Rigorous analysis for 36 cases was performed to investigate the combined effect of the impact pressure, impact angle, and wall thickness, as revealed in Table **2**. These three parameters are considered very influential for the strength of the pipeline during debris flow [33-35]. A different set of parameters were considered in the analysis to observe the critical condition of the pipeline when approaching failure in a broad spectrum, which is discussed in the subsequent sections. Meanwhile, this analysis was conducted to simulate the existing pipelines in the east of Malaysia that are available in 14 mm, 16 mm, 18 mm, and 20 mm diameters. Different diameters were adopted for the pipelines to suit the pressure requirement and the environmental conditions at the installation areas [29]. The mechanical behavior of the pipeline against the impact of debris flow was assessed using 14 mm, 16 mm, and 20 mm thick walls at 20°, 35°, 75°, and 90° impact angles, as illustrated in Figure **1**.

Table 2: Numerical modeling program for the semi-exposed pipeline.

Impact Angle (°) / Pressure (kPa)	20	35	75	90	Wall Thickness (mm)
150	150, 20, 14	150, 35, 14	150, 75, 14	150, 90, 14	14
200	200, 20, 14	200, 35, 14	200, 75, 14	200, 90, 14	
250	250, 20, 14	250, 35, 14	250, 75, 14	250, 90, 14	
150	150, 20, 16	150, 35, 16	150, 75, 14	150, 90, 16	16
200	200, 20, 16	200, 35, 16	200, 75, 16	200, 90, 16	
250	250, 20, 16	250, 35, 16	250, 75, 16	250, 90, 16	
150	150, 20, 20	150, 35, 20	150, 75, 20	150, 90, 20	20
200	200, 20, 20	200, 35, 20	200, 75, 20	200, 90, 20	
250	250, 20, 20	250, 35, 20	250, 75, 20	250, 90, 20	

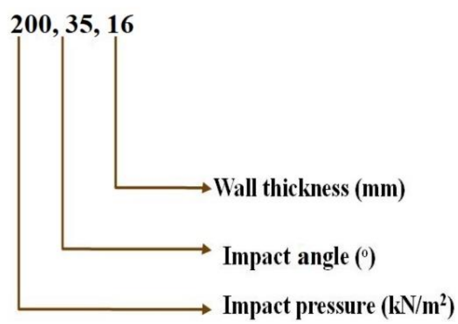


Figure 1: Description of parameters used in the analysis.

2.2.1. Assumption

The following assumptions were made in the numerical modeling to simulate the mechanical behavior of the pipeline subjected to the impact of debris flow:

(1) Mechanical and deformation behaviors of the pipeline were studied using both the elastic and plastic ranges.

(2) The impact force was assumed to act on the central axis of the pipeline at a defined angle.

(3) The lateral resistance of soil resulting from the semi-exposed condition of the pipeline was simulated by the finite slide contact and coefficient of soil resistance.

(4) The pipeline was set to be always semi-exposed during the impact of debris flow.

2.2.2. Geometry, Loading, and Boundary Condition

This study used a circular type of pipeline simulating the one existing in the east of Malaysia that has homogeneous properties of API 5L X7 steel with a dimension of 10 m length and 0.92 m diameter. According to the available literature on debris flow, the slide width depends on the channel or debris fans which may be 5 m to 60 m [36]. Thus, for this study, the width of debris flow was set as 6 m, which acted in the middle part of the pipeline for all analyses. The weight of the pipeline was also incorporated by defining the gravity loading in a downward direction. In addition, the soil pressure and traction were identified for the buried part of the pipeline, as indicated in Figure **2**.

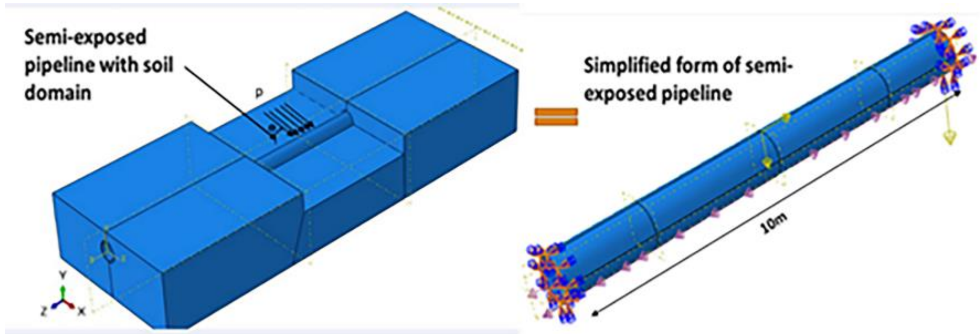


Figure 2: Semi-exposed pipeline during analysis with load and boundary condition.

2.2.3. Meshing and Convergence Study

The pipeline was discretized into 2408 shell elements of S4R, which was the final step in the modeling process. The element type used during the analysis was 4-node doubly curved thin or thick shell, reduced integration, hourglass control, and finite membrane strains [5]. The mesh convergence fixed the element size to make the solution domain mesh independent. This was achieved by changing the element size for the combined strain, and von mises stresses at a node on a longitudinal path for impact pressure of 150 kPa. Figure. **3** shows no significant change in strain and stress after a mesh size of 0.2 m. Hence, 0.1 m refined mesh was used for the area of attention, and the remaining parts of the pipeline were discretized using 0.2 m mesh. Moreover, the longitudinal path of 7.60 m was selected for observing the mechanical behavior of the pipeline in the axial direction with a debris flow impact width of 6 m, as revealed in Figure **4.**

