AN IMPROVED TRANSDUCER MOUNT FOR GROUND VIBRATION MEASUREMENTS

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1.0 INTRODUCTION

Standardization of soil vibration measurement has been an area of very limited consideration up until the last decade or so. To date measurement methodology has only been partially documented. The current demand for land in built up areas has led to building construction near, and on top of rail transportation corridors, and caused sufficient difficulties to demonstrate a requirement for reliable vibration measurement methods.

This paper discusses transducer mounting methods for obtaining accurate soil vibration measurement. Proposed, is an inexpensive system believed to offer considerable advantage over current practices.

2.0 COUPLING TO THE SOIL

It would be best to have a soil vibration transducer package which is homogeneous with the soil, thus not affecting the soil's motion. This is achievable only by matching the mechanical properties of the transducer system to the soil's bulk mechanical characteristics. Table #1 shows the pertinent mechanical properties of soil and several candidate materials from which a mount might be constructed. Matching the soil bulk characteristics is nearly impossible since:

a) most potential mounting materials are much stiffer than the soil

b) the range of Shear modulus of soils is approximately one decade. A different mount would be necessary for each type of soil.

Note that clay in particular has a range of properties varying from soft mud to soft rock. Testing noted later in this paper demonstrates this variability by showing a 2:1 change in transducer mounting resonant frequency from hard to soft clay.

Work partially carried out while in the employ of Vibron Limited

TABLE 1

Bulk characteristics of soil and possible mount material.

MATERIAL	SHEAR MODULUS (psi)	DENSITY (lb'/ft^3)
CLAY & SAND	3,000 - 20,000	100 - 120
DENSE GRAVEL	15,000 - 40,000	120
STEEL	11×10^6	487
ALUMINUM	3.8×10^6	170
WOOD	$0.30 \times 10^6 - 0.55 \times 10^6$	40 - 60
PLASTER OF PARIS	$0.08 \times 10^6 - 0.24 \times 10^6$	50 - 80

TABLE 2

Likely usable Frequency range of various Mounting Methods in soft soils (assumes worst-case soils which might reasonably be tested) (assumes plates and stakes are optimized in size to transducer mass, and careful soil preparation and installation)

	VERTICAL Hz	HORIZONTAL Hz
FLAT LIGHT, STIFF PLATE ON WELL PREPARED SOIL	0 - 300	0 - 300
TRANSDUCER ALONE BURIED IN SOIL	0 - 20	0 - 20
18" STEEL STAKE DRIVEN 14" INTO SOIL	0 - 100	0 - 25
EMBEDDED 1' CUBE OF PLASTER OF PARIS	0 - 70	0 - 70

Any practical mount is likely to be made from a stiff material and will act as a rigid body at frequencies below internal resonance. The mounting system will couple to the distributed mass and stiffness of the soil resulting in a 6 degree of freedom system with 6 potential resonant motions. If the device is symmetrical in the horizontal plane, two of the rocking modes will be identical as will be the two horizontal modes. The effects of the twisting mode about the vertical axis, (although the mode is unlikely to be excited) can be minimized by mounting horizontal transducers on or near the axis of rotation. This leaves the vertical mode, 2 identical horizontal modes and 2 identical rocking modes to be considered.

The problems have been analyzed and demonstrated by Morita and Omata (Ref. 1 & 2).

Figure 1A shows an embedded mounting system and it's simplified mechanical model (Ref. 3 & 4). A plate on top of the soil would be modelled similarly but without the coupled stiffness and mass associated with the embedded sides.

Figure 1B shows a driven stake and its model. Of particular note here is the large moment of inertia in the rocking mode and the attachment to the soil below the centre of gravity. This results in an easily excited rocking mode. On several occasions the writer has observed this mode to be in the 30-60 Hz range. This mode makes horizontal measurements above 30 Hz questionable by this method.

We have attempted to draw together the experiences of other (ref. 1, 2, & 5), our own undocumented experiences from the past plus the extrapolation, based on references 3 and 4, of testing done for this paper. For the softest soils (ie lowest resonance) one is likely to measure, we have estimated in Table 2 the reliable upper frequency limit for each mounting system.

