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Analysis of Different Noise Reduction Effects of Ground Penetrating Radar Image of Cavity Behind Tunnel Primary Support Based on Singular Value Decomposition and Wavelet Transform

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Abstract: The cavity behind the lining structure is a typical disease in tunnel engineering. Cavity seriously affects the interaction between lining and surrounding rock, resulting in uneven bearing of lining structure and stress concentration, which can easily induce lining concrete cracking, water leakage and other diseases. Accurate identification of lining structure cavities is the key to ensure the normal operation of the tunnel. However, the ground penetrating radar detection images of lining cavities often contain interference signals such as background noise, which seriously affects the accuracy and clarity of cavity detection. The application effects of wavelet transform and singular value decomposition in image denoising and resolution of tunnel lining cavity ground penetrating radar are studied. Under this background, the model test of regular and irregular cavity detection behind tunnel lining is carried out, in which the irregular cavity is located in the surrounding rock environment of filling soil to simulate the real situation of tunnel. The measured images of lining cavity under different working conditions are obtained, and the image denoising analysis is carried out. The results show that singular value decomposition can effectively suppress noise. The ground penetrating radar image after singular value decomposition denoising is clearer, and the image resolution is effectively improved, thus realizing the accurate identification of cavity diseases behind the primary support of the tunnel.
Keywords: lining of tunnel; cavity disease; ground penetrating radar (GPR); wavelet transform; singular value decomposition (SVD)

I. INTRODUCTION

With the rapid development of China's economy and the country's continuous progress towards two centenary goals, China's tunnel engineering has gradually entered a new stage of high-level high-tech development. China has become the country with the most complex geological structure and the largest scale of tunnel engineering. However, in tunnel engineering, the existence of cavity disease may bring related diseases to the construction and operation of the project and even cause casualties [1].
Ground penetrating radar is an effective tool for detecting underground targets based on the emission and reflection of wireless waves [2]. Compared with other underground detection tools, GPR has the advantages of high efficiency, high accuracy, fast and convenient, which makes it widely used in detection engineering [3]. Because there is a certain deviation between the original data collected by GPR and the real situation, the radar image cannot be accurately interpreted by the field detection personnel [4]. Therefore, it is very important to improve the accuracy of lining disease identification by quantitative analysis and judgment of the image characteristics of the ground penetrating radar of cavity behind the tunnel lining.
Clutter suppression method is an important ground penetrating radar image processing method. It can obtain accurate images with high peak signal-to-noise ratio by filtering clutter and noise in radar images. In the application of ground penetrating radar, the classical clutter suppression method is realized by data filtering in frequency domain and time domain. However, this method cannot achieve the previous effect when detecting objects close to the surface or when the time response is the same as the surface [5]. As a time-frequency analysis method, wavelet analysis has the characteristics of multi-resolution. The mixed signals composed of different frequencies can be decomposed into sub-signals of different frequency bands under its action. Therefore, wavelet analysis has unique advantages in feature extraction, signal noise reduction and signal singularity detection [6]. As an important matrix decomposition method, singular value decomposition (SVD) can eliminate the direct wave through the minimum mean square error criterion and linear transformation technology, which can effectively remove the noise and retain the underground reflection signal, and improve the quality and readability of GPR images [7].

In summary, in the face of the clutter and noise in the ground penetrating radar image, the radar image cannot be accurately identified. The existing literature introduces and explains the methods of clutter suppression and noise reduction. However, there are few studies on the optimal and most comprehensive clutter suppression method for the image of cavity detection with different spatial characteristics of tunnel lining. Based on this, this paper will fit the actual situation, in the face of different types of lining holes in engineering construction, by using wavelet analysis and singular value decomposition (SVD) method to deal with the clutter and noise in ground penetrating radar image, in a variety of image data comparison, the best radar image processing method between the two is obtained.

II. RESEARCH METHODS AND PRINCIPLES

A. *Wavelet Analysis Theory*

As a signal processing method, wavelet analysis can identify information that cannot be processed by other signal analysis methods, and can dig out important information hidden in the data that represents its structural characteristics. It has local characteristics that describe the time (space) domain and frequency (scale) domain of the signal [8].

