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Application of Geophysical Methods for Fracture Characterization

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APPLICATION OF GEOPHYSICAL METHODS FOR FRACTURE CHARACTERIZATION

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ABSTRACT

One of the most crucial needs in the design and implementation of an underground waste isolation facility is a reliable method for the detection and characterization of fractures in zones away from boreholes or subsurface workings. Geophysical methods may represent a solution to this problem. If fractures represent anomalies in the elastic properties or conductive properties of the rocks, then the seismic and electrical techniques may be useful in detecting and characterizing fracture properties.

SEISMIC METHODS

For years seismologists have known that fractures have an effect on the propagation of seismic waves. The problem has been in quantifying the effect so that useful parameters can be obtained. In the case of nuclear waste isolation, and in particular Yucca Mountain, the parameters of interest are not only the presence of fractures, but such features as length, width, orientation, density, spacing, aperture, and the degree to which the fractures are connected, and the manner of the connections.

For several years, research has been carried out to develop modeling capabilities for representing the seismic response of the repository volume at Yucca Mountain. The initial focus of this research was in the development of a model to predict how seismic waves travel through a fracture network. Whereas several numerical techniques are available for predicting fluid flow through fracture networks, the corresponding computational tools for determining how a seismic wave is affected as it is transmitted through a network of randomly located and oriented finite fractures was not available at the onset of this study. The development of such a seismic modeling tool has been a high priority of this project.

The first attempt was to modify our present one-dimensional and two-dimensional ray tracing and synthetic seismogram models that relied upon conventional welded boundary theory to admit 'stiff' fracture surfaces with arbitrary orientation. The goal was to incorporate the boundary conditions that admit slip along an interface into a ray tracing program so that very thin features such as fractures could be modeled. It is necessary to include the displacement discontinuity boundary conditions in the solution for the propagation of the seismic wavelet. The constitutive equations for this model come from the ongoing LBL study of single fractures. A second program was also developed, SYNHYD1. This code is the Cerveny synthetic seismogram generator, i.e., SYNTPL with the fracture information included. This has also been modified to include the effect of stiffness of fractures on the seismic waves in addition to the geometry information.

Using this modeling capability we can now vary fracture geometry, density and orientation in a medium and measure the seismic response. Because we used FMG to generate our fractures, we can compare the seismic response to the hydrologic response.[1] An example of the application of this program is shown in Figure 1. Although any degree of complexity can be achieved, our programs do not have the capability to model the diffractions or scattering associated with the fracture sets. Although this approach is very promising for forward modeling of fractured media, there is one drawback. One must have an idea of the relationship between stiffness, or the amount of slip along an interface, and the physical properties of the fracture.

In addition to the approach outlined above, we also believe that fractures strongly affect the anisotropy one measures in the velocity and amplitude of the seismic waves. Two programs were obtained and modified, Beam87 and ANRAY. The programs were developed by V. Cerveny, D. Gajewski and I. Psencik. V. Cerveny spent several months at LBL bringing up these programs. Beam87 is a 2-D Gaussian beam ray tracer while ANRAY is a 3-D fully anisotropic modeling code that allows one to specify 21 elastic constants and a vertically

