

TWO-DIMENSIONAL FEM MODELING OF SEISMIC WAVE PROPAGATION IN COAL SEAM

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Abstract

In-seam seismic signals are used to detect underground mine voids. Channel waves, main components of in-seam seismic, trapped in coal seam without radiate energy into the surrounding rocks, make it possible to locate coal seam discontinuity for a longer distance than traditional body wave exploration. Two dimensional Finite Element Method modeling was used to study the characteristics of wave propagation in coal seam. Both transmission and reflection tests were simulated. The results demonstrate that two dimensional FEM modeling appears to be a reasonable approach for in-seam seismic simulation.

1. Introduction

In numerical analysis, the finite element method (FEM) is used for solving partial differential equations (PDE) approximately ^[1]. Solutions are approximated by either eliminating the differential equation completely (steady state problems), or rendering the PDE into an equivalent ordinary differential equation, which is then solved using standard techniques such as finite differences, etc ^[2].

In the context of seismic exploration, numerical modeling of wave propagation has become an important research area ^[3]. The FEM is one of the most frequently used model technique to simulate seismic seam wave propagation ^[4]. In-seam seismic based mine void detection, using artificially generated channels waves for the mapping of underground void ^[5], was proposed by Penn State researchers to solve mine inundation problems like Quecreek mine disaster ^[6].

FEM was introduced by Zienkiewicz and Cheung to analysis complex underground seam structures ^[7]. A comparison of the finite-difference method (FDM) with FEM shows that in FDM approximations of a differential equation of the discrete representation of the equation is applied to a point, while in FEM the discrete equations are applicable over a region ^[4]. The FEM representation can be interpreted as simple FDM formulas integrated over the x- and z- directions ^[8].

Three different waves are concerned for In-Seam Seismic study: P-wave (compressional wave), S- wave (shear wave), and channel wave (Love wave) ^[9, 10, 11]. By introducing simplifying assumptions concerning the seismic source, the medium and the process of wave propagation itself, the propagation of seismic waves along a coal seam can be mathematically described as channel wave ^[12]. Figure 1 and Figure 2 (see appendix) illustrate the generation and propagation of channel wave ^[13, 14, 15]. The body waves continuously radiated back into the seam as total reflection at its upper and lower boundaries thereby form seams waves ^[4]. The channel waves, trapped in the coal seam they propagate without radiate energy into the surrounding rock, make it possible to locate coal seam discontinuity for a longer distance than traditional body wave exploration ^[16, 17, 18, 19]. To simplify the study, it is usually assumed that the spread of channel wave in coal seam is two dimensional instead of three dimensional ^[20, 21]. This paper aims at studying the basic principle of seismic wave propagation in coal seam.

2.1 Governing Equations

The coal seam is treated here as isotropic and uniformly continuum without considering discontinuities such as joints and faults. Based on Newton's law $f=ma$, the general conservation of momentum can be given as:

$$\frac{\partial V}{\partial t} + (V \cdot \nabla)V = \frac{1}{\rho} \nabla \cdot \sigma + g \quad (1)$$

where V represents volume, t is time, ρ is the density, σ is stress, g is the acceleration of gravity, and the symbol ∇ is the vector differential operator (gradient), defined as

$$\nabla = \left(\frac{\partial}{\partial x_1}, \dots, \frac{\partial}{\partial x_n} \right) \quad (2)$$

The space coordinates are denoted x_1, \dots, x_n , where n represents the number of space dimensions.

The constitutive relation of the propagation of seismic wave can be described by classic PDE in compact equation:

$$d_a \frac{\partial^2 u}{\partial t^2} - \nabla \cdot (c \nabla u) = f \quad (3)$$

The standard notation of two-dimensional problem is:

$$d_a \frac{\partial^2 u}{\partial t^2} - \frac{\partial}{\partial x} \left(c \frac{\partial u}{\partial x} \right) - \frac{\partial}{\partial y} \left(c \frac{\partial u}{\partial y} \right) = f \quad (4)$$

where d_a is the mass coefficient, c is the diffusion coefficient and f is the source.

The boundary conditions can be simply illustrated as the following figure, plan view of the coal pillar. The source of seismic energy (for instance: explosion) is located at the working face. The opposite side of the coal seam represents the void (reflector). Suppose the width of the model is much bigger than the distance between source and reflector (h), the left and right side of the coal seam can be considered as at infinite distance, or so called non-reflective boundary. Therefore, the Dirichlet boundary condition demands that:

$$F(y = 0, h) = 0 \quad (5)$$

that means that the up and down side of the coal seam is “free” and there is no flux of force (F).

