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EXPERIMENTAL STUDY INTO THE EFFECT OF THE CLOSED DISCONTINUITY DIP ANGLE ON THE PARTICLE ACCELERATION RESULTED FROM EXPLOSION

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ABSTRACT

The most important effect of a discontinuity when encountered with a wave is the division of wave energy. This process is conducted in the form of dividing the input waves to the reflection and transmission waves. Several researchers have studied the effect of physical and mechanical properties of these discontinuities on waves division. In this study, the effect of the closed discontinuity dip angle has been investigated in the form of experimental tests in scale model. Accordingly, the effect of discontinuity dip from 60 to 120 degrees at 10 degree steps was investigated on particle acceleration of the waves. The results indicated that by increasing the discontinuity dip, the reflection of the waves increase and the vibration is enhanced. On dips greater than 90 degrees, the amount of wave reflection is more than the transmission and at dip angles less than 90 degrees, it is opposite. It was also found that on dips greater than 90 degrees, the ratio of reflection was three times more than the 90 degrees dip and the ratio of reflection is approximately 6 to 7 times more than the transmission of waves. By increasing the angle of discontinuity dip, the attenuation rate of particle acceleration increases where this amount at an angle of 100 degrees is about 30 percent more than that of 90 degrees. Some empirical models for the reflection ratio and the attenuation of the particle acceleration were obtained in terms of the dip angle of discontinuity dip with a high determination coefficient.

Keywords: Blast-induced particle acceleration, closed discontinuity, reflection and transmission of waves, scale model test

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INTRODUCTION

The energy from blasting in mines or constructions releases waves into the surrounding environment. At very close distances, waves damage rock masses, and at long distances, cause vibration in the ground. The medium for transmitting the waves is the rock mass which include closed or open discontinuities in the form of faults, joints, fracture or layering. The interaction between these discontinuities is a complicated topic investigated by numerous researchers and tested by different methods.

Wave behaviour is affected after wave interaction with the discontinuities which is significant from different perspectives. Moreover, waves affect discontinuities which are highly important, particularly from the aspect of rock mechanic and rock mass stability. Discontinuities vary in geometrical, physical, and mechanical properties and, therefore, waves interact with them differently. A few researchers have attempted to study the properties and their interactions with waves. In this respect, there are a few seminal perspectives. One perspective deals with rock mass fragmentation and another deal with protecting the structures from waves. Tracking and determining the properties of fractures in the rock mass has also been investigated in a plethora of studies.

The most significant effect of a discontinuity on incident waves is energy partitioning of them. In this process incident waves are reflected or transmitted. The conversions in this process are affected by various parameters. Generally, the reflection of most waves reinforces vibration before discontinuity and protects the zone after it. However, the absorption of wave energy by discontinuity is of great importance.

Field and Pederson [1] conduct an experiment on the role of wave reflection in generating fractures in blast hole in line with wave propagation. Fourney et al. [2], Bogunovic and Kecojevic [3] and Wang et al. [4] studied and analysed the effect of open joints on wave attenuation and transmission. In their research, they observed that a high percent of the energy released in blasts attenuates by the joint.

Closed joints behave differently than the open ones. In this regard, numerous studies are conducted on closed discontinuities analytically, numerically and experimentally. Hudson [5] studied wave velocity and attenuation including fracture, and Boadu and Long [6] investigated the effect of fracture on wave velocity and attenuation analytically. Zhao and Chen [7] and Fan et al. [8] studied the effect of joints on wave propagation by numerical modeling. Mortazavi and

Katsabanis [9] numerical investigated the effect of strata dip on blasting process. They concluded that when strata dip is against the bench face, less back break and more toe-related issues are expected. However, when the layers were dipping toward the bench face, the effect is reverse.