3.0 SUMMARY OF CURRENT MOUNTING METHODS

The present methods of mounting vibration transducers on soil include:

1. Placing the transducer package loosely on the ground.

FIG. 1A MOUNTING BLOCK METHOD

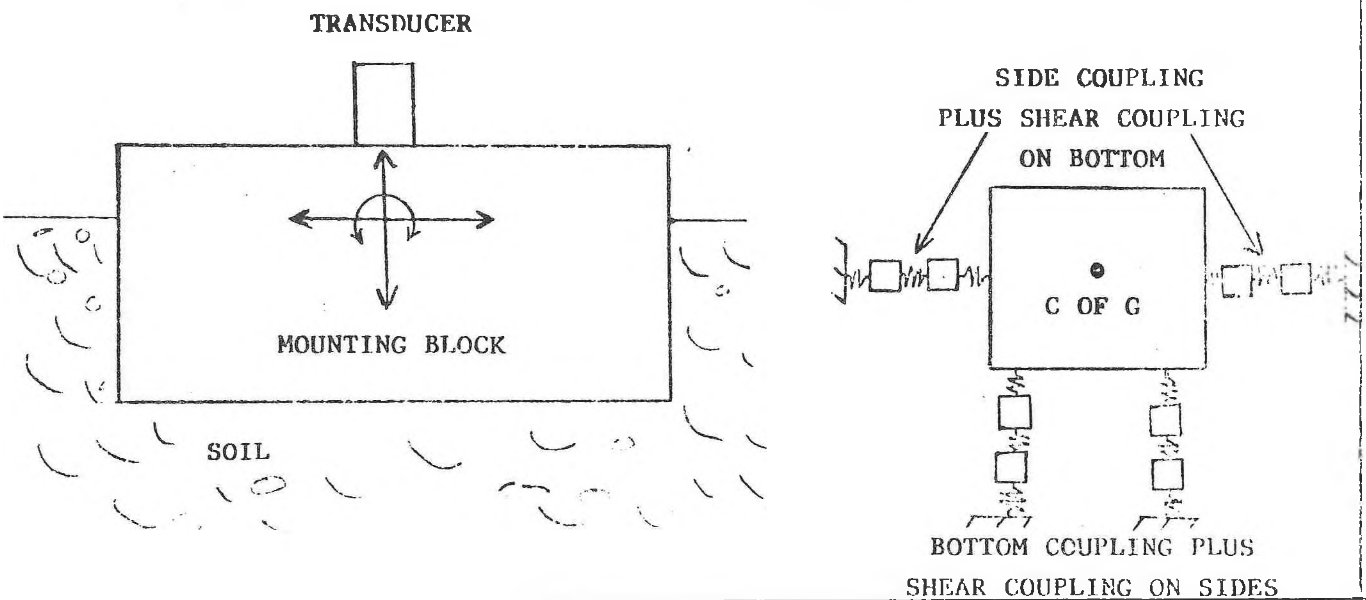
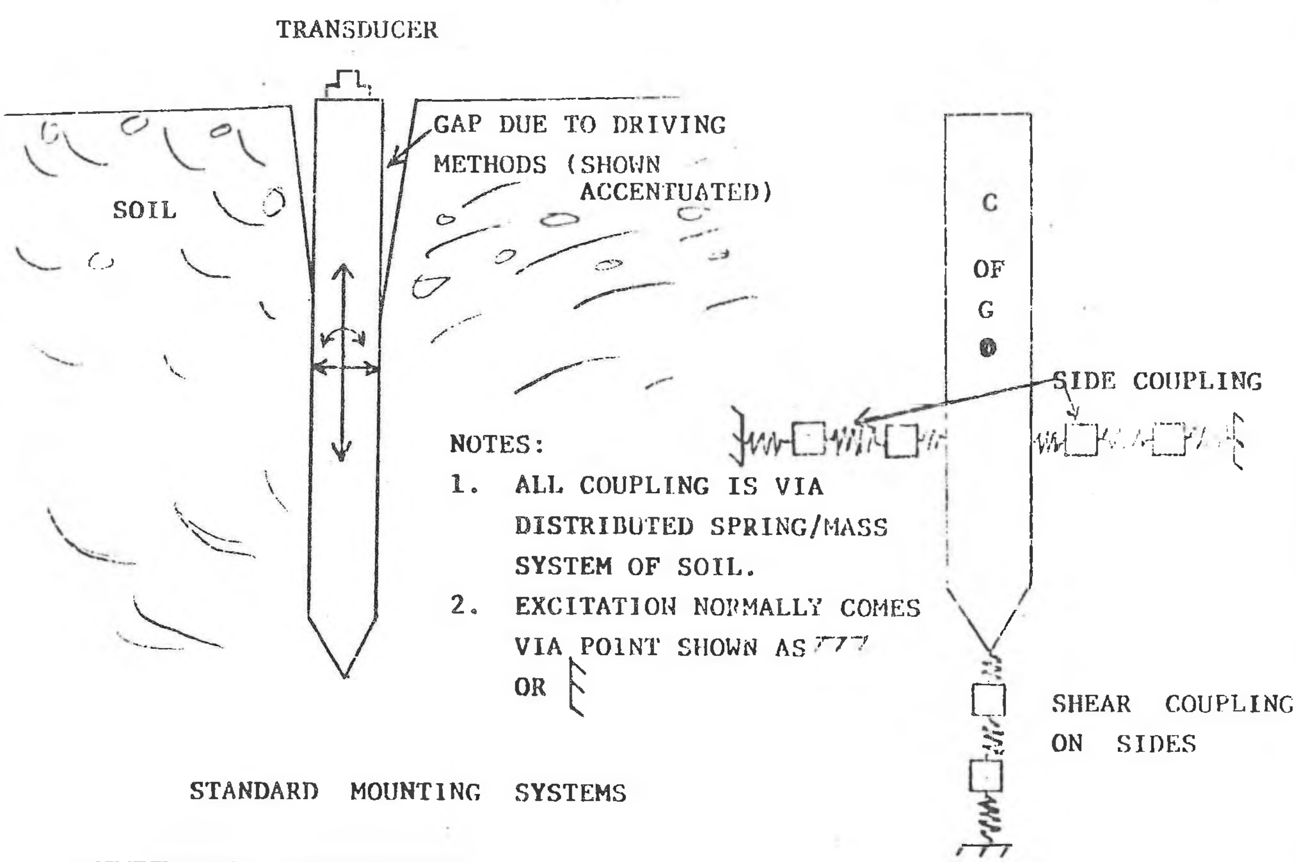


