HIGH-AMPLITUDE MOBILE VIBRATOR FOR EXCITING BODY AND SURFACE WAVES IN SOIL, PAVEMENT AND STRUCTURAL SYSTEMS

by

Kenneth H. Stokoe, II

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A servo-hydraulic vibrator mounted on a transport vehicle was purchased from Teledyne Exploration, Corp. of Houston, Texas. The vibrator was modified by Heaviquip, Inc. of Newkirk, Oklahoma, to improve its performance in the low frequency range, 0.5 to 10 Hz. The resulting system has: 1) a gross vehicle weight of approximately 44,000 lb, 2) a useable frequency range of about 0.5 to 250 Hz; and 3) a peak vertical force (estimated) of about 34,500 lb at frequencies above 5 Hz. The general function of the vibrator is the application of vertical steady-state, multiple-pulse or swept-sine loads to surface or embedded platens in geotechnical, pavement and structural systems. This equipment will form a key component in conducting field studies involving wave propagation in geotechnical materials to investigate: 1) the effect of stress state on the velocity of small-strain body waves; 2) nonlinear body wave propagation; and 3) the dispersive characteristics of surface waves.

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ABSTRACT

A servo-hydraulic vibrator mounted on a transport vehicle was purchased from Teledyne Exploration, Corp. of Houston, Texas. The vibrator was modified by Heaviquip, Inc. of Newkirk, Oklahoma to improve its performance in the low frequency range, 0.5 to 10 Hz. This frequency range is often an important but difficult-to-excite range in field seismic testing with surface and body waves. The resulting system is a mobile vibrator with the following characteristics: 1. gross vehicle weight of approximately 44,000 lb, 2. servo-hydraulic vibrator with a baseplate area of 4512 in.^{2}, 3. useable frequency range of about 0.5 to 250 Hz, with the better performance in the range of 1 to 150 Hz, 4. peak vertical force (estimated) of about 34,500 lb at frequencies above 5 Hz, with the peak force level decreasing with the square of the frequency below 5 Hz, and 5. the capability of steady-state, multiple-pulse, and swept-sine loading. In addition to the mobile vibrator, equipment purchased on this grant includes: 1. a computer-controlled, 100-lb shaker, 2. several data acquisition and recording components which were integrated into existing equipment, and 3. two, 1-Hz geophones. The general function of the vibrator is the application of vertical loads in either steady-state, multiple-pulse or swept-sine modes to exposed surfaces or embedded platens in geotechnical, pavement or structural systems. This equipment will form a key component in conducting field studies involving wave propagation in geotechnical materials to investigate: 1. the effect of stress state on the velocity of small-strain body waves, 2. nonlinear body wave propagation, and 3. the dispersive characteristics of surface waves.

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HIGH-AMPLITUDE MOBILE VIBRATOR FOR EXCITING BODY AND SURFACE WAVES IN SOIL, PAVEMENT AND STRUCTURAL SYSTEMS

1. INTRODUCTION

In situ measurement of the dynamic properties of geotechnical, pavement and structural systems is receiving much attention in research today. The generation and measurement of stress waves in these systems generally forms the basis for such measurements. One of the key components in the measurement techniques is the seismic energy source. The characteristics of the source generally create the first limitation encountered in the field tests; that is, either there is difficulty generating primarily the wave type of interest, or generating the proper amplitude spectrum, or possibly creating the magnitude of motion in terms of exciting nonlinear response. Equipment purchased on this instrumentation grant has been selected to overcome many of the typical source limitations.

The heart of the equipment purchased with this grant is a large-scale vertical vibrator on a transport vehicle. The vibrator will be used to apply dynamic vertical loads to geotechnical, pavement and structural systems over a range in frequencies from 0.5 Hz to several hundred Hz and over a range in loads from about 1,000 pounds to more than 35,000 pounds. Harmonic, impulsive or swept-sine excitation can be applied either to exposed surfaces or to load platens embedded at depth. Seismic waves of either the body type, compression and shear, or surface waves of the Rayleigh type can be generated.

With the purchased equipment, field studies of the effect of stress state on the velocity of small-strain body waves in geotechnical materials can be conducted. In addition, this equipment can be used to extend the study of seismic wave propagation into the nonlinear range which is not now possible. Further, this instrumentation represents a valuable resource for use in investigating pavement systems in the linear and nonlinear ranges, and it can be used to mimic all existing nondestructive methods for evaluating pavement systems. Finally, the instrumentation forms a valuable resource for research in surface wave testing which has *potential use in: evaluating stiffness profiles of soil and pavement sites*, evaluating the integrity of earthen and concrete structures like dams and locks, and detecting tunnels and other underground discontinuities.