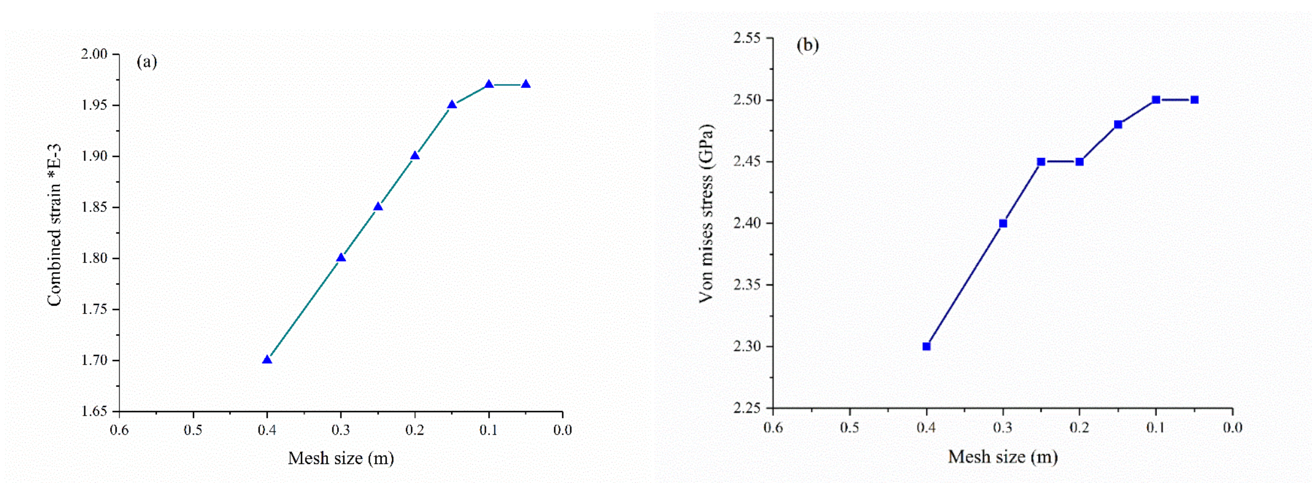


Figure 3: Mesh convergence study for (a) combined strain (b) von mises stresses observed at different mesh sizes on a selected node.

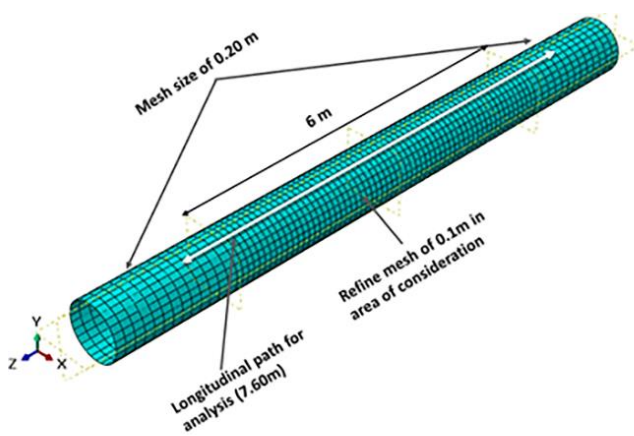


Figure 4: Mesh density of pipe model.

3. Results and Discussion

3.1. Model Validation

In this study, the developed numerical model was validated and compared with an analytical model proposed by Yuan et al. [19]. The authors developed a refined analytical model considering the interaction between the soil and pipeline. The passive resistance of soil was studied to quantify the drag force and deformation in the pipeline segment impacted by the debris flow at an inclined plane. The authors proposed a load-deformation equation for each segment of the pipeline, as presented in Figure. **5**.

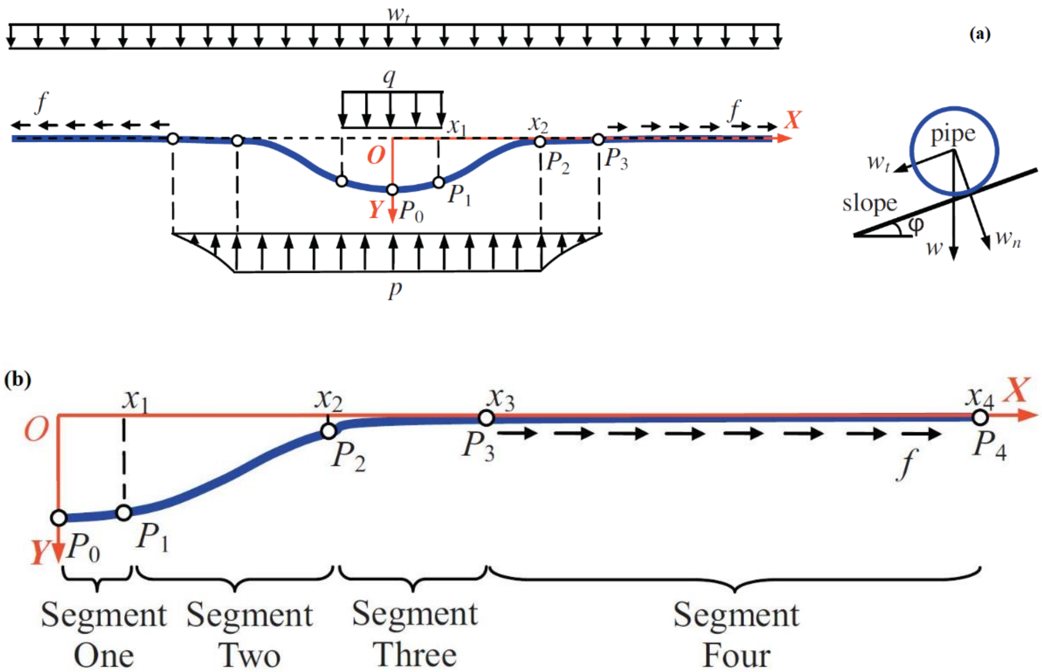


Figure 5: Scheme of pipeline subjected to the (a) impact of debris flow using different types of load and (b) the deformed shape of pipeline segment [19].

Yuan et al. [19] developed differential equations for each pipeline segment, as shown in Figure. **5(b)** due to symmetry in loading and boundary conditions. According to the applied load and boundary conditions, the solution to equations for each segment was developed and presented as follows:

Segment 1: The first segment that extends from P_0 to P_1 was loaded by the debris flow drag force p and soil resistance q from the center to x_1. This segment is the zone impacted by the debris flow, and it is essential for pipeline safety and integrity because it encounters both the drag force of sliding and the soil resistance. The governing equation for this segment can be written as in Eq. (3):

$$y_1(x) = \frac{p-q-w_t}{2T}x^2 + c_1 + c_2 x + c_3 e^{\alpha x} - c_4 e^{-\alpha x} \; (0 \leq x \leq x_1) \text{ -} \tag{3}$$

$$\text{And } \alpha = \sqrt{\frac{T}{EI}} \tag{3.1}$$

Where $y_1(x)$ is the configuration of P_0 to P_1 and x_1 is the x-coordinate at P_1.

Segment 2: This segment is expanding from P_1 to P_2, and it is only impacted by external forces. Although no landslide occurred in this region, forces from Segment 1 and the soil resistance produced large deformation, as described by Eq. (4).

$$y_2(x) = \frac{p-w_t}{2T}x^2 + c_5 + c_6x + c_7e^{\alpha x} - c_8e^{-\alpha x}\ (x_1 \le x \le x_2) \quad (4)$$

Where $y_2(x)$ is the configuration of the pipeline between P_1 to P_2, w_t is the weight of the pipeline and x_2 is x-coordinate at P_2.