FIG. 1B DRIVEN STAKE METHOD



STANDARD MOUNTING SYSTEMS

2. Burying the package in the ground.

3. Driving a stake into the ground and mounting the transducer(s) on the stake.

4. Pouring a Plaster of Paris base and mounting the transducer(s) on the plaster.

METHOD #1 - placing the transducer directly on the soil.

This can work under the following conditions:

a) the transducer system must have a large contact area with the soil in comparison to its mass and to the height of its centre of gravity.

b) the base area of the transducer package must mate well with the soil surface and the soil must be undisturbed in the contact area.

If the ground can be properly prepared, this first method can be made to work, especially if a base plate is added to the transducer to increase the contact area. However, the data so collected remains in question because of the difficulty in ensuring good contact between the soil and base plate. In a poor installation the vertical resonance may fall in the 30-60 Hz range, the most critical area for most soil vibration problems.

METHOD #2 - to bury the device in the ground several inches below the surface.

Considering the amount of soil disturbance this method is of little advantage over placing the device on the surface as above.

METHOD #3 - driving a stake into the ground.

This is in effect mounting the transducer on relaxed tip pile. It is perhaps the most common mounting method at present. For an 18" deep stake weighing five pounds, we can expect a relatively underdamped vertical resonance between 100 and 250 Hz dependent upon soil type. This would be adequate for many types of work provided that the noise in the second octave band generated by the vibration in that frequency range was not considered to be a problem. The stake has horizontal resonances that experience has shown to be as low as 30 Hz.

METHOD #4 - using Plaster of Paris, to add a base to a transducer.

Unlike Method #1, the Plaster of Paris base guarantees good contact with the soil provided the soil is relatively root free and undisturbed.

The base lowers the centre of gravity, stiffens the rocking, horizontal and vertical modes while being of low density. Thus all resonant frequencies will be raised and both vertical and horizontal monitoring can be carried out up to 300 Hz if the base area is tailored to the total transducer mass. The thickness (or depth) of the plaster should be only that required to provide sufficient internal stiffness of the mounting pad since increasing depth usually increases mass faster than it increases the soil stiffness coupled to the mount. As a rule, the thicker the plate, the lower the mounting resonances. The main drawback to this method is its awkwardness and the time involved in preparation. It has also been found wanting in damp or cold soil conditions where the extra moisture can interfere with the plaster hardening process.