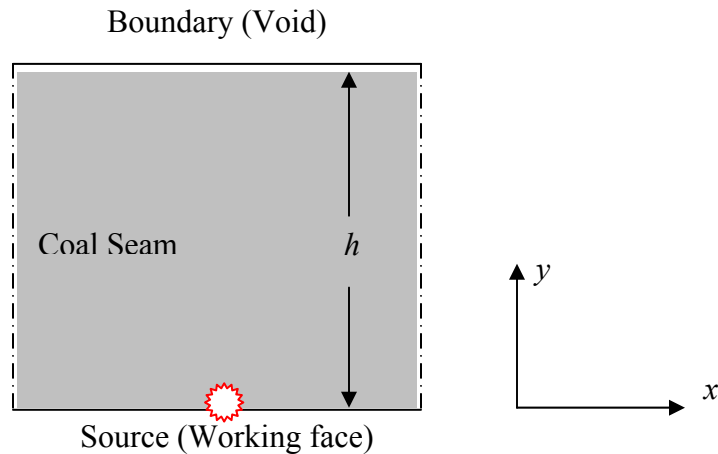


Figure 1: Two-dimensional model of coal seam (plan view).

The initial conditions can be described as:

$$u(t_0) = 0 \quad (6)$$

and suppose the energy released and converted by the explosion is E , there will be a dynamic pulse at the source location:

$$\frac{1}{2}mv^2_{(x=0,y=0)}(t) = E \quad (7)$$

2.2 Formulation with FEMLAB

FEMLAB (COMSOL Multiphysics) is an interactive environment for modeling and solving scientific and engineering problems based on partial differential equations (PDEs).

Equation

For time-harmonic propagation, the wave equation turns into the Helmholtz equation:

$$-\nabla \cdot (\nabla u) - k^2 u = 0, \quad k = \frac{2\pi}{\lambda} \quad (8)$$

Boundary Conditions

For transmission test, the absorbing boundary conditions have the form

$$n \cdot (\nabla u) + iku = 2ik, \text{ inflow} \quad (9)$$

$$n \cdot (\nabla u) + iku = 0, \text{ outflow} \quad (10)$$

(The above equations were referenced to the Manuals and documentation of FEMLAB)

For reflection test, the boundary condition for air void is:

$$n \cdot (\nabla u) + iku = 0, \text{ outflow} \quad (11)$$

Modeling Procedure with Graphic User Interface

MODEL NAVIGATOR

1. Select **2D** in the **Space dimension** list.
2. In the list of application modes, open **PDE Modes** and then **PDE, Coefficient Form**.
3. Select **Stationary analysis with Lagrange-Quadratic** selected in the **Element** list.
4. Click **OK**.

GEOMETRY MODELING

1. Draw a rectangle centered at (0, 0) with sides of 2 and 1 units for the x - and y -directions, respectively.
2. Draw a rectangle cornered at (-0.01,-1) with sides of 0.02 and 0.05 units for the x - and y -directions, respectively
3. Select both objects and click the **Difference** button to create a small cut representing blasting borehole.
4. From the **Draw** menu, choose **Create Composite Object**.

5. Click **OK**.

MESH GENERATION

1. In the **Mesh Parameters** dialog box, click the **Global** tab
2. Enter 0.1 in the **Maximum element size** edit field.
3. Click the **Remesh** button.

