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Research Article

Analysis of Shielding Effectiveness of the Cavity Built with Single-Layer Reinforced Concrete

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In view of the existing literature mainly studying the situation of infinite reinforced concrete structure, the shielding effectiveness of three-dimensional single-layer reinforced concrete cavity is studied by considering the structural parameters of steel and the electromagnetic parameters of the concrete. The influence of structure parameters of steel mesh size, the steel diameter, and electromagnetic parameters of concrete dielectric coefficient, conductivity and moisture content on shielding effectiveness of reinforced concrete are analyzed. The research shows that the shielding effectiveness of the reinforced concrete cavity structure has resonance characteristics, and the increase of concrete conductivity and moisture content weaken the resonance characteristics of it so that the shielding effectiveness of the reinforced structure is improved. The results of this paper have a reference value for the analysis of shielding effectiveness of the single-layer reinforced concrete cavity in different practical situations.

1. Introduction

In the face of increasingly complex electromagnetic environment, such as high-altitude nuclear explosion electromagnetic pulse (HEMP) [1–3] or non-nuclear explosion strong electromagnetic pulse [4, 5], it poses a serious threat to the normal operation of electronic facilities and electromagnetic sensitive equipment in buildings. Due to economy, convenience, and flexibility, reinforced concrete has been bearing the beam, column, foundation, and the whole skeleton of the building in most residential or office buildings. In addition, buildings with special functions such as bunkers, gas or explosive storage warehouses, underground rooms and telecommunications centers, and reinforced concrete structures have not only played a supporting role, but also involved the protection and leakage of electromagnetic pulse. Therefore, it is very necessary to study the electromagnetic shielding properties of three-dimensional reinforced concrete structures in buildings so that it can provide a reference for radio wave communication in some environments and electromagnetic protection of reinforced concrete protection rooms.

As a typical composite medium structure, reinforced concrete usually needs to consider the dispersion characteristics of the concrete medium [6, 7], which also brings challenge to the accurate calculation of shielding effectiveness and evaluation of shielding properties of reinforced concrete structures. The previous research mainly involved the analytical model of infinite reinforced concrete to solve the propagation characteristics of the main frequency points in communication propagation. For example, Holloway et al. used the equivalent parameter theory of composite structures [8, 9] to study the short path propagation characteristics of infinite reinforced concrete layers [10]. Savov et al. regard nonuniform reinforced concrete structure as homogeneous medium structure through the homogenization technology of the periodic structure, and then used the propagation matrix method to calculate the transmission characteristics of the infinite reinforced concrete layer [11]. To calculate the electromagnetic propagation characteristics of reinforced concrete more accurately, the semianalytical technique about Green's function is introduced later, such as Paknys [12], Dehmollaian, and Sarabandi [13], but the