Daehnke and Rossmanith [10], Rossmanith et al. [11, 12, 13] and Carcione and Picotti [14] have carried out seminal works on wave transmission and reflection coefficient caused by waves interaction with various boundaries in different environments. The results of the above mentioned studies are diagrams related to wave reflection and transmission coefficients (shear and compressive waves). Bakhshandeh [15] conducted a numerical modelling on the effect of discontinuity dip on the transmission and reflection of blast-induced waves and concluded that reverse relationship exists between the increase in discontinuity dip and the percent of reflection energy of the wave. Blaire [16] researched the vibration pulse in joint rocks and Pyrak-Nolte et al. [17] examined the effect of fracture on wave transmission experimentally. Bhandari and Badal [18] conducted small-scale experimental studies on the effect of joints on rock fragmentation. Using limestone models (20-30 mm thick), the primary model and the joints in different models were developed in horizontal, vertical and angular modes. The study revealed that the number and direction of blast-induced fractures are affected by discontinuity plates. Moreover, joint direction affects fracture pattern and growth and therefore, on fragmentation and the shape of the specimens. Fordyce et al. [19], Antoun and DeCarli [20], Fourney and Dick [21], Wu et al. [22], Leucci and Giorgi [23] and Li et al. [24] have conducted experimental studies on wave propagation in jointed rock.

The experimental studies which are mostly carried out in labs, examined the physical and mechanical properties of the discontinuities and considered the velocity reduction and attenuation in wave propagation. Wave transmission and reflection is generally tested using analytical and numerical methods in which the geometrical conditions of the joints were constant.

Considering the important role of discontinuities in wave propagation and vibration and energy division in discontinuities, this study deals with this issue. The effect of geometrical aspect of discontinuities, such as dip angles, has been mostly neglected in the literature and lacks experimental research. Therefore, this research is an attempt to experiment the issue at scale model.

EXPERIMENT METHOD

In this study, the concrete models which were made in two specimens were used. By putting the two concrete specimens together, a model with a slope discontinuity was created and its effect on wave energy division was investigated. Among these models, an integrated model was built and tested to be considered as a model without discontinuity. The characteristics of the mentioned models are presented in Table 1.

Table 1. The characteristics of the concrete models used in this study.

Dimensions cm	Pressure wave velocity m/s	Shear wave velocity m/s	Elastic modulus (dynamic) GPa	Shear modulus (dynamic) GPa
50×70×50	3960	2490	35.5	15.1

Variety of dip angles ranging from 60 to 120 degrees with respect to horizon is considered for concrete blocks. These angles are measured clockwise with 10 degree interval. Figure 1 schematically indicates different dips on the model.

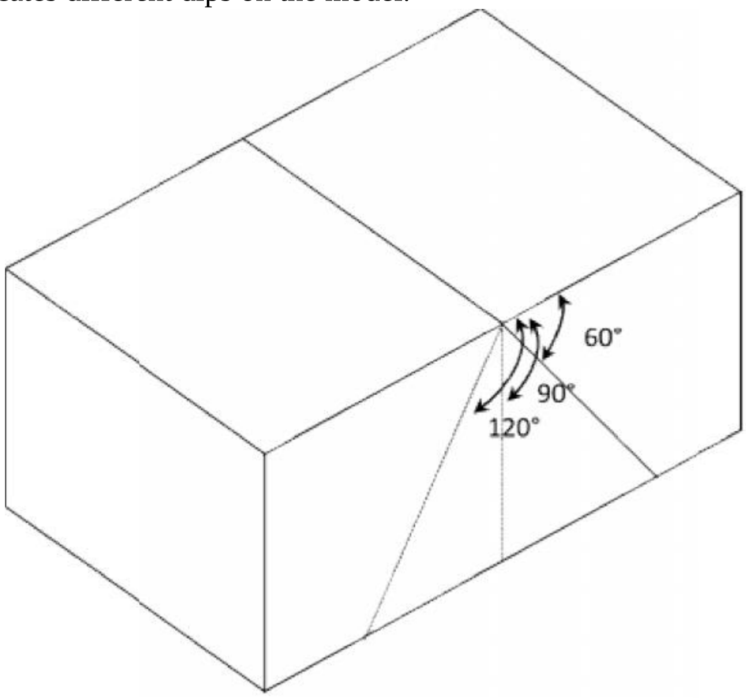

Fig.1. Schematic representation of different dip angles on the model

A total of eight models were considered for this experiment. In order to evaluate the effect of discontinuity on the waves, the particle acceleration were recorded on both sides of the discontinuity using a 7-channel Vibracord DX seismograph made by Spain and two three-component MEMS accelerometer with a maximum range of ±500g. The distance between two accelerometers were constant in all experiments (10 cm) and their distance from the edge of the discontinuity on the surface of the model was 5 cm. A steel ball with 65 mm in diameter was used as a source to induce wave. This ball was dropped on the model from a certain height in a distance of 10 cm to the record point to make constant the amount and intensity of the wave produced in experiments. In this study, in order to simulate a surface explosion or a vertical collision such as the collision of missiles or military explosions, dropping the steel ball on the model from a certain height in a vertical direction was used. On the other hand, subsurface explosions such as mine or civil explosions using the ball shot in a horizontal way (the collision of a ball to the model in the horizontal direction in the form of a pendulum) are simulated. Figure 2 indicates the position of the record and shot points on the model.

