Ground Characterization While Drilling Roofbolters in Tunneling Operations

A. Naeimipour, S. Bahrampour, J. Rostami
Pennsylvania State University, University Park, PA

C. Dogruoz,
Dumlupinar University, Kutahya, Turkey.

Abstract

Characterization of the ground surrounding the tunnel can improve safety and allow for optimizing the ground support design during the tunnel construction. Measurement while drilling (MWD) systems offers valuable information about the ground condition in probe drilling as well as drilling of blastholes and roof bolts. This paper will discuss the current efforts underway at Penn State Univ. in collaboration with J.H. Fletcher & Co for developing instrumented roof bolters which can detect bedding and discontinuities and provide a rough estimate on the rock strength along the borehole. Recent improvements in performance of MWD for roofbolters as an effective way to obtain geological information about the rock and 3D visualization of this data as a prelude to development of rock mass classification and hazard mapping of the roof and walls will also be presented.

1 Introduction

In underground construction, maintaining a safe work environment often involves installation of suitable ground support system. It is very common to use rock bolts in tunneling projects due to the relatively simple installation, low cost, and substantial support capacity. Proper selection of rock bolts depends on correct identification of the geological conditions, which can dramatically change even within a short distance (Gu, 2003). However, there is often limited information about the surrounding rock and the exploration borehole measures are few and far in between. Preparing geological maps while tunnel excavation operation is proceeding is not always practically possible and safe. The application of MWD for roof characterizations has been recently attracted many researchers because it can potentially provide the needed geological information in a short time without the need for any operational interruptions. In this approach roof bolt drilling system collects additional information such as torque, thrust and penetration rate which can be used for estimating the rock strength and evaluating rock mass conditions. This information will be utilized for development of geological map of the ground around the tunnel. Such maps will in turn allow for development of hazard-maps and 3D data visualization of the ground. Moreover, the information can potentially be employed to evaluate the suitability of the applied ground support for a given section. A series of studies has demonstrated the potential for analyzing drilling parameters from roof bolters to estimate rock properties and to identify discontinuities (Itakura et al., 2001; Itakura et al., 2008; LaBelle, 2001). West Virginia University (WVU) in collaboration with J. H. Fletcher & Co. also worked on this subject between 1999 to 2006 and have developed the first generation of the void detection system for Fletcher roofbolters (Finfinger, 2003; Gu, 2003; Mirabile, 2003; Tang, 2006; Finfinger et al., 2000; Luo, Peng, and Wilson, 2003; Luo et al., 2002; Peng et al., 2003). Additional studies are being conducted by Penn State University and J. H. Fletcher & Co. to continue the work performed at WVU. This project is sponsored by National Institute of Occupational Safety and Health (NIOSH). This paper will discuss the testing and related analysis underway in this project to improve the void detection capabilities of the roofbolters as well as rock strength measurement and implementation of the obtained results into a 3D visualization of the ground and development of hazard maps for tunnel wall. Available and applicable borehole logging systems will be explained and their use in detection of discontinuities, Rock mass
strength estimation and ground conditions will be discussed. Data visualization will also be briefly covered and its potential for use in tunneling and underground construction will be evaluated.

2 Background

Itakura et al. (1997) employed a portable pneumatic roof bolter with the ability to record torque, thrust, revolution, and stroke. Torque and thrust were monitored by using strain gauges installed on the surface of the drilling rod, while penetration and rotation rate were kept constant during the tests. They manufactured blocks included sandstone, sandy shale, and coal samples with three different discontinuity angles of 0 degrees, 30 degrees, and 60 degrees. The average value of torque and/or thrust was found to be an indicative index to allow for classification of the rock layers along the borehole. Furthermore, it has been proposed that patterns of thrust or torque along with neural network algorithms may be used to categorize the discontinuities, but the resulting error was rather large (Itakura, 1998; Itakura et al., 2001). Itakura et al. (2008) reported that the roof bolter examined in an underground coal mine in Queensland, Australia, successfully showed the distribution of discontinuities and layer boundaries using the ratio of recorded parameters of torque and thrust.

