Blast-induced ground vibration impact assessment on the sensitive receptors

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Abstract. In recent years, there has been an increasing need to assess the impact of blasting on sensitive receptors such as cultural heritages and nearby communities. The Oyu Tolgoi open pit mine is one such area where blasting is a common practice. As such, it was essential to evaluate the vibrations generated by blasting and determine their potential impact on the surrounding areas and this is the first attempt. The study was conducted using seismometers to measure the far-field ground vibrations generated by blasting. These measurements were then compared to established criteria, such as the peak particle velocity limits set by regulatory agencies. Additionally, the sensitivity of the receptors was also taken into account, and the study found that the resulting tremors were assessed as low risk for all the sensitive receptors assessed, including, nearby herder families' homes, open springs, cultural heritages, and mine some facilities. The results of this study have significant implications for the Oyu Tolgoi open pit mine, as they can be used to inform decisions regarding blast design, timing, and the location of sensitive receptors relative to blast sites. This information can help to minimize the impact of blasting on the surrounding areas, ensuring the continued safety and well-being of the nearby communities and cultural heritages. Overall, this study provides valuable insights into the potential impact of blasting on sensitive receptors around Oyu Tolgoi mine and highlights the importance of conducting regular assessments to ensure the continued safety and sustainability of mining activities in the region.

Keywords: Peak particle velocity, Open pit, Sensitive receptor.

1 Introduction

A blasting is one of the most important parts of mining operations and it is very critical to make a blasting safely and efficiently. An air shock wave, a fly rock and a ground

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vibration are major effects of mining blast and blast-induced vibration propagates through the earth over long distance from the mining [1, 2, 3]. Blasting is frequently made at open pit of the Oyu Tolgoi (OT) company, and seismic waves emitted from the blasting propagate at distance of 400 kms, averagely, and mean magnitude of the blasting is around between Ml 1 - 2 [4].

The Oyu Tolgoi deposit is one of the world's largest copper and gold deposits, containing three separate deposits of copper and gold [5]. The Southern Oyu deposit has been mined since 2012 using an open pit mining methodology, with a production rate of 100,000 tonnes per day. Currently, underground mine development is underway to access the other deposits, and significant progress has been made on the major facilities [6].

This study aims to utilize existing measurements of Peak Particle Velocity (PPV) resulting from blasting activities to predict PPV levels at various points of interest. By employing statistical methods, we aim to estimate the potential PPV at sensitive receptor points, including mining facilities, local herdsmen families, springs, and cultural heritage sites near the Oyu Tolgoi open pit. The predictions of PPV will contribute valuable insights into the environmental impact of blasting and facilitate the implementation of appropriate mitigation measures to minimize its effects on the surrounding areas, if necessary.

Moreover, the study results have been compared them with a relevant standard limit. It is important to note that currently, there is no specific regulation or standard in Mongolia for measuring ground vibration induced by blasts and evaluating their effects on humans and structures. Therefore, the study results were compared with the "Technical Basis for Guidelines to Minimize Annoyance Due to Blast Overpressure and Ground Vibration" issued by the Australian and New Zealand Environment Council (ANZEC) in 1990 [7], which has been adopted by OT since 2013 [8].

According to the ANZEC guideline, the recommended maximum level for ground vibration, specifically the PPV, is set at 5 mm/s at any sensitive site.

2 Methods and Materials

2.1 Study area

The study area locates in the territory of Khanbogd soum (a soum is the second smallest administrative unit) Umnugobi province, Mongolia, between N 42.9-43.3, E 106.7-107.3, and it covers approximately 2,170km square area (Fig.1).

The area is located in semi-desert zone according to natural zone and belt classification, and in hilly steppe circle of the Southern Gobi of Eastern Gobi Region as per physical and geographical demarcation [9].

