Stress-Electromagnetic Radiation (EMR) Numerical Model and EMR Evolution Law of Composite Coal-Rock under Load

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ABSTRACT: There is a close relationship between the electromagnetic radiation (EMR) evolution and the stress state during loading of composite coal-rock. In this research, the coal-rock EMR generation mechanism was studied and the stress-EMR numerical model was established. Finite element simulation and experiments were then used to verify their correctness, and EMR characteristics, evolution law, and the corresponding relationship between EMR and coal-rock state were studied in depth. The results show that the deformation cycle of “load compression—deformation release—load compression” occurs at coal-rock internal fractures, which together with friction make the formation of coal-rock alternating weak current sources, resulting in the EMR. In addition, the fracture structure is similar to capacitors with time-varying electric quantity and plate spacing. When the fracture is loaded, it will generate approximately sinusoidal EMR pulses whose amplitude is positively correlated with the degree of coal-rock damage. EMR will be exponentially attenuated and distorted at the medium junction when propagating, which does not affect signal characteristics. Meanwhile, EMR quality within 1.0−2.5 mm outside coal-rock is high, whose change is almost synchronous with source. EMR evolution has stages during loading, whose characteristics are different in each stress stage: In compaction and elastic stages, EMR remains stable for most of the time except for the abrupt change of 1−3 mV/m at the junction. In the yield, coal-rock transitions from elastic to plastic, and both EMR and stress increase rapidly as fracture expands. In the fracture stage, EMR maintains high and produces a peak that is synchronous with the stress. After fracture, they drop and recover to stability. The research results will help improve the basic theory of coal and rock dynamic disasters and provide support for its prediction with multi-information fusion, which will help reduce the adverse impact of coal mine disasters on people’s lives and property.

1. INTRODUCTION

In recent years, with the deepening of coal mining depth, dynamic disasters such as coal and gas outburst have become more and more frequent, which has laid a hidden danger for the safety production of coal mines. Coal-rock dynamic disaster is always accompanied by the deformation and failure of coal-rock under load, so the perception of coal-rock stress state will be beneficial to prevent disasters. At present, a large number of scholars in various countries have gradually explained the corresponding relationship between coal-rock stress state and its failure mechanisms. As a characteristic signal of electromagnetic field, the variation of electromagnetic radiation (EMR) can be monitored by a noncontact sensor, which provides conditions for scholars to study the law of coal-rock under load in a noncontact way. To achieve this goal, the generation mechanism of EMR in coal-rock under load should be mastered first. At present, many scholars have preliminarily obtained some research results: By analyzing a large number of electromagnetic radiation data in coal mining, Chen et al. believed that the larger the deformation of coal-rock, the higher the corresponding EMR energy, which is a proportional relationship. Combined with the existing research results, Wang et al. found that the coal-rock’s load state and gas...
pressure in coal would directly affect the variation rule of EMR intensity, and gas pressure is positively correlated with EMR intensity. Lou et al.\textsuperscript{13} designed a full-wave acquisition device for coal-rock and found that EMR is sporadic and discontinuous, which is highly correlated with the loading state. In addition, the EMR signal spectrum contains a certain low-frequency component. Yao et al.\textsuperscript{14} established an internal relationship model of stress-electromagnetic based on multifractal theory and verified it in the field. Yin et al.\textsuperscript{15} believed that the sliding of coal-rock surface caused by force was an important source of EMR. Through experiments, Li et al.\textsuperscript{16} concluded that the stress would lead to the separation of internal electron pairs during loading of coal-rock, which directly made the electrification and caused samples to radiate the EMR signal with the frequency mainly at 2 kHz. Based on the piezoelectric theory, Yang et al.\textsuperscript{17} believed that EMR generation was related to the existence of piezoelectric materials in coal-rock and established the corresponding stress-magnetic field intensity coupling model. To sum up, existing results establish the coupling relationship between stress and EMR in the process of loaded coal-rock and give the corresponding numerical relationship or model between them. However, at the same time, the existing research on the microscopic explanation of the EMR source is still in its infancy, and the theory on the path of stress field on electromagnetic field is still insufficient. Therefore, there is still a lot of space to study the stress-EMR coupling model of composite coal-rock.

To clarify the EMR evolution law of loaded composite coal-rock and the influence of external conditions on it, scholars of various countries have carried out a large number of experiments and field investigations on the basis of the stress-electromagnetic coupling relationship. Through the analysis of these data, many relevant results have been obtained: Through field investigation and theoretical analysis, Qiu et al.\textsuperscript{18} found that the frequency component of EMR signal was very complex. After further study, they also found that coal-rock fracture was the result of aggregation of multiple internal fractures, and in this process, the low-frequency EMR of about 1 kHz was more sensitive than the high-frequency EMR. Song et al.\textsuperscript{19} analyzed the influence of compressive strength, physical and chemical composition, internal structure, and other factors on the evolution law of EMR and found that coal-rock’s EMR signal changed slowly, but it was the highest when a fracture occurs. Wang et al.\textsuperscript{20} monitored the EMR in the process of coal deformation, and the analysis showed that the higher the compressive strength, the higher the peak value of EMR intensity, which is similar to the form of EMR obtained by oscillating electric dipoles. Wang et al.\textsuperscript{21} found that a large number of EMR signals would be generated in the process of coal deformation, and the higher the degree of rock fracture, the stronger the EMR intensity, and the more pulses. Xu et al.\textsuperscript{22} collected and analyzed EMR signals in the whole process of coal rupture, and their study showed that EMR increased when stress changed suddenly. By changing the uniaxial loading rate of coal-rock, Xiao et al.\textsuperscript{23} studied the waveform and periodic characteristics of EMR at different stress stages. The study showed that the duration of EMR was at the millisecond level. Li et al.\textsuperscript{24} studied the transformation law between EMR energy and strain energy in the deformation process of loaded composite coal-rock, and their study showed that EMR energy changes have stages, which can be used to obtain the state of coal-rock. Xu et al.\textsuperscript{25} studied the influence of gas content on the changes of the EMR signal of coal. They believed that the more serious the coal damage, the stronger the EMR intensity. Although gas concentration had an impact on EMR parameters, it had different effects on each parameter. To sum up, the existing results have systematically analyzed the corresponding relationship between the variation of EMR and deformation of coal under load, and they are beneficial for predicting the trend of coal-rock failure and preventing coal-rock dynamic disasters.

It is also discovered that the object of the current research is predominantly coal, not composite coal-rock. However, the actual coal mine structure is a staggered distribution of coal seam and rock, which is different from samples in the research,\textsuperscript{26,27} so the existing research still has limitations. In addition, with the rapid development of disaster prevention technology in recent years, research on prevention methods based on multisource information fusion has become a hot topic in the future.\textsuperscript{28} Nevertheless, the existing research mostly analyzes the interaction between EMR, stress, and other information of composite coal-rock from the macroscopic experimental phenomenon, but only part of them analyze from the microscopic or physicochemical theory perspective. Therefore, to a certain extent, it limits the in-depth study of the numerical relationship between multisource information of loaded coal-rock. In conclusion, there is still much space to study loaded coal-rock EMR evolution law of internal and external at various stress stages from the theoretical perspective.

For the shortcomings of the existing research and the early warning needs of coal and rock dynamic disasters, the paper took the composite coal-rock with the combination ratio of 1:1:1 as the research object, analyzed the EMR generation mechanism from the microscopic, and deduced the stress-EMR coupling numerical model. Then, the evolution characteristics of stress field and electromagnetic field at different loading stages were studied by finite element simulation, and the propagation law of EMR, as well as the influence of stress and loading conditions on signal morphology, amplitude, and frequency parameters was studied. Finally, several uniaxial experiments were used to verify the theoretical analysis and summarized the EMR temporal and spatial evolution law of loaded composite coal-rock. The research results of the paper are beneficial to improving the stress-EMR coupling model of loaded composite coal-rock and also have certain theoretical and reference significance for in-depth research on the prevention and control methods of coal and rock dynamic disasters based on multisource information fusion. In the future field application, the results of this research can make it possible to further realize the noncontact monitoring of coal-rock loading state. At the same time, it will also help people to master the monitoring methods of coal and rock dynamic disasters so as to further reduce the impact of disasters on people’s lives and property.

2. THEORY AND SIMULATION METHODS

2.1. EMR Generation Mechanism of Loaded Composite Coal-Rock. Existing studies have shown that composite coal-rock is a mixture with a complex internal structure, which is mainly composed of a large number of carbon, hydrogen, oxygen, nitrogen, and other elements of aromatic compounds and some mineral crystals. Under the action of van der Waals force, there are chemical bonds such as hydrogen bond, ionic bond, and covalent bond among the molecules in coal-rock, and thus forms many particles or regions with different physical and chemical characteristics. These heterogeneous characteristics make the internal structure of composite coal-rock unstable, and lead to the existence of a large number of original pores and
micro-cracks in it without loading,

which provides the structural basis for the generation of EMR.