In addition, J. H. Fletcher & Co. as a pioneer in developing instrumented roof bolters, developed a system that monitors drilling operations and drilling parameters, including thrust, torque, rotation speed (rpm), and bit position (Gu, 2003). This system has been employed to detect rock discontinuities including voids, fractures, and bed separations and to estimate the relative hardness of the rock mass (Finfinger et al., 2000). Variation of thrust or feed pressure had been found to be the most suitable identifier of discontinuities (Finfinger, 2003; Peng et al., 2003). Based on Finfinger (2003) concept of thrust valley, thrust decreases rapidly after reaching a void and increases rapidly again when it goes through the discontinuity to maintain constant penetration rate. A drop of more than 50% was then considered as an index to detect discontinuity. The distance between the two sides of the valley was also used to measure the discontinuity aperture. Although the instrumented system has been improved to a great extent, there are still some inaccuracies in detecting the location and, especially, the size of discontinuities. Collins, et al. (2004) explained that some major voids could not initially be detected by the system during a series of field experiments in a limestone mine, mainly, because of the difference between the hardness of concrete used in the laboratory used for training the drill and the limestone at the roof of the mine. In this situation, the parameters of the roof mapping algorithm needed to be updated constantly. It was also found that unlike the usual pattern observed in the laboratory, in which both thrust and torque would drop simultaneously, a sudden rise in the rotation torque happened just before encountering the voids. Meanwhile, the thrust did not have a consistent reaction. New theories were developed later to describe the observed trends. Another problem was reported by Anderson and Prosser (2007), in which the hairline and vertical cracks along with layers of the rocks were not correctly identified. Moreover, Tang (2006) elaborated that the applicability of the developed system is limited to voids with size of 1/8 inch or larger.

In a more recent study, it has been shown that vibration and acoustic measurements can also be used to improve the accuracy of the void detection and rock characterization algorithms (Bahrampour et al. 2013). For this purpose, it was observed that valuable information can be extracted from the high frequency components of the vibration and acoustic signals that can be subsequently used for void detection by modeling the problem. Moreover, the author suggested that combinations of the new measurements with the drilling parameters such as torque and thrust can potentially further improve the accuracy of the rock characterization algorithms and provide robustness by adding redundancy in the measurements.

However, further developments of the measurement while drilling systems is dependent on extensive field tests and how fast and accurate the properties of rock mass inside the drilled boreholes can be identified by means of sampling or probing. This allows the borehole drilled by the instrumented roof bolter to be logged for training and verification of the results by the related algorithms and pattern recognition programs. Borehole logging or well logging is a conventional practice in oil and gas, groundwater, and mining industries, which continuously records the information related to variation in targeted physical properties of the rocks in bore hole. There are many different logging methods namely electric, radiation, sonic or acoustic, and optical probes. Each of these methods consists of varied sub-approaches that are suitable to measure a physical parameter in a particular situation such as lateral resistivity, neutron and gamma, caliper, optical or TV logs and sonic or acoustic methods. Well logging in oil
industry utilizes probes with relatively large size and much heavier apparatuses, whereas, in mining and civil operations simpler and lighter devices should be used.

In this project, slimmer, lighter probes are needed so that they can be run easily in the roof bolt holes, which are typically about 1-1½ inch in diameter, and limited space in underground environment. Unfortunately, very limited attempts have been made to employ borehole logging methods to verify the validity of the results from the instrumented roof bolter in the field tests. Gu (2003) and Tang (2006) mentioned application of a simple borehole camera system to be used in addition to coring to verify the roof bolter results during the underground tests. However, many researchers have studied geophysical methods in order to be able to estimate different properties of the rock mass especially the strength (McNally 1990; Payne and Ward 2002; Zhou et al. 2005; Oyler et al. 2010). Also, borehole televiewers and cameras are developed to take continuous picture of the borehole wall so discontinuities could be detected and analyzed (Unrug 1994; Ellenberger 2009; Bae et al., 2011). Unlike these studies that most of the logging runs were performed in downhole boreholes, in this project upward boreholes which are usually dry need to be logged. This is a logistic issue that should be solved in order to pave the way for further investigation of the application of borehole logging in training the instrumented roof bolter. The only system that is readily compatible with this condition is optical televiewer or bore-cams. Obviously, this information can also be obtained from coring into the roof or walls and testing the core samples, but this could take a substantial amount of time and cause interruption in the operation, the results will be available with a time lag related to testing, and require additional equipment and setting that is not readily available at the site. Despite these issues, some cores will be retrieved from the formations where the coring operations are deemed not to have the least impact on normal operations. These cores will be used to validate and adjust the measurements made by various probing devices.