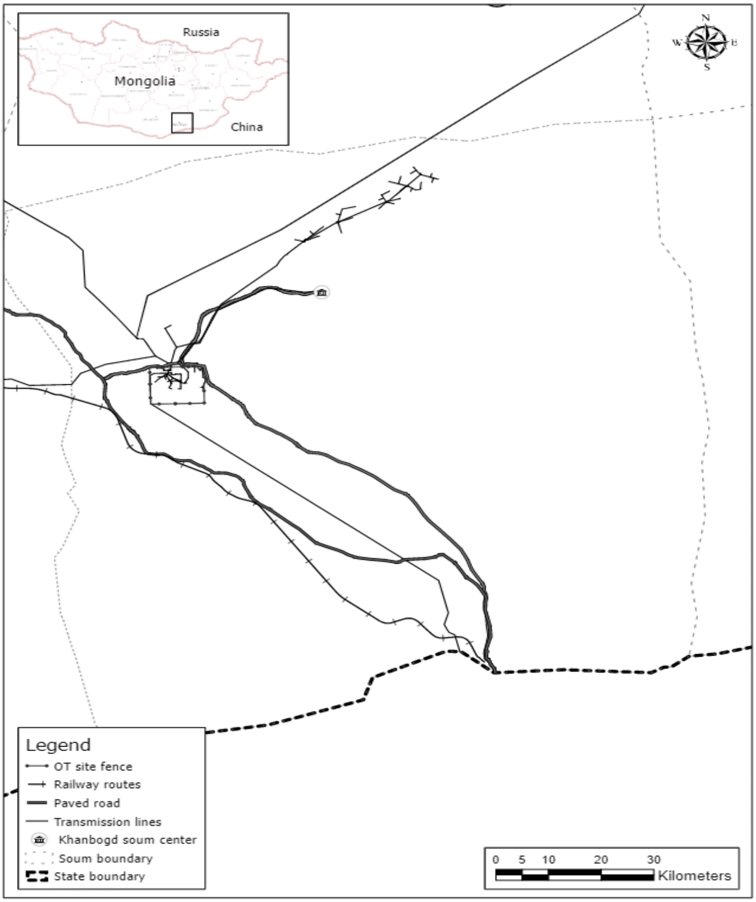

Fig. 1. The study area

2.2 Geological background

The geology of the Oyu Tolgoi deposit has been extensively studied and a detailed understanding of the deposit's structure and mineralization has been developed. This knowledge has been used to guide the development of the mine and to optimize the extraction of the mineral resources. The Oyu Tolgoi deposit is hosted in rocks of the South Gobi basin, which is a late Paleozoic to Mesozoic sedimentary basin that developed on the southern margin of the Siberian craton. The basin is bounded by the Altai Mountains to the north and the Gobi Altai Mountains to the west [10]. Narrowly, the deposit is hosted within Gurvansaikhan terrane. It is a porphyry copper-gold deposit that formed from hydrothermal fluids that were generated by the intrusion of magmatic rocks into the surrounding sedimentary rocks. The mineralization at Oyu Tolgoi is hosted in a sequence of volcanic and sedimentary rocks of Devonian to Carboniferous age, which have been intruded by a series of granitic to dioritic stocks and dykes. The mineralization is associated with the intrusion of the Oyu Tolgoi stock, which is a composite intrusion made up of a series of dioritic to granodioritic intrusions [5, 11].

Blasting regime at the Oyu Tolgoi Open pit mine

The open pit mine is projected to ultimately cover an area of 2.2 x 3.0 km and reach a depth of approximately 700 meters. The excavation process involves placing explosives in strategically drilled holes and safely detonating them to loosen the ground. Following the blast, excavators are used to scoop up the ore from the loosened ground and transport it out from the bottom of the open pit. The open pit blasting method involves loading up to 750kg of explosives into one drill hole and typical production blast consists of around 150 holes. This results in an average of 100,000-500,000 tons of rock being fragmented per blast. Blasting is carried out with a delay of at least 8 milliseconds between the holes, with the aim of minimizing the force of vibration from the explosion.