2. EQUIPMENT PURCHASED

The heart of the equipment purchased on this project is a servo-hydraulic vibrator mounted on a transport vehicle. The vibrator and vehicle (along with a utility trailer) were purchased from the Teledyne Exploration, Corp. of Houston, Texas. The purpose of the vibrator is to apply dynamic vertical loads to the surface of geotechnical, pavement and structural systems. The vibrator was modified by Heaviquip, Inc. of Newkirk, Oklahoma to improve its performance in the low frequency range, 0.5 to 10 Hz.

Pictures of the mobile vibrator are shown in Fig. 1. A close-up view of the vibrator baseplate, reaction mass, and positioning system is shown in Fig. 2. The transport vehicle is a 1981, Model 9 International truck which is described in Table 1. The servo-hydraulic vibrator is a modified Mertz Model 9 vibrator that is outlined in Tables 1 and 2. The vibrator was modified to improve its performance in the low frequency range, 0.5 to 10 Hz. The modified vibrator has a useable frequency range of 0.5 Hz to about 250 Hz, with the better performance in the range of 1 to 150 Hz. A peak vertical force (estimated) of about 34,500 lb can be applied to the baseplate at frequencies above 5 Hz, with the peak force level decreasing with the square of the frequency below 5 Hz.

Additional equipment purchased on the project includes: 1. a computer-controlled, 100-lb shaker, 2. several data acquisition and recording components which were integrated into existing equipment, and 3. two, 1-Hz geophones. This equipment is also outlined in Table 3.