The EMR generated by composite coal-rock is an electromagnetic wave, which is closely related to the micro current changes. The generation mechanism of the micro current is also consistent with the electromagnetism theory, that is, it is essentially the directional motion of charge inside the coal-rock, and the quantity of charge and its directional movement direction will directly affect the characteristics of micro current, which has been confirmed by the existing literature. However, in the existing literature, researchers have not fully elucidated the source, the direction of motion of the charge forming the micro current, and the reason for its variation, which is not conducive to further analysis of the variation of EMR. As a result, the formation of micro current, the direction of charge directional motion, and the variation of the current are analyzed as follows.

According to the thermodynamics laws, any particles that make up the material are in random motion, so it can be known that when not loaded, the charge in the coal-rock is also in motion without rest. As mentioned above, the essence of micro currents is the directional movement of charged particles, in which it is necessary that these charges have a uniform direction of movement. Before there is no directional movement, the movement of different charges will cause the electric properties of particles to neutralize, so it is difficult to form a stable potential difference throughout the coal-rock, let alone there will be no micro current. In conclusion, it is not possible to generate EMR signals when coal-rock is in the nonloading stage. In conclusion, it can be seen that when coal-rock is in the nonloading stage, it does not have the conditions to generate EMR signals, which has been verified by a large number of experiments. However, this steady-state balance is very fragile and easily broken by many external factors. During loading, because of the existence of original cracks and the different particle properties, it is easy to make imbalance of the internal force of the coal-rock so as to promote the local stress concentration, and finally cause coal-rock deformation to break the steady-state balance before loading. And the phenomenon is more likely to occur among particles with different physical and chemical properties. When the local stress inside the coal-rock meets the mechanical condition of crystal fracture, the stable chemical bond or hydrogen bond between the molecules will be destroyed, resulting in an equal amount of heterogeneous free charge on both sides of the fracture, and the electric field will be formed between fracture’s surfaces, which provides conditions for the formation of weak current inside the coal-rock.

As can be seen from the above analysis, the physical and chemical characteristics of the two sides of most fractures in coal-rock are different, so the dielectric constants of the materials on both sides of the fractures are not the same when analyzing the fracture inside different micro-unit. In addition, composite coal-rock is a mixture with a complex structure, so the original and new fractures in it can be equivalent to numerous different micro capacitors. When the composite coal-rock is under load, the distance between coal-rock’s fractures changes constantly, and the contact and friction occur at the same time, which further promotes the generation of many time-varying weak currents inside it. The generation mechanism of weak current signal at composite coal-rock internal fractures is shown in Figure 1.

The following is to analyze the generation rule of weak current at each stage in the closed-loop process proposed above by taking a micro-unit containing fracture in the loaded coal-rock as objects. The analysis is as follows: In the initial stage without loading, the charge distribution on both sides of the composite coal-rock is uniform, and there is an initial distance between the two surfaces, at which no weak current is generated. When loading begins, the two surfaces of the internal fracture are closed by external forces and rub against each other. At this time, the force of some particles or crystals in the two surfaces will gradually be greater than its compressive strength, which causes the fracture and recombination of the original chemical bonds or hydrogen bonds between some molecules so as to rapidly generate an equal amount of heterosign charge at the fracture and achieve a new charge balance under the electrostatic effect finally.

In the process of approaching a balance, all kinds of charges only move between the two fracture contact surfaces, and no directional movement occurs on the outside, which does not meet the current generation conditions. Therefore, there is no weak current signal change at this stage. After that, due to the existence of many short intervals during loading and the continuous transformation between different energies, the elastic strain energy of the coal-rock will also be released. Meanwhile, some original fractures may also have plastic
deformation, resulting in further fracture and making a tiny fracture with a distance of \( d' \) between the surfaces. This process disrupts the newly formed charge balance at the fracture and produces the same amount of different isolated charges on both sides of the fracture. To achieve charge balance again, according to the electrostatic induction theory, the outer side of the micro-unit where fracture is located will induce charges different from the contact surface during deformation release, which will gradually form an electromotive force on the outer side of the micro-unit. In addition, composite coal-rock, as a semiconductor, has certain electrical conductivity.\(^{35}\) Therefore, driven by the induced electromotive force, the excess negative charge outside micro-unit will directionally move in the external coal-rock and will form a weak current \( i \) with changing intensity in a short time. However, this weak current \( i \) does not always exist. When the deformation release is completed or the external charge amount is the same as the fracture contact surface, the micro-unit containing fracture will achieve balance of charge again, which is not satisfied with weak current generation condition, that is, \( i = 0 \). But due to the presence of isolated charges, the electric field will still exist between two fracture surfaces, which is similar to a capacitor. After that, continuous loading will again destroy the balance of charge formed after deformation release, and coal-rock’s internal fractures repeatedly close and friction. At this point, the charge on the contact surface recombines into lots of new electron pairs because of van der Waals force, and the isolated free charge is reduced, which makes the amount of induced charge outside the micro-unit begin to decline. To achieve charge balance again, the surplus negatively induced charges in the deformation release stage will move in opposite directions in external coal-rock medium, thus forming a reverse weak current \( i \). When the charge is again conserved, the weak current \( i \) disappears again, and then coal-rock will enter the deformation release stage again, recirculating the closed-loop process described above.

According to the above analysis, multiple weak currents in different directions would be continuously generated inside the composite coal-rock in the closed-loop process, which further generated a lot of different alternating current sources inside the coal-rock. The weak current from these sources continuously excites many electric fields in space, and under the superposition of these electric fields, the external time-varying electromagnetic fields are formed, which directly promotes the formation and change of EMR signal.

### 2.2. Establishment of Coal-Rock’s Stress-EMR Numerical Model

To facilitate the study, the composite coal-rock sample is divided into multiple micro-units according to the previous study of Li et al.\(^{28}\) and a micro-unit containing the original fracture in the composite coal-rock is randomly selected for analysis. According to Section 2.1, the regions on both sides of coal-rock’s internal fracture can be regarded as two media due to the heterogeneity of materials, that is, each region has its own dielectric constants. At the same time, the location of the original fracture in the micro-unit may not be centered, so the thicknesses \( d_1 \) and \( d_2 \) of the area on both sides may be different. Based on the analysis in Section 2.1 and Figure 1, the numerical relationship between stress and EMR of composite coal-rock under load is further deduced below.

According to the electromagnetic theory and Sun’s research results,\(^{56}\) the induced electromotive force \( U \) between the two contact surfaces of any fracture in loaded coal-rock can be expressed as eq 1.

\[
U(d', t) = \sigma'(d', t)\left[d_1/\varepsilon_1 - d_2/\varepsilon_2\right] + [\sigma'(d', t) - \sigma_0]/\varepsilon_0
\]

(1)

where \( U \) is the induced electromotive force, \( V \); \( \sigma'(d', t) \) is the amount of charge induced on the outside of the micro-unit, \( C; \) \( d' \) is the distance between the two surfaces of the fracture, which is the relative movement distance varying with time \( t \); \( m; \) \( \varepsilon_1 \) and \( \varepsilon_2 \) are dielectric constants on both sides of the fracture, \( F/m; \) \( \sigma_0 \) is the amount of transferred charge, \( C \); and \( \varepsilon_0 \) is the dielectric constant in vacuum, \( F/m \).

When the composite coal-rock is under load, the contact or friction process of its internal fracture can be regarded as the short circuit of fracture’s two contact surfaces, that is, the induced electromotive force \( U = 0 \) at this time. Substituting this boundary condition into eq 1, the relationship between the amount of induced charge \( \sigma' \) and transfer charge’s \( \sigma_0 \) as shown in eq 2 can be derived.

\[
\sigma'(d', t) = \frac{\sigma_0}{d_1/\varepsilon_1 - d_2/\varepsilon_2 + 1}
\]

(2)

From the above analysis, it can be seen that the relative distance \( d' \) between the fracture’s two surfaces and the amount of induced charge \( \sigma' \) outside the micro-unit are both variables related to time \( t \). To simplify the subsequent analysis, \( d' \) should be decoupled from \( \sigma' \). According to the analysis in Section 2.1, the amount of induced charge \( \sigma' \) is positively correlated with the relative distance \( d' \) when coal-rock is loaded, that is, \( \sigma' \) increases with the increase of \( d' \). Therefore, the relationship between them can be expressed by eq 3.

\[
\sigma'(t) \propto K \cdot d'(t)
\]

(3)

where \( K \) is the proportional correction coefficient.