Sensitive receptors

The sensitive receptors for vibration caused by explosions have been identified as settlements, open water resources, cultural heritages, and key mine infrastructures. **Table 1** shows that the general information of each sensitive receptor.

Table 1. Sensitive receptors

Sensitive receptors type	Name of the areas	ID	Distance from the Open pit, (km)		N
			Nearest	Farthest	
Settlement	Herders' households	HC1	5.0	9.9	5
Settlement	Herders' households	HC2	10.0	19.9	65
Settlement	Herders' households	HC3	20.0	29.9	69
Settlement	Herders' households	HC4	30.0	39.9	68
Settlement	Herders' households	HC5	40.0	50.0	67
Settlement	OT camps (Manlai, Oyut1 & 2)	OTCa	3.0	6.3	3
Settlement	Javkhlant bag center	JBCe	25.6	27.6	1
Settlement	Khanbogd soum center	KBCe	34.1	36.5	1
Open water sources	New Bor-Ovoo	NBOv	2.5	4.8	1
Open water sources	Khar khad	KhaK	7.5	9.2	1

Open water sources	Khukh khadnii zadgai	KKZ	5.5	7.6	1
Open water sources	Dundangiin us	DuUs	9.3	11.0	1
Open water sources	Maanitiin bulag	MaBu	14.9	16.8	1
Open water sources	Baga bulag	BaBu	29.4	31.3	1
Cultural heritage	Shiir uul	ShMo	23.7	25.3	1
Cultural heritage	Javkhlant khairkhan uul	JKhM	16.3	18.8	1
Cultural heritage	Khurdet cave	KhCa	33.8	36.1	1
Cultural heritage	Chavga cave	ChCa	14.8	16.7	1
Cultural heritage	Demchog monastery	DeMo	25.2	27.4	1
Cultural heritage	Ereet monastery	ErMo	25.9	28.3	1
Key infrastructures	Primary crusher	PrCr	0.7	2.3	1
Key infrastructures	Conveyer	Conv	0.8	5.5	1
Key infrastructures	Concentrator	Conc	3.6	5.8	1
Key infrastructures	Tailing storage facility Cell 1	TSF1	1.5	5.9	1
Key infrastructures	Tailing storage facility Cell 2	TSF2	2.4	7.1	1
Key infrastructures	Undai riverbed diversion pipelines	UDPi	1.6	4.5	1

Settlement.

This category includes the centers of soum and bag (a bag is the third smallest administrative unit), as well as households of residents within a 50 km radius grouped by every 10 km distance, and OT workers' camps. As of the end of 2022, there were 2,145 households in Khanbogd soum, with the majority located in the soum center. Of these households, 429 are herder households [12], and their location is relatively uneven, depending on the availability of water and pastures in the area. A typical herder household consists of a ger (a Mongolian dwelling), a wooden or brick house, and different types of fences made from dried and compressed dung, rock, wood, waste iron, or light vehicle tires, for livestock. Within a 50 km radius of the open pit mine, there are a total of 274 households, with only five households located within 10 km of the open pit mine. There are three workers' camps at the Oyu Tolgoi mine site, but they are located close to each other and are therefore analyzed as one location.

Open water sources.

Within a 50 km radius of the Open pit, there are approximately 40 springs, all located along major dry riverbed basins such as Undai, Budaa, Dugat, and Ulaan-Ereg, and others that emerged from faults of granite massifs. In our study, we specifically selected six springs and evaluated the impact of blast-induced ground vibrations on them. One of the most noteworthy springs is New Bor-Ovoo, as well as the closest one, which was artificially created to prevent the natural spring from being affected by the open-pit mining [13]. The other five springs were selected based on their distance from the open pit and popularity.

Cultural heritages.