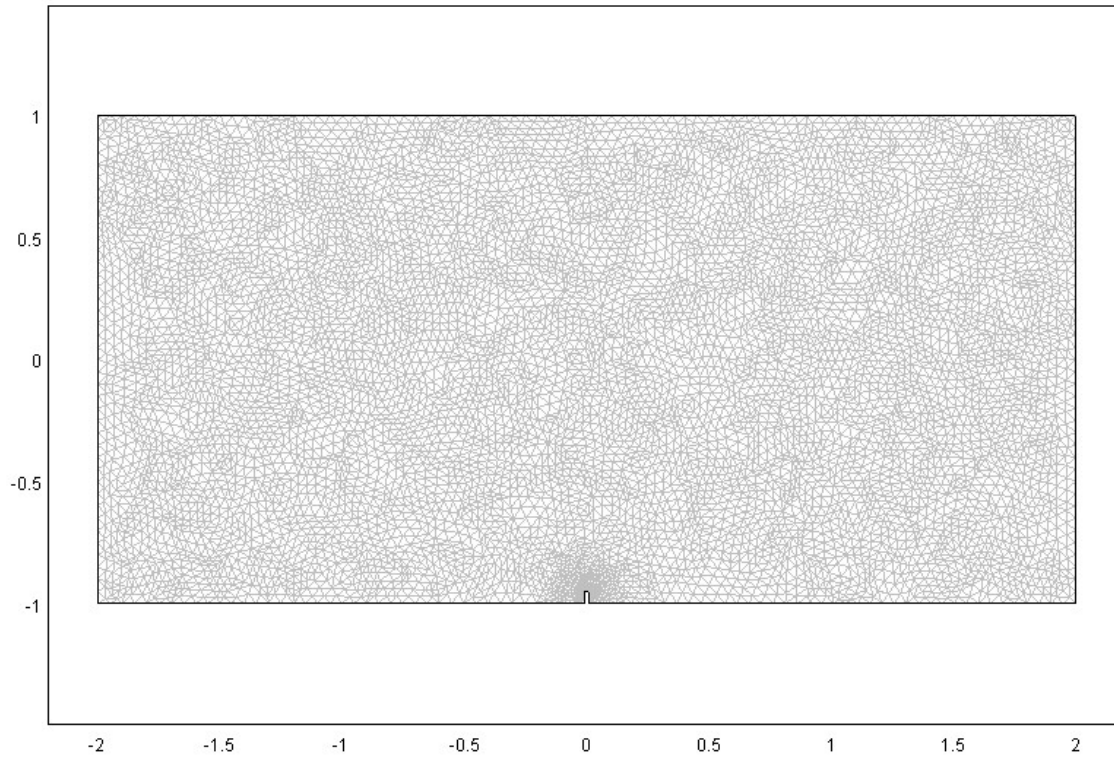


Figure 2. Mesh generation of two-dimension coal seam with a blasting borehole

2.3 Solution

1. Transmission

Transmission test means that the source (blasting) and receivers (sensors) located at different side of the pillar. To simplify the simulation of transmission test, it was supposed that receiver (void) side is absorbing boundary, so that there is no reflection or multiples. Figure 3 demonstrates the result of wave propagation with input signal frequency equals to 10000 Hz if suppose wave velocity equals to 1000 m/s.

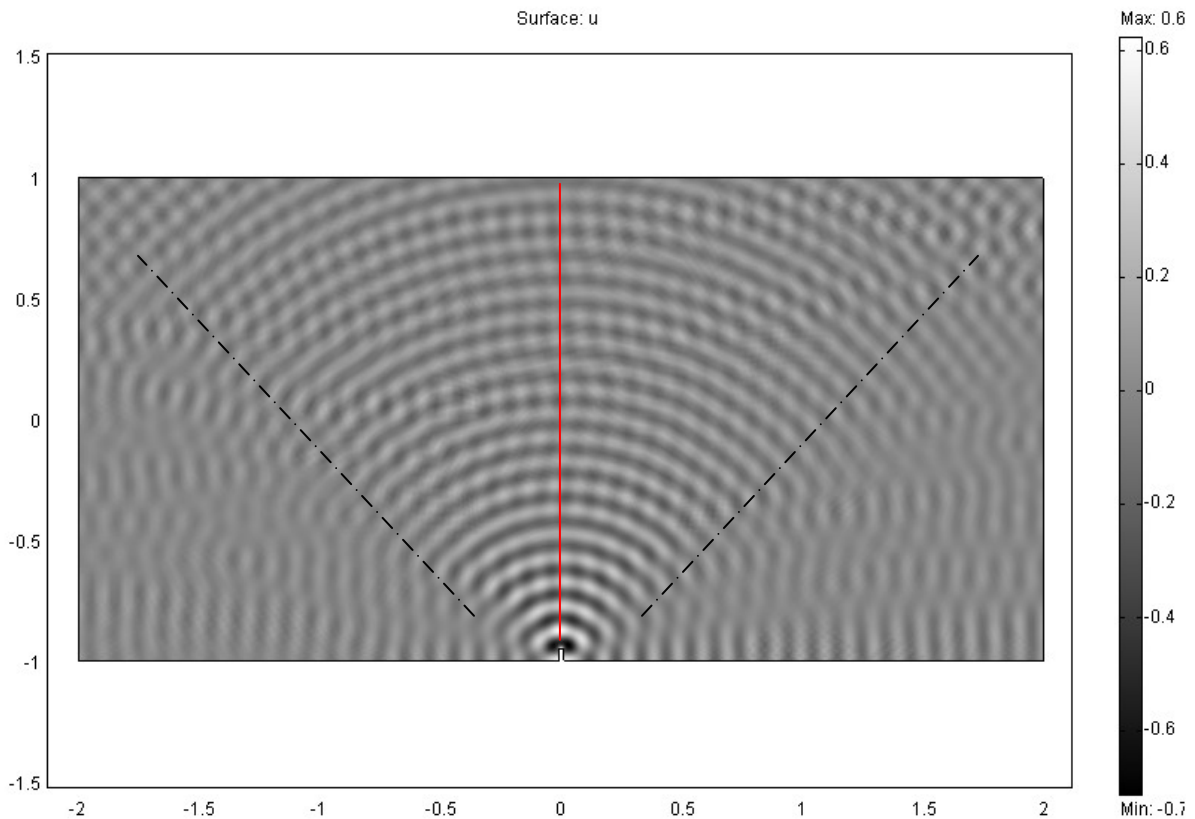


Figure 3: wave propagation pattern in coal seam without reflection ($F=10000$ Hz).

According the above figure, main part of the energy is propagated in the arch area of 90° , which is different to the general wave propagation in liquid.

2. Reflection

Reflection test means that the source (blasting) and receiver (sensor) located at same side of the pillar, the seismic signals travel to the sensor after reflection at the opposite boundary. To simulate the reflection, the up and down sides of the pillar were set as reflective boundary (Dirichlet Boundary Condition), the left and right sides of the pillar were set as absorption boundary (Neumann Boundary Condition). Figure 4 demonstrates the result of propagation pattern of reflected waves.