Segment 3: This portion lies between P_2 and P_3 that was externally subjected to the lateral soil resistance only and forces transferred from Segments 1 and 2. This caused some deformation that could be calculated using Eq. (5).

$$y_3(x) = \frac{w_t}{k} + e^{\beta x}\{c_9\cos(\Upsilon x) + c_{10}\sin(\Upsilon x)\} + e^{-\beta x}\{c_{11}\cos(\Upsilon x) + c_{12}\sin(\Upsilon x)\}(x_2 \le x \le x_3) \quad (5)$$

$$\text{Where } \beta = \frac{1}{2}\sqrt{2\sqrt{\frac{k}{EI}} + \frac{T}{EI}} \quad (5.1)$$

$$\Upsilon = \frac{1}{2}\sqrt{2\sqrt{\frac{k}{EI}} - \frac{T}{EI}} \quad (5.2)$$

In which $y_3(x)$ denotes the configuration in Segment 3, and $\alpha, \beta,$ and Υ are the variables that are dependent on the axil tension (T), modulus of elasticity (E), and moment of inertia (I) of the pipeline. The unknown coefficients are the coefficients of c1, c2, c3, c4, c5, c6, c7 c8, c9, c10, c11, and c12. For simplification, the values of c_1 to c_{10} were taken as 1 and c_{11}, and c_{12} was zero.

Segment 4: This zone was only loaded by the axial soil resistance, and the impact of debris flow was neglected in this segment. In this zone, deformation was only caused by the resultant weight of the pipeline (w_t), and the soil resistance (q) depended on the soil. Silty clayey soil, whose frictional resistance coefficient is 0.2 to 0.4, was used in this study. For validation purposes, this segment was neglected.

The relationship between load and deformation of each segment for different types of loading is described in Eqs. 3 to 5. Vertical deformation for 200 kPa impact pressure at 35° impact angle was calculated on a 16 mm thick pipe numerically and analytically. It was observed that the analytical and numerical results were compared by a 10% difference, as revealed in Figure **6**. The maximum deformation observed by Yuan et al. (2012) model was 127 mm, whereas, in the current numerical model, the maximum deformation was 121 mm, which shows a good agreement with the analytical model.

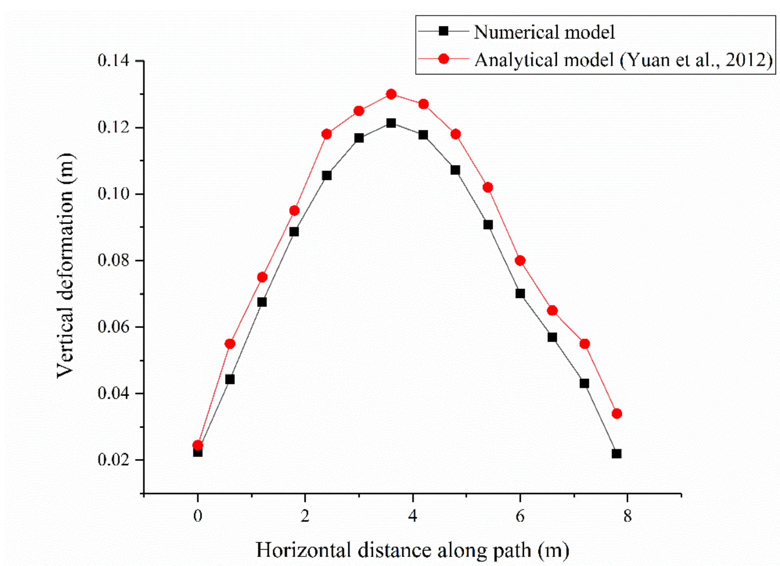


Figure 6: Resultant deformation in numerical and analytical models.

3.2. Von Mises Stresses

Von mises stresses correspond to the shear stresses within the pipeline when subjected to loading. These stresses usually depend on several factors, such as the width of debris flow, intensity of pressure, and type of passive soil resistance the soil surrounding the pipeline provides. In this study, von mises stresses were examined for each set of analyses in the longitudinal path of the pipeline using different impact angles. The distribution curves of von mises stresses were similar for all cases with different initial, peak, and final stress along the path. However, at approximately 6 m, which is considered the debris flow impact region, the stresses varied non-linearly (parabolically) for every examined case.