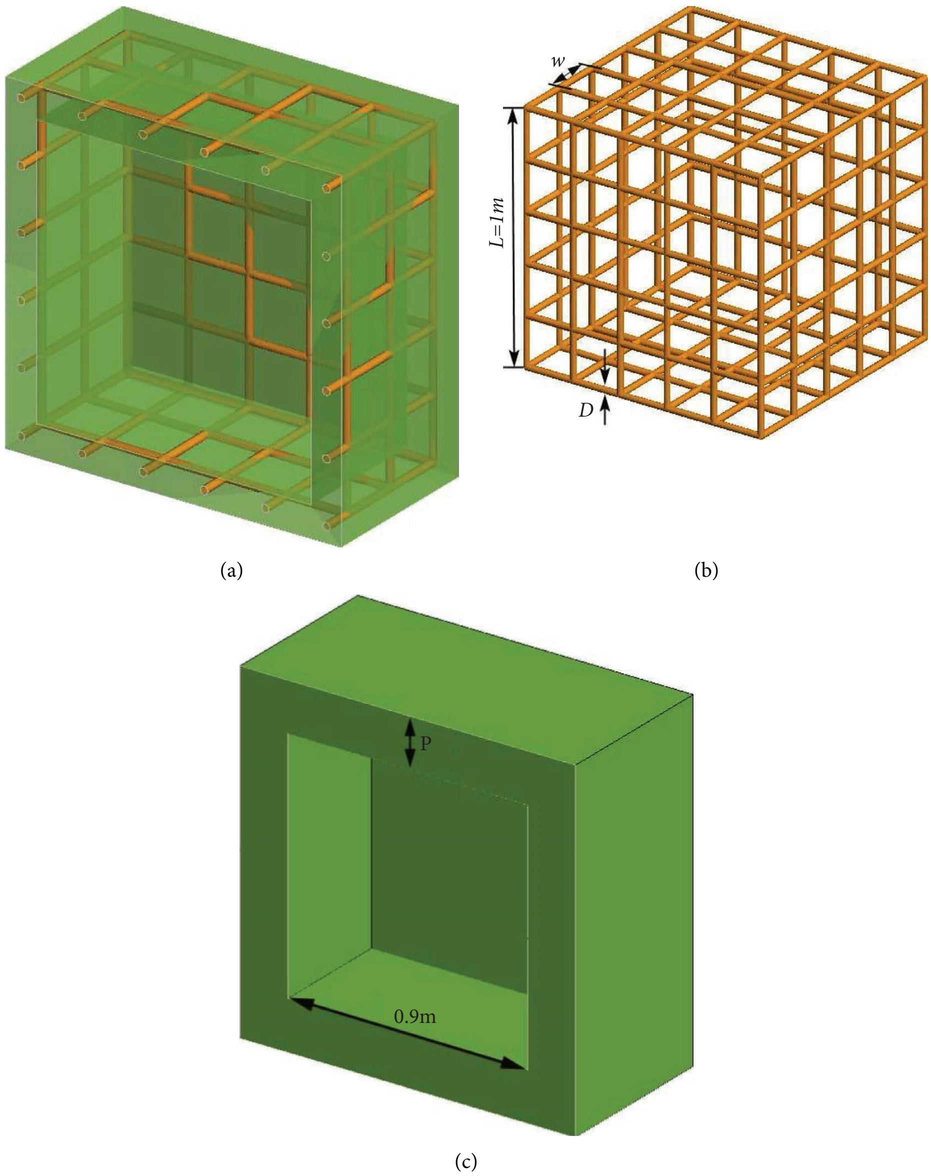


Figure 1: Different three-dimensional shielding cavity model: (a) reinforced concrete cavity, (b) steel cage, and (c) concrete cavity.

calculation process is more and more complex. With the development of computational electromagnetism, various numerical methods are also used to analyze the shielding properties of reinforced concrete structures, such as the finite difference time-domain (FDTD) method [14–16], the method of moments [17], and the finite-element method (FEM) [18]. However, different numerical methods usually regard reinforced concrete as periodic element structure and use periodic boundary conditions to study its propagation characteristics, which is more precise than the previous analytical model. Whether it is analytical model research or numerical method calculation, the research object is mainly the infinite reinforced concrete structure, and the three-dimensional reinforced concrete protective structure is relatively absent. There is no infinite reinforced concrete in practice, and it cannot be used to evaluate the shielding properties of the three-dimensional reinforced concrete structure. In addition, the dispersion characteristics of the concrete are usually not considered in the calculation of many reinforced concrete structures, and constant dielectric parameters are directly given to calculate the shielding properties of the full frequency band.

Based on our previous research on the shielding effectiveness of the infinite metal mesh [19] and reinforced cage structure [20], the shielding effectiveness of the three-dimensional reinforced concrete cavity structure is studied by considering the structural parameters of the steel mesh and the electromagnetic characteristics of concrete in this paper. The influence of steel structure parameters such as the diameter of steel bar and mesh size, as well as electromagnetic parameters such as dielectric coefficient, conductivity of concrete, and moisture content of it are analyzed. The research results of this paper have a reference value for the analysis of shielding effectiveness of the reinforced concrete cavity in different practical situations and the design of the reinforced concrete cavity with good shielding effectiveness in the wide frequency band.

2. Calculation and Verification of Shielding Effectiveness of the Center Point of Different Structures

Taking the three-dimensional reinforced concrete cavity about one cubic meter shown in Figure 1(a) as an example, it can be decomposed into the steel cage shown in Figure 1(b) and the concrete cavity shown in Figure 1(c). The overall side length L of the steel cage equals to 1 m, the mesh size is set as w, the diameter of the steel bar is set as D, and the concrete thickness is set as P. In addition, the relative dielectric constant of the concrete is set as ε_r and the electrical conductivity of it is set as σ.

According to the research of the two-dimensional infinite reinforced concrete structure [18], the structural parameters of steel and the electromagnetic parameters of the concrete will have a major impact on the shielding effectiveness of the reinforced concrete. Therefore, this paper mainly focuses on the influence of different structural parameters of steel cage and the electromagnetic parameters of the concrete on the shielding effectiveness of the reinforced concrete. The shielding effectiveness of the steel cage, concrete cavity, and reinforced concrete cavity under different parameters is calculated by using the time-domain numerical algorithm firstly, and then the corresponding frequency domain numerical technology is used to verify the shielding effectiveness results.

2.1. Shielding Effectiveness.

2.1. Shielding Effectiveness. Shielding effectiveness (SE) refers to the ratio of the field strength E_0 of a detection point without shielding the structure to the field strength E_t of the same detection point after the shielding structure is added; the larger the value, the better the shielding effect. The specific expression of the SE is:

$$\mathrm{SE} = 20\lg\left(\frac{E_0}{E_t}\right). \quad (1)$$

To evaluate the shielding properties of different shielding cavity structures, the center point of the cavity structure is selected as the reference point to represent the internal environment of different cavities in the paper. Therefore, the shielding effectiveness is calculated, and then the shielding properties of different cavity structures are evaluated.

2.2. Calculation Method of Different Cavity Models. Whether it is a single medium such as the steel cage and concrete cavity or a composite structure such as the reinforced concrete cavity, this paper mainly uses the commercial software CST based on the FITD technology to solve shielding effectiveness. To verify the accuracy of different shielding effectiveness calculation results, the frequency domain FEM technology is used to verify the shielding effectiveness results of the reinforced concrete and concrete cavities, and the MoM method is used to verify the shielding effectiveness results of the steel cage.