At the moment of contact between the fracture’s two sides, there is still charge transfer outside the micro-unit in a short time, namely, \( \sigma_0 \neq 0 \), but the induced charge no longer exists, that is, \( \sigma'(t) = 0 \). On the premise of considering eq 3, this condition can be substituted into eq 2 to achieve the purpose of separating \( d' \) from \( \sigma' \). And the relationship finally obtained is shown in eq 4.

\[
\sigma'(t) = \frac{K \cdot \sigma_0}{d_1/\varepsilon_1 - d_2/\varepsilon_2 + 1}
\]

(4)

By substituting Maxwell’s equations and electric field constitutive relation\(^{37}\) into eq 4, the expression of weak current generated externally in the process of fracture movement inside the loaded coal-rock \( J_{\text{f}} \) can be obtained as shown in eq 5.

\[
J_{\text{f}} = \frac{\partial D}{\partial t} = \frac{K \cdot \sigma_0}{d_1/\varepsilon_1 - d_2/\varepsilon_2 + 1} \frac{dd'}{dt}
\]

(5)

where \( D \) is the electric displacement vector, \( C/m^2 \), whose relationship with electric field intensity \( E \) and electric polarization intensity \( P \) can be expressed by eq 6.

\[
D = \varepsilon_0 E + P
\]

(6)

In the electric field analysis of composite coal-rock under load, the polarization effect almost does not exist, thus \( P = 0 \). Based on eq 6, eq 5 can be simplified to eq 7.

\[
\frac{\partial E}{\partial t} = \frac{K \cdot \sigma_0}{d_1/\varepsilon_1 - d_2/\varepsilon_2 + \varepsilon_0} \frac{dd'}{dt}
\]

(7)

In eq 7, \( (dd'/dt) \) is the separation movement rate between the two contact surfaces. Let \( v = dd'/dt \), which can be regarded as a
constant in a short time during loading. Equation 8 is obtained by integrating time \( t \) at both ends of eq 7.

\[
E(t) = \frac{K \sigma_0 v'}{\bar{d}_1 \varepsilon_0^2 / \varepsilon_1 - \bar{d}_2 \varepsilon_0^2 / \varepsilon_2 + \varepsilon_0} t
\]

where \( v' \) is the separation velocity of the two surfaces of the fracture, m/s. It is used to represent the separation velocity of the fracture’s surfaces.

Equation 8 reveals the relationship between fracture motion and electric field intensity, from which it can be known that when time \( t \) is constant, electric field intensity \( E \) is positively correlated with separation velocity \( v' \), and they have a linear relationship. In addition, it also can be seen from eq 8 that the electric field intensity \( E \) also will significantly increase with the amount of charge transfer \( \sigma_i \) increased in coal-rock. Although eq 8 establishes the relationship between fracture motion and electric field in coal-rock to a certain extent, it does not directly clarify the influence of coal-rock state, friction, and other factors on EMR. It can be seen from the analysis in Section 2.1 that the separation velocity \( v' \), as a variable that directly affects the change of electric field, is correlated with the state of coal-rock. In the following, a more intuitive stress-EMR numerical relationship is further derived through analysis of \( v' \).

Generally, the loading rate \( v \) of composite coal-rock is related to the natural environment or experimental settings, and the nature of the material itself has no influence on \( v \), so it can be regarded as a constant in a vertical downward direction during loading. The fracture separation velocity \( v' \) is one of the velocity components of the overall loading rate \( v \), and the fracture state (shape, force, etc.) will directly affect the value of \( v' \). However, because coal-rock has a complex internal structure and there may be further fracture after loading, the stress on each fracture in coal-rock is not the same, and it is also difficult to keep the balance of stress all the time. As a result, \( v' \) of each unit time is not constant even when analyzing the same coal-rock’s fracture, and the motion of each internal fracture all has acceleration \( a \) of different magnitude and direction in the whole process, which reflects the stress variation in the loading process of coal-rock. But when analyzed as a whole by the micro-unit, the resultant force and acceleration direction are vertical downward at any time.

Figure 2 shows the vector decomposition of stress and velocity at internal fracture of loaded composite coal-rock. It can be seen from Figure 2 that, when the composite coal-rock is under load, the force on the original fracture inside it meets eq 9.

\[
\sigma_1 - \sigma_i \cos^2 \theta - f \sin \theta = ma
\]

where \( \sigma_1 \) is the axial stress, Pa; \( \theta \) is the angle between the fracture and the horizontal direction, deg; \( f \) is the friction force on the contact surface, N; \( m \) is unit mass, kg; and \( a \) is the acceleration at each moment, m/s\(^2\). When loaded at a certain average velocity \( v \), the right end of eq 9 should be a small constant with a value close to 0. In fact, the axial stress \( \sigma_1 \) continues to increase with time \( t \), so the term containing \( \theta \) at the left end of eq 9 must decrease with \( t \), that is, the fracture will be stretched horizontally with the advance of loading process, which also promotes the breakage of fracture.

According to Figure 2, the average loading velocity \( v \) is decomposed into two velocity components along and perpendicular to fracture, which, respectively, promote the dislocation friction and opening and closing motion of the fracture. On the basis of eq 9, the average loading speed \( v \) can be obtained from eq 10.

\[
v = \frac{a t}{m} = \frac{\mu m^2 + 1}{m} \frac{\sigma_i (\sin \theta - \mu \cos \theta) \sin \theta}{m^2 + 1} = \frac{\mu m^2 + 1}{m} \frac{\sigma_i (\sin \theta - \arctan \mu) \sin \theta}{m^2 + 1}
\]

where \( \mu \) is the friction coefficient at the fracture, which directly relates velocity change to friction. When the coal-rock is loaded, the continuous opening and closing, contact, and dislocation of the internal fractures will increase the roughness between the two contact surfaces of the fractures, resulting in \( \mu \) increasing with time instead of always being a constant value. However, compared with \( \mu \) and \( \sigma_i \), the growth rate of \( \sigma_1 \) will be significantly greater than that of \( \mu \), so in general, the change of \( v \) is mainly determined by \( \sigma_1 \). Equation 10 also directly reflects the numerical relationship between friction, stress state, and EMR.

From the above analysis, it is easy to know that \( v' = v \cos \theta \), which is substituted into eq 8 and combined with eq 10, the stress-EMR numerical model of composite coal-rock under load as shown in eq 11 can be obtained.

\[
\left\{ \begin{aligned}
E(t) &= \frac{K \sigma_0 \mu \cos \theta}{\bar{d}_1 \varepsilon_0^2 / \varepsilon_1 - \bar{d}_2 \varepsilon_0^2 / \varepsilon_2 + \varepsilon_0} t \\
\sigma_1 &= \frac{\sqrt{\mu^2 + 1}}{m} \frac{\sigma_i (\sin \theta - \arctan \mu) \sin \theta}{m^2 + 1}
\end{aligned} \right.
\]

According to eq 11 and the above analysis, the axial stress \( \sigma_1 \) and friction coefficient \( \mu \) are directly proportional to the electric field intensity \( E \), and their variation trend is basically consistent. However, with the continuous advance of composite coal-rock loading, \( \theta \) will continue to decrease, and the separation rate \( v \cos \theta \) will increase, which will make the change of electric field intensity \( E \) more severe. In addition, the amount of transferred charge \( \sigma_i \) accumulated in fracture also has a great influence on the electric field intensity \( E \). According to the above analysis, the reason for its increase is mainly related to the friction and fracture movement of coal-rock’s fractures, so it and \( \mu \) could be regarded as the characteristic parameters of deformation and friction in the process of coal-rock loading.

2.3. Composite Coal-Rock Finite Element Mode and Simulation Method. To discuss the distribution of stress field and electromagnetic field of composite coal-rock under load, and to facilitate the verification of the generation mechanism of EMR mentioned above, the loaded composite coal-rock’s 3D finite element simulation model is established. On this basis, the 2D finite element simulation model of internal fracture of loaded composite coal-rock is also established, which is used to analyze internal fracture deformation and its influence on the change of electromagnetic signal during the loading.
As can be seen from Figure 3, the composite coal-rock 3D finite element model, the simulation model is mainly composed of air, coal-rock model, and internal fractures. The coal-rock model is a three-layer structure with a diameter of 50 mm and a height of 100 mm. According to the actual and previous research results, the materials of the coal-rock model from top to bottom are, respectively, set as “rock-coal-rock” and the volume ratio of each layer is 1:1:1. The outer air is spherical with a radius of 150 mm. In addition, the displacement compression motion along the Z axis is used to simulate the actual coal-rock loading process. The fracture position of the simulation model is determined according to stress’s simulation results of the model without fracture and material properties, which is located at a large gradient in the stress field. Compared with the direct determination of fracture location, this method is more conducive to the subsequent analysis of the generation and evolution of coal-rock EMR, and ensures that the conclusion is more reasonable and practical.

On the basis of the 3D model shown in Figure 3, the 2D finite element model of internal fractures of coal-rock is established as shown in Figure 4.