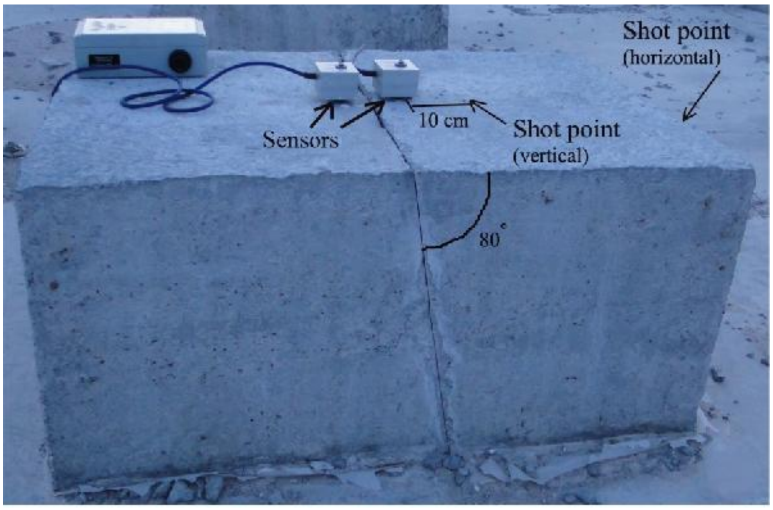

Fig.2. A view of the position of the sensors and the location of vertical and horizontal shot points on the model with a dip of 80 degrees

In all experiments, the accelerometer number one (A1) was before the discontinuity and closer to the point of hit and accelerometers number two (A2) was after the discontinuity. In order to ensure the accuracy of the data and removal of accounts containing errors, each experiment was tried to be tested for at least three times.

DATA ANALYSIS

Measurement of particle acceleration on both sides of the closed discontinuity with different dip angles was conducted and the results were plotted as diagrams for variation of particle acceleration before and after the discontinuity. In Figure 3, the variations of resultant component of the peak particle acceleration versus dip variation is presented.

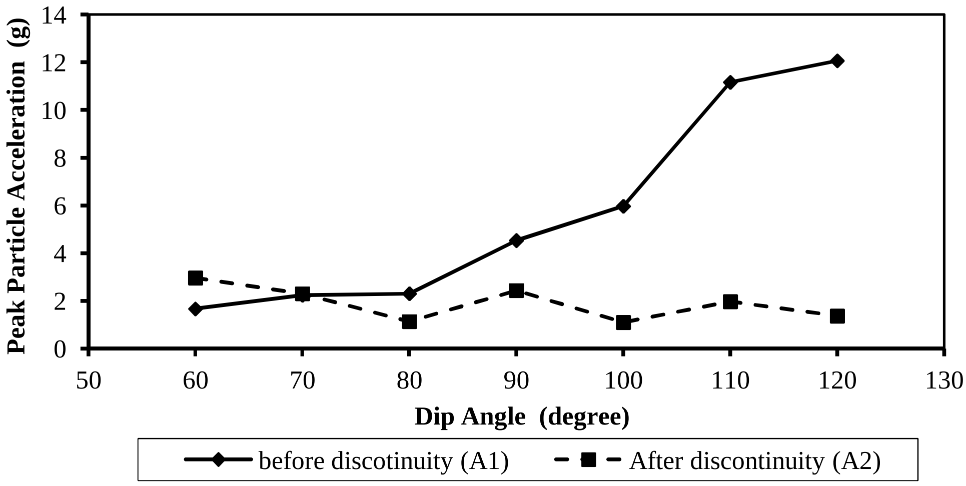

Fig.3. Variations of the peak particle acceleration versus variations of dip angles for vertical shot.