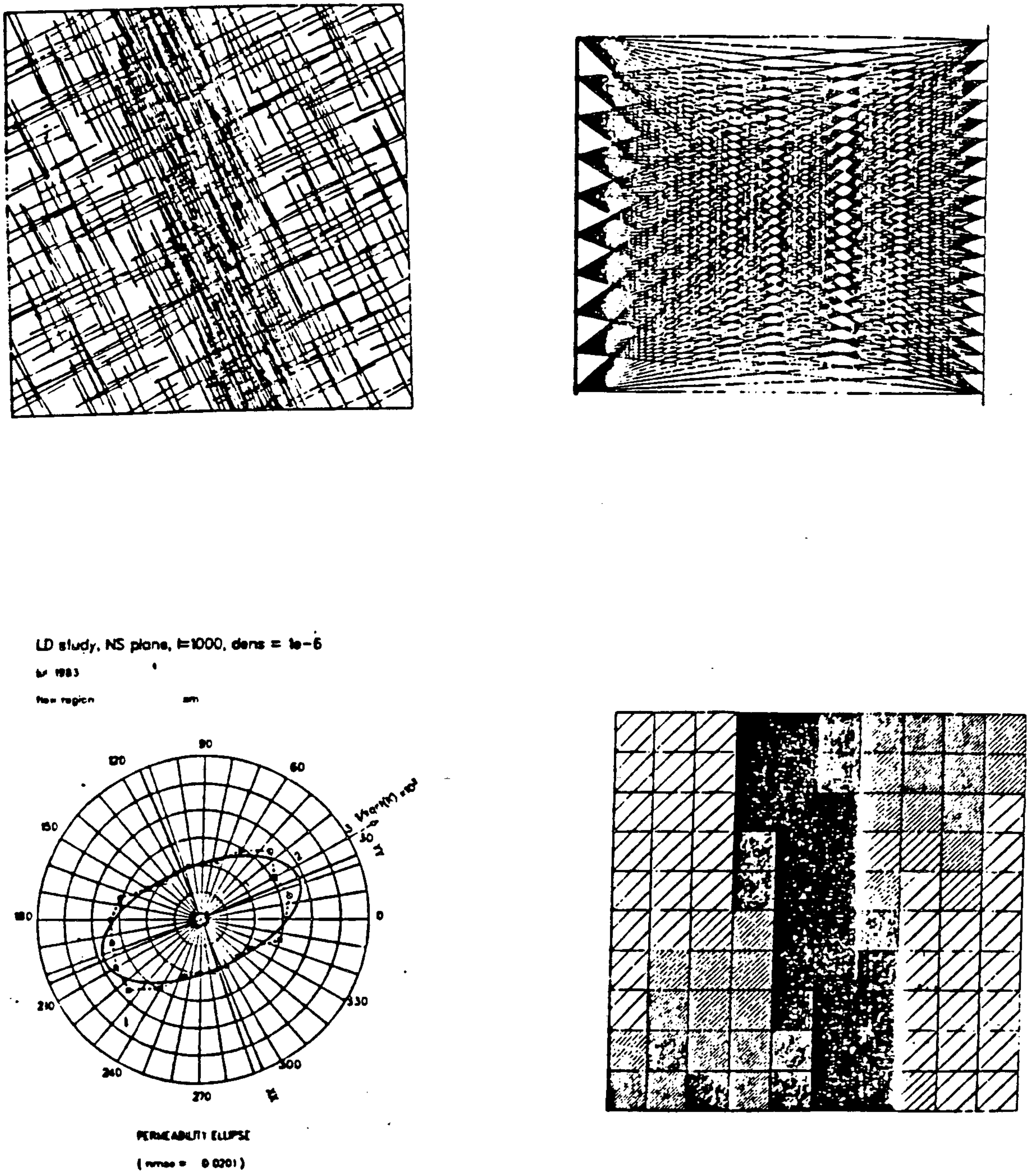

Figure 1. An example of the Program FMG Ray and a comparison of the result of seismic imaging (tomogram) to hydrologic modeling of the fracture zone.

varying velocity model. It was also necessary to allow amplitude calculations to be output for ANRAY so that full wave form information could be obtained. During the last several months we have been working with Dirk Gajewski to achieve this. An example of the results are shown in Figures 2a to 2d. In 2a and 2b are shown isotropic models of the ray paths through Yucca Mountain for the P- and S-wave. The velocity models were obtained from sonic logs of wells G-4 and G-1, the S-wave models were of course not obtained from the sonic logs but estimated using a Possions ratio of 0.25. In addition to this modeling work using these programs work is underway to combine the FMGRAY and ANRAY approach.

It has been known that elastic waves are affected, in varying degrees, by such simple linear features as bedding interfaces, faults, and fractures. Numerical solutions for the scattering by these objects have been limited to those of approximate nature due to the complexity involved with the exact solutions. A fracture response, for example, has been obtained using either essentially the Born approximation at low frequencies, or the ray tracing technique at high frequency limits. The Kirchhoff integral approximation has also been used to address the high frequency regime. As the wave propagates through a fracture or a fracture zone, it not only loses its energy resulting in a decrease in amplitude, but experiences the apparent slowing down of velocity. Approximate solutions mentioned above often do not contain precise scattering information necessary for the correct interpretation.

