Study on Rock Burst Behavior and Tendency Identification of Surrounding Rocks in Hard and Brittle Formations of Deep and Ultra-deep Wells

Yijin Zeng\textsuperscript{1,2}, Junhai Chen\textsuperscript{1,2}, Dandan Li\textsuperscript{1,2} and Xin Li\textsuperscript{1,2}

\textsuperscript{1} State Key Laboratory of Shale Oil and Gas Enrichment Mechanism and Effective Development, Beijing, China  
\textsuperscript{2} Sinopec Research Institute of Petroleum Engineering, Beijing, China

Abstract. The phenomenon of the continuous collapse or the instantaneous block-falling incidents during the drilling of deep wells cannot be sufficiently explained by traditional wellbore instability theory. This phenomenon is similar to rock bursts that often occur during tunnel excavations and other engineering projects. This paper focuses on hard/brittle formations such as limestone, dolomite, and shale, which represent the most frequently collapsed formations while drilling a borehole. Based on rock burst theory and the results of the rock mechanics experiments, combined with rock failure model and other intuitive conditions, rock bursts are divided into three categories: weak, medium, and strong bursts. We establish the calculation models of strength brittleness index $R$ and elastic energy index $W$ based on rock uniaxial compressive strength and determine the interval values of these indexes for rock burst identification. We also propose a set of comprehensive identification methods for rock burst tendency and the classification of surrounding rocks in hard and brittle formations during the drilling of deep wells. The findings of this work provide a solid foundation for the research of wellbore instability prevention and control based on the classification of hard/brittle formations.

1. Introduction

At present, Sichuan Basin and Tarim Basin are the main regions of exploration and development of deep and ultra-deep oil and gas resources in China. During the drilling process of deep wells in these regions, hard/brittle formations are prone to sustained collapse and block falling, which in turn, causes the frequent sticking of drill pipes. Moreover, a large number of instantaneous block falling and drilling-tool burying incidents have also occurred. Given that several key wells with depths of over 7000 m have been sidetracked or abandoned, this phenomenon has become one of the key problems restricting deep-well drilling activities. Traditional wellbore instability theory mainly uses the rock strength, rock fabric characteristics, and in situ stress, among other factors, to analyze and obtain the collapse pressure, in order to maintain the wellbore stability and assess the drilling fluid performance and density\textsuperscript{[1-5]}. The rocks in hard/brittle formations are generally characterized by high strength and weak water sensitivity. According to traditional wellbore instability theory, this kind of formation has good wellbore stability. In turn, this leads to the low design value of drilling fluid density and the failure to balance the wellbore collapse pressure, thereby resulting in the continuous collapse and block falling of the wall rock upon drilling. In actual practice, the operator can only rely on experience to improve the density of drilling fluid. However, this cannot effectively solve the problem of falling wall rock; in fact, it may even worsen rock falling or cause formation fracture and leakage resulting from the high density of the drilling fluid. In the laboratory, we carried out compression tests on...
hard/brittle rocks, such as limestone, dolomite, shale, etc., which are the most frequently damaged shaft wall carvings. We found several kinds of phenomena, such as instantaneous bursts, volume breakage, and irregular rock cracking during rock failure. These are often accompanied by different degrees of noise similar to the rock bursts in mining and tunnel excavation. These results reveal that such formations can easily undergo rock bursts. Hence, considering this feature in investigating wellbore instability is very important.