The finite element simulation models are mainly solved by three solvers: structural mechanics, electrostatic field, and moving grid, and these fields are coupled by indirect method. The mesh of the model is automatically divided according to the physical field, and the finer mesh precision should be selected. Especially, to observe the parameter changes near the fracture, the mesh near the fracture should use finer mesh precision than other places. During the simulation, the ambient temperature is set at 20 °C and the ambient air pressure is one standard atmospheric pressure. The specific simulation steps are as follows:

1. First, the loading process of coal-rock is simulated using the 3D composite coal-rock model without fracture at a loading speed of 0.1 mm/step. In the simulation, axial stress changes should be observed at all times. Then, the stress distribution nephograms should be analyzed to find the direction of the maximum stress gradient. And the position and shape of the fracture inside the coal-rock should be set accordingly.

2. The 2D model with fracture is loading at the speed of 0.1 mm/step. In the process, the nephogram of coal-rock also should be observed to analyze the stress change.

3. A probe is set near the fracture of the 3D model to record the stress change of coal-rock. Then, according to the data collected by the probe, the fracture deformation trend is analyzed under the same conditions using the J integral in the 2D model.

4. The 3D model with fracture is simulated at different loading speeds so as to obtain the electric field distribution nephogram at each stage of stress. At the same time, many probes are placed in coal-rock and air to sample the intensity of the electric field and then analyze the change in the character of the electromagnetic signal in space.

### Table 1. Physical Parameters Required for Simulation

| physical parameters | coal | rock | air |
|---------------------|------|------|-----|
| density (kg·m⁻³)    | 1450 | 2400 | 1.20|
| Young’s modulus (GPa) | 1.00 | 13.50 |
| friction angle (deg)   | 30   | 40   |
| cohesion (MPa)     | 1.00 | 2.06 |
| Poisson’s ratio    | 0.31 | 0.12 |
| dielectric constant (F·m⁻¹) | 3.50 | 6.00 | 1.00 |

3. SIMULATION RESULT AND ANALYSIS

3.1. Stress Field Distribution and Fracture Deformation Trend of Loaded Composite Coal-Rock. Figure 5 is the stress and equivalent plastic strain distribution of the composite coal-rock 3D model without internal fracture at different stress stages. Figure 5a–c shows the simulation results of loading to 8, 16, and 23 mm, which correspond to the three stages of elasticity, yield, and fracture in the process of coal-rock simulation. And their corresponding positions in the stress–strain curves obtained by simulation are shown in Figure 6. Because the model has no internal fracture, there is no result diagram of the compaction stage in Figures 5 and 6. Figure 5d–f
shows the equivalent plastic strain distribution nephograms of Figure 5a–c, respectively.

As can be seen from Figure 5, the stress of composite coal-rock at different stress stages is all symmetrically distributed, whose contour lines are concentrated in an “O” shape from the outside to the inside, and the model tends to bulge outward with loading. At the same time, Figure 5 also shows that in each stress stage, the stress variation of coal-rock roof and floor is not as severe as that of coal. And the internal stress of roof and floor rock is much lower than that of the outside in the horizontal direction, but in the vertical direction, the stress at the coal-rock interface is significantly higher than outside, which is the opposite of the horizontal direction.

To determine the position and shape of internal fractures in composite coal-rock model for subsequent simulation, Figure 5 is analyzed in detail as follows: As shown in Figure 5a, in the elastic stage, the stress of the coal-rock model is mainly concentrated near the coal and rock interface and inside the coal, whose value is between 18 and 20 MPa. However, the internal stress contour is fuzzy at this stage and there is no fracture trend in the model.

According to Figure 5d, the equivalent plastic strain at all places inside the coal-rock model is lower than 0.6 in the elastic stage, so the model is dominated by elastic deformation. When the coal-rock model is loaded into the yield stage as shown in Figure 5b, the stress distribution nephogram changes significantly. At this time, the stress distribution in the coal is more concentrated, which can reach more than 24 MPa in the center, and the stress isolines become clearer. Compared with Figure 5a, the phenomenon of stress concentration at the coal and rock junction weakens in Figure 5b, while the stress in other areas begins to increase. At the same time, the fracture trend along the grid edge occurs in the coal of the model. Based on this, combined with Figure 5e, it can be seen that the equivalent plastic strain in the coal’s central area at this time is up to more than 6 and rapidly attenuates outward, which makes the fracture appear along the gradient descent direction, while the equivalent
plastic strain of rock is still at a low value, whose highest value is not more than 0.6. In conclusion, in the yield stage, elastic and plastic deformations occur simultaneously in the coal-rock model, and the plastic deformation trend of coal is higher than rock, so the coal of model is more prone to fracture from the center to the outside. When loading to the fracture stage as shown in Figure 5c, the simulation of the coal-rock model has been close to convergence. Compared with Figure 5b, the stress distribution of roof and floor rock in Figure 5c is similar to the previous stage, but the stress at the center of coal drops to about 23 MPa. In addition, combined with the analysis in Figure 5c,f, at the fracture stage the equivalent plastic strain of coal is up to 13, and the plastic deformation is the main way. Although the equivalent plastic strain of rock also has a certain increase, the increase is very small, so elastic deformation is still its main form.

At this stage, the fractures in the coal of the model will continue to extend inward, resulting in some transverse fractures. At the same time, splitting fracture also occurs in the center of the coal along the boundary of the model grid, while there is also no fracture trend in the rock. In summary, the fracture of composite coal-rock is shown in eq 12. To sum up, the simulation model established in this study has universality and credibility and can be used to further explore the variation law of EMR in the process of coal-rock loading.

Based on the results in Figures 5 and 6, a short-inclined fracture was set in the coal of the 3D composite coal-rock model, and the included angle γ of fracture was set as 38° according to the result of Yang et al. Then, the coal-rock model with fracture was simulated under the same conditions as Figure 5, and the result is shown in Figure 7.

It can be seen from Figure 7 that there is obvious stress concentration and outward diffusion at the two ends of the coal-rock internal fracture. At the same time, the stress isolines at the end of the fracture are denser and the gradient changes more greatly than other areas, which makes the two ends of fracture easier to reach the compressive strength, thus further extending and destroying the existing fracture.

On the basis of the 3D model analysis, under the same condition the 2D finite element model was used to analyze the evolution trend of fracture, and the results are shown in Figure 8. It can be seen from Figure 8 that the internal fracture of composite coal-rock has an obvious trend of extension and deformation during loading. As shown in Figure 8a, the J integral of the area near two ends of the internal fracture is 16.5723 and 17.1250, so it can be seen that the loading will make the internal fracture extend to both sides along the original direction. Meanwhile, it can be observed from Figure 7b that the displacement directions of the fracture’s two surfaces are opposite in the loading process, so the fracture tends to move in reverse. It will make the shear force at both ends of the fracture more obvious and further promote the fracture damage, which is consistent with the results in Figure 5.

At the same time, Figure 8 also more intuitively reflects the changes of internal fracture in composite coal-rock under load. It can be seen that the shape of internal fractures is similar to the parallel plate capacitors, and the plate area will continue to increase with the loading advance. When the plate area increases, the chemical bonds at both ends of the original fracture are broken under the action of shear force, resulting in equal amount of different electric charges. In addition, the movement of the fracture makes the induction charge on the outside of the coal-rock, which is different from the fracture, and gradually causes charge to move in a directional direction, forming many sources of micro current inside the coal-rock. Finally, their synergistic effect will lead to the generation and change of EMR signals. The analysis results in Figure 8 are consistent with the theoretical analysis of the generation mechanism of EMR in Section 2, which also lays a foundation for the specific analysis of electrical field changes in the following text.

3.2. Electric Field Distribution Law of Loaded Composite Coal-Rock. 3.2.1. Establishment of Potential Function of Fracture Equivalent Capacitance. Based on the stress distribution analysis of composite coal-rock in Section 3.1, the electric field finite element model of coal-rock internal fracture was established as shown in Figure 9.

It can be seen from Figure 9 that the fracture of the electric field finite element model is equivalent to the capacitance where both the charge quantity and the distance between plates change with time, which is consistent with the stress field analysis results above. As the source of the electric field, the potential function of fracture equivalent capacitance should be set before simulation, whose form is analyzed and derived below.

Combined with the capacitance definition formula, the potential difference between the two surfaces of the internal fracture of composite coal-rock is shown in eq 12.

$$U_1 - U_2 = \frac{\mu q d'}{\varepsilon S}$$

where $U_1$ and $U_2$ are the electric potentials on two surfaces of the fracture, $V_t$ is the number of charged particles, $q$ is the unit charge, $C$, $\varepsilon$ is the dielectric constant between fracture, which is a constant; $S$ is the effective area of fracture, m².

