JME

Journal of Mining & Environment,
Vol.8, No.3, 2017, 455-465.
DOI: 10.22044/jme.2017.930

A field investigation of application of digital terrestrial photogrammetry to characterize geometric properties of discontinuities in open-pit slopes

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Received 27 December 2016; received in revised form 29 April 2017; accepted 16 May 2017
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Abstract

In order to analyze the slope stability in open-pit mines, the structural parameters of rock mass such as persistence and spatial orientation of discontinuities are characterized through field surveys, which involve spending high costs and times as well as posing high risks of rock toppling and rock fall. In the present work, a new application of terrestrial digital photogrammetry is introduced for characterizing the rock mass structural parameters through preparing photogrammetry images from open-pit walls and building stereomodels. The data extracted from processing the stereo-model generations using photogrammetry images with different focal distances are highly consistent with the data collected through field surveys. However, it must be noted that the weather conditions, natural lighting angle, and applied observation scale may considerably affect the results obtained from stereomodel processing. Nevertheless, by taking into account the parameters such as time, cost, and full access to the required data, this new method can effectively be used in the estimation of rock mass structural parameters for analysis of steep slopes in open pits.

Keywords: *Open Pitting, Rock Mass Structure, Slope Stability, Stereomodel, Digital Photogrammetry.*

1. Introduction

As a technique with high application in surveying, terrestrial digital photogrammetry is a technique with high potentials for the characterization of rock mass structures. Through recording the discontinuities in photogrammetry stereomodels and their interpretation, this technique allows measuring the geometrical characteristics of the discontinuities such as their location, orientation, persistence, roughness, frequency, and block dimensions.

Within the last two decades, many researchers have proved the accuracy and precision of the photogrammetry techniques in extracting characteristics of discontinuity (Krosley et al. [1]; Martin et al. [2]; Sturzenegger et al. [3, 4]; Coggan et al. [5]; Haneberg [6, 7]; Sturzenegger and Stead [8-10]; Firpo et al. [11]; Francioni et al. [12]). Moreover, some programs and softwares have been designed by the researchers such as Gaich [13], Birch [14], and Propat [15] for discontinuity characterization and making different types of stereomodels using photogrammetry images.

Despite the images with high resolution, the biggest problems are caused by the image interpretation. The terrain of open-pit mines usually does not show a variety of colors or shades of grey. Therefore, shadows can not only be advantageous but also disadvantageous. Nevertheless, there are many specific aspects in the use of digital photogrammetry in the field of open-pit mining, which have to be taken into account for getting proper results [16].

Scaioni [17] has presented modern technologies for landslide monitoring and prediction, which have been focused in the first chapter on Ground-Based Monitoring Techniques. Scaioni et al. [18] have discussed the application of close-range photogrammetry for deformation measurements in the field of landslide investigation and monitoring. They have mentioned that the main advantages of this approach are the non-contact operational capability, large covered area on the slope to analyze, high degree of automation, high acquisition rate, chance to derive information on the whole surface, not limited to a few control points (area-based deformation measurement), and, generally, a lower cost with respect to 3D scanning technology. Roncella and Forlani [19] have presented a fixed terrestrial stereo-photogrammetric system to monitor landslides, and, in general, changes in the digital surface model (DSM) of the scene framed by cameras. Mazzanti et al. [20] have developed a new approach for investigation of rock cliff and the prioritization of rock fall hazard based on the data collected by the remote-sensing techniques. They applied the approach to a real coastal cliff located in the southern part of Italy.

Wajs [21] has presented the technological process and the results of the research of using digital photogrammetry for opencast mining purposes in the scope of numerical volume computation and monitoring the mines by comparison of different sources. The results obtained showed that the presented workflow allowed to build DTM manually and remote sensed, and the accuracy assessment was presented by the volume computation pathway. The major advantages of the techniques presented illustrating how a terrestrial photogrammetry technique provides rapid spatial measurements of break-line 3D data utilized for volume calculation.

Despite the recent developments, application of terrestrial digital photogrammetry in rock engineering has been in close-range and is limited to road-cut assessment or single benches in open pits, while the main importance of slope stability in steep wall pit mines is large scales. In other words, analysis of the overall slope of an open pit (which consists of several benches or the entire pit) is sought by the slope stability assessments rather than the single-bench analysis. Although having access to the entire pit wall in the field for recording characteristics of the entire discontinuities is a time-consuming and risky issue, the photogrammetry method used for rock mass structures may provide a low-cost, reasonable, and suitable method for rock mass characterization.