Rock bursts are a kind of dynamic failure in which the hard and brittle surrounding rock is redistributed owing to unloading during tunnel, mine, and other underground engineering excavations under the condition of high ground stress. Consequently, the elastic strain energy stored in the rock mass is released suddenly, resulting in the phenomena of bursting, loosening, particle ejection, and even throwing[6]. Researchers have extensively studied the rock burst in underground excavation engineering, thereby revealing the mechanism of rock burst from the theories of strength, energy, impact tendency, and time correlation[6-9]. The classification of rock burst intensity according to the damage degree of rock mass during rock burst has also been proposed in past studies[10-13]. From the perspective of lithology, more than ten evaluation methods of rock burst tendency, such as strength brittleness index, elastic energy index, and rock burst energy ratio method, have been proposed[14-24]. The most commonly used among these are the rock strength brittleness index $R$ and the elastic energy index $W$. The quantitative evaluation criteria of rock burst tendency have also been proposed according to the lithology of limestone, sandstone, marble, and granite in shallow stratum excavations[25]. Generally, there is no rock burst when $R < 10$, whereas moderate and strong rock bursts occur when $10 \leq R < 18$ and $R \geq 18$, respectively. In addition, no rock burst occurs when $W < 2$, whereas moderate and strong rock bursts occur when $2 \leq W < 5$ and $W \geq 5$, respectively. However, for deep formations faced by the oil and gas drilling industry, rock bursts are controlled by more complex formations and operational conditions, such as rock mechanical characteristics, lithology, borehole size, and stress conditions. Therefore, the rock burst behavior and tendency discrimination method of hard/brittle rocks in deep oil and gas wells must be investigated based on the theory of tunnel and mine excavation rock burst. Doing so can help in the reasonable classification of these formations and guide the research on the mechanism and prevention and control of borehole instability in hard/brittle formation in deep-well drilling.

This paper focuses on hard/brittle formations, such as dolomite, limestone, and shale, which are the rock types that are most frequently prone to collapse while drilling deep boreholes. In this work, rock mechanics experiments, such as rock compression and tension tests, were carried out systematically. The rock burst intensity was classified by conducting a comparative analysis of the shapes of rock failures in the rock mechanics experiments. Moreover, a comprehensive analysis of rock burst tendency was carried out by using rock strength brittleness index $R$ and elastic energy index $W$. The corresponding relationship between $R$ and $W$ was established, along with the uniaxial compressive strength of rock, thus enabling is to determine the quantitative evaluation criterion of rock burst tendency based on $R$ and $W$. Finally, we propose a set of comprehensive identification methods for rock burst tendency and the classification of surrounding rocks in hard/brittle formations during the drilling of deep wells.

2. Classification of Rock Burst Intensity and Discrimination Model of Rock Burst Tendency

2.1. Classification of Rock Burst Intensity
In mining, tunnel excavation and other related projects, rock burst intensity refers to the direct damage caused by rock blasting in underground tunnels, mine tunnels, or the ore body itself, as well as the indirect damage caused by it to other mining areas and ground buildings.

Further, for oil and gas well drilling, the rock burst of wellbore rock in hard/brittle formation is a downhole complex condition that causes wellbore collapse and breakouts. It causes complex accidents such as stuck pipe, buried drilling tools, and even the loss of the borehole with varying degrees of
severity. Therefore, it is necessary to classify the intensity of rock burst to support the identification of underground complexes and accidents for oil and gas well drilling.

Rock burst intensity classification (also known as rock burst classification) is an index that describes the intensity and scale of rock burst. Rock burst classification mainly focuses on the actual apparent phenomenon and is classified according to the shape characteristics of the rock burst surface, acoustic characteristics, and failure depth. Rock burst is generally divided into three levels: 1) slight rock burst, wherein the rocks (loose and broken) burst with a weak burst sound; 2) moderate rock burst, wherein large rocks fall off accompanied by an obvious burst sound; and 3) serious rock burst, wherein rocks (mostly small pieces) suddenly and seriously collapse with a strong burst sound.

2.2. Discrimination Model of Rock Burst Tendency

Apart from using the apparent phenomenon of rock burst as a basis of qualitative discrimination and classification of rock burst behavior, the rock burst tendency can also be quantitatively determined by energy theory, thus achieving scientific and effective rock burst classification. According to energy theory, the occurrence of rock burst must meet two conditions: the energy condition and the strength condition. In the energy condition, apart from the energy released when the rock is damaged, there should be residual energy to make the rock peel or eject. Meanwhile, in the strength condition, the high stress level of the rock can eventually damage the rock. Energy theory briefly summarizes the conditions needed for rock burst, but it does not fully describe the lithology. Engineering practice has shown that rock burst usually occurs in hard/brittle formations. Thus, based on energy theory and engineering practice, the strength brittleness index \( R \) and elastic energy index \( W \) are selected to evaluate rock burst in deep wells.

