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A Study of Blast-induced Vibration on Oil Pipelines based on Numerical and Field Analysis

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ABSTRACT

Blasting is the initial stage of development in mining operations. Therefore, the use of explosives requires a technical design to control its adverse effects on nearby structures. In that regard, the blast vibrations in Izeh-Karun 3 main road project were recorded using four 3-component Blast Recorder seismographs. The seismographs recorded a peak particle velocity of 8.8 mm.s^{-1} in the nearby oil pipe. The blast pattern and the resulting ground vibration are simulated. The numerical model is verified using the recorded seismic data and the empirical model. The stresses applied on the oil pipeline were measured by the static analysis of the stress induced by the oil pipeline's internal pressure and the dynamic analysis of ground vibration. The pipeline stress was equal to 271 MPa, lower than the pipeline yield stress (414 MPa). Therefore, the vibrations induced by the blasting operation did not damage the oil pipeline. Comparing the vibration induced in the oil pipeline (8.8 mm.s^{-1}) with the critical vibration level (50 mm.s^{-1}) showed that the pipelines near the blast operation were at a safe distance.

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NOMENCLATURE

PPV	Peak Particle Velocity (mm/s)	**Subscripts**	
Q_{max}	Maximum charge per delay (kg)	*Ver*	Vertical component of PPV (mm.s^{-1})
R	Distance from the blast center (m)	*Rad*	Radial component of PPV (mm.s^{-1})
$SD = \frac{R}{\sqrt{Q_{max}}}$	Scaled distance (m.kg$^{-0.5}$)	*Tan*	Tangential component of PPV (mm.s^{-1})

1. INTRODUCTION

Due to the expansion of civil and mining activities, explosive use for rock crushing has increased. The adverse effects of blasting operations include ground vibration, air blast, and fly rock. Ground vibration can cause serious and irreparable damages. In the areas near the blast site, these effects are considered a severe threat to the surface and subsurface structures such as residential and office buildings, bridges, dams, roads, energy carrier, and supply facilities, road tunnels and servicing, underground caves, oil, gas, and water transmission pipelines and walls of mines. Hence, ground vibration as an environmental concern may invoke locals to stand against mining operations. Therefore, it is necessary to measure, predict and control the intensity of ground vibration. Since the beginning of ground vibration studies, different approaches and methods have been applied to evaluate the ground vibration range. The United States Bureau of Mines followed up ground vibration surveys and reviews from 1935 to 1942. As a result of these studies, particle acceleration became a basis for measuring and predicting damage to surface structures. Generally, blast-induced vibrations is expressed based on Peak Particle Velocity (PPV).

Researchers have presented different relations based on seismic data, each of which takes into consideration different parameters. Most of those relations express PPV as a function of the distance from the explosion center and the maximum charge per delay. Relation 1 shows the

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general form of empirical relationships in predicting blast-induced ground vibration [1].

$$PPV = K.R^{-B}.Q_{\max}^{A} \tag{1}$$

where K is the empirical constant affected by geological parameters, B and A are the empirical constants affected by the blast design parameters. Q_{max} is the maximum charge per delay (kg), and R is the distance from the blast center (m).

Despite the development of oil, gas, and water transmission pipelines in recent years, very few studies have analyzed pipeline design against blast-induced ground shock wave propagation [2]. Most of the analytical studies performed so far have applied seed waveform overlapping techniques to estimate the blast-induced ground vibration [3]. Kouretzis et al. [2] presented an analytical calculation of surface blast-induced strains to buried pipelines with Three Basic Assumptions of blast-induced vibration on pipelines, Thin-walled, Elastic, and 3D Pipeline Modeling regardless of the slip between soil and pipe. Dagasan et al. [4] conducted tests near the high-pressure gas pipelines to measure the amount of vibration on the pipe and compared them with different criteria and standards.