According to Figure 3 and diagrams related to other components, it was found that by increasing the dip angle, the particle acceleration increases in the sensor before the discontinuity. In other words, the value of wave reflection increases. On the other hand, the particle acceleration reduces after the discontinuity and this indicates that by increasing the dip angle, the transmission wave from the discontinuity decreases.

The values recorded by the sensor number 1 (A1), in all experiments, included the incoming and reflected wave. In order to calculate the amount of particle acceleration resulted from the reflected waves in the first specimen of the model, particle acceleration values in the model without discontinuity were used. Therefore, on the basis of equation 1, the values of the particles acceleration of the modified or reflective was calculated.

$$PA_c = PA_d - PA_i \tag{1}$$

Where PA_c is the modified particle acceleration (g), PA_d is the particle acceleration in the model with discontinuity and PA_i is the particle acceleration in model without discontinuity (g).

Accordingly, the portion of the input wave particle acceleration was removed from the values of the record particle acceleration before the discontinuity. The variations of the modified values of the peak particle acceleration before and after the discontinuity are shown in Figure 4.

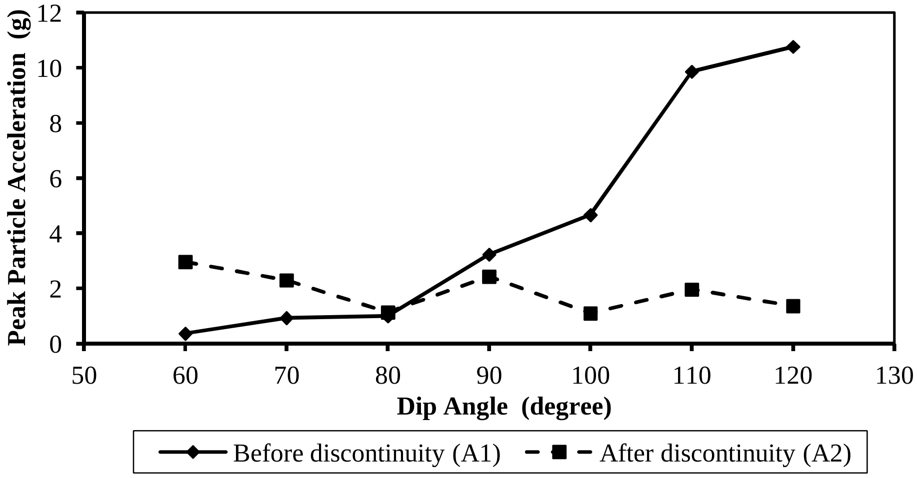

Fig.4. Variations of the modified values of the peak particle acceleration before and after the closed discontinuity versus dip angles

The variations of the modified values indicate that at dip angles of 80 and 100 degrees, particle acceleration values have extreme increase than the lower angles. This variation can be important in analyzing the blasting results in practical terms.

Considering the high validity of the relative values and the generalizing these data to other conditions, the ratio of reflection and transmission values were obtained by calculating the relative amounts of the modified particle acceleration than the values of the model without discontinuity. In Figure 5, the value of reflection and transmission ratio of the resultant of the peak particle acceleration is presented.

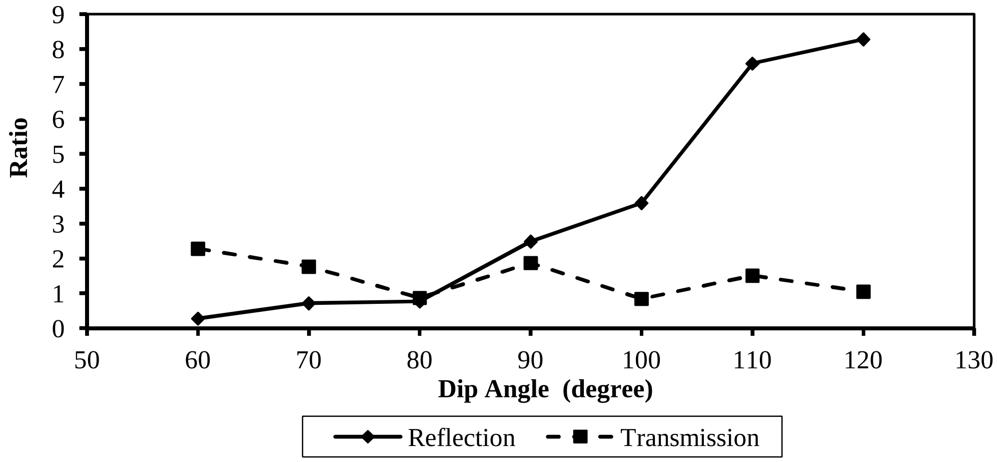

Fig.5. Values of transmission and reflection ratios of waves versus different dip angles of discontinuity.