2.2.1. Elastic energy index \( W \)

The elastic energy index \( W \), which is widely used in the assessment of rock burst tendency, was first proposed by Neyman in 1972 in investigating coal-mining problems[26]. The concept behind this index is clear, and the method is simple. As shown in Figure 1, the rock sample is uniaxial loaded to 70%–80% of its compressive strength \( (\sigma_c) \), after which it is unloaded to 5% of its compressive strength. The elastic strain energy released by unloading and the dissipated elastic strain energy are represented by \( \phi_{sp} \) and \( \phi_{st} \), respectively. The ratio of the two strain energy values is the elastic energy index \( W \) given by:

\[
W = \frac{\phi_{sp}}{\phi_{st}}.
\]

In the elastic energy index, also known as impact tendency index, the larger the index, the greater the energy released during failure. The accumulated elastic strain energy of the rock is the main internal factor of rock burst. From the aspect of energetics, rock burst also refers to the process of releasing the accumulated elastic strain energy of the surrounding rock, in which the greater the energy accumulated, the greater the released energy and the stronger the intensity of the rock burst. The elastic strain energy index can be used to quantitatively determine the accumulation capacity of elastic strain energy.

2.2.2. Rock strength brittleness index \( R \)
Rock burst usually occurs in brittle rock formations and is not only related to uniaxial compressive strength but also to the tensile strength of rock. Therefore, the rock burst tendency can be evaluated according to the ratio of uniaxial compressive strength $\sigma_c$ to tensile strength $\sigma_t$ expressed as

$$ R = \frac{\sigma_c}{\sigma_t} $$

where $\sigma_c$ is the rock uniaxial compressive strength, MPa, and $\sigma_t$ is rock tensile strength, MPa. Generally, a larger $R$ means that a piece of rock is more brittle and has a greater tendency to undergo rock burst.

The elastic energy index $W$ reflects the energy conditions, whereas the rock strength brittleness index $R$ reflects the lithology and strength conditions. The two indexes are independent but also complementary to each other. The possibility of rock burst can be better described better by combining these two indexes.

3. Experimental Scheme and Result Analysis

3.1. Experimental Sampling, Equipment, and Scheme

The dolomite, limestone, and shale samples of the Longmaxi, Linxiang, and Xixiangchi formations in South China were selected in order to study the rock burst behavior of the surrounding rocks in the hard/brittle strata of deep wells. The coring depths ranged from 2032.15–7299.23 m. The rock mechanics experiments of the uniaxial compression and tensile strengths were carried out systematically. All the test methods were recommended by the ISRM. The uniaxial compression tests adopted the standard sample of $\Phi 25 \times 50$ mm. The flatness of the end face of the rock samples was controlled within 0.02 mm. The tensile tests adopted the cylinders with a diameter of 25 mm ± 1, and the thickness was cut to 0.25–0.75 times of its diameter.

The rock uniaxial compression tests were conducted using the triaxial stress test system of Terratek. The axial loading mode was controlled by the strain loading mode at loading rates ranging from 6 to 10 mm/s. The axial and radial strains were monitored during the whole test. The tensile tests were conducted using the Terratek Brazilian cleaver. The loading rates ranged from 0.035–0.05 MPa/s.

3.2. Analysis of Experimental Results

In this study, 41 sets of uniaxial compression and tension tests were carried out for the shale, limestone, and dolomite formations of different depths. The experimental results are shown in Table 1. According to the morphologies of the rock samples after rupture and the sounds observed during rupture, the intensity of rock bursts were divided intuitively into three types: weak, medium, and strong rock bursts. The statistics are presented in Table 1.

3.2.1. Weak rock burst

The rock burst morphology shows that the ruptured rocks formed multiple cracks. Moreover, the rocks were broken along the weak bedding surfaces. Meanwhile, the main structure of the sample remained intact. This process is often accompanied by a faint cracking sound, as shown in Figure 2 (a).