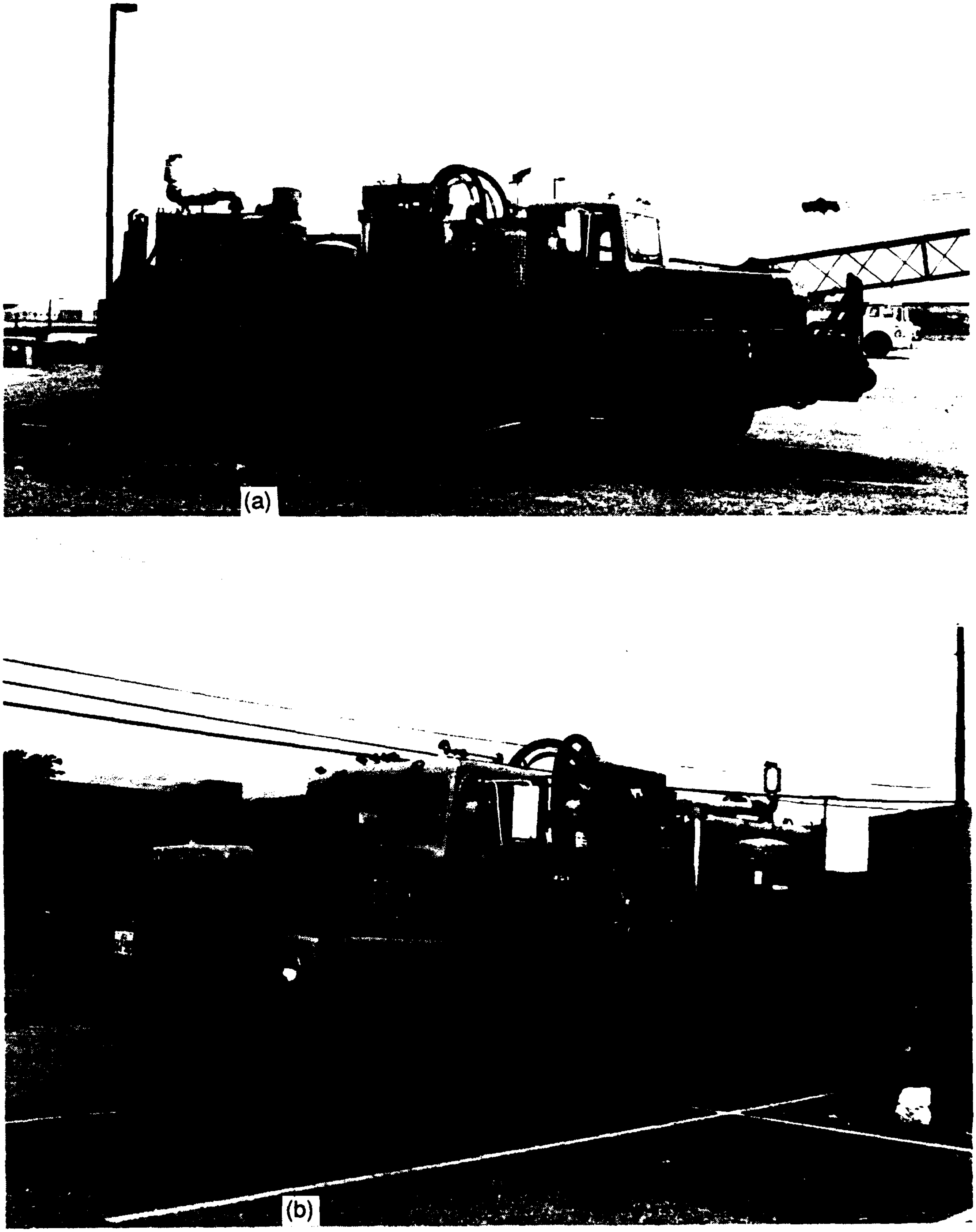


Fig. 1 - Pictures of Mobile Vibrator at Balcones Research Center, The University of Texas at Austin

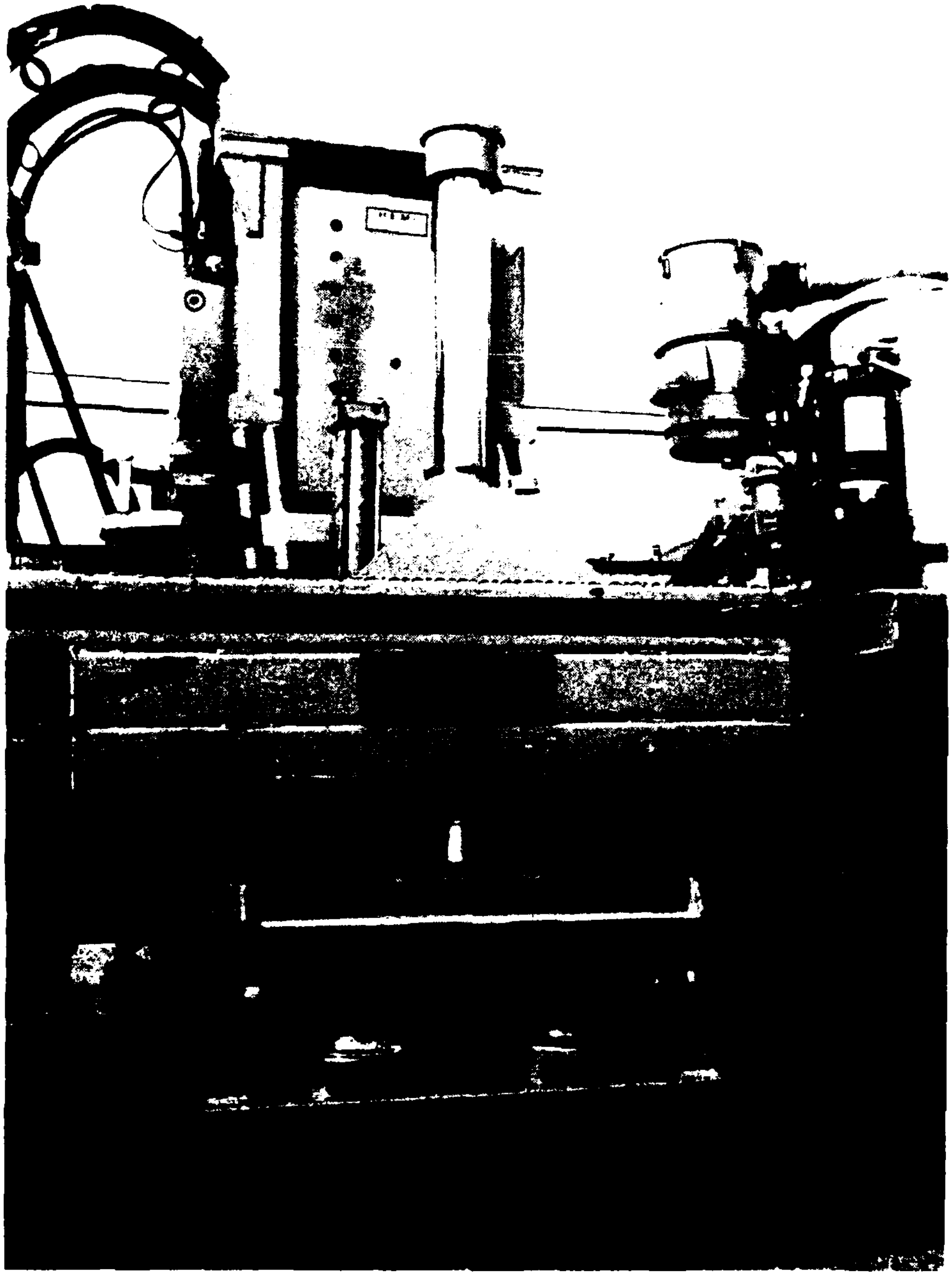


Fig. 2 - Close-Up View of Vibrator Baseplate, Reaction Mass and Positioning System

