CONF-780671--1

PREPRINT UCRL- 81294

Lawrence Livermore Laboratory

Subsurface Probing

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June 28, 1978

NSF Site Characterization Workshop, Evanston, Illinois,
12-14 June 1978

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I want to put something up that will get our thoughts collected. We all have different perspectives, and we may be a little bit going to sleep after lunch. I want to pick a subject that we will all have some common interest in. I got this out of a short story on the stress analysis of a strapless evening gown, and those who like looking at load structures and the strength of materials can have one perspective on this, people who are into probability can have another perspective of how good a structural design it really is, and people in remote sensing can just sit back and enjoy the figure.

The point of this talk is that monitoring subsurface conditions is both desirable and useful for defining the subsurface structure prior to excavation and construction in soil and rock. A geophysicist's task is to tell whether there is anything that is going to be potentially troublesome within the ground. A different array of techniques can be used; e.g., looking at the surface geology or looking at core samples coming out of boreholes. Both of these methods can give useful data on the subsurface environment. Data from core samples from different boreholes does give detailed knowledge along each line that the individual boreholes go (see Figure 1). However, that does not always insure that you have an accurate, detailed idea of what exists in between boreholes.

The topic that I present herein concerns techniques that you can use to look between boreholes to infer the structure. The operational principle behind the techniques is that how a medium effects the seismic and electromagnetic waves propagating through it provides a useful mechanism for inferring its property. The seismic wave and electromagnetic wave propagation between sets of boreholes do not sense just the line along the borehole (as core samples do), they sense the plane that exists in between the two boreholes (see Figure 2). The "observables" for wave propagation from one borehole to the other are the attenuation of the waves going from one borehole to the other and the travel time (or velocity) in going from one borehole to the other.

In March 1978, I went to a review meeting on the Forest Glen experiment! This meeting concerned the results obtained using a number of different geophysical techniques on the same site. A number of the non-geophysicists who were there came up with remarks that were constructive in terms of how geophysicists need to better communicate with people outside of the geophysical industry. One of their criticisms was that we tend to talk in terms of squiggly lines. To us, squiggly lines have a lot of information content, which is why we like to talk about them. However, to people not directly acquainted with the nuances in our area, the squiggly lines are an area of confusion. We thus need to avoid communicating only with squiggly line presentations. Another problem that was pointed out was that geophysicists tend to say, "These squiggly lines indicate that 'something' is out there." This is not very helpful to one who wants a more definitive definition of what is out there.

It is our responsibility to come up with data presentation formats that not only indicate that something is out there but give more detailed knowledge about it. I think it is possible to do that. One way that I have found to be effective is to adapt technology transfer techniques. For example, it is possible to use techniques that have been shown to be successful in terms of medical imaging in the body and apply them to the geophysical imaging problem. As an example of what is presently achievable in medical imaging, Figure 3 depicts a picture of the x-ray attenuation through the human head that has amazing detail in it. Most people agree that the use of a color format (not reproduced in this report) to represent the attenuation through this slice of the head has great diagnostic capability in it. It is also possible to use a color presentation format to show how electromagnetic and seismic waves attenuate or how their velocity is affected between two boreholes to get good diagnostic data on the environment existing between two boreholes.

The basic procedure with two boreholes was shown in Figure 1. One borehole has a source at different depths. Another borehole has a receiver at depths. A number of ray paths link the different source locations with the receiver locations, and with a combination of many source locations and receiver locations, one can effectively sample the region between the boreholes. The ray paths very effectively sample this region. The problem that you encounter is that with a large number of source locations and receiver locations, it is easy to generate masses of data. An intelligent way of assembling this data and interpreting it to generate a meaningful picture (similar to the attenuation picture in Figure 3) is needed. Fortunately, one can adapt the technology that has been developed from the medical industry (see Figure 4).