In the Khanbogd soum area, 24 licensed areas belonging to 12 companies, with a mining and exploration special license for use have conducted archeological studies. These studies have resulted in the registration and documentation of 1,158 new cultural heritages ranging from the Stone Age to the 19th century. So far, 249 monuments have been excavated [14]. Within a 50 km radius of the Oyu Tolgoi Open pit mine, there are 1,078 cultural heritages located. Among the cultural heritages within 50 radius, following six heritages were selected. The Demchog monastery, Ereet monastery, Javkhlant mountain's and Shiir mountain's petroglyphs are protected by the state and Khurdet Cave protected by the Umnugobi province. The Chavga cave is the closest to OT mine site, east 15km. The Javkhlant and Shiir mountains are home to numerous rock painting monuments that depict images of ibex, horses, seals, the sun, human figures, and human face masks. These images provide insight into the occupation, worldview, religion, and customs of the inhabitants of that time, and offer a glimpse into their daily lives [15]. In the area of Khanbogd soum, there are three monasteries of Galba: Demchog, Ereet, and another founded in 1828-1830 by nobleman Danzanravjaa. In the 1930s, the monasteries were closed and demolished, but in 2005, the temple and the sutra were restored and rebuilt [16]. Khurdet Cave is home to more than 60 Tibetan, Mongolian, and Chinese inscriptions on its walls. These inscriptions contain records of trade and journeys undertaken by voyagers and salespeople in the 18th century [17].

Key infrastructures.

OT has a wide range of infrastructures and facilities, including power lines, a heating plant, roads, warehouses, offices, and accommodation buildings, as well as various mine operational facilities [6]. Furthermore, underground facilities exist and are currently under construction. In terms of research on surface vibration related to open pit blasting, key operational facilities from the open pit to the TSF are identified, including the primary crusher, conveyor, concentrator, and tailing storage facility cells 1 and 2. These facilities are crucial to the mine's operations and are therefore considered key infrastructures for the purposes of this study. Addition to that the Undai riverbed diversion pipeline is selected since it the closest infrastructure to the open pit and to feed the New Bor-Ovoo spring and downstream of the Undai riverbed [13].

2.3 Field measurement

Since 2010, the Institute of Astronomy and Geophysics (IAG) within the Mongolian Academy of Sciences (MAS), in accordance with OT's Detailed Environmental Impact

Assessments [18, 19, 20], has conducted a total of eight ground vibration studies around the OT mining site. However, measurements of the Peak Particle Velocity (PPV) were only taken in five out of the eight years, specifically in 2014, 2015, 2016, 2019, and 2022, covering a total of 16 blasts (**Table 2**). A total of 128 events from these 16 blasts were recorded, by using a seismic station. Every complete set of the seismic station consists of a Guralp CMG-3ESPC broadband seismometer with three component, and 60 sec – 100Hz frequency band, Reftek RT130B digitizer, Trimble GPS, and other electronic components.

Table 2. PPV measured blast information

Year	Dates	Blasts	Total explosives used, kg	Average explosives size per hole, kg
	02 Dec		78,900	663
2014	05 Dec	2	147,700	713
	05 May		197,742	744
	08 May		72,985	592
2015	08 May	3	27,233	601
	15 Apr		32,000	703
	16 Apr		137,000	703
2016	18 Apr	3	36,000	703
	19 Nov		158,098	651
	19 Nov		158,098	596
2019	22 Nov	3	124,984	629
	28 Apr		238,876	631
	01 May		48,779	536
	01 May		93,093	378
	01 May		16,604	417
2022	04 May	5	138,464	656

Monitoring points.

Ground vibration monitoring was carried out at eight selected points to measure vibrations near settlements. The monitoring points were named OT01, OT02, OT03, OT04, OT05, OT06, OT07, and OT08, with an average elevation of 1159m above sea level (ASL). The lowest point recorded was at 1058m ASL, while the highest point measured was at 1208m ASL. OT02 is located within the mine lease area near to the workers camps, while OT06 is situated close to the center of Khanbogd soum. The remaining monitoring points are situated near herders' households. The distance of the monitoring points to the blasted area varied from the nearest point, which was 4.7 km away, to the farthest point, which was 37.5 km away. (**Fig. 2**).