3.2.2. Medium rock burst

The rock burst morphology is characterized by rock rupture resulting in the formation of a large block fracture. The fractures are sharp, showing typical fracture characteristics and accompanied by obvious cracking and explosion sound, as shown in Figure 2 (b).

3.2.3. Strong rock burst

This kind of rock burst is characterized by the gradual transition of blocks from flakes to irregular ones. Then, under less strain, the rock blocks suddenly burst into smaller block groups. The rock sample's main body shows a typical fragmentation pattern, which is often accompanied by a strong sound of fragmentation and explosion, as shown in Figure 2 (c).
Table 1. Results of rock mechanics experiments

| No. | Sample | Depth | Lithology   | Uniaxial compressive strength (MPa) | Tensile strength (MPa) | Rock burst intensity | No. | Sample | Depth | Lithology   | Uniaxial compressive strength (MPa) | Tensile strength (MPa) | Rock burst intensity |
|-----|--------|-------|-------------|-------------------------------------|------------------------|---------------------|-----|--------|-------|-------------|-------------------------------------|------------------------|---------------------|
| 1   | py1-1  | 2032.15 | dolomite   | 75.16                                | 9.12                   | strong              | 22  | py11-2 | 4189.47 | limestone | 48.1                                | 7.77                   | medium              |
| 2   | dy1-1  | 2057.75 | limestone  | 78.44                                | 12.78                  | medium              | 23  | dys1-9 | 4191.58 | shale     | 56.21                               | 11.47                  | weak                |
| 3   | py1-2  | 2106.32 | shale       | 100.39                               | 5.77                   | strong              | 24  | dys1-1 | 4191.62 | limestone | 106.67                              | 14.17                  | strong              |
| 4   | py1-3  | 2153.15 | shale       | 113.76                               | 7.96                   | strong              | 25  | dys1-2 | 4198.17 | dolomite  | 100.07                              | 9.31                   | strong              |
| 5   | zhy1-1 | 2158.27 | dolomite   | 42.32                                | 7.11                   | weak                | 26  | dys1-3 | 4219.4  | limestone | 101.26                              | 15.55                  | medium              |
| 6   | zhy1-2 | 2165.78 | shale       | 43.47                                | 8.05                   | weak                | 27  | dys1-4 | 4219.45 | dolomite  | 136.62                              | 17.86                  | strong              |
| 7   | zhy1-3 | 2170.91 | limestone  | 70.28                                | 8.89                   | strong              | 28  | dys1-5 | 4219.49 | dolomite  | 177.04                              | 18.3                   | strong              |
| 8   | zhy1-4 | 2175.81 | shale       | 58.28                                | 7.93                   | medium              | 29  | dys1-6 | 4219.53 | shale     | 201.02                              | 18.48                  | strong              |
| 9   | zhy1-5 | 2178.3  | shale       | 13.87                                | 12.38                  | weak                | 30  | dys1-7 | 4223.89 | limestone | 175.74                              | 18.15                  | strong              |
| 10  | zhy1-5 | 2179.14 | shale       | 41.45                                | 6.93                   | weak                | 31  | dys1-8 | 4228.85 | shale     | 77.11                               | 10.59                  | medium              |
| 11  | zy1-1  | 2185.64 | limestone  | 39.02                                | 9.86                   | weak                | 32  | ls2-1  | 4357.02 | limestone | 67.09                               | 7.38                   | strong              |
| 12  | zy1-2  | 2185.72 | shale       | 49.33                                | 9.79                   | weak                | 33  | nyl-1  | 4413.43 | limestone | 146.81                              | 12.76                  | strong              |
| 13  | zy1-3  | 2185.76 | shale       | 61.92                                | 9.93                   | medium              | 34  | ps1-1  | 5954.79 | shale     | 39.28                               | 11.06                  | weak                |
| 14  | zy1-4  | 2185.81 | dolomite   | 65.99                                | 10.27                  | medium              | 35  | ps1-2  | 5958.4  | limestone | 33.68                               | 5.65                   | weak                |
| 15  | dy3-1  | 2274.3  | dolomite   | 78.07                                | 12.12                  | medium              | 36  | ps1-3  | 5958.4  | dolomite  | 49.14                               | 6.81                   | medium              |
| 16  | zy1-5  | 3173.45 | shale       | 101.03                               | 13.78                  | medium              | 37  | ps1-4  | 5964   | shale     | 40.48                               | 10.42                  | weak                |
| 17  | dy4-1  | 3731.66 | dolomite   | 114.32                               | 10.88                  | strong              | 38  | ps1-5  | 5964.11 | shale     | 48.8                               | 10.22                  | weak                |
| 18  | dy5-1  | 3819.62 | dolomite   | 90.51                                | 12.12                  | medium              | 39  | ps1-6  | 5967.77 | limestone | 48.01                              | 10.17                  | weak                |
| 19  | yy1-1  | 3879.69 | limestone  | 123.12                               | 14.18                  | strong              | 40  | ms1-1  | 7120.5  | shale     | 102.85                              | 24.1                   | weak                |
| 20  | yh1-1  | 3980.5  | shale       | 43.99                                | 9.39                   | weak                | 41  | ms1-2  | 7299.23 | limestone | 148.21                             | 21.94                  | medium              |