The ability to do computer calculations has rapidly increased and since the mid-19th century, and the use of these computations has facilitated numerical simulation in many complex processes like blasting [5]. Ma et al. [6] simulated blast waves' propagation in the rock mass with Autodyn and analyzed the explosive, air, and rock interactions. Using ANSYS Autodyn, Park et al. [7] modeled the explosion process in a blast hole through a nonlinear hydrocode. Olarewaju et al. [8] investigated the response of buried pipelines to earthquake-induced vibrations using the FEM numerical method. Xu et al. [9] studied the dynamic response of buried pipelines to the dynamic blast loading through numerical analysis. Jones-Wilkins-Lee equation has been used for explosive behavior modeling. Mitelman and Elmo [10] predicted blast-induced damages to an underground tunnel utilizing a combination of ANSYS Autodyn and ELFEN. Fakhimi and Lanari [11] developed a hybrid of the DEM-SPH numerical model for modeling rock blasting. Applying the FEM numerical model, Yu et al. [12] investigated the impact of blast-induced vibrations on tunnels in soft grounds. Song et al. [13] examined X70 pipeline response under blast loading by a field study and numerical modelling. Jayasinghe et al. [14] studied the blasting effect on the adjacent piles by numerical methods. Abedi et al. [15] developed a mathematical model based on the theory of beam on the elastic foundation to study the behavior of buried pipelines exposed to surface blasting. In addition, they constructed a three-dimensional finite element model, compared the analytical and numerical results, and concluded that the analytically calculated PPVs were higher than the numerical ones. Yung et al. [16] used a three-dimensional numerical model to assess the safety of the DN 1200 buried water pipeline concerning the vibration loads from a tunnel blasting operation. They also evaluated the safety of empty and full pipelines.

To investigate the effects of surface blasting on Monon pipelines and the dynamic response of the buried pipelines to it; Tang et al. [17] conducted dynamic vibration studies and dynamic strain monitoring in Zhushan with an area of around 100×600 sqm. They studied the peak particle velocity of pipelines under different blast charges at different distances. Finally, they presented a relationship between the PPV of the ground and the pipeline. Wang et al. [18] experimentally and numerically investigated the effect of blasting-induced vibrations on gas pipelines. They analyzed dynamic parameters such as PPV and PPA and proposed equations to predict blast vibration parameters based on the distance. Numerical modeling and seismic analysis are also applicable in the design of oil storage facilities [19]. Hassani and Basirat [19] investigate the subsidence effect on buried pipelines through numerical modeling. Apart from numerical studies, some researchers used statistical and soft computing techniques to predict PPV [20-26]. The main drawback of these models is that they need excessive data and new studies in this field requires a collection of expanded database and test of new models. Moreover, in engineering project where the safety of infrastructures (such as buried pipelines) is of more interests, application of prediction models should be chosen carefully. While, numerical models enforced by field measurements will provide consistent result which is the motivation of current paper. In that regard, a road construction project near the vicinity to some oil and gas pipelines is considered for evaluation.

Karun 3 main road to Izeh has a length of 21 km. Due to its vicinity to the oil and gas pipelines and the possibility of damage imposed to the pipelines by the nearby blasting operation and the resulted blast-induced ground vibration, a careful controlled blasting operation is necessary. Hence a detailed seismic study is carried out to confirm the blasting parameters. In that regard, numerical modelling is used to model the blast-induced ground vibration and study its damages to the nearby oil and gas pipelines. Numerical analysis of blast-induced ground vibration is consist of two parts, (1) modeling the blast process and (2) simulating vibration wave propagation near the oil pipelines. Therefore, this paper adopts a blasting experiment near an on-site buried pipeline, while ground vibrations are monitored. These measurements will verify the numerical model. Field measurements reflect the actual behavior of the ground and the pipelines. Finally, the model is used to study the pipeline response to the nearby surface blast load.

