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Seismic Wavelet Analysis Based on Finite Element Numerical Simulation

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Abstract

The practice of exploration and production has proved that explosives are excited in different surrounding rocks and the seismic wavelets collected have different characteristics. In this paper, by establishing a numerical model of the explosion in the well, using finite element analysis technology for numerical simulation, the simulation calculated the stress structure in the near-source area of the earthquake excitation, and extracted the seismic wavelet. The results show that the simulation seismic wavelet characteristics of different thin interbedded sand and mudstone structures have changed significantly. Through excitation simulation, the amplitude and spectrum information of seismic wavelets can be compared and analyzed, and the excitation parameters can be optimized.

Keywords

Finite Element Method, Seismic Wavelet, Numerical Simulation, Thin Interbed

1. Introduction

In the process of oil and gas exploration and construction, explosive sources are widely used to generate seismic wave fields. In order to improve the quality of the collected data, continuous theoretical research and field tests have been carried out (Men, Jiang, & Wang, 2015). Explosive shock theory research and field tests are expensive and long-term needed. Using nonlinear finite element analysis software, to construct the digital models with Rocks and explosive Parameters, numerical simulations could provide the motion and amplitude characters of the elements and nodes (Zhang et al., 2018). Analysis of the amplitude and frequency spectrum of seismic wavelets is to optimize the excitation parameters and improve the quality of seismic data important means (Li, 2018).

In this study, a borehole excitation model for land-based seismic exploration was established. By analyzing the amplitude and frequency characteristics of the seismic wavelets excited in mudstone and sandstone regions, a new idea for rationally selecting excitation points was put forward.

2. Numerical Model Establishment

2.1. Model Geometric Parameters

This study simulates a single well excitation, the explosion point depth is 10 m, and the source grain weight is 4 kg. In order to reduce the amount of calculation, a two-dimensional axisymmetric method was used to build the model, with a depth of 60 m and a width of 30 m. The block structured grid model (namely node number index) is adopted, and the grid size is 0.25 m × 0.25 m × 0.25 m. Deploy Gaussian observation points along the axis of the borehole on the model, with an interval of 2 m, as shown in **Figure 1**.

In order to simulate infinite space and reduce boundary reflection effects, the top, bottom, and sides of the model are set as transmissive boundaries, allowing outward waves to pass on the grid without bringing the reflected energy into the calculation grid.

2.2. Model Material Parameters

The numerical simulation in this paper involves three kinds of materials: sand (mud) rock and explosives. Among them, explosives are used as energy supply during the blasting process of surrounding rock, which mainly acts on the rock mass through expansion and stress waves.

- Explosive parameters

Emulsion high-energy explosives are used, and JWL (Jones-Wilkins-Lee) equation of state is used to describe the pressure, volume and energy characteristics of gas products in the detonation process. Its expression is

$$p = A\left(1-\frac{\omega}{R_1V}\right)e^{R_1V} + B\left(1-\frac{\omega}{R_2V}\right)e^{R_2V} + \frac{\omega E}{V} \quad (1)$$

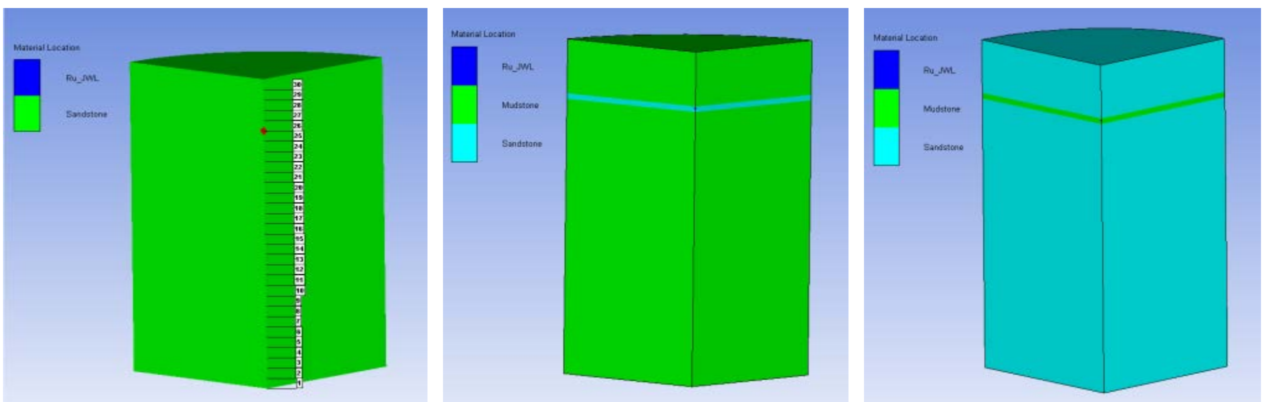

Figure 1. Numerical model of seismic excitation.

where p is the pressure; E is the internal energy of the detonation product per unit volume; V is the relative volume of the detonation product, that is, the ratio of the volume of the detonation product after the explosion to its initial volume; A, B, R_1, R_2, and ω are constants , Determined by experiment.