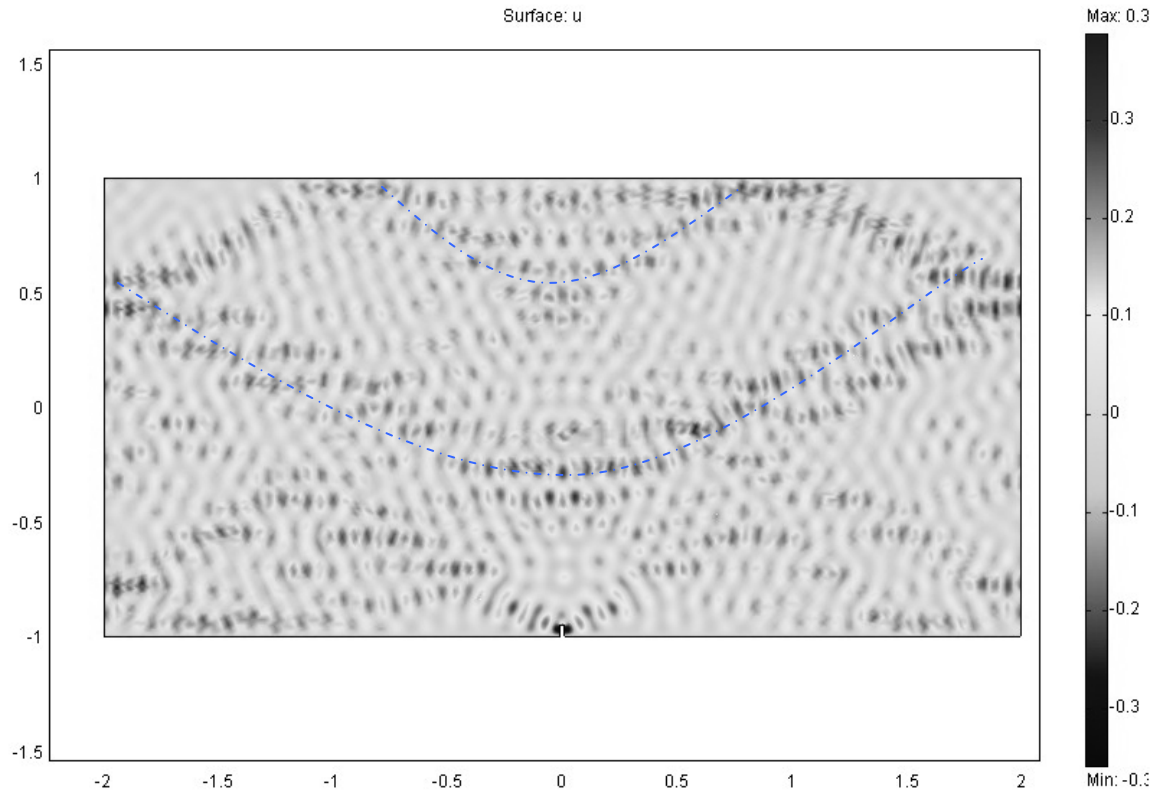


Figure 4: wave propagation for reflection test (dash lines show the reflected waves)

3. Validation

Figure 5 shows the wave propagation pattern of reflection test. This trend can be explained by the so called “law of reflection”. The “void boundary” can be regarded as a mirror. According to the law of reflection, the angle of incidence equals the angle of reflection. The reflected waves can be considered as from the “virtual source”, which is symmetric to the actually source according the reflection boundary. The diagram of

Figure 5 illustrates that the reflection waves by FEMLAB modeling outcome can be verified by the law of reflection.