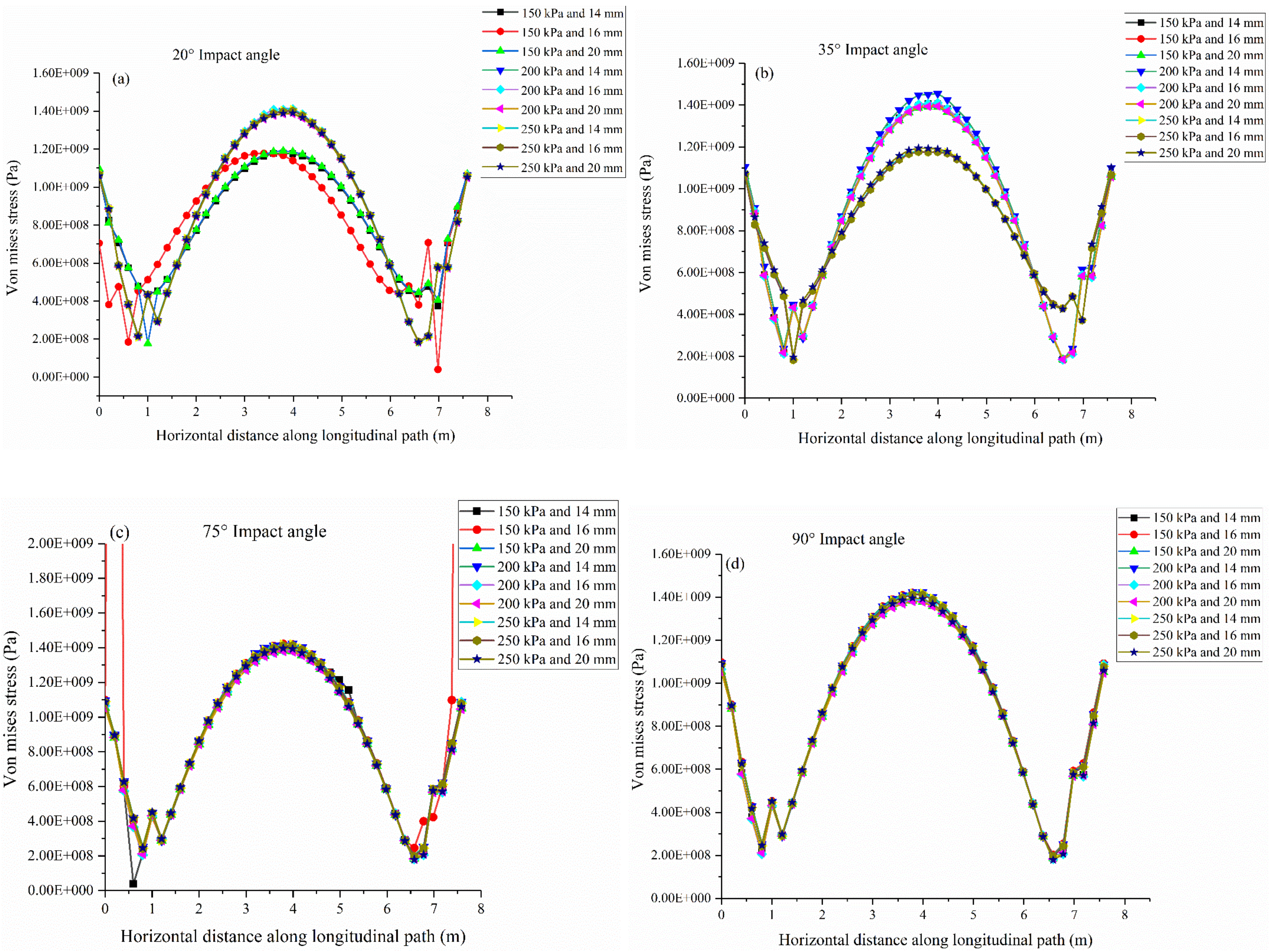


Figure 7: Distribution of von mises stresses along the longitudinal path for (a) 20° impact angle, (b) 35° impact angle, (c) 75° impact angle, and (d) 90° impact angle.

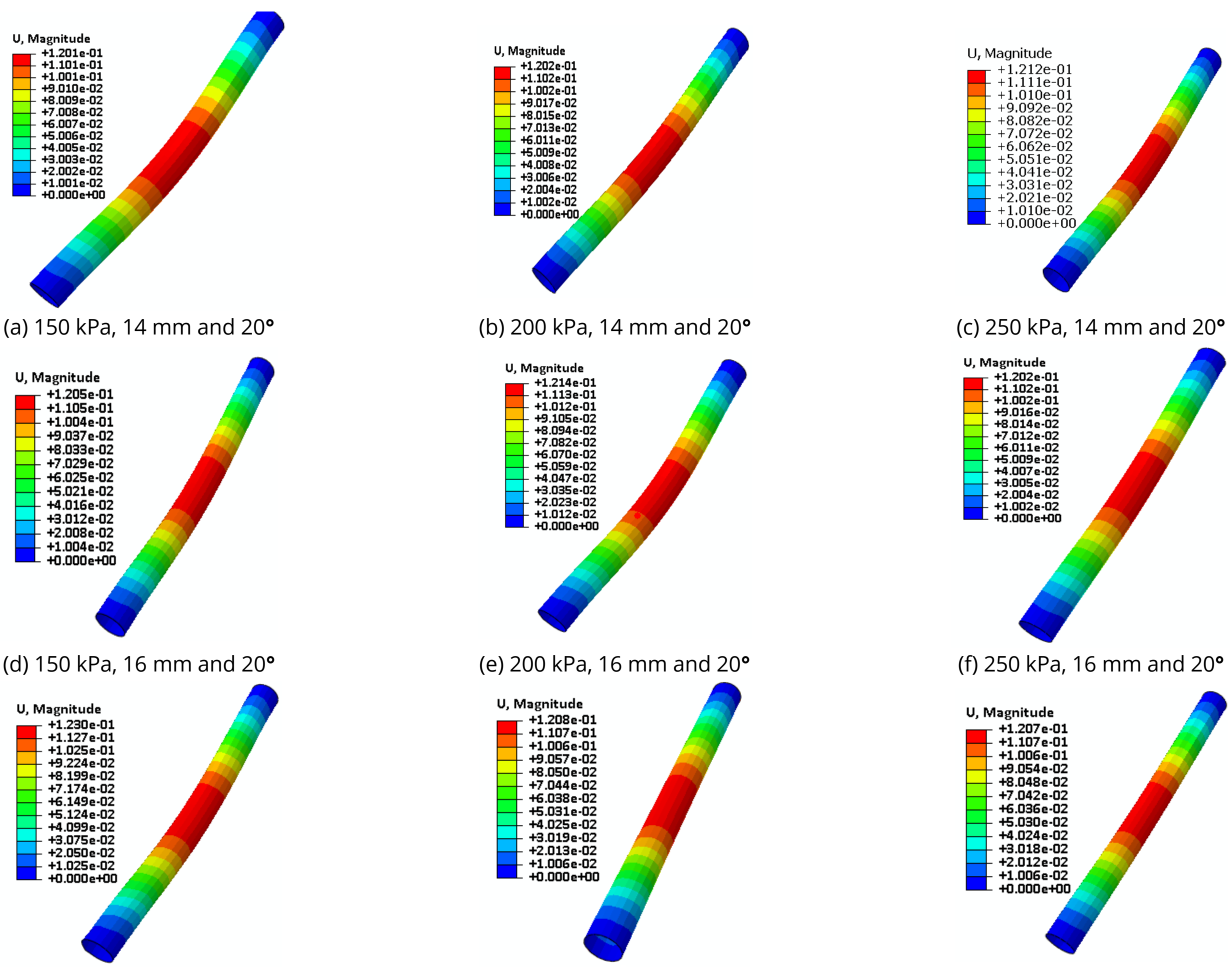
Figure **7** shows the distribution of von mises stresses along the longitudinal path at different impact angles. The Figure shows initial and final parts of the stresses had a significant rise and fall due to the transition between loading and unloading of the pipeline. Besides, the maximum stresses were detected at the center of the impacted zone in each case of analysis. For the impact angle of 20°, Figure **7(a**) revealed that the maximum stresses at the peak were recorded as1.39 GPa (1390 MPa) in the sets of 150 kPa,16 mm, and 250 kPa, 20 mm. It might be due to the increase in wall thickness that uniformly distributed the increased pressure in the pipeline.