As a first step we have assumed an elastically inhomogeneous object characterized by λ_1, μ_1, ρ_1 enclosed by a closed surface S in a uniform whole space of λ_0, μ_0, ρ_0. It has been shown that the displacement, u, can be obtained from the Helmholtz-type surface integral

$$u(x) = u^i(x) + \int_S \left\{ u(x')\cdot n'\cdot \Sigma^0(x/x') - t(x')\cdot G^0(x/x') \right\} ds' \qquad (1)$$

outside the object, and

$$u(x) = -\int_S \left\{ u(x')\cdot n'\cdot \Sigma^1(x/x') - t(x')\cdot G^1(x/x') \right\} ds' \qquad (2)$$

inside the object. Here G is the Green's displacement dyadic and Σ is a third rank Green's stress tensor. The term t(x) is the surface traction on S. These two equations can be made into a system of coupled Fredholm integral equations of the second kind if the field point x is allowed to approach the surface S. At any point on the surface there are six unknowns; three components each from u and t. When either t or u is known on S, such as in the case of a traction free void (t = 0) or a rigid inclusion (u = 0), the integral equation, Equation (1) is reduced to one in which only one unknown vector remains to be solved. The other special case of interest involves an object whose thickness in one direction becomes infinitesimally thin. Assuming continuous traction across the crack, Equation (1) is further reduced to

$$u(x) = u^i(x) + \int_{S/2} \Delta u(x')\cdot n'\cdot \Sigma^0(x/x')\, ds' \qquad (3)$$

where $\Delta u(x')$ is defined as the jump in $u(x')$ across the crack surface S. Notice that if there is no crack (perfectly welded interface h), Δu would be zero, and $u(x) = u^i(x)$ would result.

Experimental results and theoretical thin layer analysis show that the discontinuity in the displacement vector is related, independently from the frequency used, to the local traction through the stiffness, k, of the crack

$$\Delta u = \frac{t}{k} \qquad (4)$$

Substituting this relationship to Equation (3), and operating on both sides by the surface traction operator

$$L = 2\mu \frac{\partial}{\partial n} + \lambda n \nabla\cdot + \mu n \times \nabla \times$$

we finally get

$$t(x) = t^i(x) + \int_{S/2} \frac{t(x')}{k(x')}\cdot n'\cdot L \left\{ \Sigma^0(x/x') \right\} ds' \qquad (5)$$

This is an integral equation for the traction on S, where the stiffness k(x) can be a function of x. The kernel is generally singular and it is critically important that appropriate physical concepts are introduced to properly evaluate the integral over the surface. Once the traction is numerically obtained on S, we can compute displacement field u everywhere using Equation (3) with Δu replaced by t/k.

ELECTRICAL METHODS

A practical problem that occurs in the nuclear waste repository is the detection of any major fracture zone that lies close to but is missed by the boreholes. These holes provide the opportunity to use subsurface electromagnetic (em) techniques for detecting and characterizing any nearby fractures.

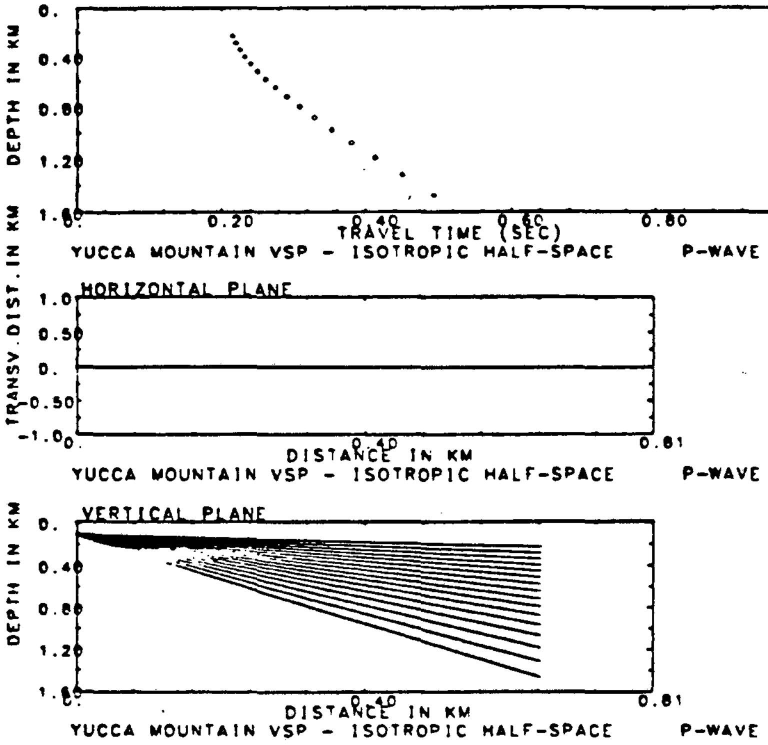

Figure 2a Beginning P-wave model for a representative section through Yucca Mountain.