In the traditional and field surveying methods, the structural properties of rock masses are typically measured and recorded case-by-case, and covering a vast area in a short time is not possible. However, in the photogrammetry procedure, depending on the sight range of the camera and its lens specifications, this method allows recording a large rock mass surface and, as a result, provides the structural characterization of a large share of the rock.

In the present work, the challenges existing in the use of terrestrial digital photogrammetry for long-range slope stability assessment of rock walls are investigated. Next, through the preliminary results obtained by the analysis of photogrammetry images from pit walls of the Angouran Lead and Zinc Complex in Iran, the structural characteristics of the rock mass are extracted and used as the input data for slope stability analysis. Finally, the effect of scale on the accuracy of structural characteristics of rock mass is studied. The results of the present work have a clear emphasis on the importance of selecting a correct scale as such by changing the observation scale in each phase, the quality and quantity of the rock mass structures indicate high variations.

2. Angouran Lead and Zinc complex

The Angouran Lead and Zinc Complex is located 135 km from Zanjan within 36° 37′ N and 47° 24° E coordinates in a mountainous area. Figure 1 illustrates a view of the Angouran open pit, and its aerial photograph is shown in Figure 2. From stratigraphy aspects, the Angouran Pit area is located in the zone between the Alborz Mountains and the Urumia-Dokhtar zone, while based on the lithological aspects, the ore body lies between the crystalline carbonates (hanging wall) and greenschists (footwall). In the structural view, the Angouran ore body is located in the center of an anticline between two schist and carbonate metamorphic parts. In the hanging wall of the ore body, the carbonate layers lie with a general slope of 20 to 25° toward SE, while in its footwall, there are metamorphic Schists with a general slope of 10 to 25° toward SE. The geometry of the ore body drawn using the exploration boreholes was found as a lens with a general slope of 20 to 30° toward SE. In the plan view, the largest length and width of the ore body lie along the NE-SW and NW-SE directions, respectively. The ore body is 2,980 m high from the ground surface, and is located at an elevation of 2700 m.a.s.l. At 2,890 m.a.s.l, the maximum length and width of the ore body are 340 and 160 m, respectively. The mining excavation is carried out through the open pit method. The bench height and wall slope are 10 m and 74°, respectively, and the overall slope of the pit in its walls and different zones varies from 20 to 45°. The highest bench and the current level of the pit are 3,085 and 2,830 m.a.s.l, respectively [22].

3. Terrestrial digital photogrammetry method

In the present work, the pit walls were imaged using a digital Canon EOS-5DS body equipped with lenses with focal distances varying from f = 20 to 400 mm. Figure 3 illustrates a view of the camera used in this work. It is notable that the smaller focal distances (F values) indicate a wider diaphragm aperture, a more light absorption, and a better depth control. For instance, f = 20 mm means that the lens mounted on the camera has a 20 mm zoom.

After imaging, the 3DM CalibCam [23] and 3DM Analyst [24] software packages were applied to process all the taken images. Next, for a better and further analysis of the models, the Maptek Vulcan software was used. The photogrammetric models of the west pit wall were prepared using photographs with focal distances of 20, 100, and 200 mm. Moreover, to study the rock mass and topographic details on a smaller scale, the photograph models with f = 50 mm and f = 400 mm were used. Figure 4 illustrates a stereomodel of the pit mine.

Figure 1. A view of Angouran open pit.

Figure 2. Aerial photograph of Angouran Mine.

Figure 3. A view of Canon EOS-5DS Body used in this work.