4.0 DEVELOPMENT OF A NEW MOUNT

A mounting system should meet the following criteria:

1. To be an improvement over a plate of Plaster of Paris it should be clean.
2. To keep the mounting system small, the transducer(s) should have low mass. Should the system be too large, it will become a significant fraction of a wave length in soft sandy soil (velocity 300-500 ft/sec, λ = 3'- 5' at 100 Hz) at the upper portion of the desired frequency range. The size should normally be kept less than 0.15 of the wave length at the highest frequency of interest.
3. To prevent rocking, the centre of gravity of the transducer/

mount system should be near the centre of the horizontal support.

4. The system should have a base with a relatively large area in proportion to the mass if resonances are to be kept above 200 Hz, the normal upper limit of most soil vibration measurements.

5. Mounting hardware should not have internal resonances which are in the frequency range of interest.

6. The coupling to undisturbed soil should be guaranteed.

7. The system should meet the proposed criteria of vibration measurement for ISO/TC 108/SC 2 Proposal 4866.

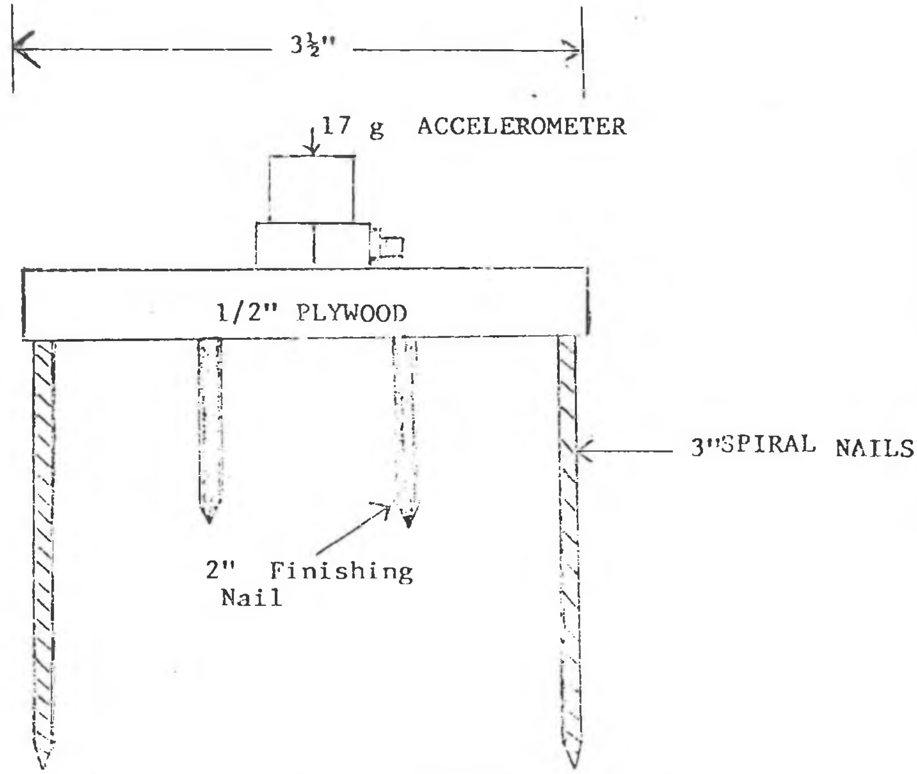
Taking the above in turn, the system should be an all mechanical one without chemicals and thus relatively clean. General purpose 20 gram accelerometers are likely to be the best choice as transducers because of their light weight, sensitivity down to levels below human perception, and ease of mounting. Where 100-200 Hz measurements are required, the accelerometers are inherently more sensitive than velocity type transducers. The centre of gravity will stay low provided the transducer is mounted immediately on a base and is small compared to the base. The base should be of a low density material to keep the resonant frequency of the system high. It should also be very stiff and well damped to control internal resonances.

The problem of guaranteed coupling to the soil must be addressed. The base could be made larger, but it becomes difficult to prepare a large area of flat soil surface on which to mount the device. For intimate contact, we can borrow the idea of the stake, placing thin piles along the edges of the base. The piles should be thin enough to allow them to be inserted iln the soil without disturbing the surface. To improve the coupling further, a second set of thinner, shorter piles may be added inside the first set. The piles guarantee contact with the undisturbed soil.
To meet the ISO/TC 108/ SC2 Proposal 4866, the system should meet the following formula:

$$\frac{Mo}{\rho Ro^3} < 2 \qquad (1)$$

where Mo is the detector systems mass
ρ is the mass density of the soil
Ro is the effective radius of contact with the soil

FIG. 2 TRANSDUCER MOUNTING SYSTEM



A mounting system was designed, and is shown in Figure 2. Plywood was used for the base plate, 3" spiral nails for the long piles, and 2" nails for the short piles. If magnetic mounting is to be used, a thin sheet of steel can be glued to the upper side of the plate. Because of the low mass of the transducer, the plate need only be $3\frac{1}{2}$" x $3\frac{1}{2}$" x $\frac{1}{2}$". For this system with a 20 gram accelerometer the ISO Formula (equation (1)) above yields the value 0.7, well within the criterion of $<$ 2. The labour involved in making the mounting pad is no more than that needed to prepare a single Plaster of Paris measurement point. However, the mechanical mount is reusable. The end result, clearly, is exceedingly simple.