As seen in Figure 5, strengthening particle acceleration reaches up to about 7.5 times (at an angle of 110 degrees) and this high value is due to reflection from the discontinuity as well as the effect of various boundaries. At angles less than 90 degrees, the value of transmission is more than reflection whereas in angles higher than 90 degrees, this result is opposite. According to these results we can say that in order to reduce the transfer of vibration after discontinuity, its dip must be greater than 90 degrees.

Considering that experiments have been conducted on models with the limited size, the effect of the boundary location and dimensions on the results is obvious. Therefore, calculating the relative particle acceleration at different angles to the amount resulted from the dip angle of 90 degrees can be a proper criterion for comparing, because in all these experiments the effect of dimensions and boundaries were almost in identical terms. Thus, the relative values were calculated for different measurements and their variations were plotted. Figure 6 indicates the value of the relative reflection and transmission of particle acceleration at different dip angles in comparison to the particle acceleration at 90 degrees.

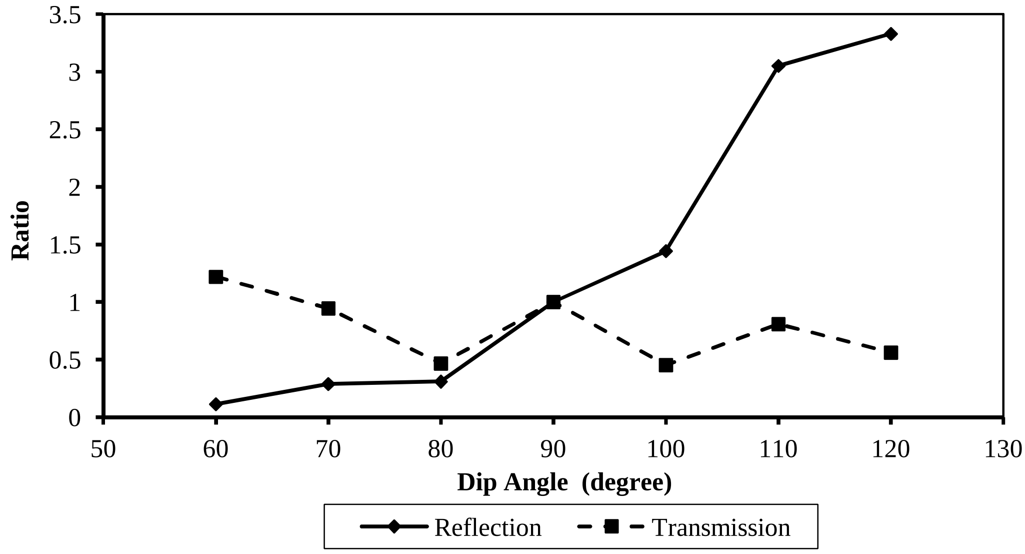

Fig.6. Relative values of the reflection and transmission of particle acceleration in different dip angles in comparison to 90 degrees

Figure 6 indicates that the relative reinforcing value at reflection reaches up to about 3 times of 90 degrees which corresponds to an angle of 110 degrees. In addition, this ratio reaches up to about 1.2 times at 60 degrees and 0.56 times at 120 degrees at the transmission of waves which indicates higher transmission at angles less than 90 degrees.

Based on the values of the two relative states, the empirical relationships between the reflection ratio and the dip angle of discontinuity were obtained and are presented in Table 2.

Table 2. The empirical equations between the reflection rate and the dip angle at two relative states.