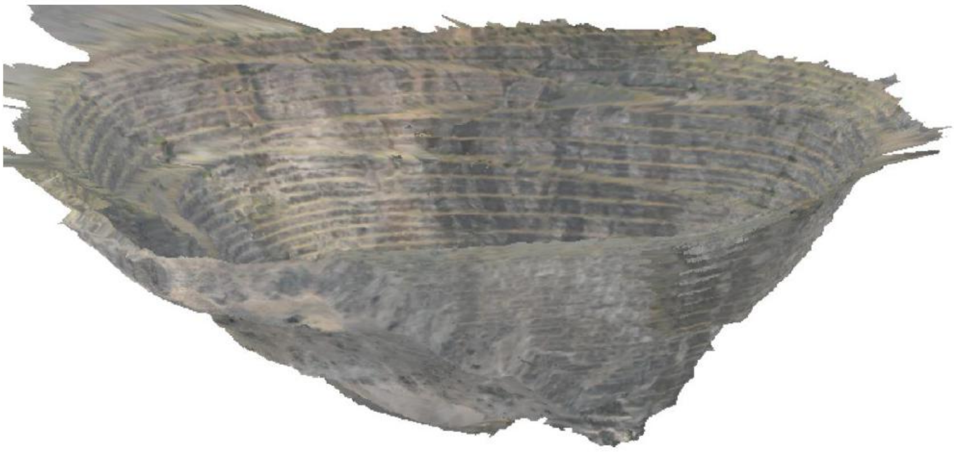

Figure 4. A stereomodel of pit mine using photogrammetric images (f = 100 mm).

4. Designing imaging network

Considering the importance of the Angouran Lead and Zinc Complex and its complicated tectonic structure, a systematic mapping and a monitoring network was defined for the mine. In order to provide the maximum consistency between the photogrammetric images and the available structural models of the mine, all the stereomodels were prepared inside the mine grid in accordance with the mapping station of the pit. In order to improve the quality of photogrammetry images, some new control points were defined, and the required images were prepared by putting the camera at these points.

In order to record the required images, a baseline equal to the one-sixth of the distance between the camera and the surface of the imaged rock was used. For a better coverage, in some cases, three camera stations were used to prepare a photogrammetric model. In addition, to maintain the scale, the image fan model layout (IFML) [14] was used by keeping the camera as perpendicular as possible to the wall.

For f = 200 mm and f = 400 mm, considering the view range and zoom of the camera, it was required to take a large number of photographs in order to cover the entire pit wall. Thus to manage the images taken, first, the photographs were divided into several subsets, and then the corresponding stereomodels of each zone were built based on its photographs. Finally, all the photographs taken were put next to each other.

5. Assessing accuracy and precision of stereomodels

Due to the field limitations and problems in the operational step, a limited number of control points (only 10 points around the pit) were used in this work. Considering the dimensions of pit walls, which had an estimated area of 100 hectares, it was only possible to prepare the models with low resolutions, which lacked the required precision. Furthermore, the locations of the fixed mapping stations were not in optimal conditions for making high-resolution photographs. Besides, the mapping prisms were very small compared to the pit wall dimensions, and were almost impossible to detect through the stereomodels. Hence, it would be more practical to mark the target points on the wall surfaces with a distinct color. Some high-resolution photogrammetric images (f = 400 mm) were also taken in this work and classified into different groups. Despite the insufficient number of control points, in order to reach a higher resolution, it was tried to plot them on the stereomodels using the control points and the detectable characteristics on pit walls. However, it must be noted that the absolute errors in these models ultimately affect all the interpretations and results and, in turn, the discontinuity properties. A random field comparison between the prepared model and pit wall surfaces at several points, and the statistical analysis of the results revealed that the maximum inaccuracy along the x, y, and z axes was 3.7, 4.2, and 0.5 m, while the maximum imprecision along these axes was 5.0, 6.5, and 1.5 m, respectively. However, since this model is merely used for measuring the relative dimension and orientation of the discontinuities rather than their absolute coordinates, the obtained accuracy and precision (considering the pit dimensions) must be enough for studying the structural properties of the rock mass. A comparison between the mapped discontinuities on a specific bench (between 2,880 and 2,890 m.a.s.l) from the 1,300 and 50 m ranges taken through the large range (f = 400 mm) and short range (f = 50 mm) lenses indicates a high consistency of the prepared stereomodels. Therefore, it can be stated that this method is suitable for recording and detecting the rock mass structural properties such as the spatial orientation of the discontinuities.

6. Resolution

The term “ground points spacing” refers to the distance between the spatial points in the stereomodels, and indicates the ground pixel size, step size, and bench dimensions. In other words, it is a representative of pixel number along the horizontal and vertical directions applied for creation of a spatial point. Table 1 presents a summary of ground point spacings used for the corresponding focal distances and the observation scale.