2. MATERIAL AND METHODS

2. 1. Field Measurements Izeh-Karun's main road project is crossing the Sarvak-Ilam formations. These formations are almost limestone. The road project is close to existing oil and gas pipelines. Due to its vicinity to the pipelines there is a possibility of any damage to those pipelines. These damages may be a result of blast-induced ground vibration. Hence, controlled blasting and detailed seismic studies should be carried out. In that regard, a blasting experiment near an on-site buried pipeline is conducted and ground vibrations are recorded. For this purpose, four 3-component Blast Recorder Seismographs (BRS) were used to record blast-induced ground vibration. These BRSs are installed along the blasting block and the pipelines. The relative position of the oil and gas pipelines and the blasting block are shown in Fig. 1. This figure shows the location of seismic record stations where a BRS is installed. According to this figure, St2, St3, and St4 are located in a particular direction between the blasting block and the pipelines. St2 is 46.6 meters, and St4 is 87.5 meters away from the blasting block.

As stated, a blasting experiment near an on-site buried pipeline is conducted. The blasting block contains 12 blastholes with a depth of 3 meters. The blastholes diameter is 3 inches, and they are drilled in 2 rows. Burden and spacing are 2 and 2.5 meters, respectively. 38% of the blasthole (i.e., 1.15 meters) is charged with ANFO, while the rest of the blastholes (i.e., 1.85 meters) are used for stemming. In this operation, the NONEL system with 42-millisecond connectors is used. The initiating pattern of blastholes is given in Figure 2a.

2. 2. Numerical Simulation of Blasting Wave Propagation Autodesk inventor software package has been used to create the model geometry. Figure 2b shows the geometry of the model and the blasting block location. The model dimensions are 120, 20, and 32 meters in length, width, and height. The mesh elements must be within the range of 0.1 to 0.125 of the propagated wavelengths to capture wave propagation accurately. Large mesh dimensions for long wavelengths can result in reasonable accuracy, but it doesn't have good accuracy for shorter wavelengths [27, 28].

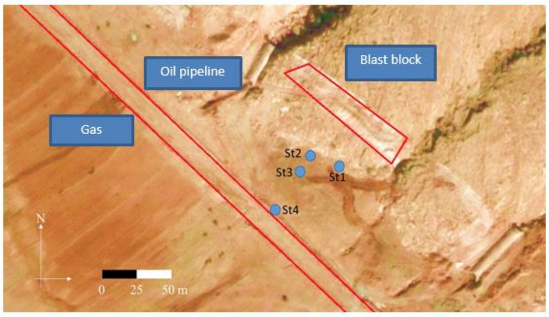


Figure 1. Location of oil and gas pipelines, seismic stations and the blasting block

For this reason, mesh generation follows a dimension of 30 cm. In dynamic numerical modeling of waves propagating, the model boundaries must be determined so that the elastic waves are allowed to exit the model. This strategy will eliminate the reflection errors within the model [29]. The impedance of model boundaries are assumed as transmitting boundary that provides a condition which prevent wave reflections inside the model.

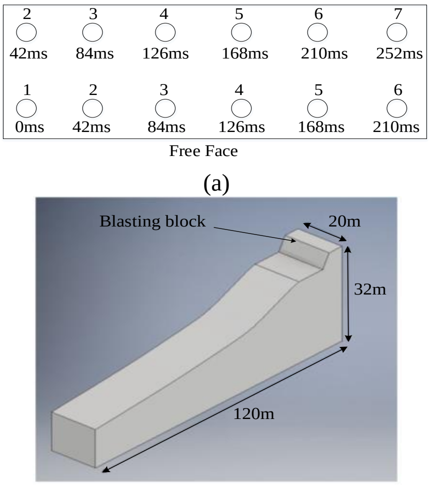
2. 2. 1. Rock Mass Characteristics The project is located on Sarvak-Ilam formation, and the dominant rock type in the area is limestone. Since the pipeline is far enough from the blasting block then it is located in the elastic zone. The model environment is assumed as continuous media. The Drucker-Prager model was considered as the constitutive model of limestone. The behavioral parameters of the limestone are shown in Table 1.

2. 2. 2. Explosive Characteristics The main explosive used in the project was ANFO. The Jones-Wilkins-Lee (JWL) model describes the ANFO behavioral equation (Equation (2)) [30].

$$P = A\left(1-\frac{\omega}{R_1 V}\right)e^{-R_1 V} + B\left(1-\frac{\omega}{R_2 V}\right)e^{-R_2 V} + \frac{\omega E}{V} \tag{2}$$

where, A, B, C, R1, R2 and ω are, constants. Table 2 summarizes the parameters and their values for ANFO.