On the other hand, the minimum peak stress was 1180 MPa in the sets of 150 kPa, 14 mm, 150 kPa, 16 mm, and 150 kPa, 20 mm, which was more than the yield stress of the pipeline, i.e., about 510 MPa. In addition, 35° impact resulted in maximum peak stress of 1450 MPa in the set of 200 kPa, 14 mm, as shown in Figure **7(b).** The minimum peak stresses were observed to be 1190 MPa in sets of 250 kPa, 20 mm, and 250 kPa,16 mm, slightly more than the 20° impact set of analysis. Likewise, for the impact angles of 75° and 90°, the maximum peak stress was 1440 MPa for the set of 250 kPa and 14 mm and for the set of 200 kPa and 16 mm, as shown in Figure **7(c)** and **(d),** respectively. The results from this numerical analysis demonstrated the stress distribution within the pipeline that was dependent on the wall thickness, impact angle, and pressure. They severely affected the mechanical behavior of the pipeline. In all reported analysis cases, the maximum equivalent von mises stresses were more than the pipeline's yield strength and tensile strength. However, obtained peak stresses were not comparable explicitly due to the combination of impact pressure, wall thickness, and impact angle. It might be due to the adjustment of stresses in the pipeline with a variation of pressure and thickness. It can be concluded that if the pipeline were subjected to a pressure between 150 kPa and 250 kPa at a small exposed length, the shear failure would happen, and the same failure mechanism was reported in similar studies in the literature [19,37].

Furthermore, analysis of von misses' stresses revealed that the impact angle between 35° and 75° will be the most critical for the shear failure of the pipeline in the debris flow region. This range of impact angles for shear failure was also reported in the literature by Wu and Li [38]. Therefore, precautions should be taken during designing pipelines, especially those crossing debris flow susceptible areas.

3.3. Resultant Deformation

The resultant deformation (U) was also studied and investigated in each set of analyses to understand how deformation within pipelines could lead to serious loss in the flow within the network of pipelines. Figure **8** shows



(a) 150 kPa, 14 mm and 20° (b) 200 kPa, 14 mm and 20° (c) 250 kPa, 14 mm and 20°

(d) 150 kPa, 16 mm and 20° (e) 200 kPa, 16 mm and 20° (f) 250 kPa, 16 mm and 20°

(g) 150 kPa, 20 mm, and 20° (h) 200 kPa, 20 mm, and 20° (i) 250 kPa, 20 mm, and 20°

Figure 8: Contours of the resultant deformation for 150 kPa, 200 kPa, and 250 kPa impact pressures with variable wall thicknesses at a 20° impact angle.

the deformation contours of a pipeline subjected to debris flow impacted at pressures of 150 kPa, 200 kPa, and 250 kPa with 14 mm, 16 mm, and 20 mm thicknesses at a 20° impact angle. The convex deformation pattern of the pipeline was observed in Figure **8** for each set of analyses with maximum bending in the impacted pipeline zone (i.e., 6 m slide width). The blue color at the end and the red color at the center of the pipeline denoted the maximum and minimum deformations, respectively. In addition, Figure **8 (a-i)** revealed a slight variation in the maximum deformation with different impact pressures and wall thicknesses at a 20° impact angle. This observed behavior in the pipeline material was due to simultaneous increases in the thickness of the pipeline and impact pressures. This resulted in balancing the stresses in the longitudinal direction. The resistance created by the soil friction around the buried part of the pipeline and the weight of the pipeline also contributed to resisting the deformation. This behavior was encountered during an investigation conducted by Wu and Li [5] for a semi-exposed pipeline impacted by a massive stone of debris flow, and it was agreeable with the results found during this study.

Meanwhile, the maximum deformation for the 20° impact angle was 121 mm in the set of 200 kPa, 16 mm, as shown in Figure **9 (a).** The observed deformation for the pipeline material was plastic which corresponded to the maximum von mises stresses. This permanently disturbed the uniformity and integrity of the pipeline as per the deflected shape revealed in Figure **8**. Similarly, the maximum and minimum deformations for 35° impact angle were 124 mm and 119 mm for the cases of 200 kPa, 14 mm, and 150 kPa, 20 mm, respectively, as shown in Figure **9 (b)**. However, for the case of 250 kPa, 14 mm, and 250 kPa, 16 mm, the maximum deformation was found to be 122 mm, which was very close to the maximum deformation. Moreover, for the impact angles of 75° and 90°, the maximum deformation was 123 mm for the case of analysis of 200 kPa and 14 mm, as shown in Figures **9 (c)** and **(d),** respectively.