Table 1. Ground point spacings and observation scale for different stereomodels.

Focal distance (mm)	Distance (m)	Ground point spacings (cm)	Observation scale
20	1300	365	Wall
50	50	3	Bench
55	1300	133	Wall
100	1300	82	Wall
200	1300	41	Wall
400	1300	21	Wall/bench

7. Engineering challenges in photogrammetry recordings of pit mine walls

Photogrammetry is a method established based upon image processing and interpretation. Evidently, the sunlight angle highly affects the image quality during the imaging. This issue is also important in the brightness level and shadow level of the images. Moreover, atmospheric conditions, rainfalls, and dust also affect the resolution of pictures during the imaging. For instance, during the dusty days, a limited sight prevents imaging some structural properties or presence of some shadows in the image cause some errors in machine processing of the image axis. Since sunlight radiation on pit walls vary in different hours of a day and seasons, in order to ensure the quality of stereomodels, the required images must be taken within a short period of time as such the sunlight radiation to be at a constant rate. Reaching such a condition is not always easy since the location defined for camera installation has sometimes several hundreds of meter spacing. Besides, having access to the defined points for camera installation on some mine benches is not always possible. Moreover, the constant alternation between the cloudy and sunny situations does not favor a suitable condition for photograph preparation. Above these, an accurate field plan is required to perform imaging at a specific date and time so that wall brightness (induced by sunlight radiation) is almost constant in all images.

Another important field component with potential outcomes is calibration of a focal distance at long ranges for lenses f = 200 mm and f = 400 mm. This calibration is considered to be an essential step in a photogrammetric imaging process that requires a precise estimation of the focal distance for each lens and adjusting the internal parameters of the camera. As the focal distance increases, a network of (typically large spaced) successive locations for camera installation is applied for its calibration [23, 24]. As a result, as noted earlier, reaching the optimum weather conditions for imaging would be a difficult task. Furthermore, at such a large scale that excavation operation of the steep rock wall is difficult by itself, the importance of calibration would be highlighted.

Calibration after field surveying in an optimum location even might be carried out twice in order to ensure the success of the process.

8. Discontinuity properties

Through studying the stereomodels with different focal distances, 2,378 discontinuities were detected and recorded. Models with f = 20 mm and f = 100 mm covered both the west and the north walls of the pit, while models f = 50 mm, f = 200 mm, and f = 400 mm mainly covered a limited area in the northern wall of the pit. The characteristics applied for investigating the stereomodels with different resolutions must be precisely incorporated to deal with the negative scale effects. In this regard, the effect of observation scale on spatial orientation and persistence of the discontinuities has previously been pointed out by Sturzenegger and Stead [9]. The stereomodels with high resolution typically provide a better presentation of the details, while the low-resolution ones can be applied in order to detect the damping properties in the main discontinuities. Indeed, this characteristic plays a key role in determining the stability condition of the steep pit walls.

In order to cover the entire pit walls at the f = 100 mm, f = 200 mm, and f = 400 mm resolutions, a large number of photographs must be taken to be able to simultaneously present the specific characteristics using several stereomodels on a computer screen. Since this requirement imposes some difficulties on determining many characteristics of the pit walls on several successive stereomodels, some characteristics must be eliminated. However, this limitation is mainly a function of the facilities and capabilities of the utilized computer such as its processing speed, RAM memory, and ROM as well as its computation speed rather than the imaging limitations with large focal distances.

9. Spatial orientation of discontinuities

A summary of the spatial orientation of the discontinuities extracted from the stereomodel with f = 400 mm for the north wall of the pit is presented in Table 2.

Based upon the performed processing, four sets of joints were detected for this wall, with three of them being almost perpendicular to each other. It was noted that the joint sets 1 to 3 were almost consistent with the field surveying results of discontinuities in the pit walls. In addition, field investigation to capture joint set 4, due to impossibility of access, failed.

Table 2. A summary of spatial orientation of discontinuities extracted from stereomodel and field surveys.