2. 2. 3. Characteristics of the Pipeline and the Surrounding Soil In the execution of oil pipelines, soft soil cushions with 5 meters distance from each other



(a)

(b)

Figure 1. a) Blasting pattern and their timing, b) 3D geometric modeling

are usually placed at the channel bottom before laying the pipelines. Then the pipelines are covered with soft sandy soil. The constitutive models considered for the oil pipeline and its surrounding soil are linear Drucker-Prager and linear elastic. The resistance parameters and specifications of the pipeline are stated in Table 3. Moreover, the filling soil specifications around the pipeline are given in Table 4.

The 3D model of the pipeline is shown in Figure 3. It should be said that the shell element is used to discretize the pipeline. And the solid element is used to discretize the surrounding material. The pipeline's static analysis showed that the appropriate dimension of the pipeline's mesh was 6 cm. Concerning the resolution of dynamic conditions, a mesh dimension of 30 cm is selected for the pipeline's surrounding environment.

TABLE 1. Dynamic parameters of limestone

Dynamic features of rock mass	Unit	Quantity
Density	$kg.m^{-3}$	2640
Modulus of elasticity	GPa	14.46
Poisson's ratio	-	0.44
Bulk module	GPa	40.17
Shear module	GPa	5.02
Uniaxial compressive strength	MPa	65
Uniaxial tensile strength	MPa	5.5

TABLE 2. JWL parameters and their values for ANFO

Parameter	Unit	Quantity
Density	$Kg.m^{-3}$	850
Velocity of Detonation	$m.s^{-1}$	4160
Weight Unit Energy	$MJ.kg^{-1}$	2.668
E	GPa	5.15
A	-	49.46
B	-	1.891
R1	-	3.907
R2	-	1.118
ω	-	0.333

TABLE 3. Pipeline Specifications

Parameter	Unit	Quantity
Material	-	API-5LX60
Operational pressure	MPa	5.2
Thickness	mm	7.14
Diameter	mm (in)	762 (30)
Stress yields	MPa (psi)	414 (60000)
Elastic module	GPa	207
Poisson's ratio	-	0.3
Density	$Kg.m^{-3}$	7850

TABLE 4. Pipeline surrounding Specifications [35]

Parameter	Unit	Quantity
Density	$Kg.m^{-3}$	1750
Elastic module	MPa	100
Poisson's ratio	-	0.35
Internal friction angle	degree	30

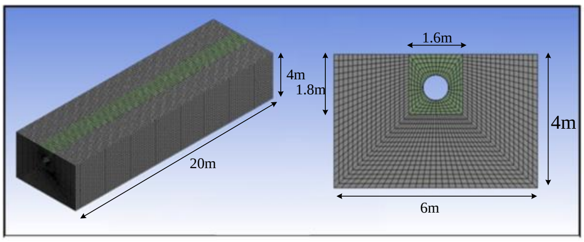


Figure 3. The pipeline and surrounding environment meshing

3. RESULTS AND DISCUSSION

The recorded seismic data was examined to determine PPV. The recorded data are processed in Origin software. In this process, instrument effect are removed and blasting block section was separated from the other parts by binary conversion. Finally, the PPV components are obtained in every station, and the results are given in Table 6. The PPV diagram is compared to the maximum charge per delay as shown in Figure 4. Checking the seismic data showed that the blast-induced ground vibration imposed to the oil pipeline was equal to 8.8 mm/s. According to Figure 1, the seismograph stations St2, St3, and St4 are located between the blasting block and the pipeline. Therefore, these three stations are considered for comparison in the rest of the paper.

After analyzing particle displacement velocity diagrams, PPV was determined separately at the stations. The numerical model is solved, and the resulting PPV was compared with field measurements. The comparison is made in each measurement station for the three tangential, vertical, and radial components of PPV. Since PPV decreases over time, and in order to reduce the computational time, problem-solving time is considered 1000 ms. Figure 5 shows the particle velocity chart for the station St4. In table 7, the predicted PPV is stated for all the radial, vertical and tangential components.