According to the stress–strain curve, we can see that the degree of rock burst is related to the full stress–strain, which is manifested as follows:

(1) For cores with or without weak rock burst, once the uniaxial compressive strength is reached, the rock samples continuously absorb the axial pressure energy through volume deformation. This is reflected in the stress–strain curve, which shows that, as the stress decreases slowly, the axial and radial strains expand obviously. The stress–strain curve decreases smoothly until it finally reaches the steady-state residual stress, as shown in Figure 3(a).

(2) For medium rock burst cores, the stress–strain curve shows an obvious drop (ranging from 20% to 60%) after reaching the uniaxial compressive strength. However, owing to the integrity of the main structure of the rock sample, it still has the ability to absorb axial stress. The stress–strain curve rises slightly after a sudden fall until it finally reaches the steady-state residual stress, as shown in Figure 3(b).

(3) For strong rock burst cores, the rock does not enter the plastic yield stage with increasing axial pressure; instead, it reaches the uniaxial compressive strength directly from the elastic stage. The rock cracks rapidly and the stress–strain curve drops off instantly, often reaching zero. The rock sample cannot absorb excess energy by expanding its capacity. Furthermore, the stress–strain curve does not increase with increasing axial pressure, as shown in Figure 3(c).

(a) Weak rock burst
(b) Medium rock burst
(c) Strong rock burst

Figure 2. Different fracture patterns of rock burst intensities in uniaxial compression tests
4. Analysis of Rock Burst Tendency

4.1. Index Analysis of Rock Burst Tendency

4.1.1. Elastic energy index

The scatter plot of the relationship between rock burst grade and rock elastic energy index is plotted based on the experimental results. Although the data distribution is discrete, the elastic energy index $W$ reflects the occurrence trend of rock burst to a certain extent, as shown in Figure 4. (1) $W < 2$ indicates weak rock burst, (2) $2 \leq W < 3.7$ indicates medium rock burst, and (3) $W \geq 3.7$ indicates strong rock burst.

For rock mass in the linear elastic state, the work done by the external force is basically equal to the elastic energy stored inside the rock mass, with a dissipated energy close to 0. In the course of rock failure (after the peak), the increase of elastic energy in rock mass is lower than the increase of the external force; thus, the dissipated energy exceeds 0. Part of the dissipated energy is consumed by the development of internal rock damage, and the rest is converted into heat, kinetic, and sound energies. These sound and kinetic energies are related to rock burst in the field of engineering. Therefore, the higher the magnitude of the dissipated energy, the greater the amount of energy that may be developed into the dynamic failure of rock mass, thus increasing the likelihood of a rock burst occurrence. However, considering that the energy storage capacity of fractured rocks varies, mostly due to peak rock strength, historical confining pressure, and the difference in the required energy for rock bursts, assessing the tendency of rock burst based on the elastic energy index $W$ has certain limitations.