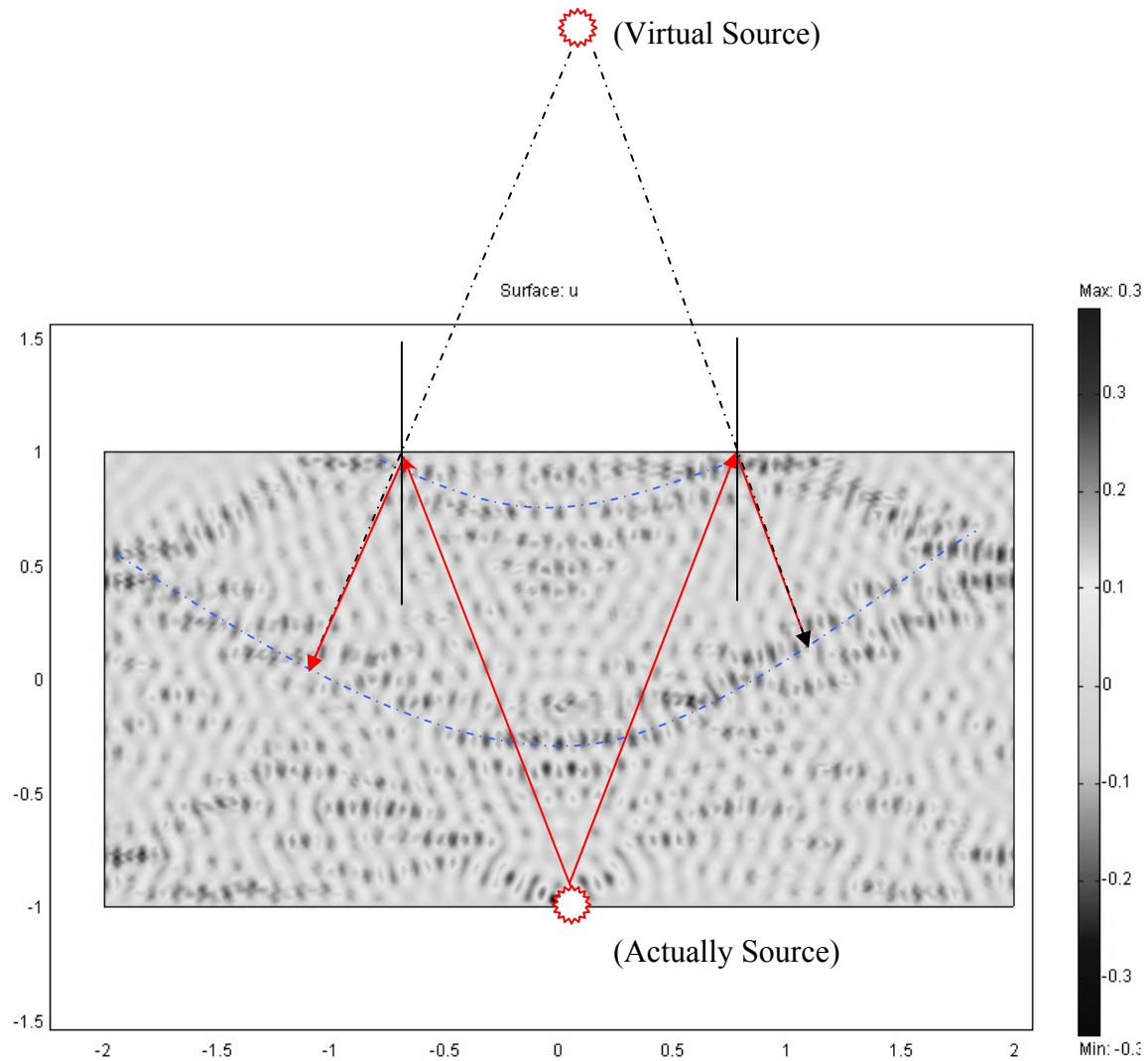


Figure 5: Validation for reflection test (dash lines show the reflected waves)

The modeling can also be validated by actual test. One reflection test was carried out at an underground mine. Based on the field test data of reflection, a water filled mine void was linedated by the envelopes of ellipses. The estimated error is around 10 ft for reflection distance around 500 ft.

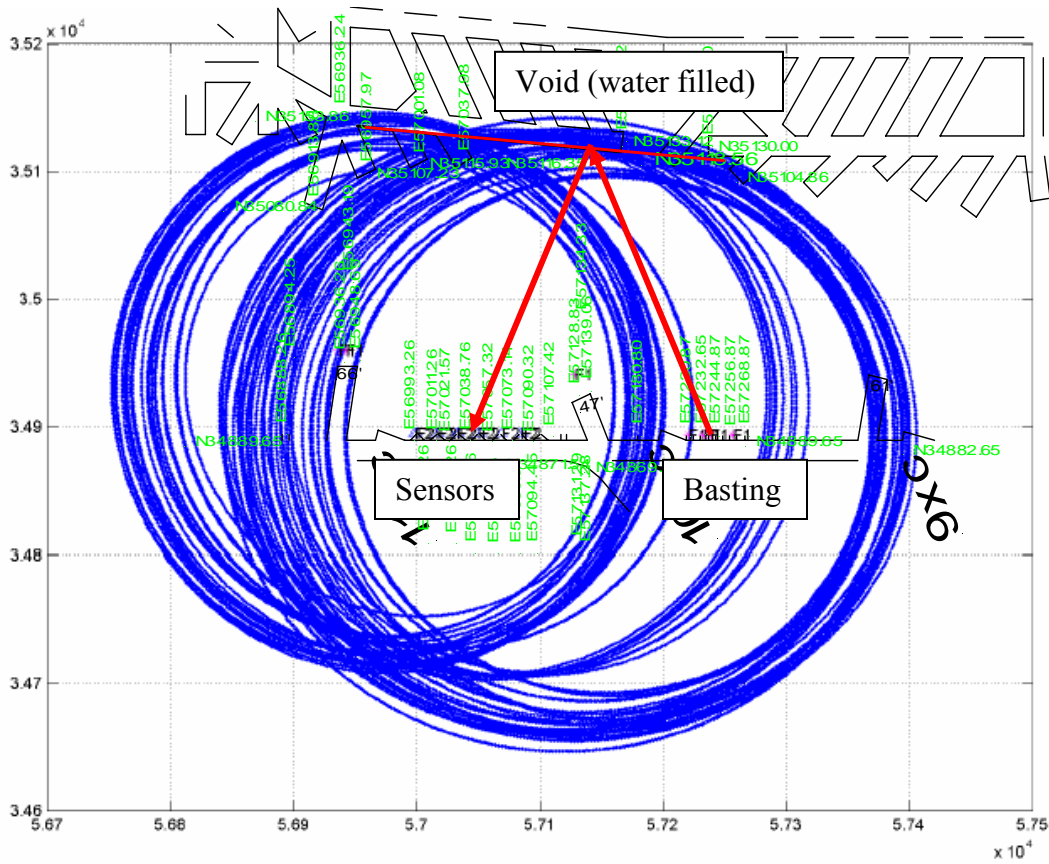


Figure 6. Void mapping by In-seam seismic reflection test.