Interpretation algorithms are needed which have good resolution, which permit rapid interpretation in the field, and have a low sensitivity to noise. If one is smart about what which interpretation algorithms are picked, interpretation algorithms can provide good resolution and rapid interpretation. These approaches can be used on a minicomputer and generate a picture in the field as you are collecting the data. Current medical technology is using 64,000 cells in which the individual attenuation is found in every one of those cells. It is possible to use a similar kind of technology, only instead of modeling the interior of the head, model the region between two boreholes. With 64,000 cells to model the region between boreholes, a unique velocity and attenuation rate for each one of those cells provides a detailed diagnostic picture. This idea was first tried in a very limited form about three years ago in a strip coal mine in Kemmerer, Wyoming. Data sampling was performed by dropping transmitter and receiver in ten foot increments. Since then, we have found that it is better to go to one foot or smaller sampling intervals to get better clarity. An example of our first experimental result that we got is shown in Figure 5. This was our first use of color (not reproduced here) to depict the ground properties. The region with skin depths of the order of 25 feet to 30 feet indicate the coal seam. The underburden of clay has a skin depth of 10 to 16 feet. The clear definition of the coal/clay boundary and the relative homogeneity of the coal was very encouraging to us in terms of the degree of clarity that you could get out with only a small number of cells in the model.

The experiment we tried was the Forest Glen experiment, which is a site for one of the potential Washington Metro stations. For this experiment, we collected enough data to model the region with 3,000 cells in the picture. The borehole configuration existing at Forest Glen (see Figure 6) consisted of four boreholes going down to the depths indicated. The potential station that was going to be put in is indicated as the region of major interest. We actually sampled a region bigger than this; i.e., from 150 feet down to 260 feet. Over 3,000 data points for different combinations of transmitters and receivers in different boreholes were collected. An interpretation picture using color (not reproduced here) to depict the rate of attenuation for that region is shown in Figure 7. The blocked-out region in the lower left corner is the region that we could not sample because one of the boreholes did not go as deep as the other three (see Figure 6). This picture shows the spatial variation of rate of attenuation as you vary position around the boreholes. The darker region near the top left a rate of high attenuation, and the lighter region near the bottom indicates a lesser rate of attenuation. The dark region correlated well with the borehole logs, which indicated heavy fracturing in these regions. This picture indicates no gross homogeneity in this site because there is not gross feature in the picture.

It is also possible to advance technology beyond what is presently being done for low frequency probing. An example of how one can improve four probe type work, where you do surface probing, is to improve the resolution using low frequency probing on core samples. The problem we considered was done under laboratory conditions. This was a rock that brine was going to be pumped into from one direction and taken out from the other end. An assessment of the change in permeability as the brine was pumped through the rock was required. Brine tends to clog up the rock because it is heavy in salt content and thus its permeability changes with time. We designed a system to monitor how fluids move through rocks using low frequency probes. An area of medical diagnostics called impedance plethysmography was adapted to this problem. For ease of presentation, I show simulation results not for a circular core, which most all cores are, but for square cores. These results for electrodes around the periphery of a square core show how low frequency probing can be used to infer the internal structure of the rock. Again, the many cell model of the region to be determined is used. By emplacing electrodes around the periphery and doing measurements by applying different voltages and monitoring the currents to these different electrodes (see Figure 8), it may be possible to get a good idea of what is on the inside of this core.

If you are familiar with typical four probe results, you would not expect to get very good resolution. Nevertheless, we modeled the problem to see what was possible. An easy example as shown in Figure 9. This depicts our ideal situation of a square core with color used (not reproduced here) to depict the interior variation of conductivity. The light region in the middle is a region of high conductivity, and the dark color on the outside here is a region of low conductivity. Imagine in your mind electrodes around the periphery of the core (see Figure 8). By doing many measurements using these electrodes, it is possible to generate a massive data set similar to what we are doing in terms of the cross-borehole probing. By applying interpretation techniques similar to those previously discussed, it is possible to infer the internal structure of the core. The technique we used for this model is an iterative approach, and the results are shown in Figure 9. After one iteration, the picture is not bad in a qualitative sense for the internal structure of the core. You can definitely see the high conductivity region in the middle, but there is not fine structure detail. After ten iterations, there is almost a one-to-one correspondence between the synthetic pattern and the interpreted pattern.