The basic method of wavelet analysis can be reflected by the following ideas: Assume that there is a wavelet basis function Ψ, after it is shifted by b units, the inner product is made at different scales a and signal y, which reflects the essence of the wavelet decomposition process.

The expression of wavelet decomposition is shown in (1):

$$W_f(a,b) = \langle f, \Psi_{a,b} \rangle = |a|^{-1/2} \int_R f(t)\overline{\Psi(\frac{t-b}{a})}dt \qquad (1)$$

where $\Psi_{a,b}$ is the wavelet basis function, a is the scaling factor; b is a translational factor.

Wavelet analysis method can be divided into three parts:

①Selecting the appropriate wavelet function and decomposition level, the original signal is decomposed by wavelet, and the high frequency coefficient and low frequency coefficient of the decomposed signal can be obtained.

②A certain threshold is selected to denoise the high-frequency and low-frequency coefficients of wavelet decomposition, and the wavelet coefficients after noise reduction are obtained.

③Through the wavelet reconstruction of the wavelet coefficients obtained by processing, the signal data after processing is obtained [9].

B. *Introduction to the principle of singular value decomposition*

Singular value decomposition (SVD) is an important matrix decomposition method in linear algebra. By using the minimum mean square error criterion and linear transformation technology, the direct wave can be eliminated. Singular value decomposition can analyze the B-Scan image collected by ground penetrating radar to obtain the data composed of two-dimensional matrix. In the direct wave processing of echo signal, the singular value decomposition method has strong stability and robustness. As an effective numerical analysis tool, singular value decomposition can realize the diagonalization of matrices and is widely used in the field of image processing [10]. The specific principle is as follows:

Ground penetrating radar data is composed of two-dimensional matrix, called B-scan, which is composed of a series of adjacent one-dimensional matrix A-scan. Here, the two-dimensional matrix of ground penetrating radar is denoted by $A_{n\times m}$, where m represents the number of one-dimensional matrices, and n represents the number of sampling points for each one-dimensional matrix [11].

The two-dimensional matrix $A_{n\times m}$ of ground penetrating radar is decomposed by SVD:

$$A = U\Sigma V^T \qquad (2)$$

It can be further expressed as:

$$A = U\Sigma V^T = [u_1 \cdots u_r][u_{r+1} \cdots u_m] \begin{bmatrix} \sigma_1 & \cdots & \cdots & 0 \\ \vdots & \ddots & \ddots & 0 \\ \vdots & \ddots & \sigma_r & 0 \\ 0 & \ddots & \ddots & 0 \end{bmatrix} \begin{bmatrix} V_1^T \\ \vdots \\ V_r^T \\ V_{r+1}^T \\ \vdots \\ V_n^T \end{bmatrix} \qquad (3)$$

where $U \in R^{m\times m}$, $\Sigma \in R^{m\times n}$, $V \in R^{n\times n}$, U and V are unit orthogonal matrices, U is a $n\times n$ order orthogonal matrix, and each column of the eigenvector $u_i(1\leq i\leq n)$ of the covariance matrix AA^T is called the left singular matrix of A; V is the $m\times m$ order orthogonal matrix, and each of its columns is the eigenvector $v_i(1\leq j\leq m)$ of the covariance matrix A^TA, which is called the right singular matrix of A.

$$\Sigma = \begin{bmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & 0 \\ 0 & 0 & \ddots \end{bmatrix}_{m\times n} \quad (4)$$

where Σ is a $m\times n$ order diagonal matrix composed of r (r is the rank of A) elements, whose elements are arranged from large to small $\sigma_s(1\leq s\leq r)$, and $\sigma_1 \geq \sigma_2 \geq \cdots \geq \sigma_r \geq 0$; σ_s is called the singular value of A, which is actually the square root of the eigenvalue of A. In (4), Σ only has a value on the main diagonal, which is composed of r elements. It is called a singular value, which is arranged from large to small as follows: $\sigma_1 \geq \sigma_2 \cdots \geq 0$, so the ground penetrating radar can be represented by formula (5):

$$A = \sigma_1 u_1 v_1^T + \sigma_2 u_2 v_2^T + \cdots + \sigma_r u_r v_r^T \quad (5)$$

From the formula (5), it can be seen that the matrix A can be decomposed into a series of different characteristic components, σ_s representing the weight factor, which determines the contribution of the corresponding characteristic components to the composition of the complete A. According to a lot of practical experience, in most cases, the sum of the first 10% or even 1% singular values has occupied more than 99% of the sum of all singular values. In other words, a very small number of singular values can be used to approximate the original data greatly [12]. It can be seen that the SVD method can be used to decompose and process the ground penetrating radar signal to suppress the clutter signal in the ground penetrating radar image and reduce the image noise.