- Surrounding rock parameters

In this paper, the Johnson-Cook constitutive relationship model is used to describe the stress-strain relationship of the surrounding rock, which is suitable for the strength performance of materials with large strain and high strain rate, and is suitable for high-speed collision and strong impact load caused by explosive detonation.

$$\sigma = \left[A + B\varepsilon_p^n\right]\left[1 + C\log\varepsilon_p^*\right]\left[1 - T_H^m\right] \tag{2}$$

Among them, σ is the dynamic yield stress of the material; A is the quasi-static yield stress of the material; B is the strain hardening modulus of the material; ε_p is the effective plastic strain; ε_p^* is the normalized effective plastic strain rate, $\varepsilon_p^* = \varepsilon/\varepsilon_0$, ε is the plastic strain rate, ε_0 is the critical strain rate, T_H is the same temperature, its expression is $T_H = (T - T_0)/(T - T_m)$, T, T_0 and T_m are the temperature during the deformation of the material, reference Temperature and melting point temperature; C, n, and m are material constants.

In order to express the plastic yield of rock under huge shear stress, a volume failure model is used to limit the maximum principal stress tensile failure strain and the maximum shear strain (tensile strength) when the material exceeds the limit (tensile strength).

3. Explosion Simulation Analysis

3.1. Simulation Analysis of Mudstone-Mudstone Intercalated Sandstone Thin Layer Excitation

- Stress cloud

After the explosive package is excited, a high pulse pressure is generated on the medium around the package, and the detonation wave energy spreads in a spherical shape to all sides. Under the ultra-high pressure of the shock wave, the structure of the medium is severely damaged and energy is consumed. After a certain distance from the explosion center point, it entered the rock elastic region, the observed pressure was relatively stable, and the attenuation was relatively slow. Excited in a thin layer of sandstone, the energy is diffused in a spherical shape, and is rapidly released along the sandstone interlayer. The seismic wave field changes from a spherical shape to a flat spindle shape, and the fracture shape in the rock fragmentation area also changes to a certain extent (**Figure 2** and **Figure 3**).

- Seismic wavelet

The particle vibration velocity and acceleration time history curve of each observation point corresponds to the seismic waveform collected by the geophone (velocity/acceleration geophone) in the geophysical prospecting construction, and the mudstone excited seismic wavelet is obtained (**Figures 4-6**). It can be

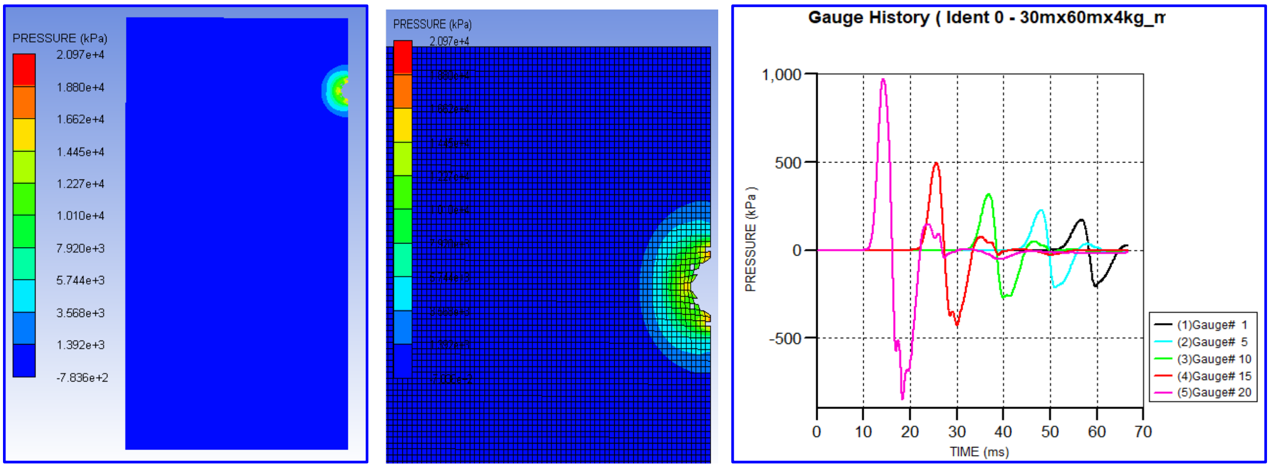

Figure 2. Explosion cloud diagram in mudstone (left-stress cloud diagram, middle-part of erosion model, right-observed pressure curve).