An example of what we designate a harder problem is shown in Figure 10. The middle of the picture is a low conductivity (dark color) region that is difficult to pass current through. It is surrounded by a high conductivity region (light color), with additional low and high conductivity regions. Again, electrodes around the periphery are used for multiple measurements. The result after the first iteration has a good qualitative comparison with the ideal pattern. After ten iterations, there is almost a one-to-one correspondence between the ideal and interpreted patterns except for the low conductivity region in the middle.

This lack of definition of the low conductivity region in the middle surrounded by the high conductivity region was expected and is a limitation of low frequency probing (hence the designation of the difficult problem).

A question that commonly arises when presenting cross-borehole data interpretation results is, "What is the effect of ray-bending?" It is possible to properly account for ray-bending using ray-optics and still solve the inverse problem (see Figure 11). An example which helps illustrate comparative results has been constructed using a computer to study a synthetic profile (see Figure 12). Regions 1 and 2 in Figure 12 have a 60% contrast in velocity. By representing the region between boreholes with many cells, an iterative data inversion procedure can be used to infer the bending ray paths and the velocity of each cell. In figure 13 are shown the ideal profile (a), the interpreted profile ignoring the bending rays and assuming in the interpretation that the rays were straight-line paths linking source and receiver (b), and the iterative interpretation accounting for and solving for the bending rays (c). Note that the straight-line assumption (b) gives a rough idea of the structure, and the bending-ray approach gives much better resolution. Thus, for some problems, it is possible to solve the inverse problem even with significant ray-bending.

For remote sensing results to be effective, research and development work is needed in a number of different areas. There are five important areas. No one area is any more important than any other area. I have listed them here in arbitrary order. The first area in which work is needed is fundamental studies. This involves not only mathematical studies but also laboratory and controlled in-situ experiments to develop empirical curves relating the parameters of importance to the construction industry to remotely sensed observables. Another area that is significant is instrument development. In order for a sensing method to be effective and routinely used, you need a functioning device that can be quickly, easily, and cheaply used in the field. This means that money should be made available for instrument. Most likely, a minicomputer is needed in the field so that the data can be instantly processed and displayed. The prior examples show how data processing can be used to improve ~~the~~ resolution over what is conventionally done. Further data processing needs support. The next area is data interpretation. Once you have a functioning system and empirical curves generated in fundamental studies, you get to data interpretation. Data interpretation does not stand on its own. It takes into account all the known information that applies to the site. An intelligent way of routinely utilizing this data needs to be designed. The last area, and the one that is almost never done, is verification studies. There need to be many more experiments done at specific sites where numerous techniques are used, and then the site is later excavated in a manner such that the validity of the results that the different techniques provide can be verified or refuted. There is very little of this done, and verification needs to be encouraged. I was very encouraged by the intent of the Forest Glen experiment as one way of doing that. In summary, the development goals of geophysical probing are: increased depth of exploration, increased lateral and vertical resolution, an ability to map three dimensional features, and an ability to do it all regardless of the surface and suboverburden tomography.

ACKNOWLEDGEMENT

Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore Laboratory under contract number W-7405-ENG-48.

Figure 1

CORE SAMPLES [redacted] GIVE [illegible]
DATA ON THE BOREHOLE ENVIRONMENT

Figure 2

THE SUBSURFACE IS SAMPLED
USING MANY SOURCE AND
RECEIVER LOCATIONS

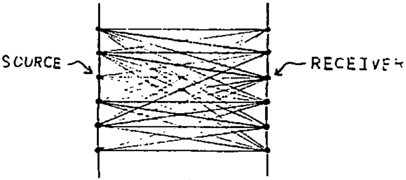


Figure 3. Color coded x-ray of head (from National Geographic, March 1978).