III.MODEL DETETION TEST

A. Primary support model and detection test of concrete with cavity

1) Model of Concrete Primary Support with Cavity

Two test models of tunnel lining and back cavity under the condition of grade IV surrounding rock are made, which are model i and model ii respectively. Among them, the model i is an integrated model of initial support and surrounding rock. Three different shapes of regular cavities are arranged inside the concrete model. The side length of the square cavity is 15cm, the bottom and height of the regular triangle cavity are both 15cm, and the diameter of the circular cavity is 15cm. The overall size of the model is 400cm long, 50cm wide and 70cm high. The thickness of the initial support of the concrete is 20cm, and the I14 I-steel is assembled with an interval of 1m. Model ii is the initial support and the actual filling surrounding rock model. The size of the concrete model is long× high× thick=400cm×70cm×50cm.Different from model i, the back of the initial support concrete is filled with soil, and the thickness of the soil is 50cm. Two different forms of complex irregular cavities are buried in the filling soil, which are irregular pentagonal prism cavity and irregular semi-cylindrical cavity. The embedding of irregular cavities in model i and model ii and model ii is shown in Figure 1~3.

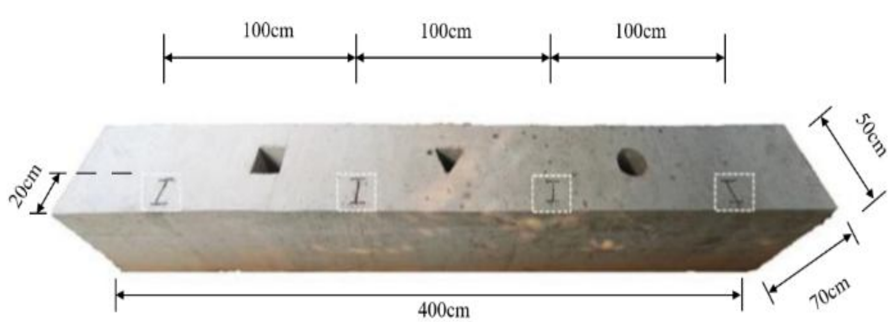


Fig. 1. Integrated coupling model of lining cavity under the condition of grade IV surrounding rock (Model i)

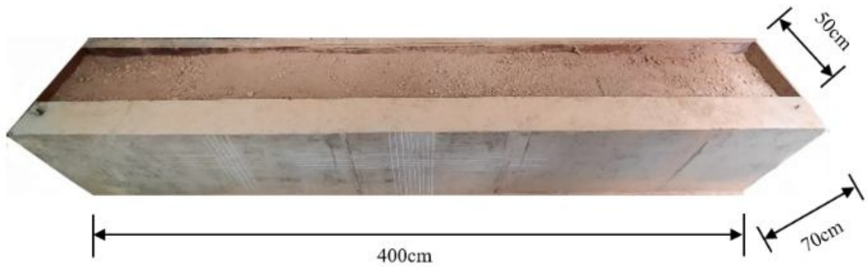


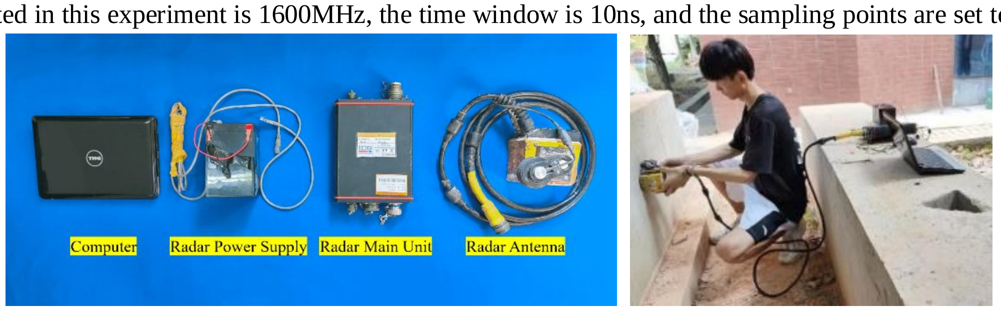
Fig. 2. Irregular cavity model of primary support under IV grade surrounding rock condition (Model ii)