Based on the above analysis of the stress field, the two surfaces of the fracture have the same amount of charge but opposite polarity. Therefore, when the electric potential at the center of the fracture is set to 0, the values of $U_1$ and $U_2$ are equal but the signs are opposite, that is, $U_1 = -U_2$. In addition, it can be seen from eq 12 that the change of the distance $d'$ between the
fracture two surfaces will have an effect on $U_1$. According to the analysis in Section 2.1, the increase and decrease of $d'$ is related to the closed-loop cycle process of composite coal-rock under load. When the fracture is in the process of loading closure, the $d'$ decreases, while increases in the deformation release process, that is, the distance $d'$ change periodically during loading, whose frequency is $f$. For the same fracture, the separation velocity $v'$ of the fracture is positively correlated with the loading velocity $v$, so the frequency $f$ will be affected by the loading speed $v$, that is, the larger $v$ is, the shorter the time for the fracture to complete an opening and closing motion, thus leading to the increase of $f$.

Assuming that the change of the fracture movement speed $v$ is a cycle of “0—acceleration—deceleration—0”, the potential function of the fracture equivalent capacitance can be expressed by eq 13.

$$U_1 = \frac{nqd_m}{2\varepsilon S} \sin(nf(v) \cdot t + b_0) \tag{13}$$

where $d_m$ is the maximum value of $d'$ in a closed-loop cycle of loaded composite coal-rock, m. Although $d_m$ increases with loading before the coal-rock broke, the increase rate is very small, so $d_m$ can be regarded as a constant in adjacent closed-loop cycles; $f$ is the opening and closing movement frequency of the fracture, Hz, which is a function positively related to the average loading rate $v$, and $v$ could be calculated by eq 10. $b_0$ is the initial phase of fracture, which is related to the initial state of coal-rock.

It can be seen from eq 13 that $U_1$ is also affected by the change of charge quantity $n$ and effective area $S$, but the change of $n$ and $S$ in adjacent periods is much smaller than its cardinal number, so it can be approximately constant in a short time. Therefore, it can be known from eq 13 that in each stress stage the change of internal fracture surface potential $U_1$ is approximately a periodic function. In addition, based on the analysis of eqs 13 and 10, it can be seen that $f$ is positively correlated with axial stress $\sigma_0$, and the change frequency $f$ of surface potential $U_1$ increases when loading advances.

3.2.2. Analysis of Electric Field Signal Form and Distribution Characteristics in Each Stress Stage. Based on eq 13 and above analysis, and referring to the results of Li et al. and Qiu et al., the electric field finite element model sets four frequencies ($f = 2, 4, 8, 12$ kHz) to calculate the potential $U_1$ of composite coal-rock in the early and middle elastic stage, the end of elastic stage, the yield stage and fracture stage, which is used to simulate the change of internal current source in coal-rock model. The simulation starts from the beginning of the deformation release after the internal fracture is closed for the first time due to loading. To obtain the form of electric field characteristic signals in the air at different stress stages, any point in the air near the coal-rock model was selected to monitor the characteristic signals in the air at different stress stages, any point in the air near the coal-rock model was selected to monitor the change of electric field intensity within $1$ ms. Finally, the change curve of the electric field intensity in the air at different stress stages is shown in Figure 10.

It can be seen from Figure 10 that the curves of electric field intensity variation in air outside composite coal-rock under different stress states are similar in shape, which are continuous pulses of approximately sinusoidal signals. And the frequency of electric field intensity change is the same as the frequency $f$ of fracture opening and closing, so it can be considered that each fracture opening and closing can correspond to an electric field intensity pulse. It can also be seen from Figure 10 that the amplitudes of the four electric field intensity pulses are $31.57, 33.68, 47.92,$ and $61.02$ V/m, respectively, which increase with the loading advance.

In conclusion, the change of electric field in air of loaded composite coal-rock is related to the periodic deformation of internal fracture, and the change of stress stage does not affect the pulsation form of electric field strength but has an impact on its peak value. The later the stress stage of coal-rock, the more
severe the deformation of its internal fracture, which leads to the increase of the electric field intensity pulsation peak value. Therefore, the higher the peak value of the measured electric field intensity pulsation in the air, the more serious the internal damage of the coal-rock.

The above analysis indicates that at different stress stages, the opening and closing laws of the composite coal-rock’s internal fractures and the variation laws of electric field intensity are similar. Therefore, it is possible to take the electric field distribution of coal-rock’s internal fracture in a single deformation cycle (from the start of deformation release until the deformation release is ready again) during the middle and early elastic stage as an example to investigate the variation law of electric field distribution of loaded composite coal-rock. Figure 11 shows the electric field distribution nephogram of the loaded composite coal-rock model in any single deformation period, in which the isolines are the electric field strength modulus and the arrow points to the direction of electric field strength.

Figure 11 shows that when the two surfaces of the internal fracture reciprocate, the electric field intensity and electric potential inside and outside the coal-rock will change accordingly. Both the electric field strength and electric potential propagate outwardly in a ring from the fracture in the whole loading process, but they are obviously distorted at the center between the fracture of two surfaces and the interface between composite coal-rock and air, which is different from the annular characteristics of other parts. In addition, it can be seen that the distribution of electric field inside and outside the composite coal-rock is different in the loading process. The following is a specific analysis based on Figure 11.

1. As shown in Figure 11a, when the fracture inside the coal-rock is closed for the first time due to loading and begins to expand, the electric field intensity inside and outside changes but is very weak. At this time, the electric field intensity near the fracture is the largest, but only up to $10^{-5}$–$10^{-6}$ V/m, and that of air is close to 0, which is difficult to detect.

2. Figure 11b is the electric field distribution nephogram during the coal-rock deformation release. As can be seen in the figure, the charge amount on the fracture will increase in this process, and the electric potential of each point of coal-rock and air will increase compared with before. Meanwhile, the isolines of electric field intensity in the space are dense and the variation gradient in the region is large, so it can be seen that the electric field intensity changes dramatically. At this point, the electric field intensity near the internal fracture is 70.012 V/m, the electric field intensity in the air near the coal-rock is 13.972 V/m, and the electric potential on coal-rock’s outer surface can reach 0.259 V. In addition, it can also be seen from Figure 11b that the electric field intensity at two ends of the internal fracture changes most dramatically in the process of the deformation release of coal-rock, and its maximum value is 287.290 V/m, which is much higher than that in other areas. So, the characters of this moment are completely consistent with the EMR generation mechanism and stress field analysis mentioned above. In summary, the characteristic parameters of the coal-rock electric field change dramatically and increase rapidly in the process of deformation release.

3. As shown in Figure 11c, in the process of internal fracture closure due to loading again, the electric field intensity in the edge area of internal fracture and the adjacent air of coal-rock can reach 39.787 and 4.457 V/m, respectively. Thus, it can be known that the electric field intensity at this stage is still at a high level. The electric field distribution of coal-rock at this stage is similar to the deformation release process. There are closed electric field strength isolines at the interface between air and coal-rock in both stages, which proves that the electric field strength at the boundary has distortion and symmetry characteristics. Moreover, it can be seen that in this stage, although the gradient of electric field intensity isolines around the fracture is more obvious than other areas, and...
the variation of electric field intensity at two ends of the fracture is still the most drastic, its amplitude has been not as prominent as Figure 11b, which is related to the continuous decrease in the amount of induced charge at the fracture during the process.

(4) As the loading continues, the fracture tends to close again, and the electric field intensity and potential at each point of coal-rock model decline rapidly. When the fracture closes to the maximum under compression, the electric field distribution is shown in Figure 11d. It can be seen that the electric field intensity of the composite coal-rock is very weak at this time, and the electric potential magnitude at each point is under $10^{-13}$ V. Moreover, the electric field intensity in the air will become close to 0 again, which is difficult to detect. After the fracture is pressed to the limit, it will enter the deformation release stage again, and the process of Figure 11a−d is repeated until the coal-rock is completely broken.

In conclusion, the variation of electric field distribution in the process of coal-rock under load is periodic, and the electric field strength and potential will rise and fall continuously with the reciprocating movement of fractures. This change rule is consistent with the theoretical analysis above.

3.2.3. EMR Space Propagation and Distribution Law of Composite Coal-Rock under Load. EMR comes from the electromagnetic field, which is essentially a wave energy. Electromagnetic field includes electric field and magnetic field, and the two excitation energy values are equal\[14\] so the study of EMR only needs to consider the change of electric field without the magnetic field. As an important physical quantity of electric field, the variation of electric field intensity can be used to represent the variation of EMR.