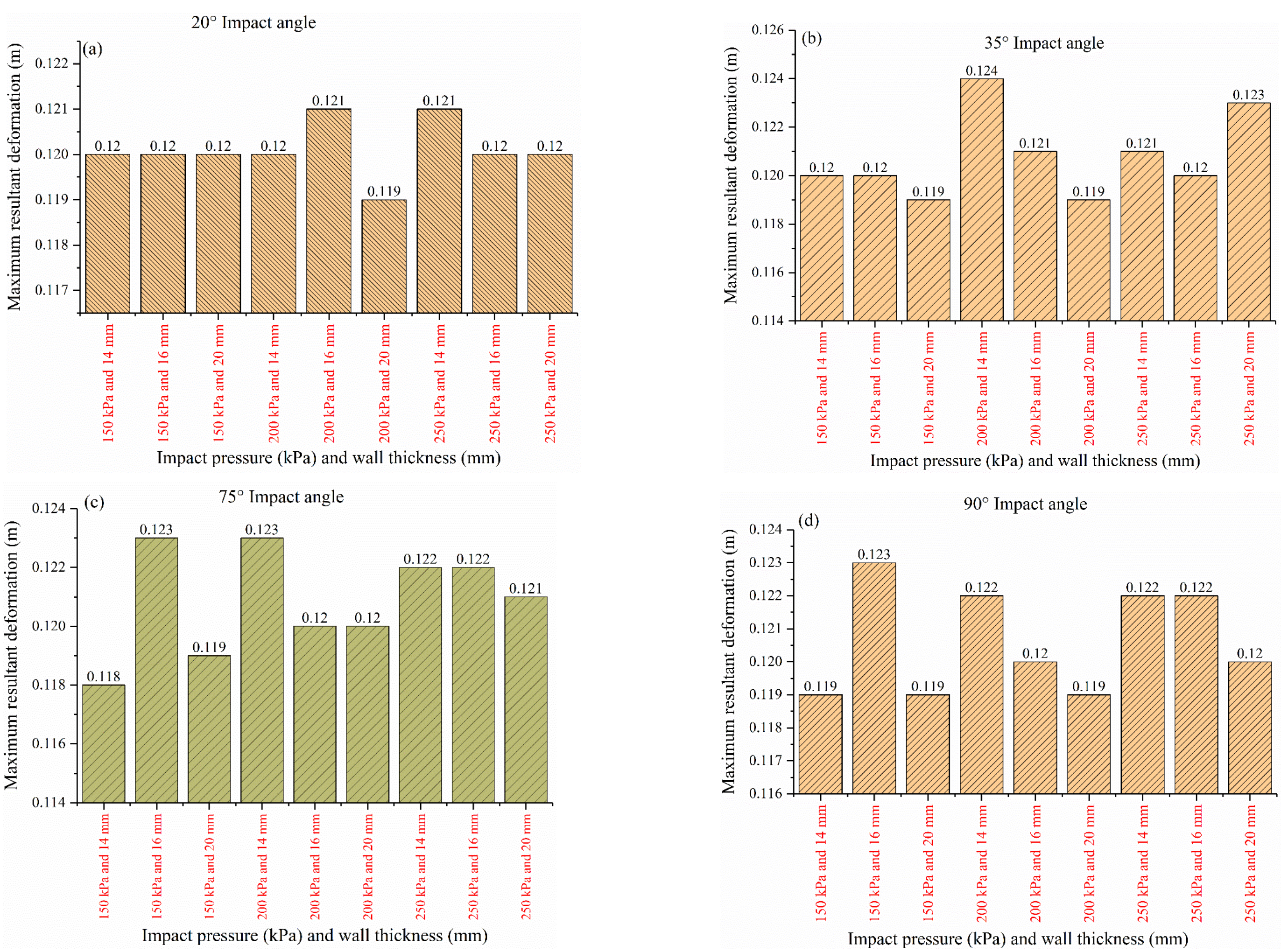


Figure 9: Maximum deformation for each set of analyses; (a) 20° impact angle, (b) 35° impact angle, (c) 75° impact angle, and (d) 90° impact angle.

Furthermore, Figure **9 (b-d**) revealed that the further increased value of impact angle beyond 75° resulted in decreasing the maximum deformation due to the increased resistance within the soil particles around the pipeline. This phenomenon was also found by Yuan et al. [19] for a 60 m pipeline impacted using different angles. Overall, the resultant deformation was influenced by the combination of the impact pressure, wall thickness, impact angle, soil resistance, and the strength of the pipeline. According to Kunert et al. [3], plastic deformation usually affects the workability and durability of the pipeline which may lead to its complete damage.

3.4. Combined Strain

The combined strain along the longitudinal axis of the pipeline was examined for each set of analyses at 20°, 35°, 75°, and 90° impact angles. The action of peak von caused the combined strain misses and tensile stresses on the pipe. Figure **10** shows the magnitude of strain initially decreased in the unloaded part of the pipeline. Then, the strain was gradually increased in the loaded part to reach the maximum at the center of the pipeline. There was a slight difference detected in the distribution of combined strain for individual cases of 20°, 35°, 75°, and 90° impact angles due to the simultaneous effect of the impact pressure, wall thickness, and the lateral resistance of soil around the pipeline. However, initial and peak strains were significantly varied at the different impact angles. The initial and final strains for the 20° impact angle were 0.005, and the peak strain was recorded as 0.019 in the cases of 150 kPa, 14 mm, 200 kPa, 16 mm, and 250 kPa,16 mm, as demonstrated in Figure **10 (a).**

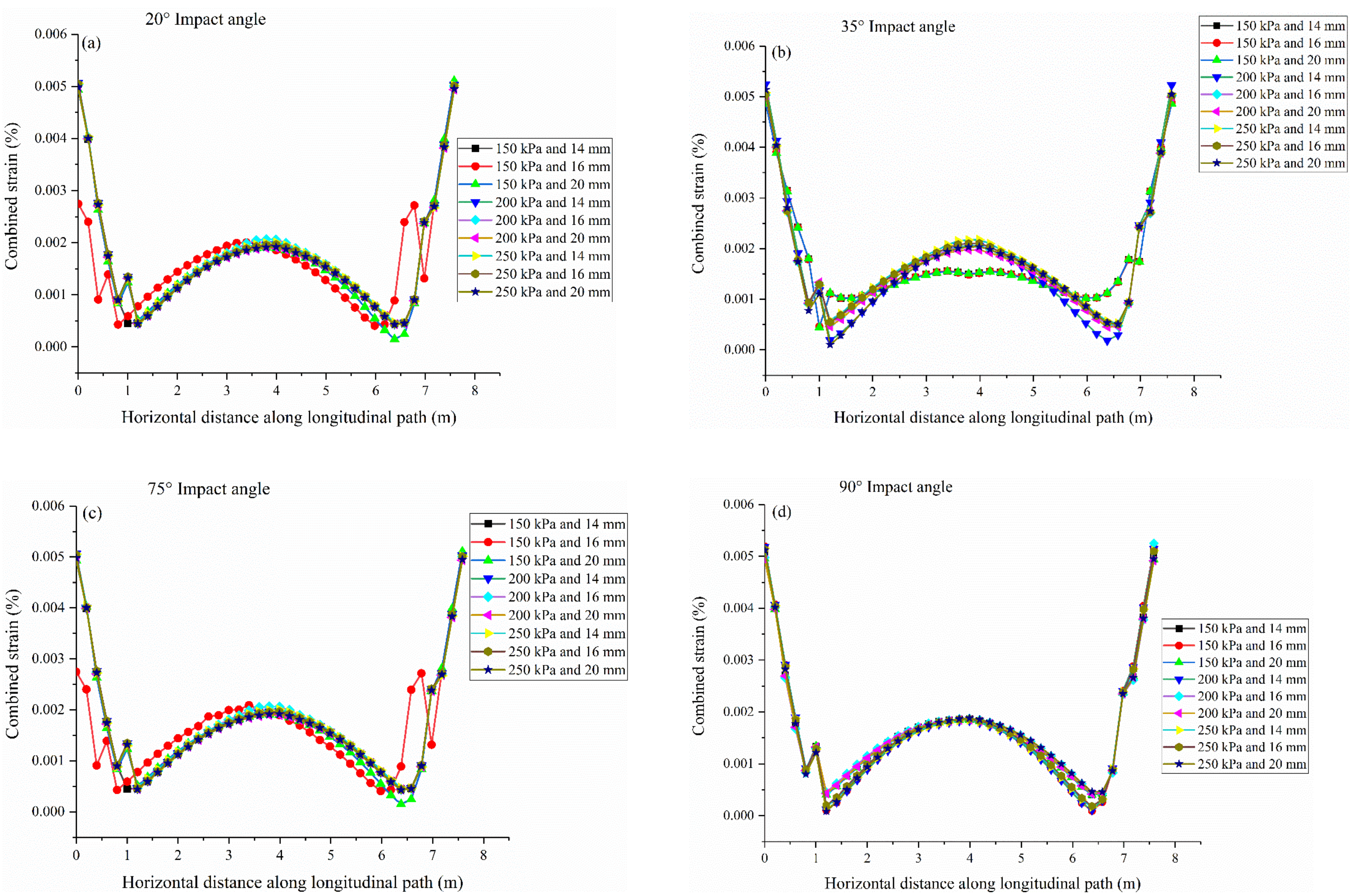


Figure 10: Variation of strain in longitudinal direction using different impact angles; (a) 20° impact angle, (b) 35° impact angle, (c) 75° impact angle, and (d) 90° impact angle.