3 Void detection

Void detection is a feature that could help identify the discontinuities and joints in various rock mass conditions. These features are known to dominate rock mass behavior. The term void typically refers to a joint with open aperture or other conditions in the rock mass that represents open space or area filled with weak deposits. However, in this study, void refer to any discontinuity that could weaken the rock mass, including but not limited to bedding, joints, cracks, fractures, fissure, etc. in any type of rock. A series of full scale experimental tests were conducted at J.H Fletcher & CO facilities in Huntington WV. Figure 1 shows the picture of the test setup. In these tests concrete blocks with various strength as well as rock samples from the sedimentary layers of mid-Atlantic region casted in concrete were drilled using an instrumented roof bolter. Test results are consistent with previous studies by WVU and Fletcher and it has been observed that the feed pressure, which can be translated to thrust, drops within the void. This pattern is used for void detection using a new algorithm as it will be explained. The pattern of dropping thrust force has been previously studied (Collins et al, 2004), but no adaptive algorithm yet exists to model this behavior and correctly detect the voids independent of the rock strength. In other words, feed pressure signal is tightly correlated to the strength of the rock being drilled. Consequently, the drop in the feed pressure is dependent on the strength of the rock. In this study, the void detection problem was modeled as a mean change problem and an efficient mean change detection algorithm, known as cumulative sum (CUSUM) algorithm (Basseville et al, 1993), was used to detect the voids. Preliminary results of using this algorithm for void detection has proven to be effective. The CUSUM algorithm has an adaptive threshold that does not need careful fine tuning when dealing with different rock strengths and various drilling parameters such as desired penetration rates and rpm.
Figure 1. J. H. Fletcher & Co. instrumented roof bolter setup.

Pattern of Feed Pressure for Void Detection

Fig. 2 shows a typical sensory data collected while drilling into a stack of two concrete blocks with a void at the intersection of the two concrete blocks. The measured attributes are rotation pressure, feed pressure, rpm, position, bite rate (penetration per revolution), and vacuum pressure. It is seen here that feed pressure (thrust) has a sudden decrease when the drilling bit approaches the void while the rotation pressure (torque) is almost constant during the drilling. This pattern was observed in almost all the experiments performed. Having this in mind, void detection can be mathematically formulated as a mean change detection problem. In this formulation, it is assumed that the mean of the stochastic signal (i.e. feed pressure) is almost constant when there is no void and it undergoes a change (decrease here) when a void appears. The goal was to detect the change as quickly as possible with high detection rate and small false alarm rate.

For solving this problem, the CUMSUM algorithm which is a well-known change detection algorithm will be used. In this real time change detection algorithm, the initial mean of the signal is estimated using the initial samples and a cumulative sum is computed and monitored at each time step. Deviation from the initial mean is then detected by comparing the cumulative sum to an adaptive threshold. As soon as a change is detected, the CUSUM algorithm will be restarted and will initialize to detect the possible changes in following samples. The details of the CUSUM algorithm are omitted here and interested readers are referred to (Basseville et al, 1993) for detailed derivation of the algorithm. In the above formulation, it is assumed that feed pressure drops when the drill bit approaches a void. For this purpose, the void detection algorithm is turned off during the first 5 inches of the drilling and the initial time series is used to estimate mean and variance. Information about the magnitude change is usually not known a-priori. One good choice is to replace mean with minimum possible magnitude of the jump. In this paper, $\eta$ or change in amplitude is selected to be 40% of the mean $\mu$. In other words, the algorithm would be sensitive to all change greater than 40% of the mean value of the time series. More sophisticated algorithms can be used to estimate the parameter $\eta$ such as the generalized likelihood ratio method but this will significantly add the computational costs.
Figure 2. Typical sensory data collected while drilling into a stack of two concrete blocks with a void at the intersection of the two concrete blocks. Samples represent the time scale, where every 10 sample is 1 sec.