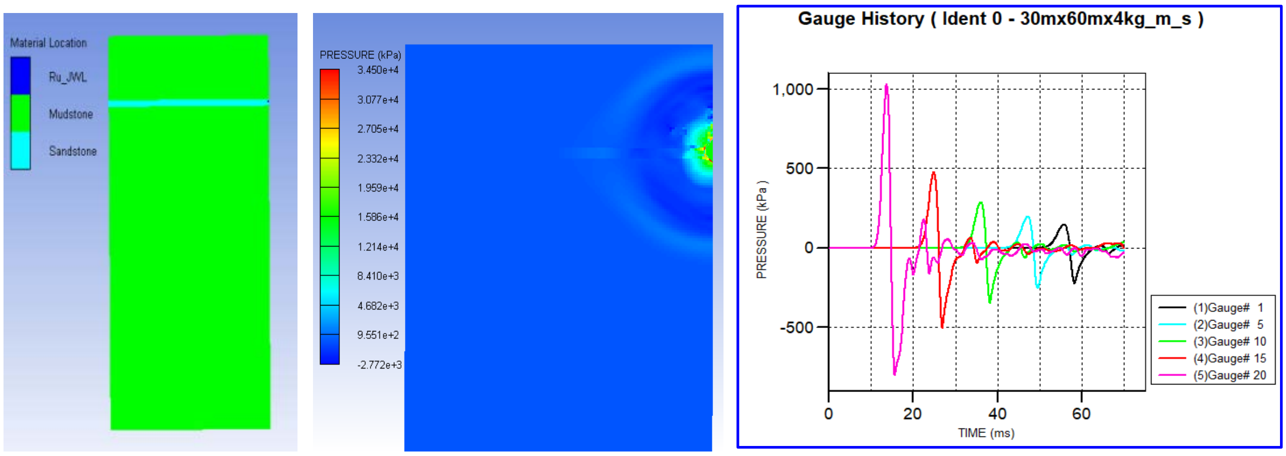

Figure 3. Explosion cloud diagram of a thin layer of sandstone in mudstone (left-stress cloud diagram, middle-part of erosion model, right-observed pressure curve). Note: The interval between observation points is about 10 m, the distance between No. 1 and the center of burst is 50 m, and the distance between No. 20 and the center of burst is 10 m).

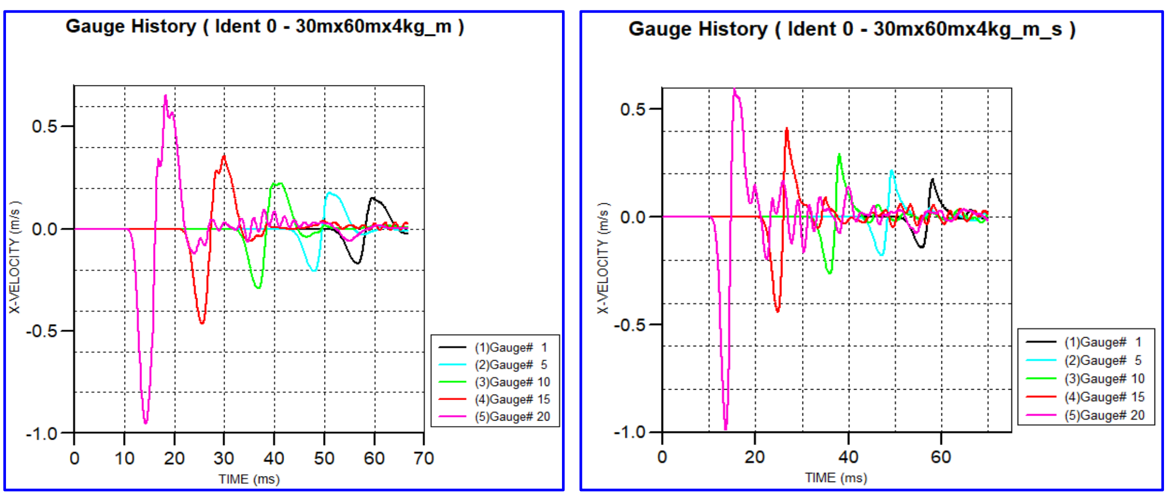

Figure 4. Vibration velocity-time history curve of the observation point (left-mudstone, right-thin layer of sandstone in mudstone).