To study the propagation law of EMR signal inside and outside coal-rock, seven probes (no. a−g) were taken on the same axis outside the fracture, whose distance from air is 7 mm, and the electric field intensity at different positions was detected to obtain the EMR value in this area. The positions of the seven probes are shown in Table 2.

| no. | distance to fracture (mm) | description                  |
|-----|--------------------------|------------------------------|
| a   | 1                        | near the internal fracture   |
| b   | 2                        | near the fracture of the coal-rock |
| c   | 4                        | far from the fracture of the coal-rock  |
| d   | 6                        | the coal-rock side area near the interface of coal-rock and air  |
| e   | 8                        | the air side area near the interface of coal-rock and air  |
| f   | 11                       | air area near coal-rock      |
| g   | 16                       | air area far from coal-rock  |

Based on the above analysis, the signal form and variation trend of electric field strength in each deformation period of different stages are basically consistent. Therefore, the following sample analysis is only carried out on the composite coal-rock model in the middle and early elastic stage within 1 ms, and the results of electric field strength (EMR intensity) obtained are shown in Figure 12. As can be seen from Figure 12a, except for the EMR intensity curve near the internal fracture, which has significant distortion in each cycle, the time-varying curves b−g of the EMR intensity at other locations have the same trend, which are almost sinusoidal pulses. Moreover, the EMR intensity changes in all areas are basically synchronous without obvious delay effect, which also makes it possible to judge the state of coal-rock in real time using EMR changes externally.

As shown in Figure 12b, the EMR intensity inside and outside the loaded composite coal-rock has a nonlinear attenuation trend at different times. However, in the area near the interface 6−10 mm away from the fracture, the intensity of EMR outside is significantly higher than that inside, which results in the abrupt change of the signal at the interface, and it is consistent with the characteristics that curve e is higher than curve d in Figure 12a and the electric field has a closed isoline at the interface in Figure 11 above. In addition, it can also be found from Figure 12b that when the interface of coal-rock and air is taken as the boundary, the attenuation rate of EMR intensity in composite coal-rock is significantly higher than that in air.

When the interface between coal-rock and air is taken as the boundary, exponential fitting is carried out for the data at 6 moments in Figure 12b and the fitting results are shown in Table 3.

As can be seen from Table 2, no matter in the inner area of composite coal-rock or the air, when the EMR is not distorted, the relationship between the EMR intensity $E'$ and the distance $L$ to the fracture is an exponential function, and the correlation coefficient $R^2$ of all fitting curves is above 0.999, which has high reliability. However, the specific expressions of fitting results in the same area are different at different moments. Moreover, it can be seen that the variation range of the base of the exponential function obtained by fitting the EMR intensity $E'$ at different times in the same medium is relatively fixed, and the variation range in the composite coal-rock and air is between 0.57−0.60 and 0.77−0.90, respectively. Therefore, it can be seen that whether in coal-rock or air, the attenuation law of EMR intensity at different times is basically the same, except for amplitude. The curve fitting results of coal-rock and air shown in Table 3 generally conform to the electromagnetic wave equation in a single coal or rock medium proposed by Wang et al.\[42\] as shown in eq 14. And Figure 13 shows the curve results of fitting results in Table 3.

\[
E'(t, L) = E(t) \cdot e^{-\beta L + i(\omega t - \alpha L)}
\]

\[
\alpha = \frac{\omega \mu_b}{2} \sqrt{\varepsilon^2 + \left(\frac{\sigma_e}{\omega}\right)^2 + \varepsilon}
\]

\[
\beta = \frac{\omega \mu_b}{2} \sqrt{\varepsilon^2 + \left(\frac{\sigma_e}{\omega}\right)^2 - \varepsilon}
\]

(14)

where $E'$ is the EMR intensity with the distance $L$ from the electric field center, $V/m$; $E$ is the intensity of the source of the coal-rock, $V/m$ (the value changes with time $t$, and its variation law conforms to eq 11); $L$ is the distance, $m$; $\alpha$ and $\beta$ are phase shift constants and attenuation constants, respectively, which are only related to material parameters; $\omega$ is the angular frequency, rad/s; $\mu_b$ is the permeability, H/m; $\sigma_e$ is the electrical conductivity, S/m; and $\varepsilon$ is the dielectric constant, F/m.

Composite coal-rock and air as different media, their own dielectric constant $\varepsilon$, magnetic conductivity $\mu_b$, electrical conductivity $\sigma_e$, and other physical parameters are different. According to eq 14, when the source of electric field $E$ is constant and the distance $L$ is similar, the electric field intensity $E'$ on
Figure 12. Simulation results of the EMR intensity propagation change. (a) Curve of EMR intensity with time and (b) attenuation curve of the EMR.

Table 3. Fitting Results of the EMR Intensity Attenuation Curves at Different Times

| area           | fitting result         | $R^2$  | area           | fitting result         | $R^2$  |
|----------------|------------------------|--------|----------------|------------------------|--------|
| 0.06 ms coal-rock | $E' = 1.54 + 73.88 \times 0.60^L$ | 0.9998 | 0.06 ms air    | $E' = 1.72 + 67.37 \times 0.74^L$ | 0.9997 |
| 0.10 ms coal-rock | $E' = 9.11 + 158.89 \times 0.58^L$ | 0.9950 | 0.10 ms air    | $E' = 1.07 + 39.91 \times 0.88^L$ | 0.9999 |
| 0.14 ms coal-rock | $E' = 9.29 + 257.55 \times 0.58^L$ | 0.9983 | 0.14 ms air    | $E' = 3.75 + 130.44 \times 0.77^L$ | 0.9998 |
| 0.16 ms coal-rock | $E' = 4.31 + 371.13 \times 0.59^L$ | 0.9990 | 0.16 ms air    | $E' = 6.98 + 70.77 \times 0.90^L$ | 0.9999 |
| 0.38 ms coal-rock | $E' = 7.64 + 244.02 \times 0.57^L$ | 0.9991 | 0.38 ms air    | $E' = 3.84 + 130.36 \times 0.76^L$ | 0.9998 |
| 0.42 ms coal-rock | $E' = 1.70 + 110.36 \times 0.60^L$ | 0.9993 | 0.42 ms air    | $E' = 2.51 + 65.22 \times 0.77^L$ | 0.9998 |

Figure 13. Data fitting curves at different moments. (a–f) Fitting curve at 0.06, 0.10, 0.14, 0.16, 0.38, and 0.42 ms, respectively.
both sides of the interface of different media will change significantly so that the electric field intensity in air and coal-rock, namely, the attenuation curves of the EMR intensity, are different. Figure 13 fits this feature, but at the same time, it also magnifies the curve features of Figure 12, from which it can be seen that EMR has obvious distortion points at the interface between coal-rock and air. Although the whole results cannot directly meet the description in eq 14, they don’t affect the eq 14 feasibility. The distortion at the interface is related to the electric field boundary condition. In space, the electric field intensity $E'$ is a vector, and only its tangential component is continuous when it is at the interface of the medium, while the value of the normal component is different, which is related to the ratio of the dielectric constant on both sides. The electric field intensity $E'$ detected in the simulation and experiment is the modulus value of the vector, resulting in the mutation point at 7 mm in Figure 13, which also facilitates the detection of EMR signal changes in air to judge the state of coal-rock. It can also be seen from Figure 13 that the discontinuity of internal and external $E'$ restrains the continuous attenuation characteristics in a single medium, resulting in a larger EMR signal in the air which is far from the fracture than in the coal-rock within the ±2.5 mm area of the interface. In addition, it can be seen that the EMR in air is large in the range from 1.0 to 2.5 mm from the coal-rock surface and its variation characteristics are obviously without distortion. Therefore, to collect the electromagnetic radiation signal without contact in practice, the probe could be kept within this range to avoid distortion.

In summary, combined with Section 3.2, the EMR signal distribution law of loaded coal-rock in each stress stage is obtained: The closed-loop motion of the fracture inside the loaded composite coal-rock is the source of the EMR signal, which basically attenuates exponentially but is not continuous when propagating outward. In addition, EMR signals will be distorted at the edges of fractures and the interface between coal-rock and air, but this will not affect the overall smoothness and basic characteristics of the EMR. At the same time, EMR signal is a group of pulses with different amplitudes, which increases with the progress of loading, and the higher the pulse amplitude is, the more serious the damage of coal and rock will be. And when other conditions are the same, the higher the loading rate, the higher the amplitude of the EMR pulse.

4. EXPERIMENTAL ANALYSIS

4.1. Experimental Scenes and Specific Steps. To verify the correctness of the EMR model of loaded composite coal-rock and the evolution law of the EMR signal obtained from the simulation established above, multiple groups of uniaxial loading experiments of composite coal-rock with different loading rates were carried out in the experimental scene shown in Figure 14.

As can be seen from Figure 14, the experimental object is the cylindrical three-layer coal-rock sample, whose upper and lower layers are sandstone and the middle layer is raw coal from a coal mine in Datong, Shanxi Province, China. Each layer is bonded to each other, and their volume ratio is 1:1:1. The height and bottom diameters of all samples were 100 and 50 mm, respectively.