In order to evaluate the suitability of this algorithm, data from full scale testing experiments were used to detect the interface between concrete blocks. The experiments consisted of a set of 16 concrete blocks with different strength. The blocks are approximately 0.5 x 0.5 x 0.75 m (~20 x 20 x 30 inches), and the concrete mix was designed for various strengths: low (~20 MPa or 3,000 psi), medium (50 MPa or 7,500 psi), and high (70 MPa or 10,000 psi). Different combinations of concrete blocks were used to test robustness of the algorithm to deal with different setups. For examples, a hard concrete block on top of a soft concrete block (H-S) or a hard concrete block on top of another hard concrete block (H-H). The gap between the blocks were less than a 1-2 of millimeters and was considered to represent a “void” in this study. Additional tests were performed in samples of rock from several different mining operations in PA and WV that were case in the concrete block to simulate the variation of strata in the roof and walls of an underground openings. These samples were subjected to various rock mechanics testing to measure their strength and other related properties.

Table 1 summarizes the different concrete combinations studied in this paper with the number of holes drilled in each setup along with void detection rate and false alarm rate where ‘S’, ‘M’, and ‘H’ letters stand for soft, medium, and hard concrete, respectively. Different values of penetration rate and rpm are used in the tests to evaluate the performance of the algorithm with respect to various drilling parameters. As it can be seen, the voids have been detected with high detection rate and a few false alarms. Overall, the detection rate of 93.3% is obtained with false alarm rate of 6.2% in 161 holes. It should be emphasized that the above algorithm used only feed pressure for detection of the voids. Using other sensory data such as vacuum pressure and rotation pressure can further improve the results which will be discussed more as future research topic in next section.
6

As mentioned earlier, further improvement in the capability of the drilling system to characterize the ground is largely dependent on extensive field tests and how fast and accurately the rock masses surrounding the drilled boreholes can be analyzed. The conventional method of coring/testing requires considerable time and budget. Borehole logging is an effective alternative to address this issue in which variation in some physical properties of rocks in the bore hole is continuously recorded and later would be related to rock type and rock mass mechanical and physical properties. This is because usually accessing the target area is not practical due to their relative depth from the surface. The only exception is borescoping which is commonly used in mining applications where the side wall of the boreholes are inspected for joints and voids. However, the information generated from borescoping is very limited, has high chances of missing some features, is unable to verify the direction of the joints, and cannot be used in additional analysis of the spatial distribution of the joints in the ground. Uniaxial Compressive Strength of intact Rock (UCS) and condition of the discontinuities are among the most important parameters of the rock mass classification to be defined for stability evaluation. In the following, estimation and detection of these features by means of borehole probing will be elaborated in more details.

4 Borehole Logging

As mentioned earlier, further improvement in the capability of the drilling system to characterize the ground is largely dependent on extensive field tests and how fast and accurately the rock masses surrounding the drilled boreholes can be analyzed. The conventional method of coring/testing requires considerable time and budget. Borehole logging is an effective alternative to address this issue in which variation in some physical properties of rocks in the bore hole is continuously recorded and later would be related to rock type and rock mass mechanical and physical properties. This is because usually accessing the target area is not practical due to their relative depth from the surface. The only exception is borescoping which is commonly used in mining applications where the side wall of the boreholes are inspected for joints and voids. However, the information generated from borescoping is very limited, has high chances of missing some features, is unable to verify the direction of the joints, and cannot be used in additional analysis of the spatial distribution of the joints in the ground.

Evaluating the Conditions of Discontinuities

Condition of discontinuities, such as frequency, orientation, roughness, filling and etc., is one of the main factors that control stability of the underground spaces. There are methods which employ borescope or endoscope as the device for evaluation of the fractures and other discontinuities (Ellenberger, 2009). Figure 3 (a) shows a strata-scope. This device is a simple monitoring tool for checking the mine roof condition mainly to see if there is any fracture near the opening boundary or if any fracture or bed separation is initiated because of the mining operations. A more advanced tool with almost the same application is bore-scope. Different parts of a bore-scope package are shown in Figure 2 (b).

![Figure 3](a) strata-scope and its schematic application in mining industry (“Optim Stratascope,” 2013); (b) Typical bore-scope package and its different components (“BOREHOLE INSPECTION SYSTEMS,” 2013).

Table 1. Results of the void detection algorithm on different combinations of concrete soft (S), medium (M), and hard (H) blocks.