(a) Irregular pentagonal prism cavity (b) Irregular semi-cylindrical cavity

Fig. 3. Irregular-shaped cavities buried in the backfill behind the primary support

2) Detection Test and Process

The detection instrument selected for the test is the RIS type ground penetrating radar produced by IDS company in Italy, which is composed of the computer, the radar power supply, the radar main unit and the radar antenna. The ground penetrating radar has a special antenna array that can be used in different fields, and has the advantages of portability, high scanning efficiency and high accuracy. In the detection research of the actual cavity model, aiming at the regular cavity and irregular cavity in the lining structure under the condition of grade IV surrounding rock, the RIS ground penetrating radar is used to detect the horizontal survey line of the two models respectively. The experimental instrument and detection process are shown in Figure 4. The center frequency of the radar antenna selected in this experiment is 1600MHz, the time window is 10ns, and the sampling points are set to 1024.



(a) RIS Series Ground Penetrating Radar (b) Cavity detection test diagram

Fig. 4. Experimental instruments and detection process

B. Processing and Analysis of Detection test Results

In order to study the best clutter suppression and noise reduction method of ground penetrating radar images with different geometric characteristics of tunnel cavities, the radar image of the regular cavity of the initial support of the model i is smoothed by Gaussian filtering to uniformly add noise to simulate the actual engineering situation. On the basis of control variables, wavelet analysis and singular value decomposition noise reduction methods are used to denoise the regular cavity radar images after adding noise, and their respective noise reduction effects are judged and measured by quantitative indicators. Model i detects the original image, the image after adding noise, and the image processed by wavelet analysis and singular value decomposition filtering method are shown in Figure.5.

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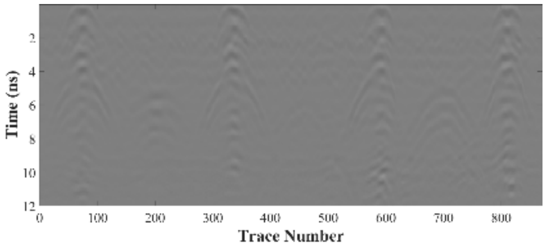
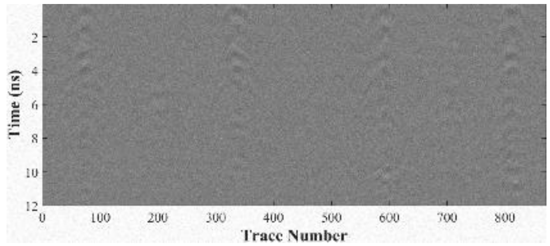
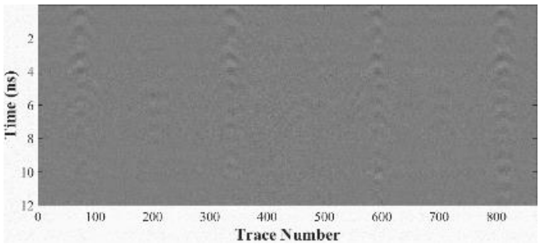


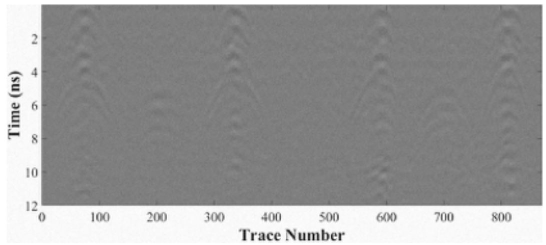
(a) Original GPR image



(b) Adding Gaussian noise image



(c) After wavelet analysis processing



(d) After SVD processing

Fig. 5. Regular cavity GPR images and images with Gaussian noise and noise reduction