Meanwhile, for the combined strain resulting from bending of more than 5%, von mises and tensile stresses in a long continuous pipeline may affect the durability of the pipeline in the long term [36]. The maximum strain was observed to be 0.0201 for a 35° impact angle in the case of 250 kPa,16 mm, which was 6% more than that recorded for the 20° impact angle, as revealed in Fig. **10(b)**. In addition, Similar results were obtained for the cases of 75° and 90° impact angles. The maximum stain was found to be 0.020 and 0.019 for 75° and 90° impact angles, respectively, in the case of 250 kPa, 16 mm. This combined strain was developed within the pipeline due to the combined effect of bending and tensile stresses, and it was detected in the longitudinal path of the pipeline. Thus, based on the results obtained from this study, it can be concluded that the integrity of the long continuous pipeline is greatly influenced by the impact angle greater than 35° for the impact pressures of 150 kPa, 200 kPa, and 250 kPa. However, further research on the corrosion effect on pipelines along with debris flow impact will provide a better understanding of pipeline behavior in an extreme environment. In addition, pressure and non-pressure pipelines interact differently with debris flow impact, which was not considered in this study.

4. Conclusions

Exposed pipelines located in mountainous areas are severely threatened by the geohazards such as landslides, debris flows, and rockfalls. Hence, in this study, debris flow hazard impacted the finite element analysis for semi-exposed pipeline with a length of 10 m and a diameter of 0.92 m. The combined effect of debris flow width, impact pressure, and impact angle with variable wall thicknesses was observed on the stability and integrity of the pipeline. The surrounding soil block was modeled as passive soil resistance with a passive coefficient of 0.40, whereas the pipeline was considered as an elastoplastic model with an S4R shell type element. The element size in impacting zone was adopted as 0.1 m, whereas it was 0.20 m in the adjacent region after the mesh convergence study. Further developed model was validated with an analytical model, and the results were comparable within 10% error. Results were analyzed for shear failure criteria adopted for this study, and the following conclusions can be drawn:

- Debris flow impact between 35° and 75° was critical for the pipeline failure because maximum von misses' stresses observed at 35° and 75° were 1450 Mpa and 1440 Mpa, respectively.
- The magnitude of maximum resultant deformation was observed as 121, 124, 123, and 121 mm for 20°, 35°, 75°, and 90° impact angles at 200 and 250 kPa impact pressure, respectively. Besides, a deformed convex shape of the pipeline was observed in each set of analyses, which significantly reduced the efficiency of long pipes in the mountainous region
- Combined strains were recorded as 0.019 in the case of 200, 20, and 14, which was more than the permissible strain (i.e., 0.002) in the oil and gas pipeline.
- The results showed that the pipeline failed in shear criteria at 150 kPa, 200 kPa, and 250 kPa impact pressures as the maximum equivalent von mises stresses were much more than the yield strength (520 Mpa) of the pipeline.

Overall, pipeline crossing in variable geographic terrain should be designed by considering the impact pressure at a different angle to safeguard against integrity loss to oil and gas pipelines.

Conflicts of Interest Statement

On behalf of all authors, the corresponding author states that there is no conflict of interest.

References

[1] Jakob M, Porter M, Savigny KW, Yaremko E. A geomorphic approach to the design of pipeline crossings of mountain streams. Proceedings of the Biennial International Pipeline Conference, IPC. 2004;1(January 2004):587-94.

[2] Qinglu Deng XS and DZ. Risk Analysis of Oil Pipeline under Collapse and Rockfall at Different Heights of Rock Slope. In: Icptt 2011 © 2011 asce 1598. 2011. p. 1598-609.

[3] Kunert HG, Marquez AA, Fazzini P, Otegui JL. Failures and integrity of pipelines subjected to soil movements. Handbook of Materials Failure Analysis with Case Studies from the Oil and Gas Industry. 2016;105-22.

[4] Baum BRL, Galloway DL, Harp EL. Landslide and Land Subsidence Hazards to Pipelines. 2008;

[5] Wu Y, Li J. Finite element analysis on mechanical behavior of semi-exposed pipeline subjected to debris flows. Engineering Failure Analysis [Internet]. 2019;105(June):781-97. Available from: https://doi.org/10.1016/j.engfailanal.2019.06.055

[6] Gartner JE, Jakob M. Debris-flow risk assessment and mitigation design for pipelines in British Columbia, Canada. Debris-Flow Hazards Mitigation: Mechanics, Monitoring, Modeling, and Assessment - Proceedings of the 7th International Conference on Debris-Flow Hazards Mitigation. 2019;677-84.

[7] Service T. Guidelines for Evaluating Pipeline Channel Crossing Hazards to Ensure Effective Burial. 2019;(September).

[8] El Amine Ben Seghier M, Keshtegar B, Correia JAFO, Lesiuk G, De Jesus AMP. Reliability analysis based on hybrid algorithm of M5 model tree and Monte Carlo simulation for corroded pipelines: Case of study X60 Steel grade pipes. Engineering Failure Analysis. 2019;97(December 2018):793-803.

[9] Dadfar B, El Naggar MH, Nastev M. Vulnerability of buried energy pipelines subject to earthquake-triggered transverse landslides in permafrost thawing slopes. Journal of Pipeline Systems Engineering and Practice. 2018;9(4):1-12.

[10] Yiğit A, Lav MA, Gedikli A. Vulnerability of natural gas pipelines under earthquake effects. Journal of Pipeline Systems Engineering and Practice. 2018;9(1):1-14.