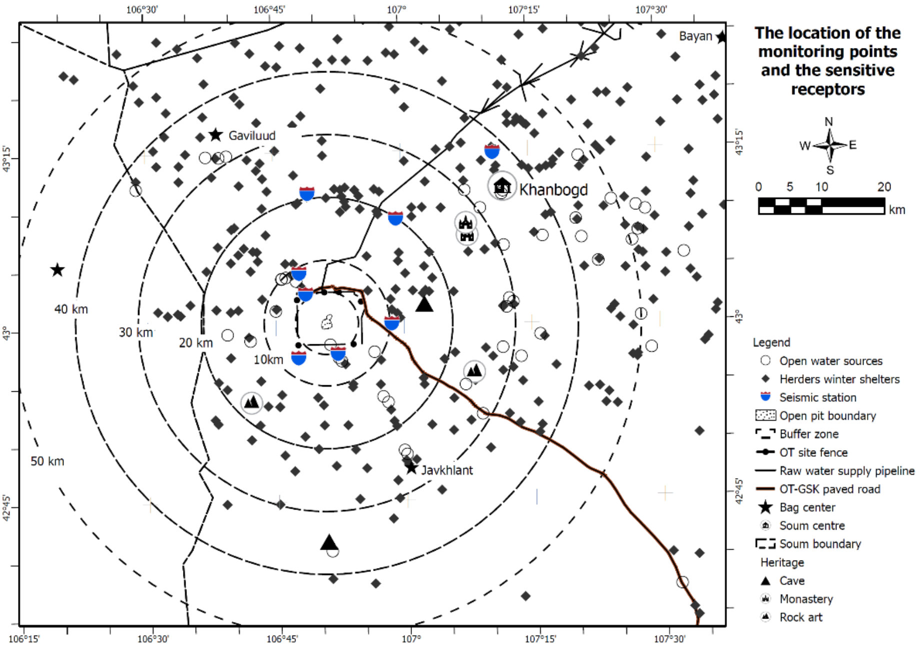

Fig. 2. The location of the monitoring points and the sensitive receptors

2.4 Data and data analysis

In order to estimate a maximum amplitude of ground vibration induced by blasts, conducted in the Oyu Tolgoi open pit, observed raw recordings were corrected by removing instrument response from the signal and converted to seismograms with a unit of nm/sec. In addition, observed seismograms were filtered by a 0.5Hz high pass filter to reduce a long period noise. The maximum amplitudes of peak particle velocity (PPV) were calculated by the square root of the maximum amplitude of every single component.

The Two-way Analysis of Variance [21] is a statistical method used to determine whether there are significant differences in the level of vibration generated by blasts of varying both total explosive sizes.

In order to develop the empirical model, we employed the power law model, which describes the relationship between vibration and distance. The equation for this model is given as:

$$PPV = a * distance ^\wedge b$$

$$a = 0.6836$$

$$b = -1.2833 \tag{1}$$

where "a" and "b" are site-specific constants that represent the intercept and slope of the relationship, respectively. The decision to adopt the power model is explained in the Results section, outlining the rationale for choosing this model for analyzing the data. In general, regression equations are commonly employed in studies to estimate Peak Particle Velocity (PPV) from Scaled Distance, as there exist various methods for predicting PPV [22, 23].

The power law model provides a useful tool for predicting PPV levels based on distance between blasted area and sensitive receptor. Additionally, the model can be used to optimize the design of blasting or drilling operations by selecting appropriate distances to minimize the PPV generated.

Software.

Raw data of seismic stations were converted into SAC format [24], and CPS 3.30 seismological software [25] was used to estimate the level of ambient seismic noise at the measurement points. The map drawing and calculation of distances from Open pit to the sensitive receptors are done using ArcGIS Pro 10 version [26]. All the analyses and graphical visualization were done using R 4.0.3 version [27].