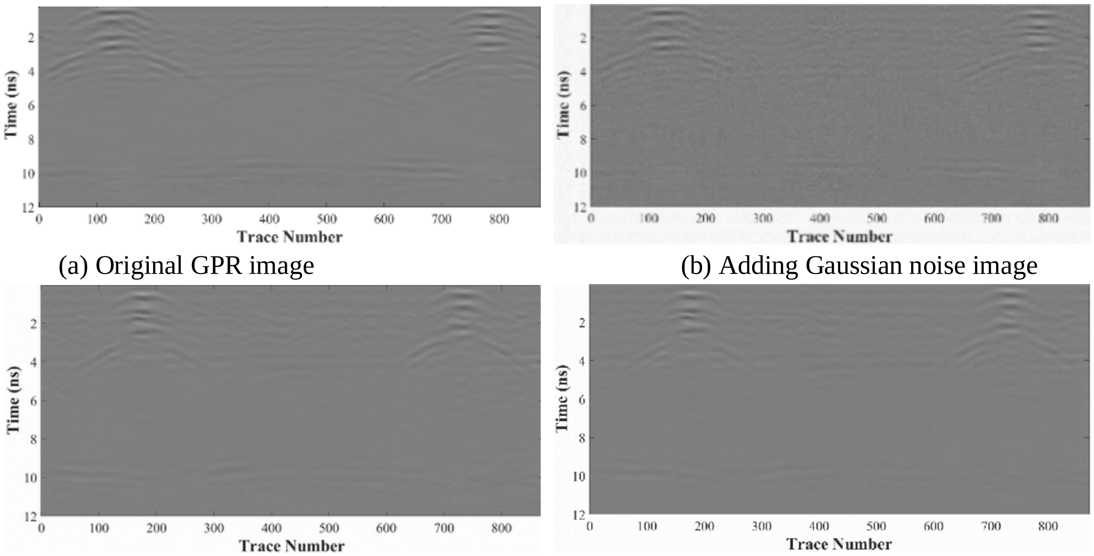
The signal-to-noise ratio, variance, Roberts function and sharpness improvement ratio of each sub- images in the figure are calculated respectively. The results are shown in TABLE I.

TABLE I
COMPARISON OF NOISE REDUCTION EFFECTS OF DIFFERENT NOISE REDUCTION METHODS FOR REGULAR CAVITY DETECTION IMAGE

Image type	Signal-to-Noise Ratio	Variance	Roberts Function	Clearness Enhancement Ratio
Add Gaussian noise image	34.9943	4.0848e+03	13631406	0.00%
Image after wavelet analysis noise reduction	35.6301	3.9016e+03	16715592	22.63%
Image after singular value decomposition noise reduction	36.5397	3.8820e+03	48385188	254.95%

According to the data in TABLE I, wavelet analysis and singular value decomposition noise reduction are carried out on the radar image of grade IV surrounding rock regular cavity with Gaussian noise respectively. The image obtained by the latter has a larger signal-to-noise ratio and the smallest variance. The clarity improvement effect obtained by Roberts function operation is better. The radar image obtained by noise reduction is similar to the human perception effect in vision, which reflects that the image noise obtained by singular value decomposition is smaller than the image processed by wavelet analysis.

Because the irregular cavity in the model ii is in the filling environment, the size of the filling particles is not uniform and contains impurities, and the filling environment is more complex. Here, Gaussian noise is added only to the pentagonal prism cavity radar image, but not to the semi-cylindrical cavity radar image. The original image, the image after adding noise and the results after wavelet analysis and singular value decomposition filtering of the detection of I-steel and irregular pentagonal prism cavity in model ii are shown in Figure 6.