TABLE 6. The seismic data related to the blast operation

Seismograph station	St1	St2	St3	St4
R (m)	48.1	46.6	58.5	87.5
SD (m.kg-0.5)	16.6	16.1	20.2	30.2
PPV_{Ver} (mm.s^{-1})	6.9	12	7.8	4.9
PPV_{Ver} (mm.s^{-1})	10.6	16.3	15.7	6.5
PPV_{Ver} (mm.s^{-1})	10.6	11.7	6.3	3.3
Resulting PPV (mm.s^{-1})	16.5	23.4	18.6	8.8

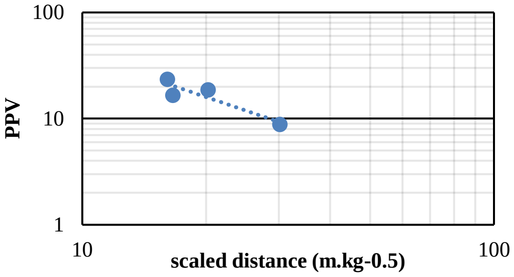


Figure 4. The PPV compared to the scaled distance

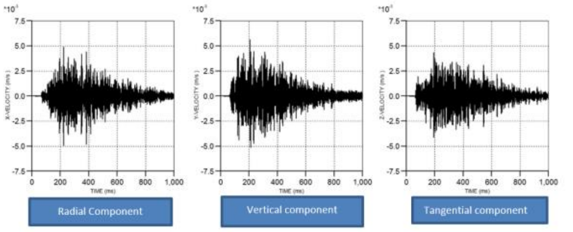


Figure 5. Particle velocity with time for radial, vertical and tangential components of St4 (R=87.5 m)

3. 1. Validation of Numerical Modeling with Seismic Data

Figure 6 shows the PPV graph concerning the scaled distance (SD) for the three radial, vertical, and tangential components. The average error of 10.4% between numerical analysis and field measurement shows a good match between numerical simulation and recorded field data.

3. 2. Validation of Numerical Modeling with Empirical Models

Many researchers have discussed empirical relations for predicting ground vibration. Most of these models express PPV based on the scaled distance. By studying the data from 659 seismographs in limestone, Ozer [31] presented the empirical model in Equation 3. Considering the similarity of the conditions with Ozer's data, this model was used to recheck the numerical modeling.

$$PPV = 3019.95\ SD^{-1.69} \tag{3}$$

In order to compare the numerical results and the empirical values calculated by Equation (3), the PPV vs. scaled distance was drawn (Figure 7). Moreover, in Table 8, the model error was calculated by comparing the results. According to Table 9, the average error of the numerical modeling results and Ozer's empirical model is 9.1%, indicating reasonable numerical modeling accuracy.

TABLE 7. Predicted PPV at different stations by the model

Station	R (m)	SD (m.kg-0.5)	PPV_{Ver}	PPV_{Ver}	PPV_{Ver}
St2	46.6	16.1	13.2	13	11.6
St3	58.5	20.2	7.1	14.3	7.5
St4	87.5	30.2	4.92	6.9	4.3

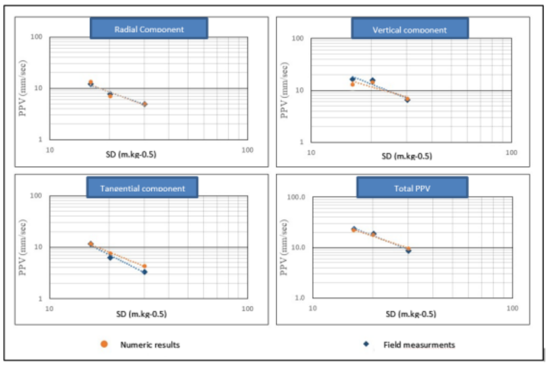


Figure 6. PPV diagram recorded by seismographs and numerical modeling with scaled distance for PPV components