Discontinuity set	Dip/dip direction (°)	
	Stereomodel	Field survey [22]
1	235/70	225/80
2	351/90	320/80
3	276/74	270/82
4	063/03	---

10. Discontinuities persistence

Persistence means the trace length of discontinuity on the rock mass body. The persistence of discontinuities is typically among the important structural features with an important role in the rock mass behavior analysis. In the photogrammetry method, persistence is obtained by interpreting the images taken from the rock mass surface. Generally, with a decrease in the crack and discontinuity length, their trace line becomes less detectable or even undetectable in the images. This issue is fully associated with the image resolution; a higher resolution would result in detecting even joints with less consistency. Furthermore, in order to increase the image resolution, it is necessary to decrease the focal distance, which leads to the reduced sight range. As a result, the covered imaged area would be smaller in the image, while the number of image pixels would increase, leading to a lower processing speed. Therefore, considering the studied conditions, the minimum trace line of the joints or the analysis importance in terms of the discontinuity length must be identified; it is required to determine how long the discontinuity length would be. Next, the image resolution is determined based on the minimum discontinuity length and its importance in order to estimate the focal distance based on the relationship between the image resolution and the focal distance. This process can be done empirically and through the trial and error approach. In this regard, Sturzenegger and Stead [9, 10] also have proposed some regression-based mathematical relations for estimating a suitable focal distance for a given resolution, an imaging area, and a joint persistence length. Figure 5 illustrates the persistence distribution of the discontinuities extracted from the stereomodels f = 100 mm and f = 400 mm. Figure 5 clearly shows that the persistence distribution is shifted toward the left, meaning that shorter persistencies are more distinct at greater resolutions. In comparison, in low-resolution images, the joints with a small trace line are not clearly recorded in the image, and thus not visible in the processing step.

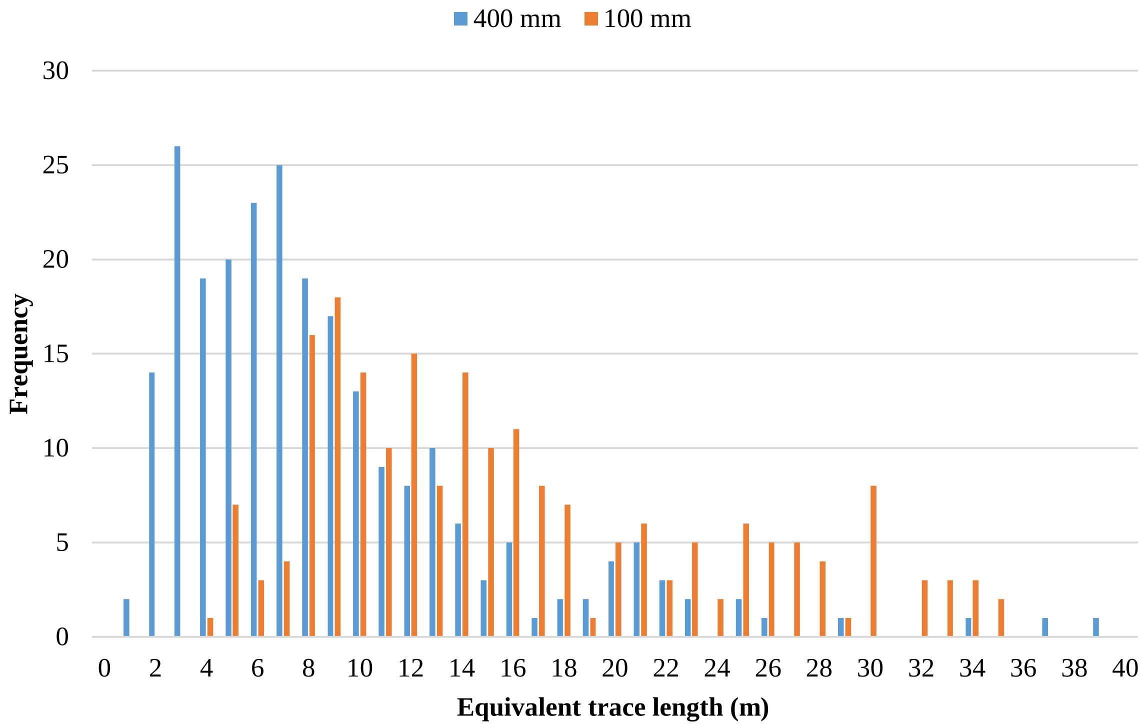

Figure 5. Diagram of persistence distribution of discontinuities.