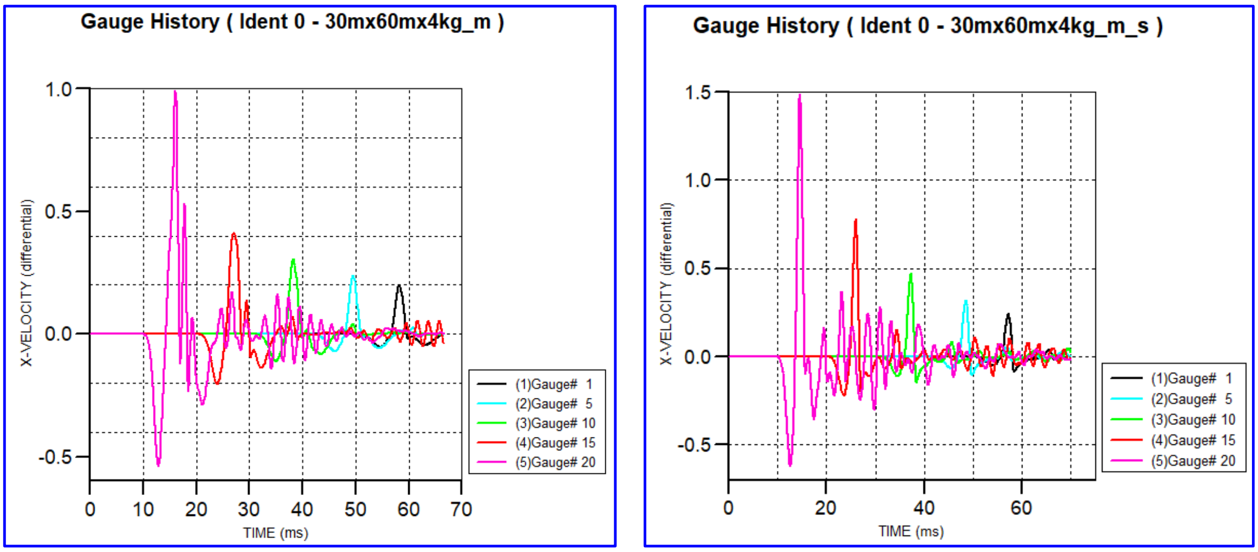

Figure 5. Vibration acceleration-time history curve of observation point (left-mudstone, right-thin layer of sandstone in mudstone).

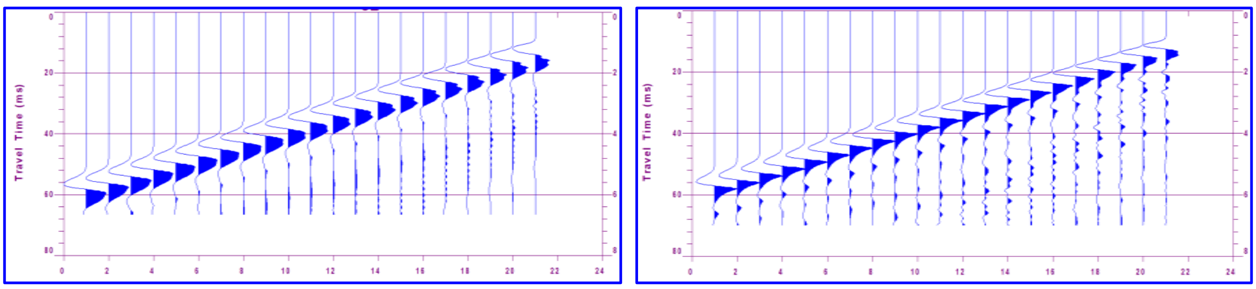

Figure 6. Original seismic wavelet record (left-mudstone, right-thin layer of sandstone in mudstone).

seen that the excitation seismic waves in the thin sandstone layer have changed, and some high-frequency noise has appeared.

- Seismic wavelet spectrum analysis

Spectrum analysis shows that the main frequency of mudstone excitation is 95 Hz; when excited in thin sandstone interlayers, the high frequency components are enhanced (**Figure 7**).