![Figure 4. Distribution diagram of the relationship between elastic energy index and rock burst degree](image)

4.1.2. Strength brittleness index

The rock strength brittleness index $R$ is calculated from the compressive and tensile strength of the rock. Figure 5 presents a scatterplot showing the relationship between rock burst degree and rock strength brittleness index at different well depths. As can be seen, the larger the value of $R$, the greater the brittleness of the rock and the greater the energy released during the failure process, thereby increasing the likelihood of rock burst. Specifically, $R < 6$ corresponds to a weak rock burst in which the stress drop characteristics are obvious. This is mainly caused by the energy release from deep longitudinal crack burst. Meanwhile, $6 \leq R < 7.5$ indicates a moderate rock burst in which tensile strength and shearing failures result in sharp larger-grained irregular blocks and rock fragments with sharp fractures. Finally, $R \geq 7.5$ indicates a strong rock burst in which tensile and shear failure have a combined effect, resulting in sudden cracking under a small amount of strain. This results in relatively small groups of rocks suddenly bursting out.
Therefore, given that other conditions (e.g., in situ stress and geological structure) are consistent, a higher rock brittle strength index means stronger rock brittleness, which makes it more prone to rock burst. The ratio of the tensile strength of rock and uniaxial compressive strength can be used to evaluate rock burst tendency.

4.2. Analysis of Rock Burst Tendency

The basic factors affecting the occurrence of rock burst in hard/brittle formations are the mechanical characteristics of the surrounding rock of a deep well, especially the compressive strength of rock. A rock’s uniaxial compressive strength is a mechanical parameter that can be easily obtained. Therefore, establishing the relationship among elastic energy index, strength brittleness index, and uniaxial compressive strength is conducive to the quantitative analysis of rock burst tendency. Moreover, further exploring the interaction between elastic energy index and strength brittle index and the rock burst tendency of different lithological rocks can promote the establishment of the rock burst tendency discrimination method for wellbore rocks in hard/brittle formations.

4.2.1. Analysis of the relationship between elastic energy index and uniaxial compressive strength of rock

The relationship between rock elastic energy index $W$ and uniaxial compressive strength $S_c$ is drawn from the experimental results of rock mechanics (see Figure 6). The relationship model between $W$ and $S_c$ is obtained by the following regression:

$$W = 0.6333e^{0.0143S_c},$$

where $S_c$ is the rock uniaxial compressive strength, MPa.

As shown in Figure 6, the relationship has a high coincidence rate for weak rock burst. However, the quantitative analyses of moderate and strong rock bursts show larger deviations.

4.2.2. Analysis of the relationship between strength brittleness index and uniaxial compressive strength of rock

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**Figure 5.** Distribution diagram of the relationship between rock strength brittleness index and rock burst degree

**Figure 6.** Relationship between rock elastic energy index and uniaxial compressive strength
Figure 7 shows the relationship between rock strength brittleness index $R$ and uniaxial compressive strength $S_c$. As can be seen, there is a positive correlation between the strength brittleness index $R$ and uniaxial compressive strength $S_c$:

$$ R = 0.4457S_c^{0.6319}, $$(4)

where $S_c$ is rock uniaxial compressive strength, MPa.

As can be seen, a higher uniaxial compressive strength means better rock energy storage property. Thus, the higher the strength brittle index $R$, the higher the risk of rock burst. Overall, the model shows good coincidence rates for weak and medium rock bursts and a large deviation for strong rock burst.

![Figure 7. Relationship between rock strength brittleness index and uniaxial compressive strength](image)

4.2.3. Analysis of the relationship between rock strength brittleness index and elastic energy index

The relationship between rock strength brittleness $R$ and elastic energy index $W$ is further explored in this section, and Figure 8 illustrates the interaction between the two. The relationship between strength brittle index $R$ and elastic energy index $W$ is expressed as follows:

$$ R = 3.852e^{0.1952W}. $$(5)

As shown in Figure 8, the relationship between $R$ and $W$ can be used to better analyze the rock burst tendency in a quantitative manner from which an effective classification of rock burst can be obtained. The model has good conformity for weak, medium, and strong rock bursts.