5.0 TESTING

To design and build a system turned out to be rather simple. In fact, had one asked a bright civil engineer how to design a high frequency foundation, he would give the solution of a capped pile grouping in short order.

Testing the system is another matter. As acousticians, we tend to test systems by comparing them with older ones that we have used in the past. Thus new equipment is compared to older, often less accurate methods. In this case we could try each of the mounting methods, comparing them to each other. If there are differences we then have to determine which system is correct. Generally, it is difficult to reliably excite the ground at frequencies above 60 Hz and below 20 Hz. Thus testing a measurement system's response by

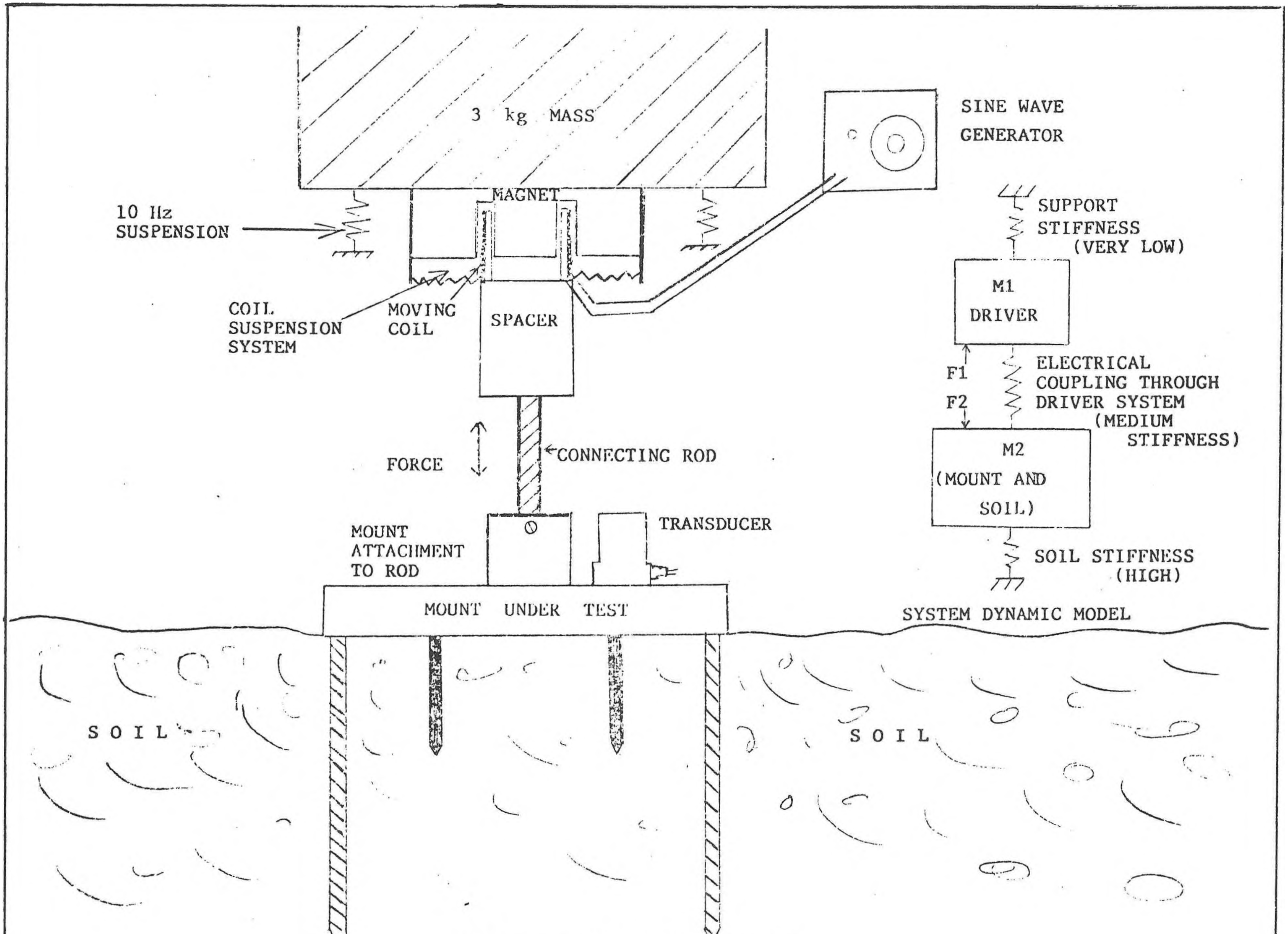


FIG. 3 - MOUNT TESTING SETUP

comparing it to other systems is difficult in controlled conditions. To date we have limited our testing to vertical measurements.

We chose to find the mount's characteristics by driving the mount rather than the soil. The mount was driven by a moving coil transducer derived from a speaker. Figure 3 shows a schematic of the test set up. Three types of soil were used; a well compacted clay soil undisturbed for 15 to 20 years, a very soft clay soil heavily disturbed several weeks before the test and a clay soil under a typical suburban lawn. The three soils represent a large range of soil types as far as shear modulus and density are concerned. Figure 4 shows the results of testing. The transducer mounting vertical resonance appears at about 600 Hz for the very soft soil (low soil stiffness) and 1000 to 1200 Hz for the harder soils. The driver resonance shown to the left of the graph is the result of the test mount stiffness being connected to the driver mass via the driver coil's electro-mechanical coupling. This coupling could be virtually eliminated if the driver amplifier were a constant current rather than a constant voltage device.