3.2. Simulation Analysis of Excitation of Thin Sandstone-Sandstone Intercalated Mudstone

Numerical simulations are carried out for the excitation of thin sandstone and mudstone layers.

- Stress cloud

Excited in homogeneous sandstone, the seismic wave field spreads in a spherical shape; Excited in thin mudstone interlayer, the seismic wave energy converges into an ellipsoid along the interface of mudstone and sandstone toward the burst center, and the destruction circle caused by the explosion extends to both sides along the interface, The pressure of the shock wave is observed to weaken, and there is obvious shock phenomenon (**Figure 8** and **Figure 9**).

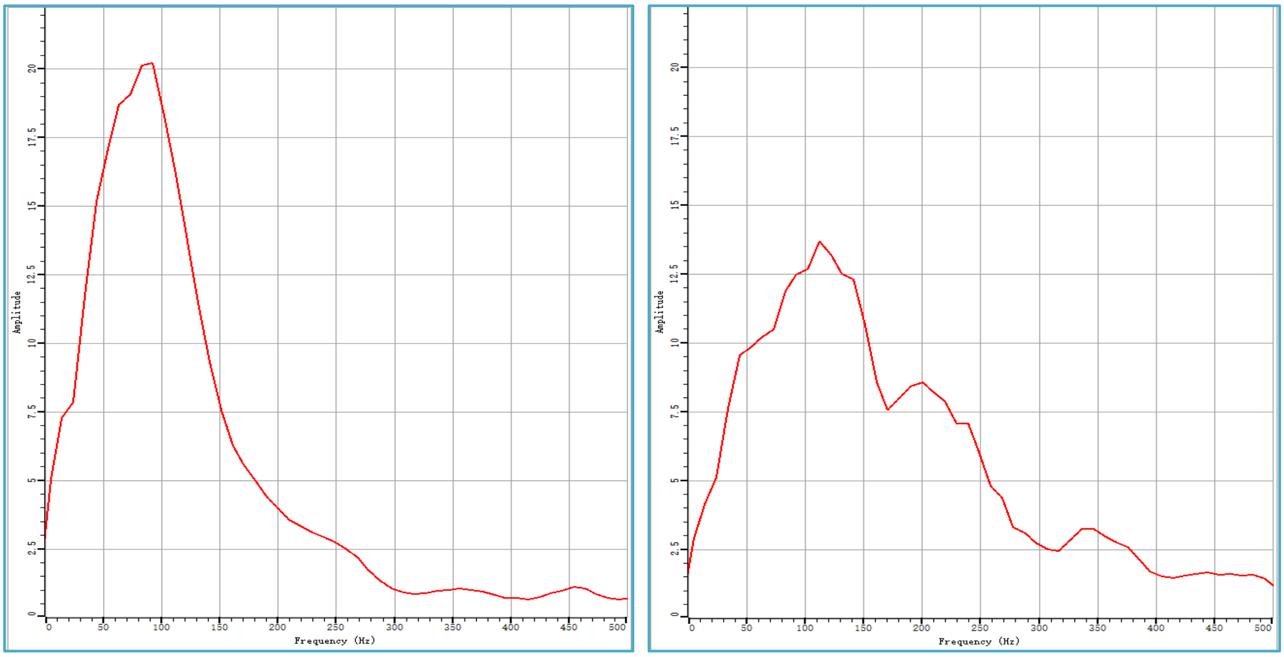

Figure 7. Frequency-amplitude curve of seismic wavelet (left-mudstone, right-thin layer of sandstone in mudstone).