To explore the shielding properties of the three-dimensional shielding cavities shown in Figure 1, the initial parameters are defined firstly. The relative permittivity ε_r of the concrete is set as 4.5 and the conductivity of it is set as 0.0005 S/m or 0.021 S/m. The mesh size w is set as 200 mm, the steel diameter D is set as 24 mm or 40 mm, and the concrete thickness P equals 100 mm. Two different cases are set for the three structures, respectively. In each case, two different methods are used to calculate the central point shielding effectiveness of different cavity structures. The shielding effectiveness calculation results of different cavities are shown in Figure 2.

The shielding effectiveness results calculated by time-domain solver and different frequency domain solvers are basically consistent for the same shield cavity, indicating the accuracy of shielding effectiveness calculation results. Therefore, the following examples of shielding effectiveness calculation of the steel cage, concrete cavity, and reinforced concrete cavity under different parameters will be calculated using the time-domain solver with the commercial software CST.

At the same time, it can be preliminarily seen that the resonance characteristics of the concrete cavity and reinforced concrete are gradually eliminated with the increase of concrete conductivity (Figures 2(a) and 2(c)). However, the resonance strength is significantly enhanced with the increase of the steel diameter D (Figure 2(b)). It shows that the concrete has a good regulating effect on the resonant characteristics of the steel cage. Therefore, quantitative analysis on the influence of the structural parameters of the steel cage is conducted in the following section firstly, and then quantitative analysis on the influence of the electromagnetic parameters of the concrete is conducted.

3. Influence of Different Steel Structure Parameters on the Shielding Effectiveness of the Reinforced Concrete Cavity

The shielding effectiveness that have been verified in Figure 2 of the three kinds of shielding cavities is compared, and the results are shown in Figure 3(a). Obviously, the shielding property adjustment of the steel cage to the reinforced concrete accounts for the main part before the resonance frequency point. The shielding property adjustment of the concrete to the reinforced concrete accounts for the main part after the resonance frequency point. Overall, the resonance frequency point of the reinforced concrete is shifted to the left relative to that of the steel cage. It is easy to understand this phenomenon. It is that the coupling effect between the electromagnetic wave and steel cage is advanced due to the wavelength of free space decreases in the concrete medium. However, the influence of steel structure parameters on the shielding effectiveness of the reinforced concrete cavity needs to be further explored. Therefore, this section conducts parameter effect research such as the steel diameter