4. Parametric Study

The most critical factor concerned for in-seam seismic is the frequency of the seismic signals. Generally speaking, the higher the frequency, the survey is more accurate. If the frequency is low, the wave may bypass some small discontinuities or voids and there is no reflection. On the other hand, the attenuation rate is bigger for higher frequency, which means the traveling distance of the signal is shorter.

Transmission test was used for the attenuation study. Figure 3 shows that the amplitude of the waveform is decreases along with propagation, where frequency of 10 Hz is applied. Figure 7 shows the cross- section plot at the center line. Now, change the frequency of the input signal to 20 Hz, the wave propagation turns out to be Figure 8. And the attenuation curve is Figure 9. When the frequency doubled, the propagation distance of the signals is around half the original distance.

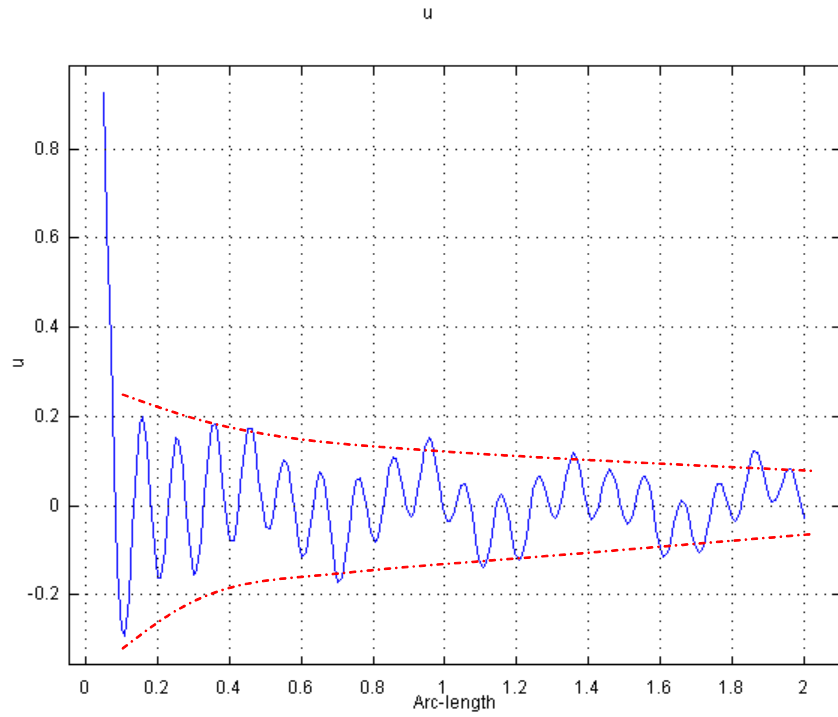


Figure 7. Wave Propagation from source to receiver shows attenuation ($F=10000$).

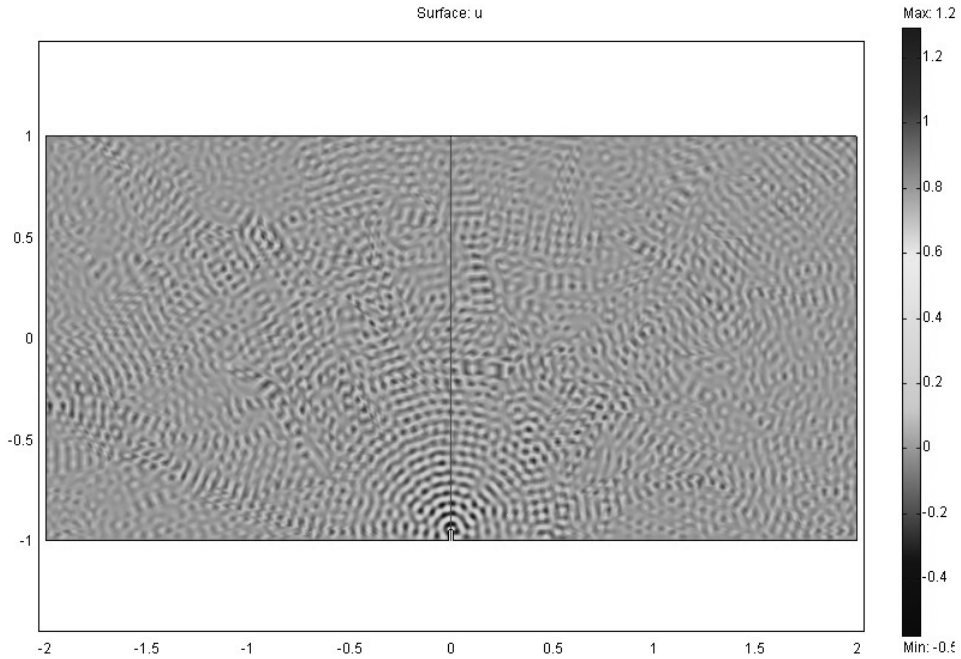


Figure 8. Wave propagation pattern in coal seam without reflection ($F=20000$ Hz).