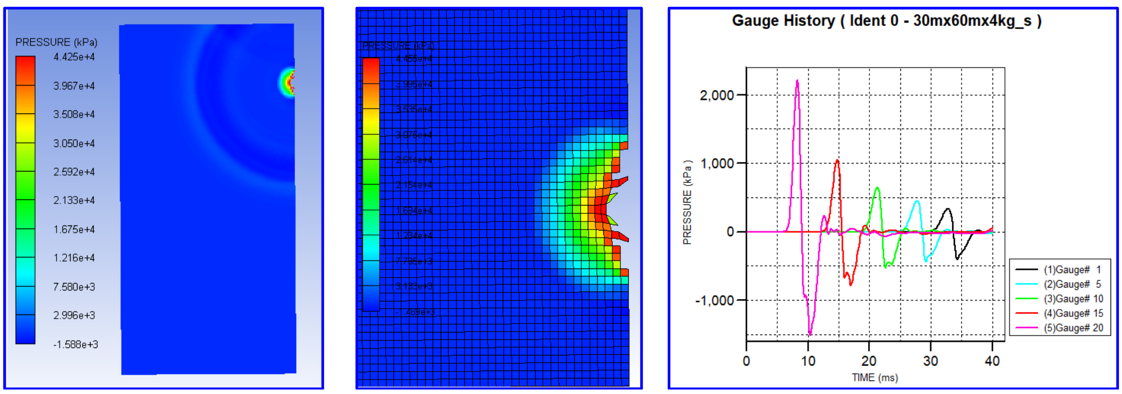

Figure 8. Explosion stress cloud diagram in sandstone (left-stress cloud diagram, middle-part of erosion model, right-observed pressure curve).

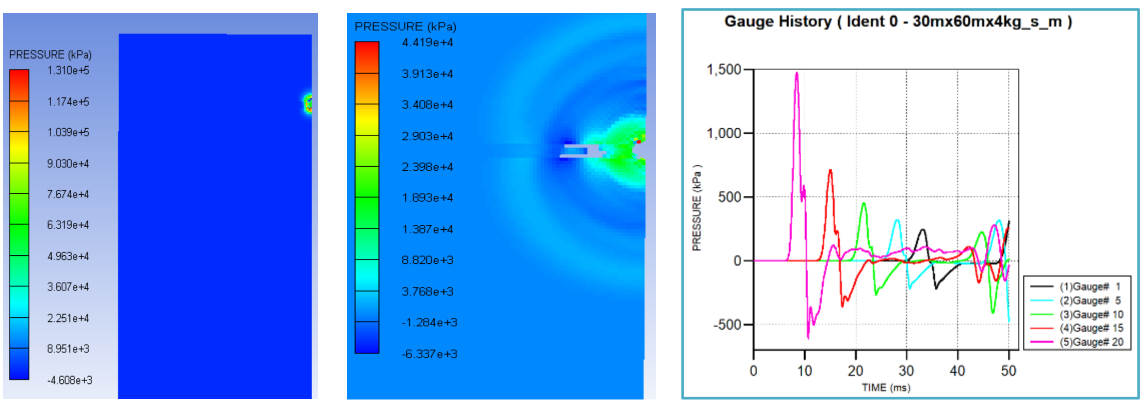

Figure 9. Induced stress cloud diagram of a thin layer of mudstone in sandstone (left-stress cloud diagram, middle-part of erosion model, right-observed pressure curve). Note: The interval between observation points is about 10 m, the distance between No. 1 and the center of burst is 50 m, and the distance between No. 20 and the center of burst is 10 m).

- Seismic wavelet

According to the particle vibration velocity and acceleration time history curve of the observation point below the explosion point, the seismic wavelet is analyzed. It can be seen that when excited in the mudstone interlayer, the amplitude of the seismic wavelet is obviously weakened, and the high-frequency oscillation phenomenon is strengthened (**Figures 10-12**).

- Seismic wavelet spectrum analysis

Spectrum analysis shows that sandstone excites the main frequency of the seismic wavelet at 150 Hz; after excitation in the mudstone interlayer, the energy of the observation point decreases, but the energy of the seismic wave in the frequency range of 50 - 100 Hz increases (**Figure 13**).