	Empirical Equation	**Determination Coefficient (R^2)**
Compared to without discontinuity	$Rr = 0.216D^{5.1}$	0.97
Compared to dip angle 90 degree	$Rr = 0.087D^{5.1}$	0.97

Rr: Reflection ratio D: Dip angle (radian)

Calculating and investigating the attenuation percentage of particle acceleration on both sides of the discontinuity was also performed in this study. Figure 7 shows the variations of particle acceleration attenuation. Observing this diagram, it becomes clear that by increasing the dip angle, the attenuation percentage increases as well and reaches up to about 85 percent at angles of 110 and 120 degrees.

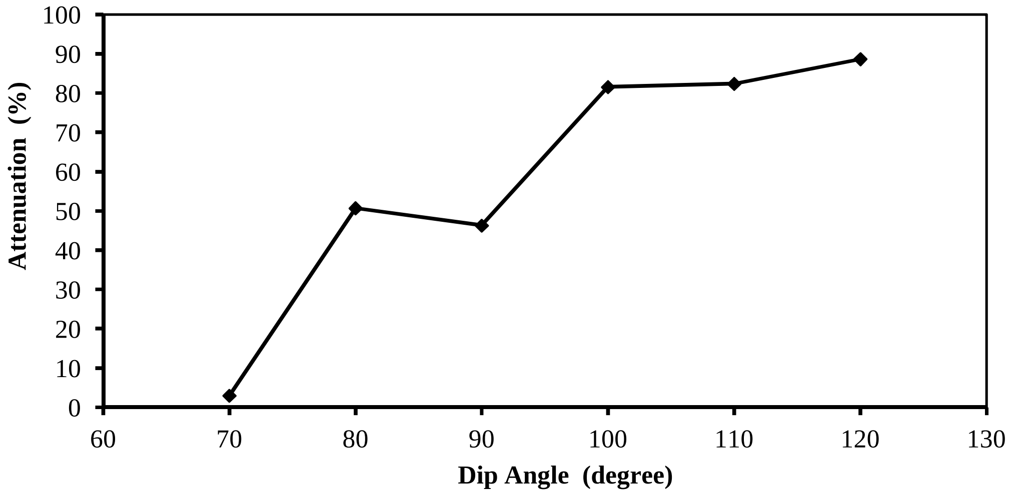

Fig.7. The variations of the particle acceleration attenuation versus the different dip angles

The empirical relationship of the attenuation rate was obtained based on the dip angle of discontinuity as equation 2.

$$At = -206.66D^2 + 790.35D - 667.17 \qquad R^2 = 0.95 \tag{2}$$

Where At is attenuation of particle acceleration (%) and D is dip angle of discontinuity (radian). The uptrend of the attenuation percentage was observed with increasing the dip angle in all components of particle acceleration. Figure 7 indicates that by increasing the dip angle of discontinuity, even in the closed state, the attenuation rate dramatically increases and this amount is about 30 percent more than 90 degrees, at an angle of 100 degrees. This issue is of a great importance in designing and creating attenuation waves in the transmission path.

CONCLUSION

According to the results obtained from experiments and their analysis the following conclusion may be drawn:

- By increasing the discontinuity dip, the reflection of the waves increase and ground vibration (particle acceleration) is reinforced.
- At dip angles more than 90 degrees, the reflection of the waves is more than the transmission and it is opposite at angles less than 90 degrees.
- At dips greater than 90 degrees, the ratio of reflection reaches to about 8 times of the without discontinuity condition which is related to the angles of 110 and 120 degrees. On the other hand, the transmission ratio on dips less than 90 degrees reaches to about 5 times of the without discontinuity condition, at an angle of 60 degrees.
- In high dip angles (110 and 120 degrees) the ratio of reflection is about 6 to 7 times the ratio of transmission while at low angles (60 degrees) the ratio of transmission to reflection is about 4 to 5 times.
- Reinforcing wave reflection at angles more than 90 degrees is almost three times the amount of 90 degrees dip. At angles less than 90 degrees, the reflection of waves decreases where its ratio for the dip of 60 degrees is about 0.11 times the dip of 90 degrees.
- Transmission ratio of waves varies between 0.4 to 1.2 times the 90 degrees dip the higher values of which is related to dips less than 90 degrees. Therefore, by reducing the dip angle, the levels of vibration transmission increase.
- By increasing the dip angle of discontinuity, attenuation of the particle acceleration increases and this increase is high at degrees more than 90. This amount at an angle of 100 degrees is about 30% more than 90 degrees.

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