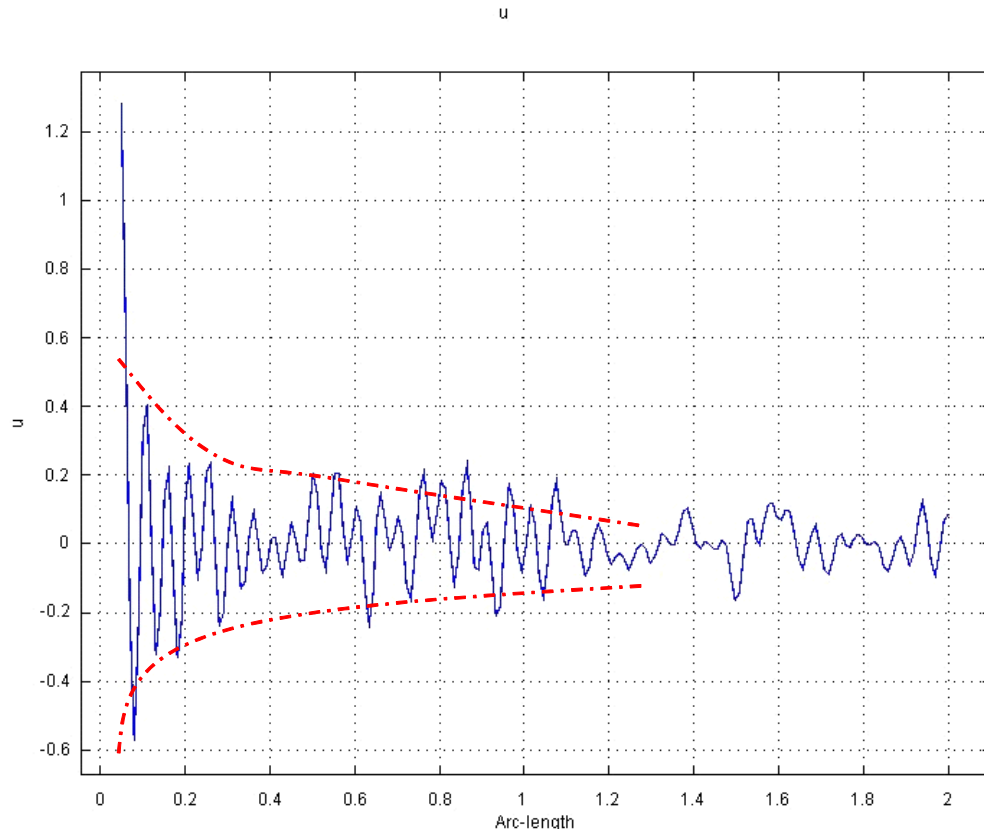


Figure 9. Wave Propagation from source to receiver shows attenuation (F=20000 Hz).

5. Conclusions

Two dimensional FEM modeling was conducted for in-seam seismic wave propagation in coal seam. The result of transmission test simulation shows that main part of the seismic energy is spread toward the opposite side of the pillar. The reflection test simulation demonstrates that reflected wave follows the law of reflection. Finally, the relationship between attenuation and frequency of the signals was studied, which proved that the higher the frequency, the bigger the attenuation rate.

This study is the first step in order to develop better understanding of the seismic wave propagation in coal seam. Future work may include three dimensional FEM modeling of wave propagation. An important ambition is to figure out the difference of seismic signal between air-filled void with water-filled void.

6. References

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Appendix:

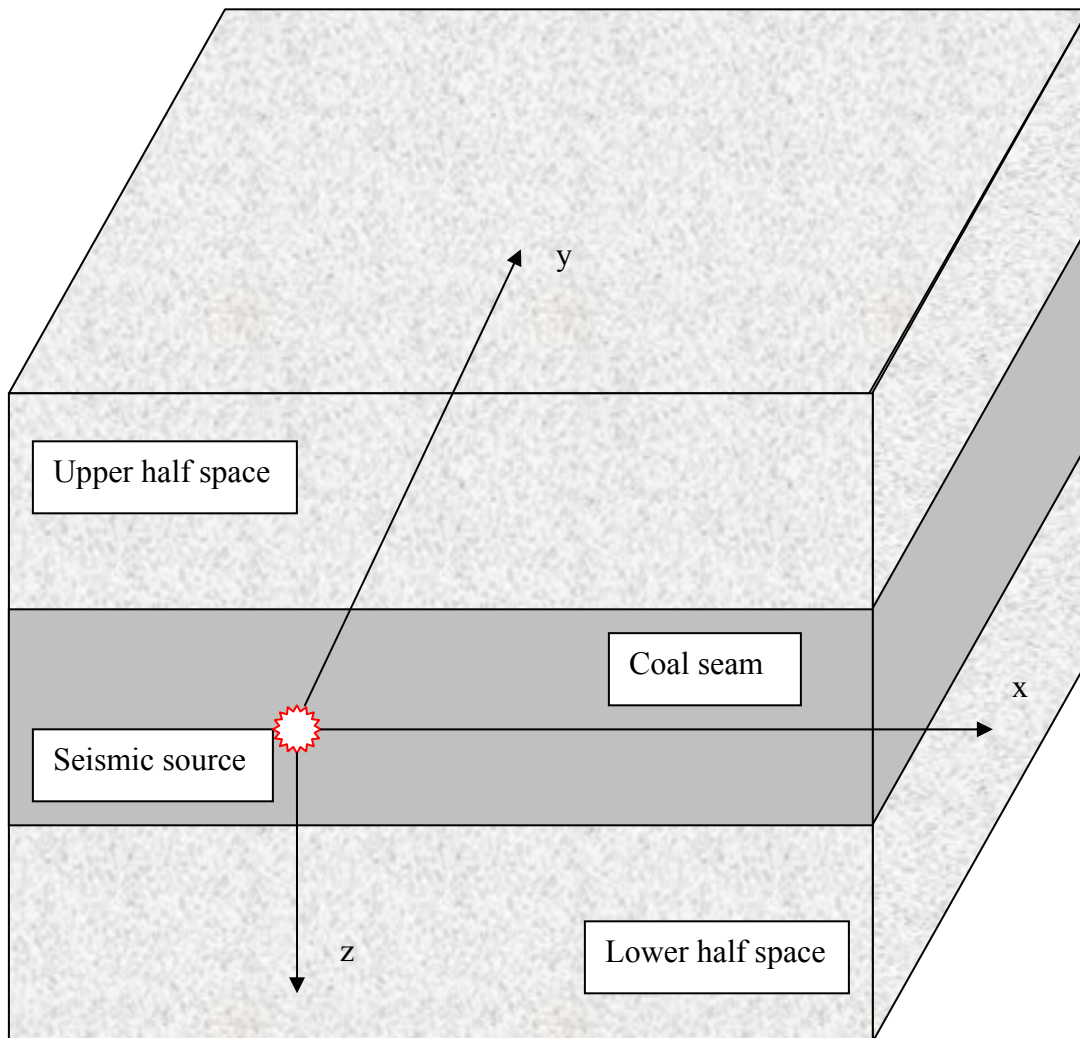


Figure 1 Illustration of seismic source and coal seam layer sequence embedded between two half spaces.

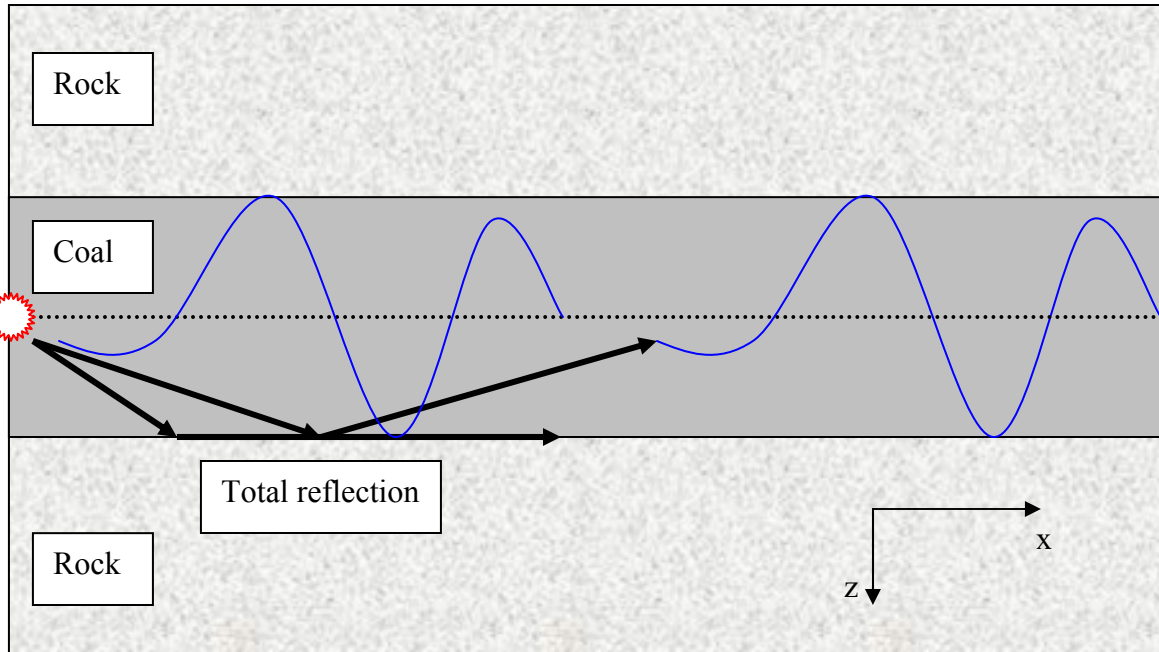


Figure 2 Sketch of numerical model of two dimensional symmetrical sequence rock-coal-rock