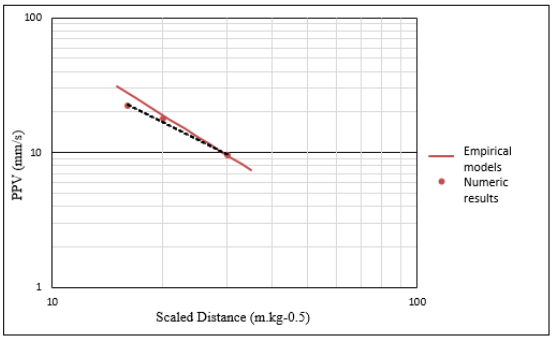


Figure 7. Comparing the numerical results and Ozer's model

TABLE 8. Comparison of the numerical and empirical results

Measurement point	PPV (mm/s)		error (٪)
	Numerical model	Empirical model	
St2	21.9	27.6	20.7
St3	17.6	18.8	6.3
St4	9.5	9.52	0.2

3. 3. Blast Induced Ground Vibration Effects on Pipelines

First, a separate static analysis is conducted. In static analysis, oil pressure inside the pipeline, displacements, and the induced stresses was measured. Then, ground vibration near the oil pipeline was investigated by dynamic analysis. In this study, the fluid weight inside the pipeline was neglected. Finally, the blast-induced ground vibration in the pipelines' vicinity was compared with different standards.

After the model's equilibrium, the liquid's operational pressure inside the pipe and the initial condition of dynamic analysis are determined. The results showed that the fluid's maximum stress was equivalent to 255 MPa and the maximum displacement in the upper part of the pipe was 821 µm. The ground vibration was simulated as a dynamic load applied to the model in 1100 ms. Figure 8 shows the vibration diagram applied to the pipeline. Considering pipeline specifications, the Von-Mises equivalent stress is 274.9 MPa. It indicates the accuracy of the static analysis compared to the equivalent stress obtained by numerical modeling (i.e., 255 MPa). Then the vibration velocity and Von-Mises equivalent stress for the pipeline were obtained. The maximum equivalent stress on the pipeline was 271 MPa. Figure 9 shows the stress diagram of the Von-Mises equivalent stress at the most critical point of the pipeline. Considering the yield stress of the oil pipeline (i.e., 414 MPa), the equivalent stress caused by the internal pressure of the pipe and the blast-induced vibration is less than the yield stress. It means that the blasting operation may not damage the oil pipeline. Moreover, the vulnerability of the pipelines near the blast operation was measured by comparing the effect of the blast-induced ground vibration on the oil and gas pipelines with several standards (Table 9). Considering that the most critical PPV is for Canadian Standard, which is equal to 50 mm/s, and the PPV applied to the oil pipeline is 8.8 mm/s, one could conclude that the vibration in the oil pipeline is lower than all permissible limits. Thus the blasting operation does not damage the pipelines.