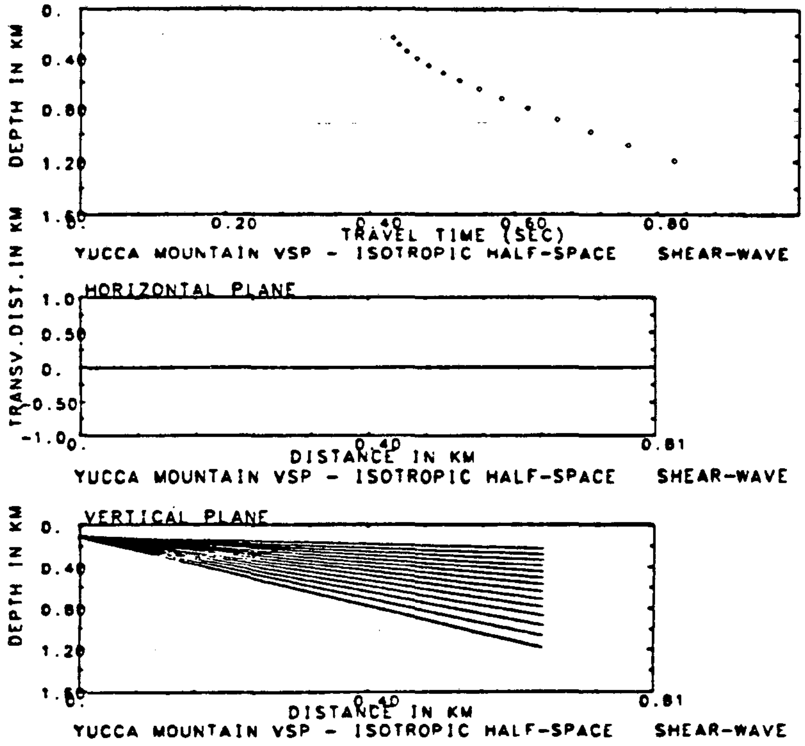

Figure 2b. Beginning S-wave model for a representative section through Yucca Mountain.

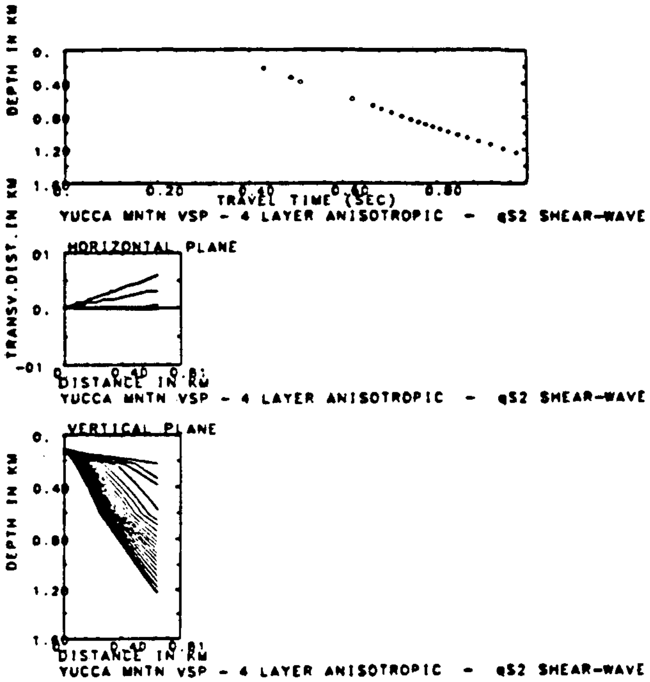

Figure 2c. The effect introducing a 10% anisotropy in the P-wave model.