[11] Syarifuddin M, Oishi S, Legono D. LAHAR FLOW SIMULATION IN MERAPI VOLCANIC AREA BY HyperKANAKO MODEL. Journal of Japan Society of Civil Engineers, Ser B1 (Hydraulic Engineering). 2016;72(4):I_865-I_870.

[12] Su H, Zio E, Zhang J, Li X. A systematic framework of vulnerability analysis of a natural gas pipeline network. Reliability Engineering and System Safety [Internet]. 2018;175:79-91. Available from: https://doi.org/10.1016/j.ress.2018.03.006

[13] Bugnion L, McArdell BW, Bartelt P, Wendeler C. Measurements of hillslope debris flow impact pressure on obstacles. Landslides. 2012;9(2):179-87.

[14] Wang Y, Liu X, Yao C, Li Y. Debris-Flow Impact on Piers with Different Cross-Sectional Shapes. Journal of Hydraulic Engineering. 2020;146(1):04019045.

[15] Matias LM, Cunha T, Annunziato A, Baptista MA, Carrilho F. Tsunamigenic earthquakes in the Gulf of Cadiz: Fault model and recurrence. Natural Hazards and Earth System Science. 2013;13(1):1-13.

[16] Ali AM, Kareem HK. Numerical modelling of small scale model piles under axial static loads. Journal of Engineering Science and Technology. 2020;15(6):3528-46.

[17] Xiong J, Deng QL, Zhang HL, Pang WJ. Safety assessment on the response of buried pipeline caused by rockfall impact load. Safety and Environmental Engineering. 2013;20(1):108-14.

[18] Peng S, Liao W, Liu E. Pipe-soil interaction under the rainfall-induced instability of slope based on soil strength reduction method. Energy Reports [Internet]. 2020;6:1865-75. Available from: https://doi.org/10.1016/j.egyr.2020.07.012

[19] Yuan F, Wang L, Guo Z, Shi R. A refined analytical model for landslide or debris flow impact on pipelines. Part I: Surface pipelines. Applied Ocean Research [Internet]. 2012;35:95-104. Available from: http://dx.doi.org/10.1016/j.apor.2011.12.001

[20] Liu B, Liu XJ, Zhang H. Strain-based design criteria of pipelines. Journal of Loss Prevention in the Process Industries. 2009;22(6):884-8.

[21] Dinovitzer AS, Smith RJ. Strain-based pipeline design criteria review. In: International Pipeline Conference — Volume II ASME 1998 IPC1998-2089 STRAIN-BASED. 1998. p. 763-70.

[22] Esford F, Porter M, Savigny KW, Muhlbauer WK, Dunlop C. A risk assessment model for pipelines exposed to geohazards. Proceedings of the Biennial International Pipeline Conference, IPC. 2004;3(April):2557-65.

[23] Gao H, Yu Z, Zhenyong Z, Shi H. The concepts for pipeline strain-based design. Proceedings of the International Offshore and Polar Engineering Conference. 2010;4:476-82.

[24] Zhang J, Liang Z, Han CJ. Failure analysis and finite element simulation of above ground oil-gas pipeline impacted by rockfall. Journal of Failure Analysis and Prevention. 2014;14(4):530-6.

[25] Trust PS. Pipeline Basics & Specifics About Natural Gas Pipelines. In: Pipeline Briefing Paper #2 [Internet]. 2015. p. 1-9. Available from: http://pstrust.org/wp-content/uploads/2015/09/2015-PST-Briefing-Paper-02-NatGasBasics.pdf

[26] Khan MA, Mustaffa Z, Balogun ALB, Al-Bared MAM, Ahmad A. Role of the Rheological Parameters in Debris Flow Modelling. IOP Conference Series: Materials Science and Engineering. 2021;1092(1):012041.

[27] Stead D. The Zymoetz River rock avalanche , June 2002 , British Columbia , The Zymoetz River rock avalanche , June 2002 , British Columbia , Canada. 2006;(December 2017).

[28] Lee EM, Fookes PG, Hart AB. Landslide issues associated with oil and gas pipelines in mountainous terrain. Quarterly Journal of Engineering Geology and Hydrogeology. 2016;49(2):125-31.

[29] Ismail WMMW, Napiah MNMA, Zabidi MZM, Tuselim ASM. Managing Risk: Effective Use of Structural Reliability Assessment (SRA) and Quantitative Risk Assessment (QRA) for Sabah-Sarawak Gas Pipeline (SSGP). In: Salama MM, Wang YY, West D, McKenzie-Johnson A, B A-Rahman A, Wu G, et al., editors. Pipeline Integrity Management Under Geohazard Conditions (PIMG) [Internet]. ASME Press; 2020. p. 0. Available from: https://doi.org/10.1115/1.861998_ch41

[30] Kim BT, Kim YS. Back analysis for prediction and behavior of laterally loaded single piles in sand KSCE. J Civ Eng. 1999 Sep 1;3:273-88.

[31] Khan MA, Sadique MR, Zaid M. Effect of Stratification on Underground Opening: A Numerical Approach. In: Advances in Transportation Engineering. Springer; 2019. p. 133-42.

[32] Ahmed J, Taha MR, Ghazali MA, Abdullah CH, Kuraoka S. Debris-flows in Peninsular Malaysia: Topography, geology, mechanism and sediment discharge. ARPN Journal of Engineering and Applied Sciences. 2020;15(2):270-83.

[33] Zhang W, Askarinejad A. Ultimate lateral pressures exerted on buried pipelines by the initiation of submarine landslides. Landslides. 2021;18(10):3337-51.

[34] Li RY, Chen JJ, Liao CC. Numerical study on interaction between submarine landslides and a monopile using cfd techniques. Journal of Marine Science and Engineering. 2021;9(7).

[35] Liu J, Tian J, Yi P. Impact forces of submarine landslides on offshore pipelines. Ocean Engineering. 2015;95:116-27.

[36] Randolph MF, Seo D, White DJ. Parametric Solutions for Slide Impact on Pipelines. Journal of Geotechnical and Geoenvironmental Engineering. 2010;136(7):940-9.

[37] Zhang J, Liang Z, Han CJ. Failure Analysis and Finite Element Simulation of Above Ground Oil-Gas Pipeline Impacted by Rockfall. Journal of Failure Analysis and Prevention [Internet]. 2014;14(4):530-6. Available from: https://doi.org/10.1007/s11668-014-9847-x

[38] Wu Y, Li J. Finite element analysis on mechanical behavior of semi-exposed pipeline subjected to debris flows. Engineering Failure Analysis [Internet]. 2019;105(June):781-97. Available from: https://doi.org/10.1016/j.engfailanal.2019.06.055