(a) Original GPR image (b) Adding Gaussian noise image

(c) After wavelet analysis processing (d) After SVD processing

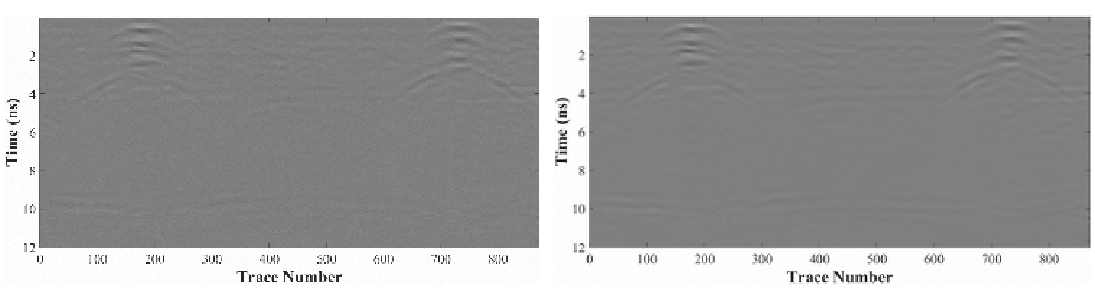
Fig. 6. Irregular pentagonal prism cavity radar image and its noise reduction image

The signal-to-noise ratio, variance, Roberts function and sharpness improvement ratio of different sub-images in the figure are calculated. The results are shown in TABLE II.

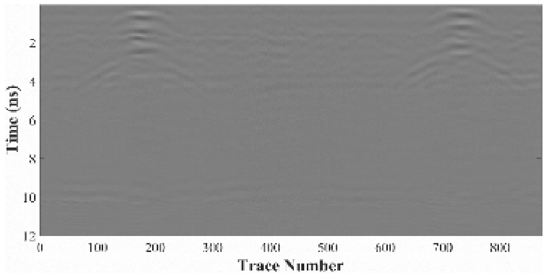
Table II
COMPARISON OF NOISE REDUCTION EFFECTS OF DIFFERENT NOISE REDUCTION METHODS FOR IRREGULAR PENTAGONAL PRISM CAVITY DETECTION IMAGE

Image type	Signal-to-Noise Ratio	Variance	Roberts Function	Clearness Enhancement Ratio
Add Gaussian noise image	36.0989	4.1242e+03	15222012	0.00%
Image after wavelet analysis noise reduction	36.0790	3.9800e+03	10813140	-28.96%
Image after singular value decomposition noise reduction	36.9324	3.9148e+03	22101414	45.19%

The original image of the detection of I-steel and irregular semi-cylindrical cavity in model ii, and the results of wavelet analysis and singular value decomposition noise reduction are shown in Figure 7.



(a) Original GPR image (b) After wavelet analysis processing



(c) After SVD processing

Fig. 7. Irregular semi-cylindrical cavity radar image and its noise reduction image

Similarly, the signal-to-noise ratio, variance, Roberts function and sharpness improvement ratio of different sub-images in the figure are calculated, and the results are shown in TABLE III.

TABLE III
COMPARISON OF NOISE REDUCTION EFFECTS OF DIFFERENT NOISE REDUCTION METHODS FOR IRREGULAR SEMI-CYLINDRICAL CAVITY DETECTION IMAGE

Image type	Signal-to-Noise Ratio	Variance	Roberts Function	Clearness Enhancement Ratio
Add Gaussian noise image	35.0588	4.1197e+03	14154072	0.00%
Image after wavelet analysis noise reduction	36.1933	3.9825e+03	8991240	-36.48%
Image after singular value decomposition noise reduction	36.2718	3.9125e+03	14174670	0.15%

Combined with the data in TABLE II and TABLE III, the wavelet analysis and singular value decomposition method are used to denoise the radar images of I-beam, irregular pentagonal prism cavity and irregular semi-cylindrical cavity in Model ii. It can be seen from the clarity improvement ratio of Roberts function that the image clarity improvement after wavelet filtering is not obvious, and even shows negative effects in the two kinds of irregular cavity radar images after noise reduction. After the singular value decomposition processing, the image signal-to-noise ratio and the Roberts function value are relatively high, and the image variance is small, indicating that the filtering method is better than the wavelet analysis in the noise reduction effect of the lining cavity ground penetrating radar image to some extent.

IV. CONCLUSIONS

From the analysis of the denoising results of the radar detection image of the lining structure of the model test, it can be seen that the ground penetrating radar image after singular value decomposition denoising has better performance than wavelet analysis in terms of signal-to-noise ratio, variance, and Roberts function sharpness improvement ratio.

It fully shows that the singular value decomposition is significantly better than the wavelet analysis method in noise reduction performance. This method has the best clutter suppression effect and the best noise reduction effect in the actual ground penetrating radar image filtering processing.

V. ACKNOWLEDGMENT

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