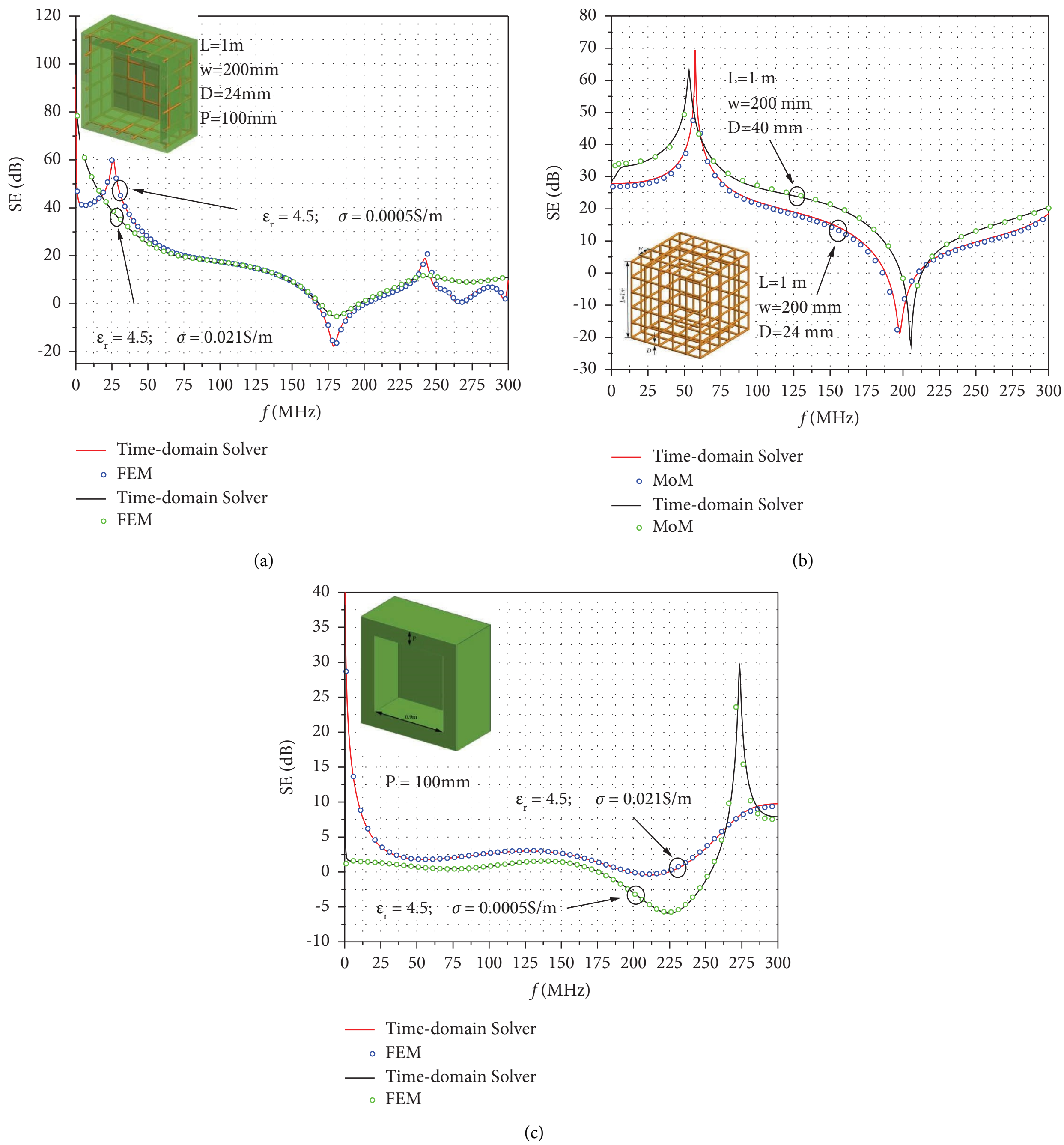


Figure 2: Shielding effectiveness calculation and verification of different cavity models: (a) reinforced concrete cavity, (b) steel cage, and (c) concrete cavity.

D and the mesh size *w* ensuring that the overall size of the reinforced concrete cavity remains unchanged.

3.1. Influence of Steel Diameter D. When the steel diameter *D* is set to as 40 mm, the electromagnetic parameters and structural parameters *P* of the concrete are consistent with those shown in Figure 3(a). The shielding effectiveness of different shielding cavities are calculated, respectively, and the comparison results are shown in Figure 3(b).

Comparing the shielding effectiveness results in Figure 3(a) with that in Figure 3(b), the shielding effectiveness of the steel cage and reinforced concrete cavity is enhanced as the diameter *D* increases. Therefore, the

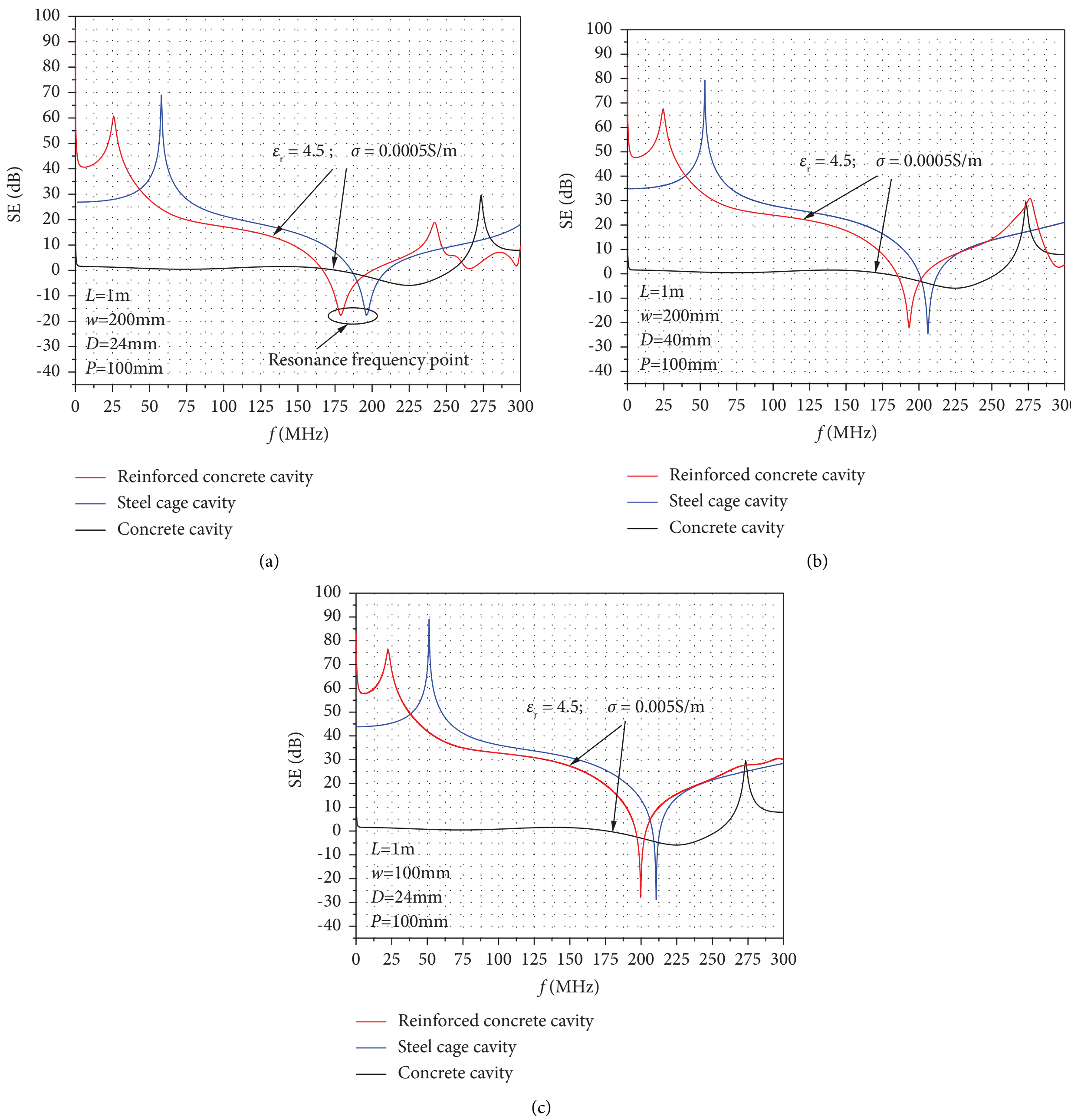


Figure 3: Comparison of shielding effectiveness of three shielding structures under different steel structure parameters: (a) $L = 1$ m, $w = 200$ mm, $D = 24$ mm; (b) $L = 1$ m, $w = 200$ mm, $D = 40$ mm; (c) $L = 1$ m, $w = 100$ mm, $D = 24$ mm.

resonance strength is also gradually enhanced, which makes the adjustment of the concrete weaker.