The reason for a large shift in driver resonant frequency from approximately 45 Hz to approximately 25 Hz was a change in the driver used. The two drivers had different coupling coefficients.

Calculations based on foundation design methods indicated that a vertical resonance could be expected near 1200 Hz in hard soil. They also indicate horizontal resonance at 1000 Hz and rocking resonance at 2000 Hz. The correspondence of the field data to calculations of the vertical characteristics gives confidence in the calculation methods. We are therefore reasonably assured that the mount is adequate for horizontal as well as vertical soil vibration measurements below 500 Hz.

6.0 TESTS FOR OTHER MOUNTING METHODS

For comparison, tests were carried out on a 18" stake and a 1' x 1' x 9" deep block of Plaster of Paris in a stiff clay soil, (See Figure 5). The stiff soil used resulted in higher natural frequencies than will normally be encountered. The results are shown in Figure 6. The block's and stake's characteristics indicate a relatively low resonant frequency. The Plaster of Paris system would be useful at higher frequencies if it is made as a thin plate.

7.0 FIELD APPLICATION

A few notes on the use of the mount might be helpful. We recommend that any disturbed soil or soil filled with grass roots be removed carefully. The mount should sit on flat undisturbed soil. Occasionally soil is found with hard crust on the surface. This crust can act somewhat independently of the soil beneath. In the extreme cases, the soil can be made up of several layers all acting somewhat independently.