Figure 4

[illegible]

[illegible]

[illegible]

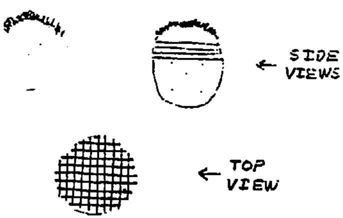
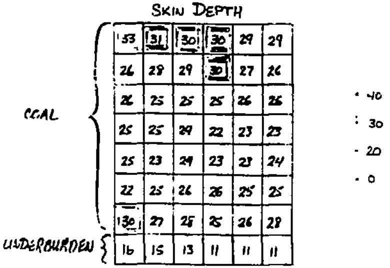


Figure 5. The skin depth (feet) within cells 10 feet high and 10 feet wide.



33	31	30	30	29	29
26	28	29	30	27	26
26	25	25	25	26	26
25	25	29	22	23	23
25	23	24	23	23	24
22	25	26	26	25	25
30	27	25	25	26	28
16	15	13	11	11	11

Figure 6. The Forest Glen site of a future Washington Metro station had four boreholes extending into the prospective station area.

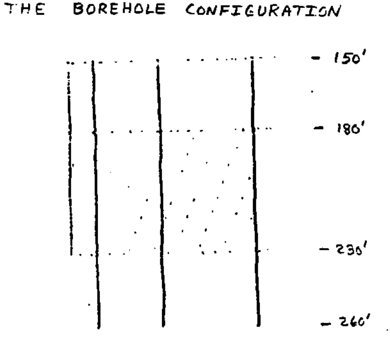


Figure 7. The region between the plane and between the boreholes shown in Figure 6 is presented via a color (not reproduced here) presentation of the spatial variation of attenuation throughout the sampled region.

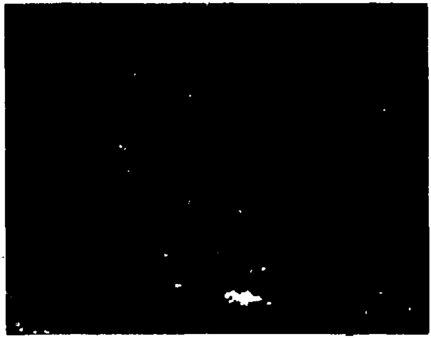


Figure 8. Numerous elec s about the square core are used to sample the resultant currents for applied voltages.

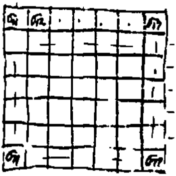


Figure 9. An easy problem consisting of a high conductivity (light color) region within a low conductivity (dark color) region. This configuration concentrates current into the center region.

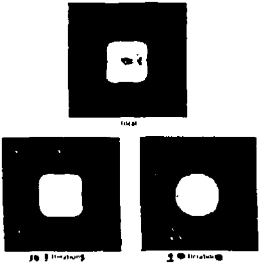


Figure 10. A hard problem consisting of a complicated pattern of high and low conductivities, with a low conductivity surrounded by a high conductivity in the middle of the picture.

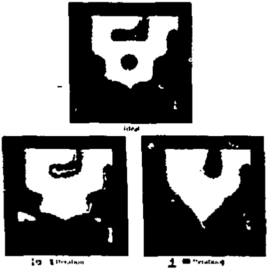


Figure 11

THE "INVERSE" PROBLEM
CAN BE SOLVED EVEN WITH
SIGNIFICANT RAY BENDING

Figure 12. A synthetic profile of differing velocities ε_1 and ε_2.

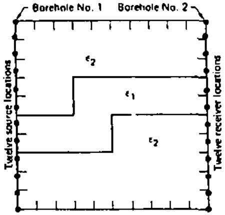


Figure 13. The color (not reproduced here) representation of the ideal model (same as Figure 12) -a, the straight-line interpretation -b, the bending-ray interpretation -c.