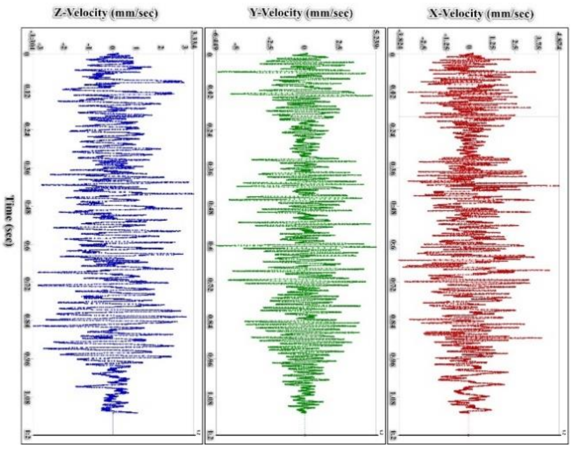


Figure 8. The pipeline vibration in radial, vertical and tangential components

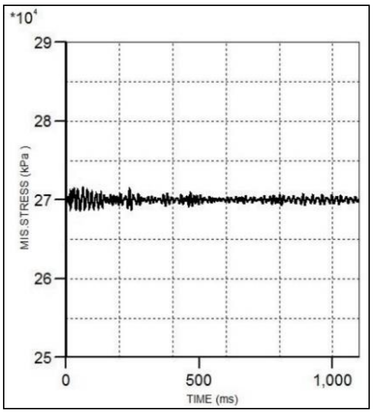


Figure 9. Equivalent stress applied to the pipeline

TABLE 9. Allowable PPV for gas and pipelines in different standards

Standards	PPV (mm.s^{-1})
United State Bureau of Mines	**127**
DIN_4150-3	**100**
Northern Gas Network	**75**
Canada	**50**
API	**50.8**
Austria Standard	**75**

4. CONCLUSION

The study of controlled blasting and detailed seismic analysis is necessary for safety analysis of infrastructure, which is the motivation of this paper. In this paper combining the field measurements, the safety evaluation of the buried pipeline under surface blast loads is studied. In the engineering project with similar conditions, the buried pipeline will operate normally. In that regard, numerical modeling is used to study the blast-induced ground vibration and evaluate its damages to the nearby oil and gas pipelines. Some field measurements verify the numerical model before any further applications. Through numerical modeling of a blast process, the propagation of elastic waves in the rock mass and the probability of any damage to the oil and gas pipelines were studied, and the following results were obtained.

After recording and analyzing seismograph data, a PPV of 8.8 mm.s^{-1} at the seismic station near the pipeline was recorded. Model verification results show a good relationship with the propagation of vibration waves based on the seismic data and the empirical relation. The results' average error compared with seismic data and the

Ozer empirical model is equal to 10.4% and 9.9%, respectively.

By dynamic analysis of the fluid pressure inside the pipeline and the ground vibration applied to the pipeline, the Von-Mises equivalent stress was measured to be 271 MPa, which is almost 35% less than the yield stress of the oil pipeline. As a result, the blast-induced vibrations do not damage the oil pipeline. According to the standards, the critical threshold for oil pipelines is 50 mm.s^{-1}. Analysis of the seismic data and its comparison to that standard indicated that the maximum vibration applied to the oil pipeline (8.8 mm.s^{-1}) is acceptable. Therefore, according to the main roads' vibration standards, the oil and gas pipelines near the Karun 3 road to Izeh are safe.

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Persian Abstract

چکیده

عملیات انفجار به‌عنوان یکی از مراحل اصلی چرخه عملیات معدنی است. در استفاده از مواد منفجره باید تاثیر منفی فرایند انفجار بر سازه های اطراف کنترل شوند و این امر نیازمند طراحی فنی است. برای بررسی تأثیر لرزش‌های ناشی از انفجار بر خط لوله نفت، لرزش‌های ایجادشده از عملیات انفجار پروژه راه اصلی ایذه-کارون۳ توسط ۴ لرزه‌نگار سه مؤلفه‌ای ثبت شد. بر اساس نتایج میدانی، حداکثر سرعت ذرات در مجاورت خط لوله نفت ۸/۸ میلیمتر بر ثانیه ثبت شد. پس از ثبت داده‌ها، الگوی انفجار و لرزش‌های ناشی از انفجار مدلسازی شدند و مدل بر اساس داده‌های ثبت شده و همچنین مدل‌های تجربی اعتبارسنجی شد. سپس تنش‌های وارد بر خط لوله محاسبه شدند. این تنش‌ها ناشی از سیال داخل لوله و لرزش زمین هستند. طبق نتایج مدل، مقدار تنش وارد بر خط لوله ۲۷۱ مگاپاسکال است که کمتر از مقاومت لوله (۴۱۴ مگاپاسکال) است. طبق نتایج مدلسازی، لرزش‌های ناشی از انفجار آسیبی به خط لوله نفت وارد نمی‌کندو این لرزش‌ها به طور قابل توجهی کمتر از حد مجاز (۵۰ میلیمتر بر ثانیه) است و در محدوده امن قرار دارند.