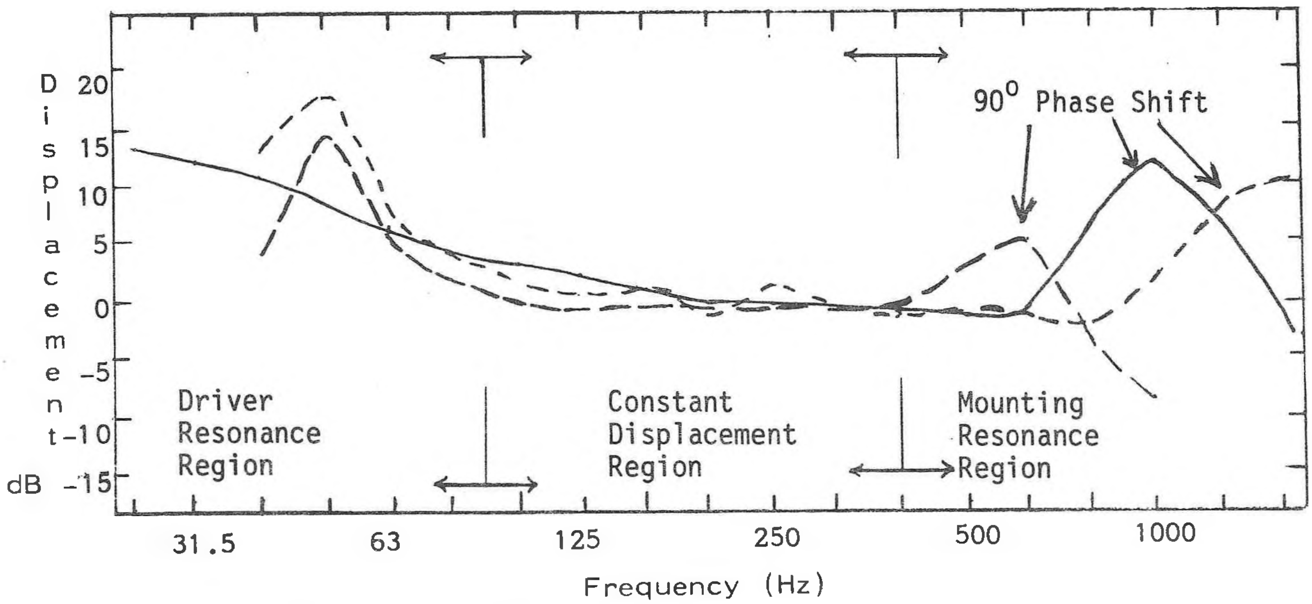


Fig. 4 VERTICLE DISPLACEMENT VS FREQ. FOR 3" x 3" PAD MOUNT

- - - - - - Hard Packed Clay (G > 10000 psi)
— — — Very Soft Disturbed Clay Loam (G < 3000 psi)
——— Typical Clay Loam Mix (G = 4000 - 8000 psi)

Note: All curves shifted vertically to an arbitrary 0dB reference to allow comparison of curve shapes.

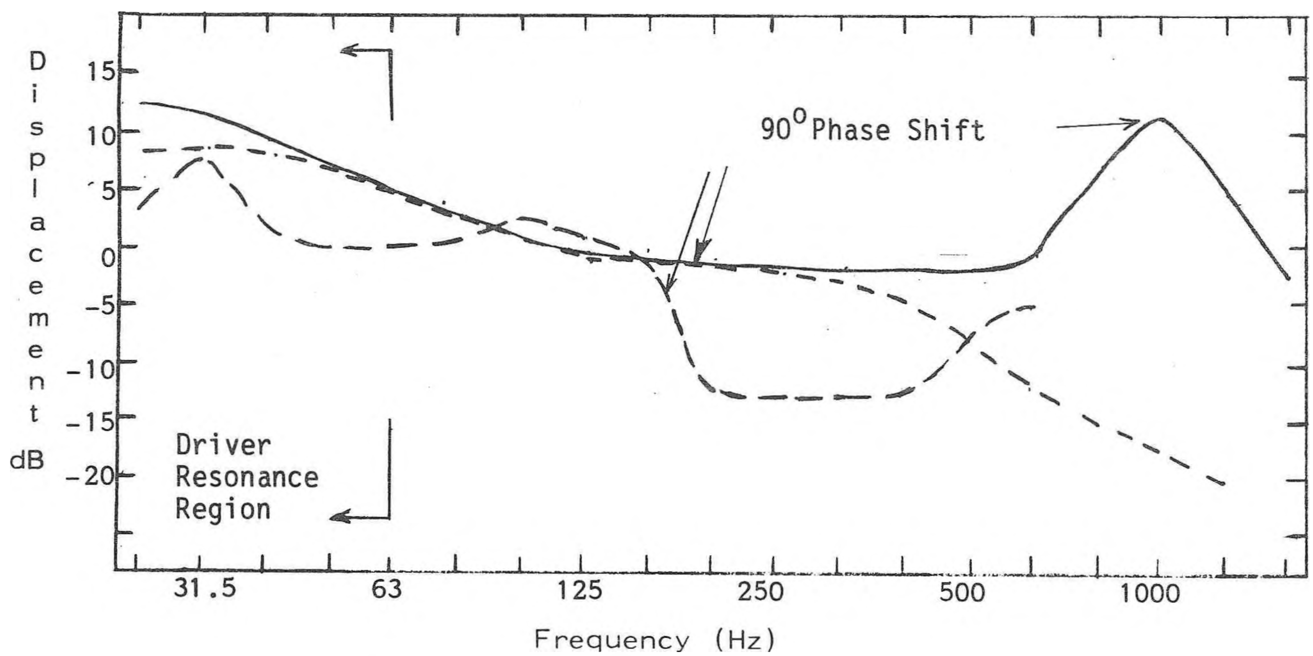


Fig. 6 COMPARISON OF TRANSDUCER MOUNTING SYSTEMS

- - - - - - 1' x 1' x 9" Plaster Block
— — — 18" Steel Rod 1" Diameter
——— 3" x 3" Pad Mount

Note: All curves shifted vertically to an arbitrary 0dB reference to allow comparison of curve shapes.