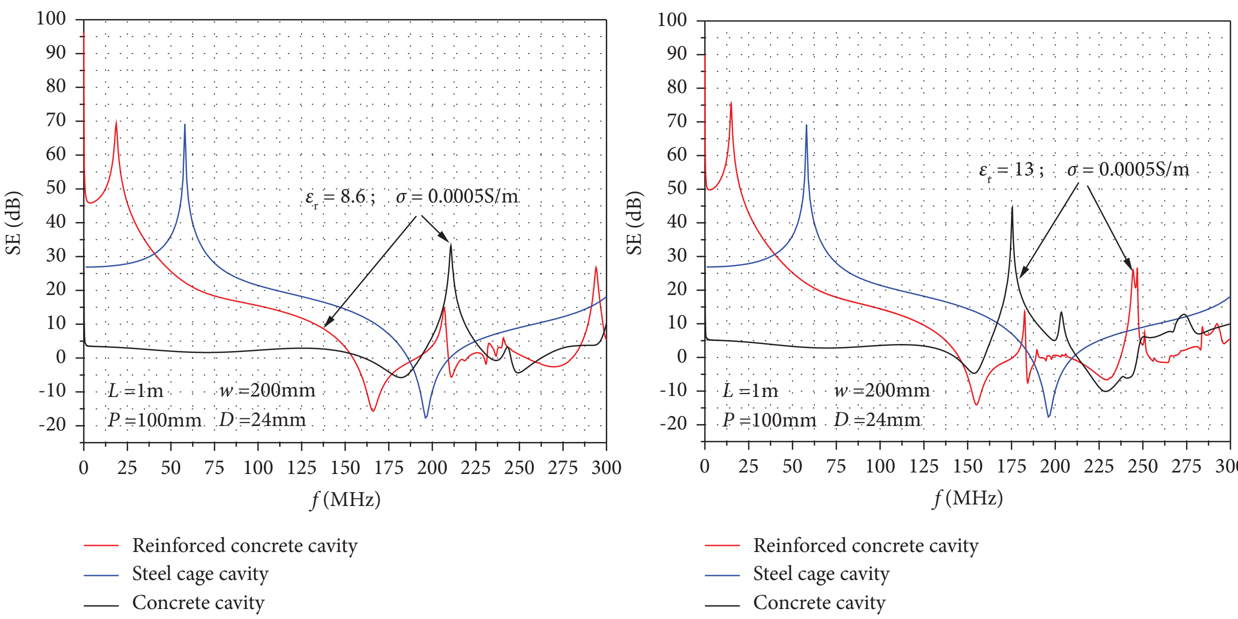
3.2. Influence of Mesh Size w. When the mesh size w is set to 100 mm, the electromagnetic parameters and structural parameters P of the concrete are still same as those shown in Figure 3(a). The shielding effectiveness of different cavity structures are calculated respectively as well. The comparison results are shown in Figure 3(c).

The shielding effectiveness of the steel cage and reinforced concrete cavity is enhanced with the reduction of the mesh size w by comparing Figures 3(a) and 3(c). Obviously, the resonance strength is also gradually enhanced, which makes the adjustment of the concrete to the shielding effectiveness of the reinforced concrete cavity almost have little effect in the frequency band after the resonance point.

3.3. Quantitative Result Analysis. In general, the increase of the steel diameter D or the decrease of the mesh size w both increase the shielding effectiveness of the reinforced concrete. At the same time, it will enhance the resonance of the reinforce concrete and inevitably weaken the influence of the concrete on the reinforced concrete.

Table 1: Comparison of the resonance point shielding effectiveness under different steel structure parameters.

Parameters of the steel cage	The resonance point shielding effectiveness of the steel cage (dB)	The resonance point shielding effectiveness of the reinforcement concrete (dB)
$L = 1$ m, $w = 200$ mm, $D = 24$ mm	−17.6635	−17.6373
$L = 1$ m, $w = 200$ mm, $D = 40$ mm	−24.3997	−22.0796
$L = 1$ m, $w = 100$ mm, $D = 24$ mm.	−28.9229	−27.5003



(a) (b)

Figure 4: Comparison of shielding effectiveness of three shielding structures under different relative permittivity: (a) $\varepsilon_r = 8.6$ and (b) $\varepsilon_r = 13$.

To quantitatively compare and analyze the influence of different steel structure parameters on the shielding effectiveness of the reinforced concrete cavity, the resonance point shielding effectiveness of the steel cage and reinforced concrete in Figure 3 is compared to Table 1. The resonance point shielding effectiveness of the steel cage and reinforced concrete decreases with the increase of the steel diameter D or the decrease of mesh size w indicating that the resonance characteristics of them are enhanced. At the same time, the resonance point shielding effectiveness of the reinforced concrete is greater than that of the steel cage in the same case, which indicates that the concrete plays a role in adjusting the resonance characteristics of the reinforcement concrete.