From Figure 14, it can also be seen that the experimental equipment consists mainly of the SANS universal test press, rock mechanics loading system, metal shield, and EMR monitoring system. SANS universal test press can realize the loading process of samples under the control of rock mechanics loading system and can monitor the changes in samples’ stress and strain in real time. In addition, its maximum load can reach 300 kN, which can meet the requirements of experimental loading. The EMR monitoring system used in the experiment is mainly composed of the magnet antenna, signal conditioning circuit, NF5035 electromagnetic radiometer, and computer, and its signal acquisition range of the system can reach 1 Hz to 1 MHz. During the experiment, the system continued to collect EMR signal changes through an NF5035 electromagnetic radiometer and uploaded the relevant data to the upper computer so as to realize real-time display and storage of EMR data. The metal shielding cover is covered by 200 mesh copper mesh, which can shield the electromagnetic interference from the outside world and ensure that the electromagnetic variation measured by the EMR monitoring system is caused by the deformation of composite coal-rock under load.

Comparing the experimental system, environment, and other conditions with previous studies, it can be seen that the biggest difference between them lies in the sampling method of EMR signal. This experiment was through an NF5035 electromagnetic radiation detector to monitor EMR change data. Its recording performance and resolution are significantly improved compared with the self-made system used in previous experiments, which lays a foundation for further study of the variation law of EMR signal.
The specific experimental steps are as follows:

1. The composite coal-rock sample was placed in the center of the press. Then, the magnetic antenna of the EMR monitoring system was installed and suspended with insulated wire in the middle of the sample. According to the simulation analysis, the distance between the magnetic antenna and the sample surface was 3–5 mm.

2. The metal shielding cover was installed outside the sample, and nonessential equipment, lighting, and other electrical equipment around the laboratory should be closed to avoid the influence of the power frequency electromagnetic field on the data obtained.

3. Turned on the power, started the press, and synchronously opened the NF5035 of the EMR monitoring system and the recording monitoring software of the upper computer. First, the EMR signal intensity in the experimental environment was detected when it was not loaded. After that, the device was reset and ready to officially start the experiment.

4. At the beginning of the experiment, the press compresses the coal-rock sample uniaxial at the set displacement loading rate. During the process, the loading rate should be kept constant and the axial stress curve of the sample should be monitored in real time. When the axial stress reached the peak and the coal-rock was damaged, the loading should be stopped immediately.

5. The stress, strain, and EMR data recorded during the experiment are derived from the system. Steps (3)–(5) are repeated until the end of all experiments.

To fully verify the model and conclusion obtained above, four groups of different loading rates of composite coal-rock were set: 0.1, 0.3, 0.7, and 1.0 mm/min, and 20 identical composite coal-rock samples which were all collected from the same rock or coal mine under different mining intensities. Sixteen samples were randomly selected from the 20, numbered 1#–16#, and evenly divided into 4 groups according to the order, corresponding to 4 loading rates. To ensure the rationality of the analyzed data, these interference items should be filtered out before analysis.

Different interference items have different characteristics and can be filtered by different methods: The electromagnetic noise $E_0$ in the natural environment can be regarded as a constant function in a certain time, so it can be removed directly by measuring the bottom noise in the experiment. When coal-rock is under load, the power frequency harmonics within 11 times $E_{11} = E_{11}$ have an influence on the results. These harmonics are integer multiples of 50 Hz, so they have obvious periodicity. At the same time, $E_i$ is related to the movement of the press, and the frequency of cutting the magnetic induction line also has obvious periodicity. As can be seen above, both $E_0$ and $E_i$ are periodic signals, so their removal methods are similar. Therefore, the experiment referred to the previous results and used filtering algorithm to the original acquisition signal so as to improve the signal-to-noise ratio of EMR signal, and then achieve the expected goal. The average of the bottom noise measured for many times in the experiment is 5.81 mV/m. After that, all of the collected original EMR signals were filtered and de-noised. Finally, the size, compressive strength, and pretreated EMR peak of samples 1#–16# are shown in Table 4. According to the compressive strength and EMR peak value in Table 4, the variation trend of composite coal-rock characteristic parameters under different loading rates can be obtained, as shown in Figure 15.

### Table 4. Samples Size and Experimental Results

| no. | uniaxial loading rate (mm·min⁻¹) | height (mm) | diameter (mm) | compressive strength (MPa) | EMR peak (mV·m⁻¹) |
|-----|----------------------------------|-------------|---------------|----------------------------|------------------|
| 1#  | 0.1                              | 100.34      | 49.82         | 24.021                     | 68.699           |
| 2#  | 0.1                              | 100.18      | 49.94         | 23.575                     | 72.974           |
| 3#  | 0.3                              | 99.74       | 49.68         | 25.693                     | 79.868           |
| 4#  | 0.3                              | 99.86       | 50.06         | 23.221                     | 71.031           |
| 5#  | 0.3                              | 100.10      | 50.14         | 29.998                     | 91.286           |
| 6#  | 0.3                              | 100.02      | 50.04         | 27.576                     | 88.022           |
| 7#  | 0.3                              | 100.28      | 49.96         | 29.388                     | 90.214           |
| 8#  | 0.3                              | 100.12      | 49.96         | 28.024                     | 84.576           |
| 9#  | 0.7                              | 99.98       | 49.82         | 33.382                     | 97.446           |
| 10# | 0.7                              | 100.22      | 50.08         | 30.879                     | 98.210           |
| 11# | 0.7                              | 100.08      | 50.28         | 32.124                     | 100.055          |
| 12# | 0.7                              | 99.68       | 49.02         | 31.924                     | 99.434           |
| 13# | 1.0                              | 100.24      | 49.98         | 35.298                     | 197.652          |
| 14# | 1.0                              | 100.16      | 50.02         | 36.129                     | 120.724          |
| 15# | 1.0                              | 100.02      | 50.12         | 36.383                     | 121.307          |
| 16# | 1.0                              | 99.98       | 49.76         | 34.997                     | 195.325          |
from Table 4 and Figure 15 that the variation trend and characteristics of the EMR peak are consistent with the compressive strength, and the EMR peak values of different samples under the same loading condition also have discreteness. These are actual experimental errors, not errors. In summary, the characteristics of experimental data meet the theoretical analysis and simulation results above and effectively and indirectly verify the EMR generation mechanism of loaded composite coal-rock.

4.3. EMR Evolution of Composite Coal-Rock under Load. The variation trend of axial stress and EMR intensity of different composite coal-rock samples obtained in the experiment was similar under the same loading rate. Therefore, the relatively clear curve was selected among the four samples under different loading rates to further analyze the axial stress change and EMR evolution law. Variation curves of loading characteristic parameters of samples 2#, 5#, 9#, and 15# are shown in Figure 16.

By comparing Figure 16a–d, it can be seen that the axial stress and EMR intensity of samples under different loading rates have the same variation trend. So it is feasible to select any set of data for more specific analysis. In addition, it can be seen that the change curves of loaded coal-rock axial stress and EMR intensity have stages, and there is an obvious correspondence between their change characteristics. Moreover, the stress curves of each sample obtained in the experiment are similar to the simulation results shown in Figure 6. Therefore, the experimental curve can also be divided into four stages, namely, compaction, elasticity, yield, and fracture.

To verify the consistency of EMR characteristics obtained by the above simulation and experiment, the EMR curve in Figure 16b is used as an example to compare it with the EMR signal characteristics in the preceding simulation. Figure 17 shows the local amplification of the EMR in four stages of Figure 16b. As can be seen from Figure 17, EMR signals obtained in experiments at different stages are presented as approximately sinusoidal pulses of different amplitude, and the later the loading stage is, the higher the peak value of the signal is. There is some error between the EMR curve obtained in the experiment and the simulation, but it does not affect the consistency between the simulation and the experiment. The main reasons for the error are as follows: (1) The state of simulation is relatively ideal, but there are some gaps with the actual situation. (2) The EMR changes rapidly, and there are inevitable numerical errors when the system collects experimental data. Therefore, the conclusions obtained by simulation analysis in Section 3 have practical significance, which also makes it possible to further discuss and analyze the EMR evolution law of loaded composite coal-rock. Next, the 2# experimental results with a loading rate of 0.1 mm/min (Figure 16a) are taken as an example for specific analysis.