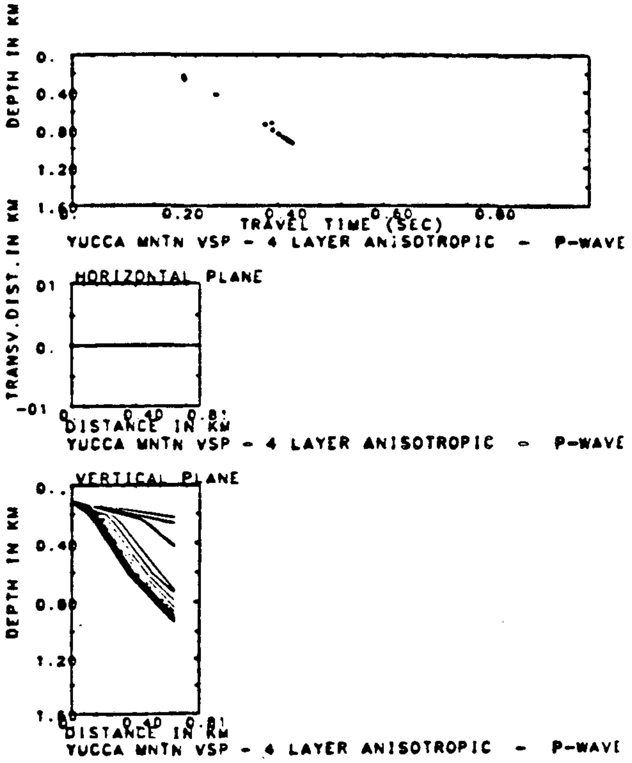

Figure 2d. The effect of introducing a 10% anisotropy in the S-wave model.

A number of techniques have been used to address the fracture detection problem and each has its own advantages and limitations. To date, however, most of the work centered on the use of conventional geophysical borehole logs to detect and characterize fractures intersected by drillholes. Because most holes are drilled close to vertical, conventional logging techniques are mainly sensitive to flat-dipping structures. In order to detect the possible presence of a major, more generally oriented, fracture zone not intersected by a borehole, other types of techniques need to be studied. Among these is the cross-hole em technique. The technique is particularly useful since an open but water-filled fracture zone in otherwise resistive rock has a much lower resistivity (Green and Mair, 1983).[2] Deadrick et al. (1982) and Ramirez et al. (1983) used cross-hole em geotomography in mapping fractures.[3,4] Lytle et al. (1979) also used cross-hole em probing to locate high-contrast anomalies, and Chang et al. (1984) developed a down-hole VHF radar apparatus with directional source and receiver antennas in the borehole.[5,6]

Primarily because of the high attenuation at radar frequencies, lower frequencies may be more suitable for fracture detection between widely spaced holes or where the host rock is more conductive than a low permeability granite. In this paper we consider downhole dipole sources. The position of the source can be either fixed or moving depending upon the desired type of source-receiver geometry. The fracture zone is represented by a thin rectangular conductor with finite dimensions, embedded in a host rock with much lower electrical conductivity. The source can be either a grounded vertical electric dipole or a vertical magnetic dipole.

The approach used to calculate the frequency domain magnetic field responses is based on the algorithm for a conductive thin sheet developed by Weidelt (1981).[7] The following is a brief summary of the algorithm.

From the Maxwell's equations

$$\nabla \times \mathbf{E} = -\,i\omega\mu\mathbf{H} \qquad (6)$$

$$\nabla \times \mathbf{H} = (\sigma + i\omega\varepsilon)\mathbf{E} + \mathbf{J} \qquad (7)$$

the following equation for the electric field is obtained by using the thin sheet approximation (Price, 1949).[8]

$$\mathbf{E}_s(\mathbf{r}_0) = \mathbf{E}_{ns}(\mathbf{r}_0) - i\omega\mu_0 \int_S \tau(\mathbf{r})\mathbf{g}_s(\mathbf{r}_0/\mathbf{r}) \cdot \mathbf{E}_s(\mathbf{r})\,ds \qquad (8)$$

Here the integration is carried out on the sheet surface s. $\mathbf{E}_s$ is the total tangential electric field on the sheet, and $\mathbf{E}_{ns}$ is the incident tangential electric field on the sheet. $\mathbf{g}_s(\mathbf{r}_0/\mathbf{r})$ is the Green's dyadic function relating the tangential current distribution on the sheet at $\mathbf{r}$ to the tangential electric field at $\mathbf{r}_0$. The conductance τ is the product of the conductivity and the thickness of the sheet, and can be a variable over the sheet.