4. Influence of Concrete Electromagnetic Parameters on the Shielding Effectiveness of the Reinforced Concrete Cavity

According to the results in Section 3, the shielding effectiveness of the reinforced concrete cavity appears as a negative value due to the existence of the resonant frequency point of the steel cage, which has a serious impact on the shielding performance of the structure. However, the concrete has a certain improvement on the resonance of the reinforced concrete cavity from the results in Figure 3 and Table 1.

4.1. Shielding Effectiveness of the Reinforced Concrete Cavity with Different Dielectric Parameters in the Concrete. In order to further understand the influence of the concrete under different electromagnetic parameters, the authors further discuss the situation of the concrete under different relative dielectric constant and different conductivity on the basis of the reinforced concrete cavity in Figure 3(a) (the side length L of the steel cage equals to 1 m, the mesh size w equals to 200 mm, the steel diameter D equals to 24 mm, and the concrete thickness P equals to 100 mm).

Case 1. effect of relative permittivity of the concrete. As shown in Figure 4, the shielding effectiveness of three shielding cavity structures is compared, in which the concrete media is with the same conductivity under different relative permittivity. The results show that the resonance

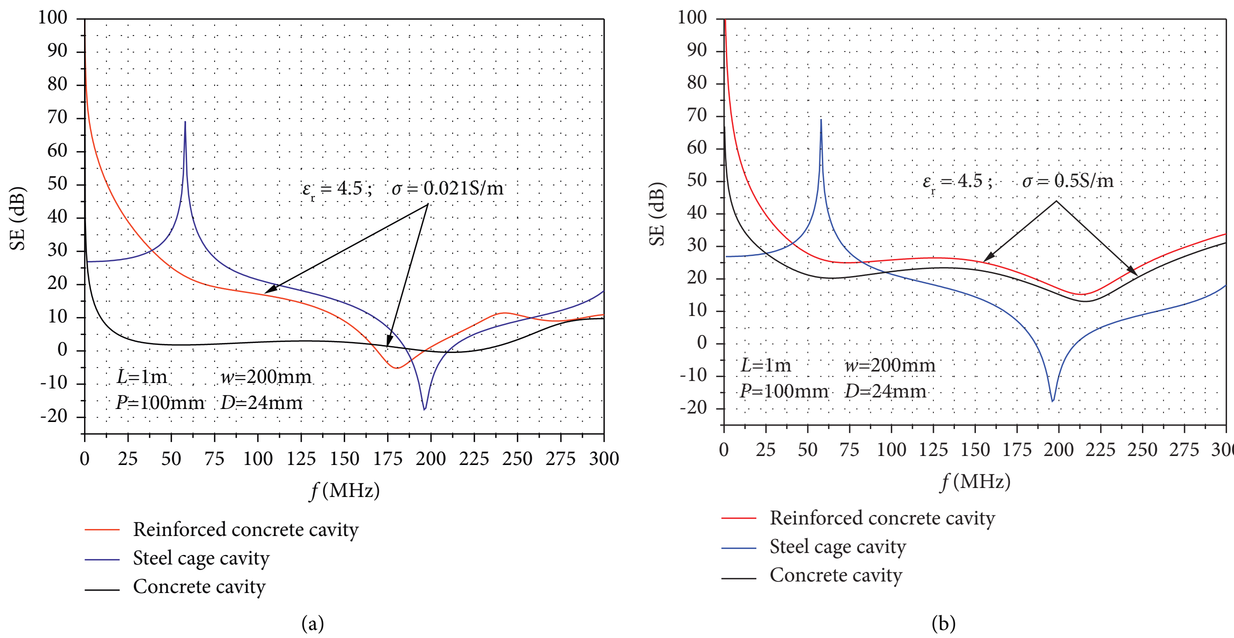


Figure 5: Comparison of shielding effectiveness of three shielding structures under different conductivity: (a) $\sigma = 0.021$ S/m and (b) $\sigma = 0.5$ S/m.

frequency point shielding effectiveness of the reinforced concrete decrease more significantly than that of the steel cage with the increase of the relative dielectric constant of the concrete, but it has little effect on the increase of the reinforced concrete shielding effectiveness.

Case 2. effect of conductivity of the concrete. Figure 5 shows the comparison of the shielding effectiveness of three shielding cavity structures, in which the concrete media is with different conductivity under the same dielectric parameters. The shielding effectiveness of the reinforced concrete cavity has been significantly enhanced and the existing resonance is gradually disappearing with the increase of concrete conductivity. This is an expected result and the main reason is that the increase of concrete conductivity will inevitably lead to the enhancement of electromagnetic wave attenuation in it so that the shielding effectiveness at the resonance point will also be weakened.

4.2. Shielding Effectiveness of the Reinforced Concrete Cavity with Different Moisture Content in the Concrete. Considering the actual weather conditions, the moisture content of the concrete caused by different seasons will also affect the shielding effectiveness of the reinforced concrete. Therefore, this section will explore the influence of the published concrete moisture content parameters on the concrete moisture content. The reinforced concrete structure is the same as that in section 4.1.