From Figure 16a, it can be seen that the EMR intensity variation characteristics of loaded composite coal-rock were different in each stress stage, and the EMR evolution trend was stable at first and then drastic gradually on the whole. EMR changes in each stress stage are analyzed as follows:

1. Compaction stage: Most of the time during the compaction stage, the amplitude of EMR pulse basically did not change and fluctuates smoothly, which basically kept about 10 mV/m, and the variation trend of EMR intensity and axial stress were consistent. In this stage, stress was mainly applied to compacting a large number of micro-fractures originally existing in coal-rock, and the motion amplitude of internal fractures was relatively regular, which would not cause obvious fracture extension and charge quantity increase, so there was not much change or violent fluctuation of EMR signal intensity. However, at the end of the compaction stage, the EMR signal locally fluctuated 1–3 mV/m higher than the average, which symbolized the coal-rock sample transition from the compaction stage to the elastic stage. At this time, the stress was still mainly used for compaction of internal fractures, but because of the differences in the structure of original fractures, the stress at a few fractures in coal-rock would reach its own limit, resulting in the deformation of fractures extending and generating electric charges, which directly led to the fluctuation of EMR signal. However, due to the small number of fractures where such changes occur and the sample was still in a steady state, the EMR signal at the compaction end stage
was abrupt, but the amplitude of increase was not high. It can be seen that the experimental results at this stage are consistent with the above microscopic theoretical analysis.

(2) Elastic stage: After entering the elastic stage, the axial stress of composite coal-rock increased linearly and mainly occurred elastic deformation. At this time, the EMR signal still maintained a stable fluctuation of 10 mV/m at most times, but also occasionally mutated, and abrupt increment gradually increased with the loading advance, whose value was between 11 and 20 mV/m. These changes can also be explained through the theoretical analysis proposed above: The increase in the abrupt increase of the EMR signal is related to the number of fractures reaching the compressive limit. At this stage, as the stress continued to increase, the number of fractures reaching the compressive limit gradually increased, which led to the increase of fracture surface charge and the formation of multiple time-varying weak current sources in coal-rock. However, at this time, most of the internal fractures had not reached the compressive limit and elastic deformation was still the main occurrence, so it was still an occasional phenomenon that the weak source formed. Therefore, in the elastic stage, EMR signals are characterized by overall stability but occasional mutations.

(3) Yield stage: In the yield stage, the stress of coal-rock rose rapidly, which had obvious nonlinear characteristics, and the weak crack sound can be heard outside. At the same time, it can be seen that the coal-rock expands and deforms outward. It was proved that at this stage, the sample had been transformed from elastic deformation to plastic deformation, and a large number of the coal-rock internal fractures began to extend and break. These mechanical changes will continuously increase the maximum single-movement distance $d_m$ of each fracture in the coal-rock and the frequency $f$ of reciprocating movement. Meanwhile, the amount of charge will also continue to increase because of the chemical bond fracture between particles during the fracture expansion. Under the combined action of the above conditions, the composite coal-rock external electric field will change dramatically, and it is easy to make the EMR signal fluctuate and increase rapidly. As can be seen from Figure

![Figure 16](https://doi.org/10.1021/acsomega.2c05389)

Figure 16. Characteristic parameter curve of composite coal-rock under load. (a−d) Result of 2# at 0.1 mm/min, 5# at 0.3 mm/min, 9# at 0.7 mm/min, and 15# at 1.0 mm/min, respectively.
16a, at this stage, the EMR signal fluctuation became more intense and the pulse peak increased with the loading advance, and the upper limit reached 53 mV/m, which was completely different from the EMR characteristics of the first two stages. As can be seen above, the experimental results in Figure 16 are completely consistent with theoretical analyses.

(4) Fracture stage: In the fracture stage, the axial stress of composite coal-rock rapidly reached the peak, accompanied by violent fluctuations. In addition, when the axial stress exceeded the stress peak, obvious cracks can be seen outside the coal-rock, and a huge cracking sound can be heard. As can be seen from the figure, there was still a correspondence between the EMR signal and stress at this stage. Before reaching the stress peak, the EMR signal fluctuated at a high frequency and changed dramatically. At this time, the EMR pulse amplitude was obviously higher than other stages, and its peak appeared near the stress peak, which can also be explained by the above theory. At this stage, the stress of composite coal-rock reached the compressive strength, and significant plastic deformation can be seen outside the sample, so the failure of internal fracture would be more obvious at this time. These changes made the maximum distance \( d_m \) and movement frequency \( f \) increase continuously, which provided a structural basis for the rapid change of EMR. In addition, with the expansion of original fracture and the continuous generation of new fracture, the charge quantity in coal-rock increased rapidly, which made the intensity of weak current source increase obviously. The above changes comprehensively led to drastic changes in the electric field, which made the EMR signal fluctuate rapidly with high amplitude at this stage. This effect is most violent when the axial stress reaches maximum, so the stress peak and EMR peak of coal-rock tend to synchronize. After the stress exceeded the peak, the coal-rock had been obviously damaged, and the large gap between fracture surfaces was not enough to form a stable electric field, which led to a cliff-like reduction in the amount of charge that actually formed the EMR signal.

**Figure 17.** Characteristic curves of EMR signal changes at different stages. (a−d) EMR curve of compaction stage, elasticity stage, yield stage, and fracture stage, respectively.
Therefore, it can be seen from Figure 16 that the EMR amplitude dropped again after the peak and regressed to the characteristics of the compaction stage.

The experimental results show that EMR evolution and stress change are highly correlated, and both have the same stage. In addition, it can be seen that the experimental results are the same as the theoretical analysis results, which further verifies the above EMR signal generation mechanism of composite coal-rock and the correctness of the stress-EMR coupling numerical model. Based on the experimental and simulation results, the EMR signal evolution law of loaded composite coal-rock is shown in Figure 18. The research results will provide ideas and possibilities for the actual coal-rock state detection, and also help to further realize the multiparameter coal mine dynamic disaster prevention in the future.

5. CONCLUSIONS AND DISCUSSION

Through theoretical analysis, finite element simulation, and experimental verification, this study draws the following conclusions:

(1) The periodic deformation of “load compression—deformation release—load compression” at the fracture of coal-rock will cause multiple alternating micro currents inside, which promote the generation of EMR, and there is a numerical relationship between EMR and stress as shown in eq 11.

(2) The internal fracture structure of coal-rock is equivalent to the capacitance, and its charge amount and plate spacing change with time. The EMR signal forms of each point inside and outside the coal-rock are almost sinusoidal pulses, each pulse corresponds to a closed-loop deformation process of a fracture, and the EMR peak is positively correlated with the degree of fracture.

(3) The EMR signal of composite coal-rock decays exponentially from the fracture, and it will be distorted at the junction of medium, which will not change the overall characteristics of the signal. In addition, the delay effect of EMR signal can be neglected, and the EMR signal at 1.0–2.5 mm outside the coal-rock is stable and has obvious characteristics, which is more suitable for EMR collection.

(4) The evolution of EMR has stages: in the compaction stage, it mainly fluctuates slightly, but before the end of the stage, it will increase by 1–3 mV/m. In the elastic phase, the signal fluctuates occasionally, whose amplitude increases slightly with the loading. In the yield and fracture stages, the signal changes sharply with the increase of stress, and the amplitude increases rapidly. When rupture is imminent, the EMR peak appears synchronously with the stress. After fracture, the EMR returns to the stable state of the compaction stage again.

In this study, we focus on explaining the evolution of the EMR during the loading of composite coal-rock and develop a numerical model of the stress-EMR coupling that provides a theoretical basis for noncontact monitoring of coal-rock state changes. This coupling relationship also provides convenience for the fusion analysis of multidimensional information of loaded coal-rock, and subsequent researchers can further analyze the numerical relationship between different physical quantities on the basis of this study so as to deduce a more comprehensive coupling relationship of coal-rock characteristic parameters, which will help people understand the process of coal-rock fracture under load. The limitation of this research is that the conclusions obtained in this paper were obtained by analyzing the changes of physical characteristics. Although it can reflect the objective facts better, there are still some limitations in the depth of theoretical analysis. Future research can analyze the fracture process of coal-rock under load from the perspective of energy transformation, which will be more helpful to grasp the nature of coal-rock dynamic disaster. In conclusion, the results of this study will also help in the early warning of coal-rock...
dynamic disasters, which will contribute to the safety of coal mining in reality.

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**Notes**

The authors declare no competing financial interest.

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■ NOMENCLATURE

- alternating current signals
- $U$: induced electromotive force
- $\sigma'$: amount of charge induced on the outside of the micro-unit
- $d'$: distance between the two surfaces of the fracture
- $t$: time
- $\varepsilon_i$: dielectric constants on both sides of the fracture ($i = 1, 2$)
- $\varepsilon_0$: dielectric constant in vacuum
- $\sigma_4$: amount of transferred charge
- $K$: proportional correction coefficient
- $D$: the electric displacement vector
- $E$: electric field intensity
- $P$: electric polarization intensity
- $\nu'$: the separation movement rate between the two contact surfaces, $\nu' = d\nu / dt$
- $\theta$: angle between the fracture and the horizontal direction
- $m$: unit mass
- $v$: average loading speed
- $\sigma_1$: axial stress
- $\gamma$: angle between the fracture and the vertical direction
- $U_i$: electric potential on two surfaces of the fracture ($i = 1, 2$)
- $n$: number of charged particles
- $q$: unit charge
- $\varepsilon$: dielectric constant between fracture

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