Both the incident field and the Green's dyadic function are related to the dipole fields in the layered medium, and are easy to evaluate. After these are calculated, the integral equation is then solved for $\mathbf{E}_s$, which in turn is used to calculate the magnetic field everywhere using

$$\mathbf{H}(\mathbf{r}_0) = \mathbf{H}_n(\mathbf{r}_0) + \int_S \tau(\mathbf{r})\mathbf{E}_s(\mathbf{r}) \cdot \nabla_0 \times \mathbf{g}(\mathbf{r}_0/\mathbf{r})\,ds \qquad (9)$$

Here $\mathbf{H}_n$ is the incident magnetic field and the product $\tau\mathbf{E}_s$ is called the scattering current. The function $\nabla_0 \times \mathbf{g}$ is now considered the Green's tensor for the magnetic field. Some typical numerical results have been obtained to demonstrate the properties of the anomalous magnetic fields due to different type of sources, frequencies, and source-receiver geometries. The model used is typically a rectangular sheet of 150 m by 100 m in size (Figure 3). The sheet is vertically oriented and has a conductance of 1 S while the host rock has a conductivity of 10 mS/m. Because the sheet conductor is placed far below the surface, the observed response will be basically the same as that for a conductor in a homogeneous whole space. It should be pointed out, however, that the code can handle the more general realistic problem of a target close to the ground surface or to a layered interface.

For the case when the grounded electric dipole source is used, the cross-hole moving source in one hole with the magnetic field receiver in another hole show better resolution of the fracture than the cross-hole fixed source configuration. The moving source-receiver configuration also allows for easier data interpretation because the primary field is constant, as long as the target is located well below the surface of the earth. With the same amount of dipole moment, the grounded electric dipole source (moment = current × dipole length) results in much stronger anomalous fields than its vertical magnetic dipole (moment = number of turns × current × area) counterpart. Nevertheless the relative values of these are about the same for either source. It is difficult to employ a large moment vertical magnetic dipole source since the diameters of most boreholes are small, and the number of turns of the coil is limited. On the other hand, the anomalous field generated by a grounded electric dipole can be easily made detectable by simply employing longer dipoles.

The inductive coupling between the source field and the target largely depends on the relative geometry.

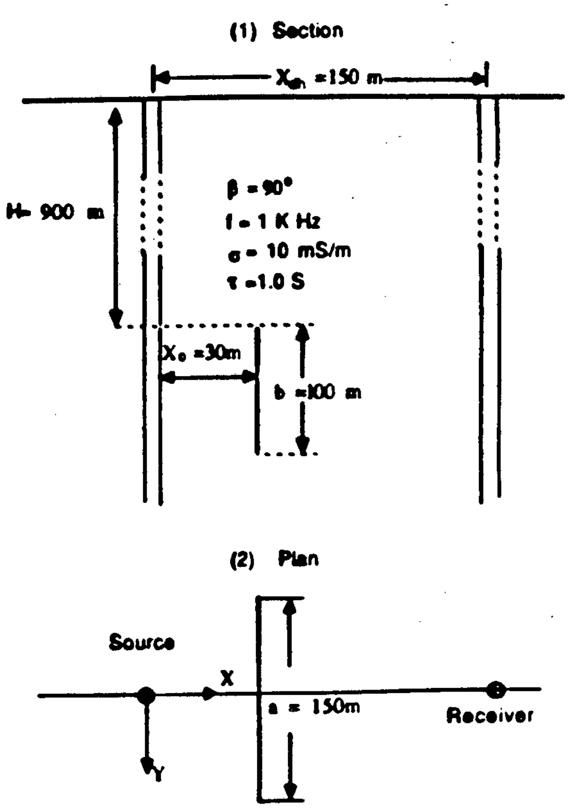

Figure 3. A conductive thin sheet simulating a fracture between boreholes.

When the target is horizontal the maximum coupling occurs if a vertical magnetic dipole is used. On the other hand if the target is vertical with zero strike angle, maximum coupling can be achieved if a vertical electric dipole is used. Therefore, it is necessary to use both type of sources if an accurate interpretation for the fracture distribution between holes is desired.

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