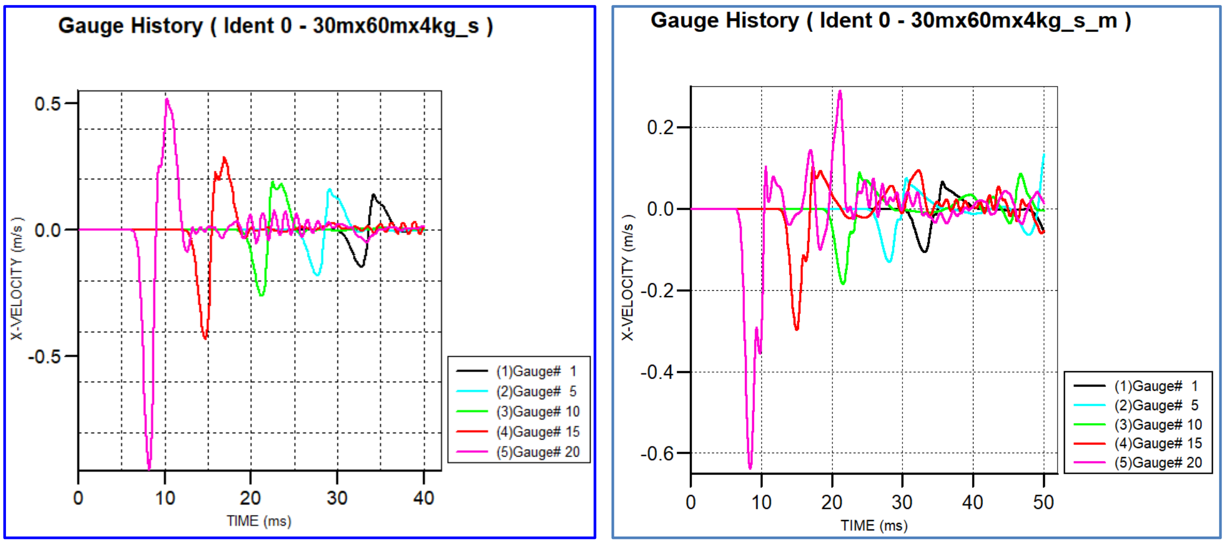

Figure 10. Vibration velocity-time history curve of the observation point (left-sandstone, right-thin layer of mudstone in sandstone).

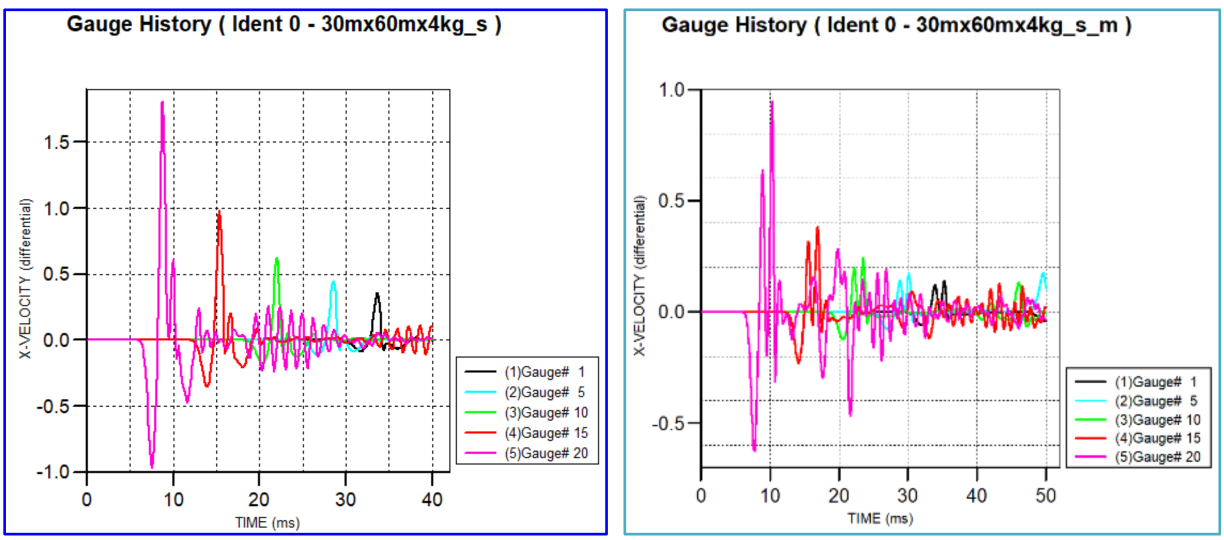

Figure 11. Vibration acceleration-time history curve of observation point (left-sandstone, right-thin layer of mudstone in sandstone).

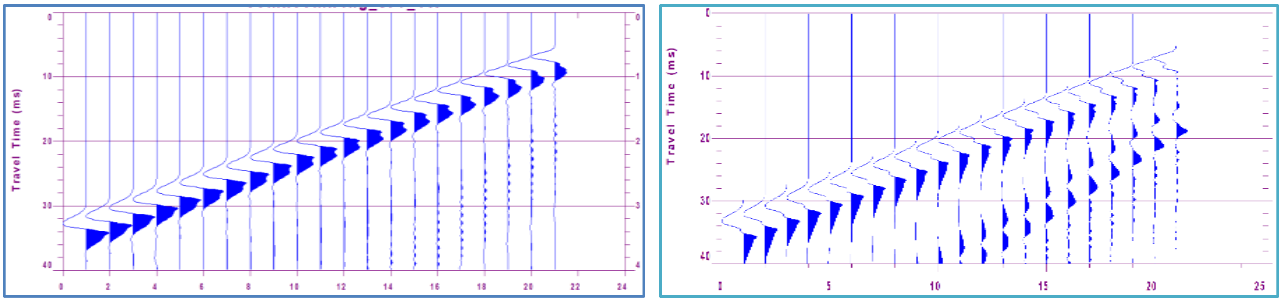

Figure 12. Original seismic wavelet record (left-sandstone, right-thin layer of mudstone in sandstone).