3 Results

The results of the ANOVA analysis indicate that there is no statistically significant impact of the total explosives size and explosive per hole on the Peak Particle Velocity (PPV) measurements ($F = 0.23$, $p = 1$). It indicates that the sizes of total explosives and the distribution of explosives per hole do not have a statistically significant impact on the Peak Particle Velocity (PPV) measurements. This finding suggests that variations in these parameters do not significantly influence the resulting PPV values. Consequently, these parameters were excluded from the equation, simplifying the regression analysis.

The power law model, derived from the measured PPV values as a function of distance, is depicted in the **Fig. 3**. The regression analysis revealed a robust and statistically significant relationship between the two parameters, indicating a strong correlation between PPV and distance ($R^2=0.82$, $p=0.00047$), indicating that 82% of the variance in PPV can be explained by distance.

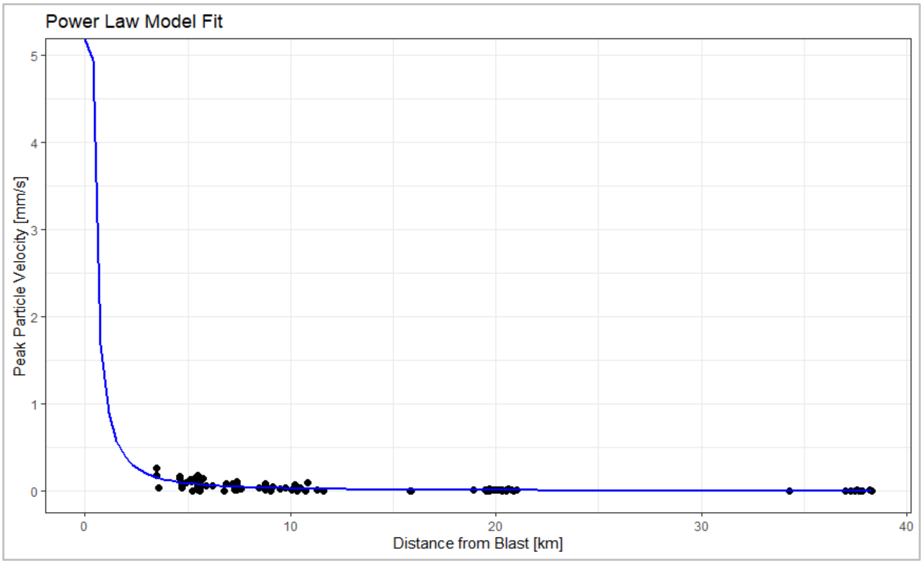

Fig. 3. The Power law model on between PPV and distance relationship, R^2=0.82

The relationship established through the power law model was found to be sufficiently robust, enabling the calculation of PPV at any distance from the blast. As a result, the equation derived from this model, as depicted in equation (1), was utilized to calculate the estimated PPV generated at the selected sensitive receptor. This approach allows for predicting the potential PPV levels at various distances from the blast site, providing valuable information for assessing the impact on sensitive receptors (**Fig. 4**).

The results of the analysis reveal the estimated Peak Particle Velocity (PPV) levels experienced by different locations and infrastructure near the Open pit mine. The herders' households located within the distances of 5-9.9km, 10-19.9km, 20-29.9km, 30-39.9km, and 40-50km from the center of the Open pit mine experience PPV levels ranging from 0.0361-0.0867 mm/s, 0.0147-0.0356 mm/s, 0.0087-0.0146 mm/s, 0.0060-0.0087 mm/s, and 0.0045-0.0060 mm/s, respectively. In the largest town, Khanbogd soum center, located within 50 km away from the open pit mine, blast-induced tremors were estimated to range between 0.0068-0.0074 mm/s. However, in the OT mine camps, the PPV levels were relatively higher, ranging from 0.0644-0.1669 mm/s, since they are located more closer than other settlements.