<table>
<thead>
<tr>
<th>Concrete combinations</th>
<th>S-H</th>
<th>H-S</th>
<th>M-H</th>
<th>H-H</th>
<th>H-M</th>
<th>M-S</th>
<th>S-M</th>
<th>M-M</th>
<th>S-S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of holes</td>
<td>17</td>
<td>17</td>
<td>17</td>
<td>18</td>
<td>21</td>
<td>18</td>
<td>18</td>
<td>18</td>
<td>17</td>
</tr>
<tr>
<td>Detection Rate</td>
<td>82.3%</td>
<td>88.2%</td>
<td>100%</td>
<td>94.4%</td>
<td>100%</td>
<td>100%</td>
<td>88.8%</td>
<td>88.8%</td>
<td>100%</td>
</tr>
<tr>
<td>Number of false alarms</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>
With bore-scope, unlike the strata-scope, the picture of the borehole can be recorded for future reference. In some cases, it is also possible to record the operator voice so the main features observed and their depths can be mentioned to make the video more informative. Moreover, the real-time picture can be seen in a LCD monitor. Both strata-scope and bore-scope are designed to be used in slim boreholes with the diameter of one inch or more. Also, one operator with a short-time training can conduct the inspection and carry the equipment. These tools are generally inexpensive (<~$10k). However, since these types of instruments provide a narrow directional view and not a full 360 degree image, picture of borehole wall is of limited application in analysis of discontinuities. It should also be highlighted that even if the recorded video is available for future evaluations, it is not convenient to review the information and compare the data from multiple boreholes. Furthermore, some features, such as hair cracks, cannot be detected easily with these tools. Figure 4 shows two sample photos related to borescoping operation in R&D laboratory of J.H. Fletcher & Co. as part of instrumented roof bolt development project. The aim of this operation was to investigate the condition and location of the contact area between the concrete blocks, stacked on top of each other after drilling.

![Two sample photos related to borescoping operation in J.H. Fletcher & Co. R&D laboratory.](image)

**Figure 4.** Sample photos of borescoping operation in J.H. Fletcher & Co. R&D laboratory.

More advanced and expensive tools for borehole imaging are resistivity, sonic and optical televiewers. For each of these methods several products are manufactured. Both resistivity and acoustic viewers need a fluid-filled borehole. Optical TVs (OPTVs) can be used in borehole filled with clear, fresh fluid or empty borehole. Acoustic televiewers work based on amplitude and travel time of the reflected acoustic signals. Resistivity tools provide the image of the strata by means of the sensor pads which record the difference in resistivity between various layers on the borehole wall. Generally, the main components in the head of OPTV tools are a fish-eye mirror, LED light ring, and image sensor or camera. The obtained images are particularly suited to fracture and fault analysis and can also be used for interpretation of the near-wellbore stress field from borehole breakouts and drilling-induced fractures. Furthermore, unlike the borescopes they produce an unwrapped 360 degree picture, and not a pointed video of the borehole wall; therefore, comparison of different logs is more convenient. The depth relative to the collar of the borehole is also recorded automatically. The orientation of boreholes can be determined by the built-in 3-axis magnetometer or three accelerometers.

Optical televiewer or OPTV seems to be a better option for this study since it is dealing with empty boreholes. However, it also should be checked if the geometry and physical features of the probe are also suitable for this application. In addition, they may need to be explosion proofed in case they are to be used in coal mines or gassy tunnels. Figure 5 (a) and (b) show the OPTV probe heads of ALT-Mt Sopris and DMT, respectively which are the two systems considered for application in our current study.
Estimation of Rock Strength