11. Intensity of fracture

Numerous studies have been conducted so far on the early estimation of the fracture intensity in rock masses. Areal fracturing indicates the overall length of all fractures that intersect the sampling window. In order to determine this parameter, the FracMan software is used [26]. For this purpose, first, a virtual circular window with a diameter of 10 m and an orientation equal to the general dip of the pit is prepared using the stereomodel on specific benches on the north wall of the pit. Next, the tracing maps are prepared and used for a direct estimation of areal fracturing intensity. This process was also repeated on the other stereomodels designed using different focal distances. Figures 6-9 present the steps involved in this process including defining a 10 m diameter sampling window, recording discontinuities in the sample window, detecting discontinuities intersecting the sampling window, and discontinuity map preparation, respectively.

It must be noted that defining the sampling window based on the average orientation slope might result in a biased estimation of the areal fracturing intensity. Furthermore, the minor discontinuities that have smaller dimensions compared to the studied scale are indeed eliminated during the processing. The results obtained from this work show that the dimensions of the defined sampling window in the stereomodel considerably affect the estimations of areal fracturing intensity. In other words, this estimation is directly controlled by the observation scale. Thus it is required to consider the effects of defining appropriate dimensions of the sampling window on photogrammetric stereomodels through the future studies. Figure 10 presents the trend of areal fracture intensity based on ground point spacing.

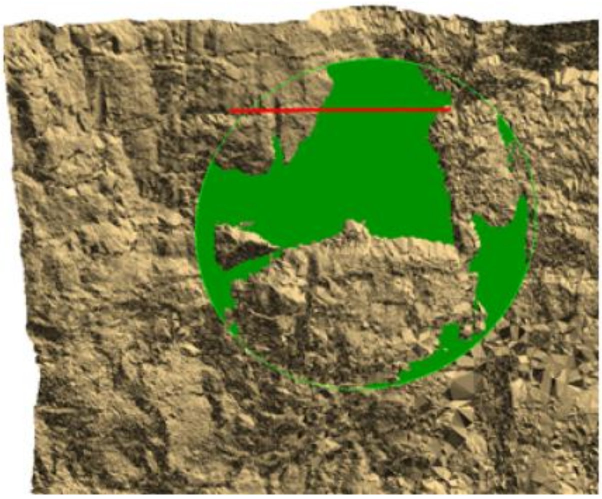

Figure 6. Defining a circular sampling window with a diameter of 10 m.

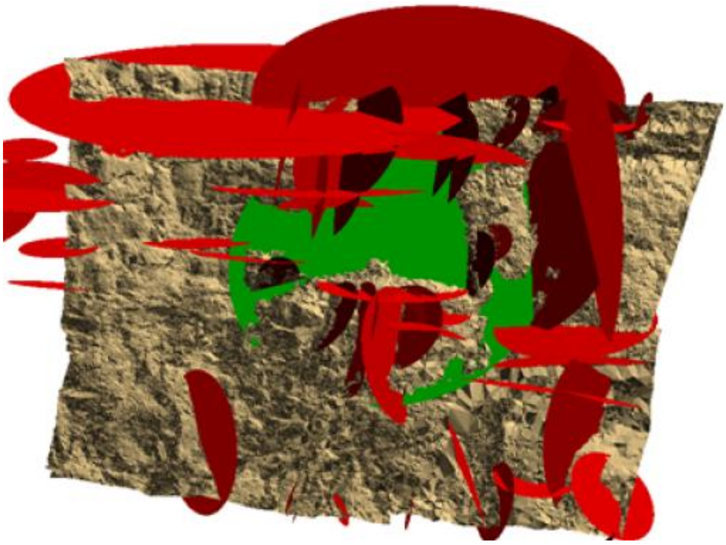

Figure 7. Recording discontinuities observed through sampling window.