![Figure 8. Relationship between rock strength brittleness index and elastic energy index](image)

4.2.4. Analysis of rock burst tendency of three lithological rocks

The relationship between the $S_c$ and $R$ values of dolomite, limestone, and shale are plotted, and the results are shown in Figure 9. As can be seen, shale is basically distributed in weak rock burst areas. Limestone is distributed in areas with weak, medium, and strong rock bursts with less regularity, and dolomite is distributed in medium and strong rock burst areas. Thus, the overall sequence of the rock burst tendencies of lithological rocks is as follows: dolomite > limestone > shale.

![Figure 9. Interaction between uniaxial compressive strength and strength brittleness index of three types of lithological rocks](image)
Figure 9. Relationship between the uniaxial compressive strength and strength brittleness indexes of the three types of lithological rocks

As shown in the analysis above, the strength brittleness index $R$ and elastic energy index $W$ can be well obtained by using uniaxial compressive strength. However, the correlation between $R$ and $Sc$ is better than that between $W$ and $Sc$. In addition, the relationship between $R$ and $W$ is more advantageous in distinguishing rock burst tendency.

4.3. Discriminant Method of Rock Burst Tendency for Wellbore Surrounding Rocks in Hard/Brittle Formation

The discrimination method of the rock burst tendency of hard/brittle formations in deep wells based on the study of the rock burst tendency of dolomite, limestone, and shale is presented in Table 2. using this method can help explain the frequent collapse of blocks and the instantaneous collapse of wall rocks in hard and brittle formations, thus providing scientific basis for the design and implementation of effective prevention and control measures.

| Basis                      | Classification            | Weak rock burst | Medium rock burst | Strong rock burst |
|----------------------------|---------------------------|-----------------|-------------------|-------------------|
| Elastic energy index $W$   |                           | $<2$            | 2–3.7             | $\geq 3.7$        |
| Strength brittleness index $R$ |                       | $<6$            | 6–7.5             | $\geq 7.5$        |
| Damage characteristics and intensity | The rock is ruptured to form multiple cracks and is often broken along weak bedding surfaces. The main structure of the sample remains intact. | The rock burst morphology is characterized by rock rupture forming a large block fracture. The fracture is sharp, showing typical fracture characteristics. | The rock burst morphology is characterized by the gradual transition of blocks from flakes to irregular ones. Rock blocks suddenly burst into smaller block groups under less strain. The main body shows a typical fragmentation pattern accompanied by strong fragmentation and explosion sound. |
| Acoustic characteristics | accompanied by faint cracking sound | accompanied by obvious cracking and explosion sound | | |

5. Conclusions and Recommendations

- Based on experimental studies, rock burst theory can be used to explain the surrounding rock collapse of hard/brittle formations in deep-well drilling. The rock burst intensity can be reasonably classified according to the sound and apparent characteristics of rock fracture degree, which can be obtained through uniaxial compression tests.
- The rock strength brittleness index $R$ and elastic energy index $W$, which are determined based on rock mechanics experiments, indicate that both higher $R$ and $W$ values mean higher rock burst intensity. Furthermore, the $R$ and $W$ values have a good corresponding relationship with rock burst classification, which can be used to distinguish and classify the rock burst tendencies of wellbore rocks in hard/brittle formations. Our results show that the rock burst tendency of dolomite is higher than those of shale and limestone.
- The uniaxial compressive strength $Sc$ can be used to obtain the strength brittleness index $R$ and elastic energy index $W$. The quantitative discrimination and classification of rock burst tendencies can be achieved by performing the interactive analysis of $R$ and $W$, which can provide reasonable classification methods for hard/brittle formations encountered in deep wells.
- In this study, the method of identifying the rock burst tendencies of borehole wall rocks in hard/brittle formations is explored and studied. The structural characteristics, complex drilling conditions, and stress environments of deep formations must be further considered. In relation to this, the systematic investigation of the mechanisms of wellbore instability and the
theoretical method of prevention and control must be carried out in order to solve the problem of wellbore collapse and block in hard/brittle formations.

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