For intact rock strength \((\text{UCS})\) estimation, sonic logging seem to be the most commonly used method (McNally, 1990; Guo & Zhou, 2011). Full wave-form sonic probes and acoustic TVs can provide useful information related to the strength of the rock in addition to the conventional sonic tools (Guo & Zhou, 2011). As mentioned earlier, McNally (1990) and Oyler et al. (2010) developed equations to estimate UCS of intact rocks in the immediate roof of mines in Australia and the U.S., respectively. However, most of the studies were done on the surface and in down-hole boreholes. In these cases, filling the borehole with a fluid is not an issue; but these systems cannot be applied to this research since the boreholes are upward and most likely dry. Employing rubber packer system for filling the upward dry hole with a fluid such as water or gel to conduct sonic logging through the packer can be a simple solution. In addition, the size of the existing acoustic and sonic probes do not match short and slim borehole about 10 ft. long and 1” in diameter commonly used for roof bolting. The height restriction of the underground spaces especially in small tunnels can also be a problem for inserting the probes, which are typically around 2 m (6 ft) in the borehole. To get a more accurate data from the closely bedded layers, a high vertical resolution is needed which needs employment of more receivers in the sonic log. This will leads to a longer probe which is already unfavorable for the logging operation in an underground space. Overall, these issues make it very unlikely that the conventional sonic televiewers could be used for tunneling applications. However, employment of Acoustic TV can still be considered in conjunction with fluid-filled upward/slim/short drill-holes. The advantage of this method is that the transmitter works as the receiver, which maximizes the covered area. However, the initial processed data from this log is qualitative and just indicates the rock strength relative to the adjacent layers and feature. More studies should be done to produce localized or general quantitative information about the UCS of the intact rock.

As an alternative, mechanical probes could be used or developed to measure UCS. Stamp test and borehole penetrometer test are among the methods that could be used in the borehole to estimate the strength of the rock (Wagner and Schümann 1971; Wijk 1989; von Unrug 1999). However, these methods will be unable to provide continuous information about rock strength as the stamp penetration are performed at certain intervals. On the other hand, scratch test showed to be a relatively accurate and reliable approach (Roberto and Fabrice 2002; Schei and Detournay 2000). This method can provide continuous information about the strength of the rock along the borehole by making a scratch on its surface and measuring the forces and subsequent analysis of data to estimate rock properties. Extensive studies are needed to develop this system for boreholes. Efforts are underway to design and deploy a mechanical borehole logging unit as part of the current study which will pave the way for further investigation of the application of borehole logging in rock characterization and in training the instrumented roof bolter.

5 Data Visualization

Since this project involves dealing with a large amount of data, there is a need to be able to visualize the recorded data from various boreholes in a 3D so that it could be interpreted and presented easier and in a more...
useful manner for practical applications. Initial efforts in developing a 3D visualization of the borehole ground characterization data has been done by using commercial software packages, namely GEMCOM© by Dassault Systemes Geovia Inc. and Surfer© by Golden Software Inc. The objective of this exercise was to illustrate the encountered rocks and possibly voids and bed separation detected in a borehole around the underground opening in 3D. By detecting the position, distance, and frequency of the discontinuities in boreholes using the instrumented roof bolter, it is possible to calculate the RQD of each borehole and further plot the RQD variation in different sections. Figure 6 shows the result of preliminary trials using GEMCOM software package. Additional efforts are underway to work with other visualization software to select a platform for future developments and to enable the programs to show the stratification around the opening and to develop an algorithm for ground support evaluation and mapping of the failure risks.

Figure 6. 3D visualization of an unreal situation of boreholes drilled in a tunnel and the developed contour map for RQD (rock quality designation) of those boreholes, by Gems and Surfer Software Programs.

6 Conclusion

The use of data obtained from roof bolter to characterize the ground around an opening can be a substantial resource in understanding the ground conditions without interruption of the tunneling operations and related activities. This includes evaluation of the rock strength as well as detection of voids and joints using various operational parameters of the drills such as feed pressure, rotation pressure, drilling rate, and RPM. The CUMSUM algorithm was used to identify joints and bed separation from the full scale drilling test data collected from J.H. Fletcher test unit. The algorithm enjoys an adaptive threshold that does not need fine tuning and works well in different studied scenarios. Moreover, the algorithm has a recursive formulation which facilitates real-time computations. The results demonstrate the suitability of the proposed algorithm to achieve high detection rate with small false alarm rate.

For training of the drilling unit, a variety of borehole probing and logging systems will be used. This allows for quantifying rock properties and rock mass characteristics in shortest possible time so that pertinent data needed to estimate rock properties for correlation with drilling information can be generated. The rock strength and joint and discontinuity information can be used to develop a real time rock mass classification that can subsequently be used in related analysis to evaluate optimize ground support design. Ultimately, the generated information will be used to develop a 3D image of the geology of the ground and a hazard map for the roof and walls using a commercial program for data visualization.
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