The selected open water sources in the study showed varying PPV levels. The nearest water point, New Bor-Ovoo, has PPV levels ranging from 0.0913-0.2109 mm/s, while the farthest water point, Baga Bulag spring, has PPV levels in the range of 0.0082-0.0089 mm/s.

Cultural heritage sites such as Javkhlant Khairkhan and Shiir Uul mountains with preserved petroglyphs experience relatively low vibration levels, ranging from 0.0158-0.0190 mm/s and 0.0108-0.0118 mm/s, respectively. Khurdet and Chavga caves have PPV values of 0.0069 mm/s and 0.0215 mm/s, respectively. Monasteries located in close proximity to each other have similar PPV levels and ranging from 0.0094-0.0105 mm/s.

In terms of key infrastructures, the Primary Crusher, located closest to the open pit, experiences a minimum PPV of at least 0.2347 mm/s and a maximum of 1.0804 mm/s if the blasting occurs at the most north-west edge of the mine. The Conveyer, Concentrator, and Tailings Storage Facility Cell 1 and Cell 2 also experience varying PPV levels during open pit blasting, with the Conveyer ranging from 0.0767-0.9103 mm/s, the Concentrator from 0.0716-0.1321 mm/s, and the Tailings Storage Facility Cell 1 and Cell 2 from 0.0701-0.4063 mm/s and 0.0553-0.2223 mm/s, respectively.

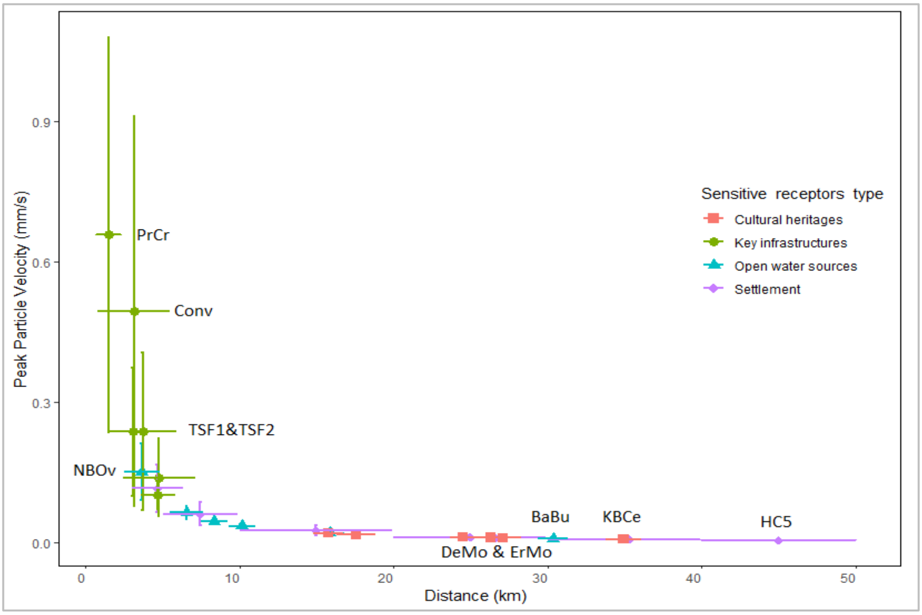

Fig. 4. Estimated PPV on the sensitive receptors

By employing the model, we conducted calculations of PPV values within distances ranging from 0.1 km to 400 km. These values were then compared against the permissible level of 5 mm/s, as depicted in **Fig. 5**. The analysis reveals that the predicted PPV value line intersects with the permissible level at approximately 0.2 km from the blast source. Considering that all designated sensitive receptors are situated between 0.7 km and 50 km away from the Open pit, it can be confidently concluded that they are in a safe zone.