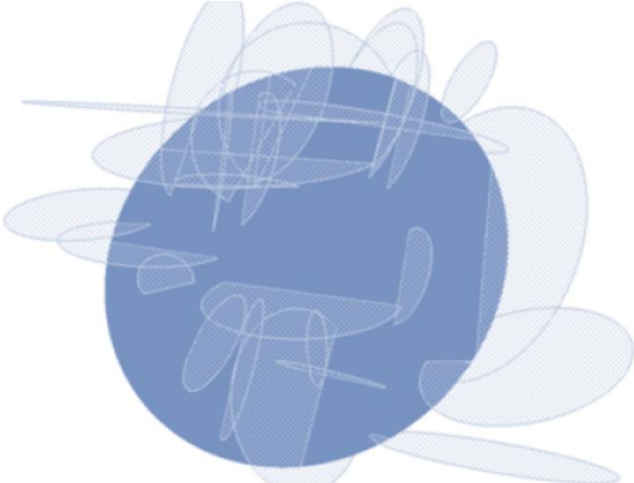

Figure 8. Detecting discontinuities intersecting sampling window.

Figure 9. Preparing trace map of discontinuities.

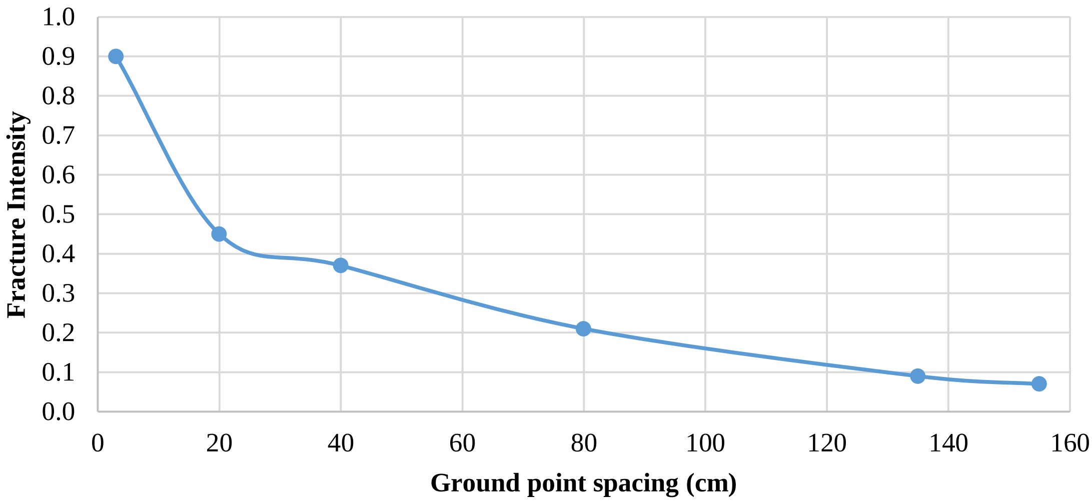

Figure 10. Variation trend of areal fracture intensity with ground point spacing.

12. Results and discussion

In the present work, the long-range terrestrial digital photogrammetry technique was applied to determine the structural properties of the rock mass in the open-pit Angouran Lead and Zinc Complex, Iran. The field access to the entire wall areas of this mine is practically impossible and involves high risks. During and after the field operations and imaging process and during the stereomodel designing, some engineering challenges were encountered that could be summarized as follows:

1) Registration of the stereomodels using a limited number of control points due to the lack (or shortage) of proper and accessible targets in the studied area;
2) The lighting issues induced by the non-optimal weather conditions during the imaging necessitates a careful planning for fieldwork according to the position of the sun; otherwise, the required accuracy and precision would not be met.
3) Handling a large set of photographs and bundling the recorded images taken from different sections of the pit is a difficult and time-consuming process.

Clearly, the experiences gained in the present work can improve the pursued trend of applying the terrestrial digital photogrammetry technique for determining the structural characteristics of the rock mass, especially in the issues related to slope stability of open-pit mines. Concerning the discontinuity characterization, the results of this work show that, considering dimensions of an open-pit mine, the stereomodels designed using photographs with f = 50 mm are more suitable. These photographs not only provide an adequate area coverage, volume, and quality but also display the details. The stereomodels prepared using these photographs would allow detecting the main rock mass structures that control the stability or instability condition of the pit. Moreover, the main discontinuity characteristics such as persistence are highly consistent with field surveys. However, a more detailed characterization of the rock mass structures including the areal analyses requires applying the stereomodels prepared using the photographs with f = 400 mm.