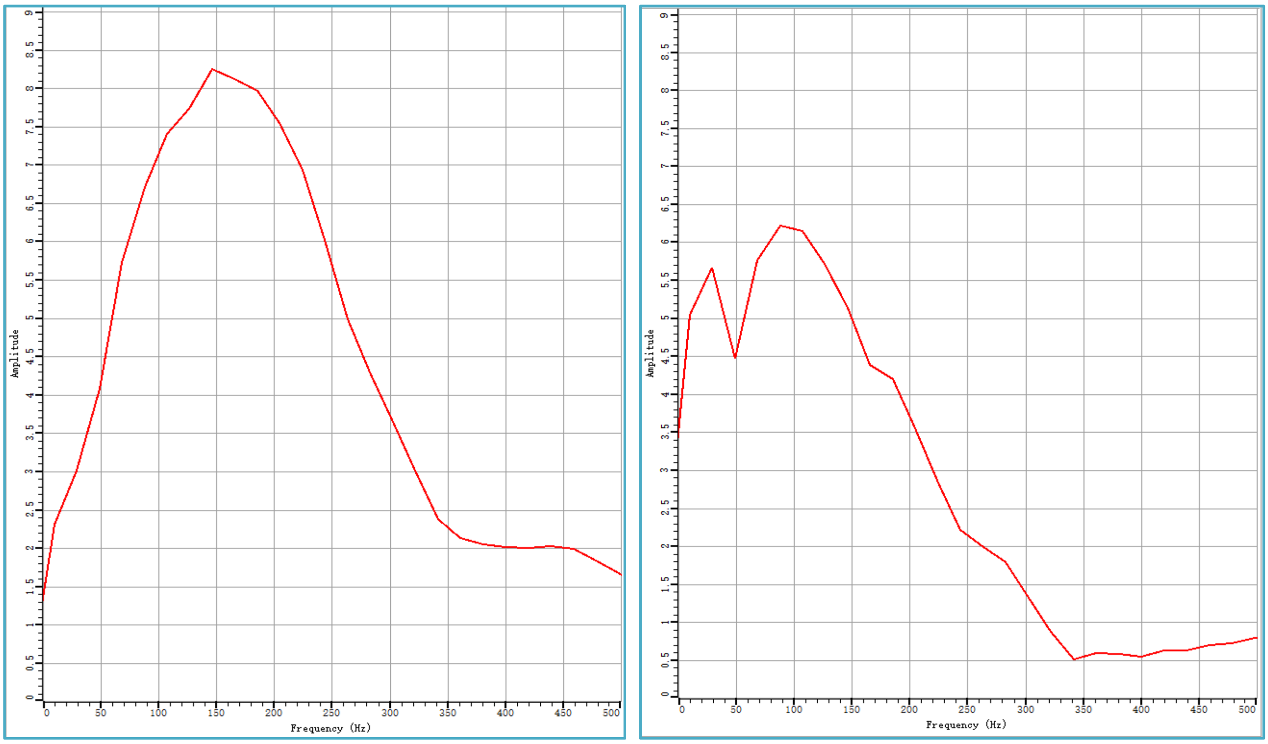

Figure 13. Frequency-amplitude curve of seismic wavelet (left-sandstone, right-thin layer of mudstone in sandstone).

4. Conclusion

The above numerical simulation of seismic excitation shows that the excitation data in mudstone is better than sandstone excitation in the main frequency band, and the excitation in the thin interbed of mudstone and sandstone plays a role in transforming the frequency and amplitude of seismic wavelets. Especially the excitation in the mudstone interlayer, although the seismic wave frequency band is widened, it also weakens the energy of the seismic wave. Therefore, in the seismic exploration data acquisition and construction, when optimizing the excitation lithology, the matching of seismic excitation energy should also be considered to effectively ensure the quality of the data.

Existing problems: Although the transmission boundary was set in the modeling to simulate the seismic excitation in an infinite space in this study, a certain boundary reflection wave interference phenomenon still occurred.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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