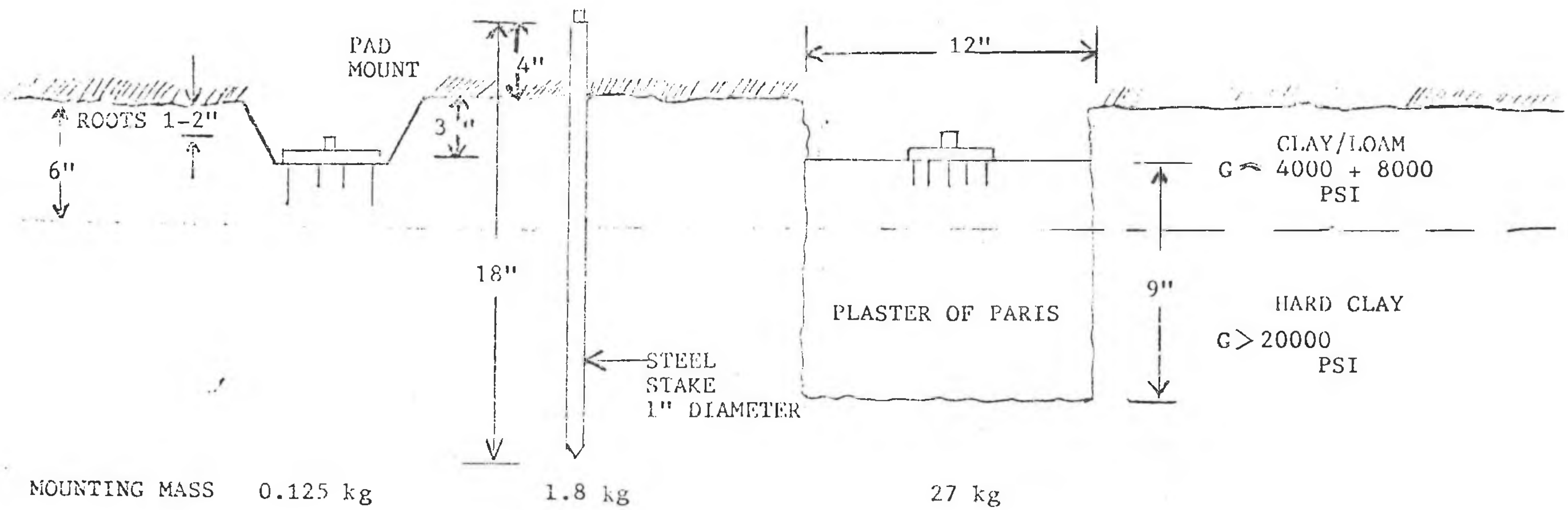


FIG. 5 - MOUNTING TEST CONDITIONS

In carrying out measurements, it is necessary to determine which layer should be monitored. The transducer mount should then be embedded in that layer.

To achieve highest horizontal and rocking frequencies, the mount should be pushed (preferably not hammered) straight down into the soil. This will minimize the disturbance of the soil in the area at the top of the spikes.

8.0 CONCLUSION

A simple, reliable method of mounting general purpose accelerometers on soil has been demonstrated. Its characteristics are such that for frequencies and vibration levels of importance to acousticians and vibration engineers, the device gives a proper coupling of the transducer to the soil immediately under it.

References

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(Continued from page 39)

The session was closed by Dr. E.A.G. Shaw (Acoustics, Division of Physics, NRC, Ottawa, Ontario, K1A 0R6), who spoke on "THE ACOUSTICAL PERFORMANCE OF HEARING PROTECTORS". In this paper the theoretical background of how a hearing protector works was presented. The author showed equivalent circuits of both muffs and plugs. Then he explained how their different mechanical characteristics can influence their final performance, which can never be better than the theoretical limit set by the bone conduction. He discussed some practical aspects such as the attenuation reduction due to the wearing of safety glasses. Finally future trends in new protectors such as using electronic negative feedback to reduce the noise were described.

In summary, thanks to the excellent papers presented, the session was lively, interesting, stimulating, and of practical benefit to the audience.

A. Behar