According to the research in [6], the extended Debye dispersion model of concrete electromagnetic parameters is considered to approach the actual measurement results of concrete parameters with different moisture contents. First, the Debye dispersion model is as follows:

$$\begin{aligned}\varepsilon(\omega) &= \varepsilon_{\infty} + \frac{\varepsilon_s - \varepsilon_{\infty}}{1 + j\omega\tau} \\ &= \varepsilon_{\infty} + \frac{\varepsilon_s - \varepsilon_{\infty}}{1 + \omega^2\tau^2} - j\frac{\omega\tau(\varepsilon_s - \varepsilon_{\infty})}{1 + \omega^2\tau^2}.\end{aligned} \tag{2}$$

Therefore, the real part and imaginary part of concrete dielectric parameters can be obtained as follows:

$$\begin{aligned}\varepsilon'(\omega) &= \varepsilon_{\infty} + \frac{\varepsilon_s - \varepsilon_{\infty}}{1 + \omega^2\tau^2}, \\ \varepsilon''(\omega) &= \frac{\omega\tau(\varepsilon_s - \varepsilon_{\infty})}{1 + \omega^2\tau^2}.\end{aligned} \tag{3}$$

However, the loss of concrete conductivity is considered in [6]. Therefore, it is necessary to correct the imaginary part and it is as follows:

$$\varepsilon''(\omega) = \frac{\omega\tau(\varepsilon_s - \varepsilon_{\infty})}{1 + \omega^2\tau^2} + \frac{\sigma_{dc}}{\omega\varepsilon_0}. \tag{4}$$

Combining the parameters shown in Table 2 and Equations. (2)~(4), the dispersion effect fitting curve of the concrete with moisture content of 0.2%, 5.5%, and 12% within 1 GHz can be obtained in Figure 6(a). Obviously, the dispersion effect increases with the increase of moisture content within 300 MHz. Therefore, it is necessary to consider the dispersion effect in this frequency band, especially when the moisture content is large.

The shielding effectiveness calculation results of different concrete moisture content situations are as follows:

Table 2: Fitted parameters of the concrete with different moisture content [6].

Moisture content (%)	ε_s	ε_∞	$\tau\,(ns)$	$\sigma_{dc}\,(\Omega^{-1}m^{-1})$
0.2	4.814 ± 0.002	4.507 ± 0.002	0.82 ± 0.01	$6.06 \times 10^{-4} \pm 0.06 \times 10^{-4}$
5.5	8.630 ± 0.020	6.023 ± 0.009	1.00 ± 0.02	$5.15 \times 10^{-3} \pm 0.06 \times 10^{-3}$
12.0	12.84 ± 0.030	7.420 ± 0.020	0.611 ± 0.006	$20.6 \times 10^{-3} \pm 0.20 \times 10^{-3}$