One of the main limitations in the analysis of high-resolution stereomodels is their simultaneous display on a computer screen, which might be due to the hardware and software issues. With an increase in the resolution of the stereomodels, this problem becomes even worse and may lead to adjust the persistence plains. Accordingly, detecting the trace line length of the discontinuities would be more difficult. However, the capabilities of the Maptek Vulcan software [25] are being enhanced, and the problem involved might be dwindled by further (software and hardware) technological advancements.

The results of this research work generally show that the long-range terrestrial digital photogrammetry can detect the intensity, persistence, and spatial orientation of discontinuities with an acceptable precision. These three parameters, as the main components of the discrete fracturing network (DFN) method, are widely applied in slope stability analyses.

Through applying this technique in the Angouran Lead and Zinc Complex, it was revealed that fracture intensity and persistence of discontinuities was considerably dependent on the observation scale of the stereomodels. Thus further investigations are required for finding a better observation scale based on an estimation of rock block size. Moreover, although low-resolution stereomodels are enough for an overall large-scale characterization, the stereomodels with higher resolution are required for a more detailed and small-scale study of the discontinuities.

13. Conclusions

In this work, many stereomodels were prepared for pit walls of the Angouran Lead and Zinc Complex using the terrestrial digital photogrammetry images. By processing and interpreting these stereomodels, the structural characteristics of the rock mass, particularly in highly sensitive areas, were determined. These characteristics can be applied as an input variable in analytical models and numerical software for slope stability analysis.

A comparison between the data obtained through the analysis of stereomodels and field surveys of discontinuities indicates a considerable consistency between them, particularly in the main discontinuities with similar fracture intensity and consistency. However, it must be noted that the observation scale can considerably affect the discontinuity parameters such as spatial orientation, persistence, and fracture intensity. Furthermore, weather and natural lighting conditions may have considerable effects on the recorded images as they result in errors during the determination of discontinuity traces. Nevertheless, the results are generally reasonable. Hence, through a continuous photogrammetry scanning of the pit walls and the relative comparison of the images, it is possible to determine the structural properties of rock masses, monitor variation trend of discontinuity parameters such as persistence or aperture, and provide valuable information for safety issues and slope stability analysis of the pit walls.

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ارزیابی میدانی به کارگیری فتوگرامتری دیجیتال زمینی برای تعیین خصوصیات هندسی ناپیوستگی‌ها در شیب‌های معدن روباز

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ارسال ۲۰۱۶/۱۲/۲۷، پذیرش ۲۰۱۷/۵/۱۶

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چکیده:

به منظور تحلیل پایداری شیب در معادن روباز، معمولاً باید پارامترهای ساختاری توده سنگ از جمله شدت، میرایی و جهت یافتگی فضایی ناپیوستگی‌ها با برداشت‌های میدانی مشخص شود که این برداشت‌ها معمولاً پرهزینه و زمان‌بر بوده و با خطرات گوناگونی از جمله سقوط و ریزش سنگ همراه می‌باشند. در این پژوهش، رهیافت جدیدی با تکیه بر قابلیت‌های تکنیک فتوگرامتری دیجیتال زمینی ارائه شده است که با تهیه تصاویر فتوگرامتریک از دیواره‌های پیت معدن و ساخت استریومدل‌های متعدد، امکان تشخیص پارامترهای ساختاری توده سنگ را تا حدود زیادی ممکن می‌سازد. داده‌های حاصل از پردازش استریومدل‌های ساخته شده بر اساس تصاویر فتوگرامتریک با فاصله‌های کانونی مختلف، تطابق مناسبی با داده‌های حاصل از برداشت‌های میدانی نشان می‌دهند. البته باید توجه داشت شرایط آب و هوایی، زاویه تابش خورشید و همچنین مقیاس مشاهده، می‌تواند تأثیر قابل‌توجهی بر نتایج پردازش استریومدل‌ها داشته باشد. با این حال، با در نظر گرفتن پارامترهایی همچون زمان، هزینه، دسترسی کامل و غیره، این روش جدید می‌تواند به طور مؤثری در تعیین پارامترهای ساختاری توده سنگ، برای تحلیل پایداری دیواره‌های شیب‌دار در معادن روباز به کار گرفته شود.

کلمات کلیدی: معدنکاری روباز، ساختار توده سنگ، پایداری شیب، استیرومدل، فتوگرامتری دیجیتال.