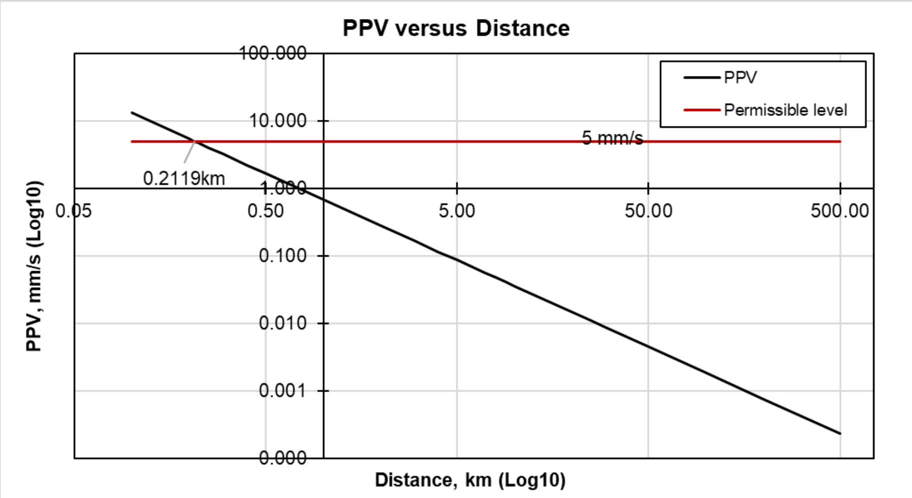

Fig. 5. Predicted PPV values versus the distance from the Open pit

Overall, the results provide valuable information for understanding the effects of open pit blasting on various receptors and infrastructure. The findings can support decision-making processes, allowing for better planning, monitoring, and management of blast-induced vibrations in mining operations. Implementing appropriate mitigation measures based on the estimated PPV levels can help minimize potential risks and ensure the sustainable and responsible operation of the Open pit mine.

4 Discussion

In our study, the observed PPVs at receptor points were found to be significantly lower than the threshold value mentioned in the ANZEC guideline [7]. This suggests that the ground vibration levels induced by blasts at the OT Open pit mine are well within acceptable limit. These findings indicate that the ground vibrations experienced at cultural heritage sites and other sensitive receptor points are below the levels that could potentially cause significant damage or disturbance.

In order to provide a broader perspective, it is valuable to compare our study results with other mine blasting experiences. Several studies conducted in different mining contexts have assessed the impact of ground vibrations induced by blasts, considering the near-field vibrations [28, 29], which are not comparable with our study. In near-field vibration perspective, plenty of mathematical models were developed by the researchers [30, 31, 32].

Moreover, it should be mentioned that this kind of studies barely conducted in Mongolia, or their information is not publicly available. We found a study conducted at Baganuur coal mine in Mongolia, the reported PPV values ranging from 3.0-12.4 mm/s at a sensitive receptor, a water catchment structure, which is 0.7 km away from blasted area [33]. For our case, at same distance PPV was around 1.1 mm/s the nearest sensitive receptor, the Primary crusher.

Comparing our study results with these similar mine blasting experiences, it is evident that the ground vibration levels at the OT mining site are relatively lower. This suggests that the blasting practices and measures implemented at the OT mine are effective in minimizing the potential impact on nearby receptors and infrastructure.

However, it is important to acknowledge that despite the overall low PPV levels observed in our study, some sensitive receptors, such as unique cultural heritage sites, still experience a certain degree of vibration. Even though the recorded PPV values are below the recommended thresholds, continuous monitoring and assessment of these sensitive areas are crucial to ensure the long-term preservation and stability of these valuable cultural assets.

5 Conclusion

We studied level of ground vibration induced by blasts at open pit mining of Oyu Tolgoi company. Result of the study suggests that observed and estimated values of PPVs are still lower than recommended maximum level for ground vibration. Therefore, one can conclude that potential risk of blasting at the Oyu Tolgoi open pit for the sensitive receptors in the question is humble.

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