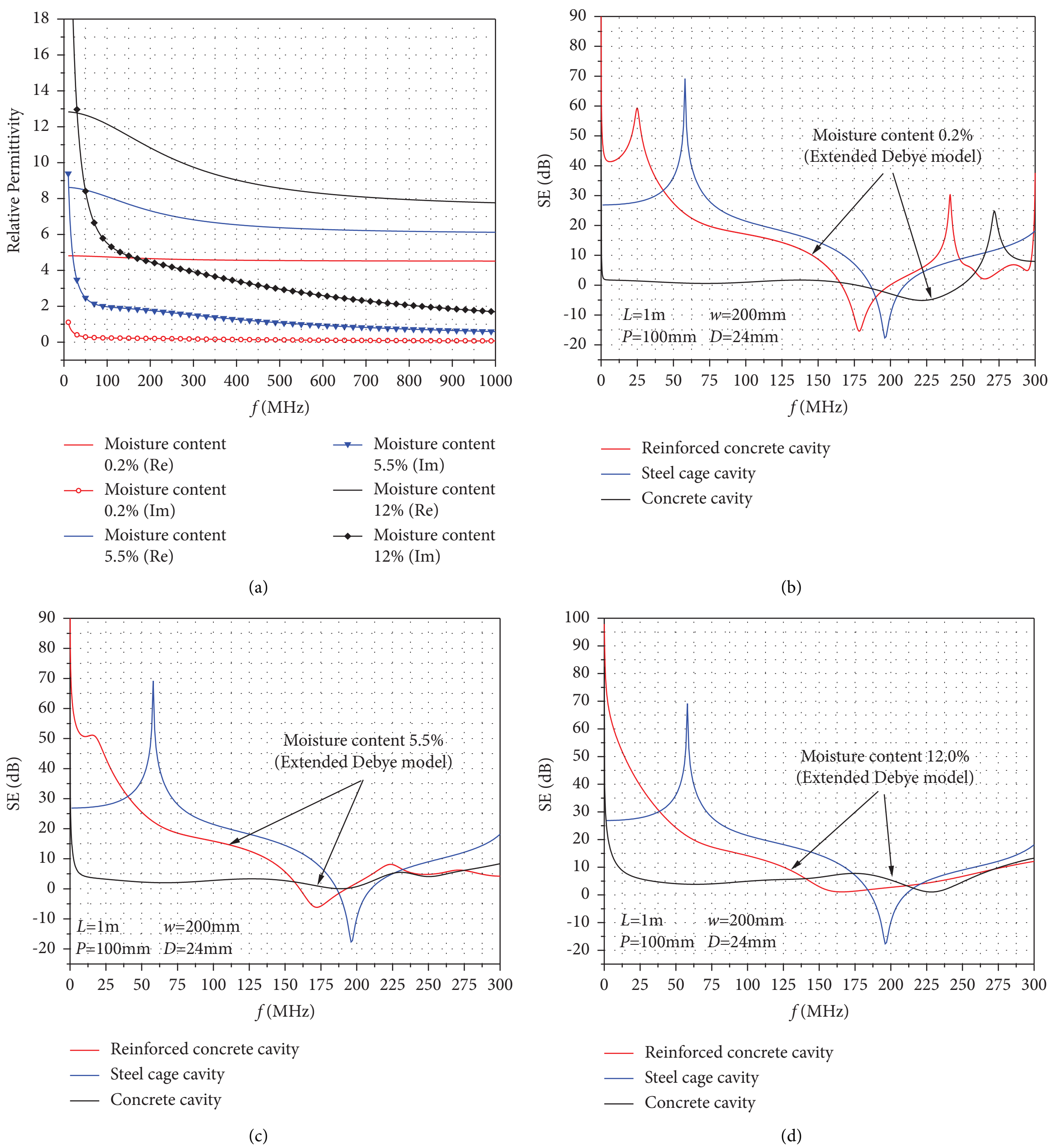


Figure 6: Comparison of the shielding effectiveness of three shielding structures under different moisture content: (a) complex permittivity of the concrete with the moisture content, (b) moisture content 0.2%, (c) moisture content 5.5%, and (d) moisture content 12%.

Table 3: Comparison of the resonance point shielding effectiveness under different concrete electromagnetic parameters.

Parameters of the concrete	The resonance point shielding effectiveness of the steel cage (dB)	The resonance point shielding effectiveness of the reinforcement concrete (dB)
$\varepsilon_r = 4.5$, $\sigma = 0.0005$ S/m	−17.6335	−17.6673
$\varepsilon_r = 8.6$, $\sigma = 0.0005$ S/m	−17.6635	−15.7141
$\varepsilon_r = 13$, $\sigma = 0.0005$ S/m	−17.6635	−14.0856
$\varepsilon_r = 4.5$, $\sigma = 0.021$ S/m	−17.6635	−5.2077
$\varepsilon_r = 4.5$, $\sigma = 0.5$ S/m	−17.6635	15.2321
Moisture content 0.2%	−17.6635	−15.3911
Moisture content 5.5%	−17.6635	−6.1476
Moisture content 12.0%	−17.6635	1.0986

Figure 6(b) shows the case that the concrete moisture content is 0.2%, Figure 6(c) shows the case that the concrete moisture content is 5.5%, and Figure 6(d) shows the case that the concrete moisture content is 12%. It is observed that the resonance characteristics of the reinforced concrete cavity gradually disappears with the increase of the concrete moisture content, which indicates that the increase of the concrete moisture content can well improve the resonance characteristics of the reinforced concrete.

4.3. Quantitative Result Analysis. We can naturally obtain that the resonance characteristics of reinforced concrete cavities can be well weakened with the increase of concrete conductivity or moisture content based on the shielding effectiveness analysis in sections 4.1 and 4.2.

Therefore, Table 3 shows the comparison of the resonance point shielding effectiveness of the steel cage and reinforced concrete under different concrete parameters. It can be clearly seen from that the resonance point shielding effectiveness of the reinforced concrete is increasing with the increase of concrete conductivity or moisture content, indicating that the resonance characteristics of the reinforced concrete is weakened, and the concrete plays a good role in regulating the resonance characteristics of the reinforcement concrete.

5. Conclusion

In this paper, the three-dimensional single-layer reinforced concrete cavity protection structure is taken as the research object to represent a simple three-dimensional space building, and the shielding effect considering the concrete dispersion effect is studied. The influence of the structural parameters of the steel cage and the electromagnetic parameters of the concrete on its shielding effectiveness and how to eliminate the resonance characteristics are analyzed in detail. The results show that the concrete with different dielectric parameters or moisture content has great improvement on the shielding performance of the reinforced concrete cavity. However, the stronger the resonance characteristics of the steel cage, the harder it is to eliminate the resonance characteristics by the adjustment of the concrete. In general, the resonance characteristics of reinforced concrete cavities can be weakened with the increase of concrete conductivity (such as adding conductive medium in the concrete) or moisture content (such as rainy season or snow season).

The research results in this paper have reference value for the analysis of shielding effectiveness of the reinforced concrete cavity in different practical situations and the design of the reinforced concrete cavity with good shielding effectiveness in a wide frequency band. Although the one cubic meter single-layer reinforced concrete is taken as an example in this paper, it may not be the same with the actual situation. However, under the condition of ensuring the same electrical size, the results of this paper are still meaningful. For example, as for a reinforced concrete cavity 10 times the size of that in this paper, its resonance frequency point is reduced to about 1/10 of the result in this paper and it is about 20 MHz. At this time, we should focus on the protection of the frequency point. In addition, this paper only considers the shielding effectiveness of the single-layer reinforced concrete, and the shielding properties of double-layer or multilayer reinforced concrete cavities would be further studied in the next topic.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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