Table 1 - ORIGINAL SPECIFICATIONS OF MOBILE VIBRATOR PURCHASED FROM TELEDYNE EXPLORATION CORPORATION, HOUSTON, TEXAS

I. TRANSPORT VEHICLE

a. 1981 Model 9 International
b. 6 x 4 truck #7448 Bed #8108-850
c. Single Gas Tank
d. Engine: diesel engine 210 H.P. IHC MFG
e. Main transmission: automatic 653 Allison Mfg.
f. Aux transmission 4 speed Spicer Mfg.
g. Three axle--with capacity of 56,000 #GVW
h. I-beam front 18,000 capacity
i. Tandem rear 38,000 capacity, ratio 6.57
j. 18 x 22.5--16 ply super single, rear grip, 85% new tires front and rear with spare tire and wheel
k. Power steering, air brakes, air conditioning, and spark arrestor on exhaust outlet
l. Front mounted heavy duty winch 20,000# pull with 150 ft of 5/8 in. wire rope with tail-chain and hook
m. Truck with heavy duty trailer hitch for towing 10,000# trailer with ball
n. Fuel capacity--155 gallons/586.7 liters
o. Front bumper and brushguard and rear bumper with spare tire mount
p. Tool box in rear bed
q. Seat belts

II. MERTZ M-9 VIBRATOR

a. Diesel engine--200 HP Detroit Mfg, with spark arrestor on exhaust outlet
b. Hydraulic pump--Sundstrand model 25.90 GPH
c. Hydraulic oil cooler 450 CFM or better
d. Hydraulic pall filters low and high side
e. Hydraulic hoses in good working condition
f. Three hydraulic accumulators in safe working condition
g. All controls for starting and stopping engine from cab of truck in good working condition
h. Vibrator instruments to be in 100% working condition
i. Pelton model V no options, all cadling, accelerometers, servo valves 100% working condition

Table 1 (cont.)- ORIGINAL SPECIFICATIONS OF MOBILE VIBRATOR PURCHASED FROM TELEDYNE EXPLORATION CORPORATION, HOUSTON, TEXAS

III. STORAGE TRAILER

a. 94 in. x 120 in. box with storage racks, all steel over all 94 in. x 168 in. with walk-in rear steel door with dead bolt lock
b. Rear step with screw type jack in front
c. Two (2) 7,500-lb axle heavy duty with 8 hole studs with 8 or 10 ply--12 x 16.5 duplex tires
d. Electric brakes on each axle
e. 2 5/16" ball coupling to fit hitch on vibrator truck, spare tire and wheel
f. Completely water and dust proof

IV. GENERAL REQUIREMENTS

a. 8 hours of instruction on use of equipment
b. Long distance calls for help available at no cost
c. Warranty on used equipment if replacement parts are used from Teledyne's materials yard.

Table 2 - SPECIFICATIONS OF MODIFICATIONS TO MOBILE VIBRATOR PERFORMED BY HEAVIQUIP, INC., NEWKIRK, OKLAHOMA

I. Specifications:

a. Large servovalve manifold (HEMI 44 design)
b. Rear balance weight (HEMI 44 design)
c. 2,950 lbs of weights added to sides of mass
d. Air bag centering system
e. Modification to existing stilt structure for air bag centering to replace hydraulic cylinders with air bags
f. Extra overtravel bumpers on mass
g. 6-in. SF beam baseplate
h. Atlas 8437 servovalve w/Moog 73-232 pilot (rebuilt and warranted)
i. Replace guide rod feet (stronger than original design) for heavier load
j. Replace spherical rod couplers on lift cylinders for heavier load
k. Stronger travel lock bearings installed for heavier load
l. Hoses to actuator with protective boots
m. Anti-rotation pads with 5/16 rub strips welded on original stilt structure
n. Eight baseplate chains, boots, bolt sets (unit originally has four)
o. Repair of radius rod brackets on baseplate
p. New bolts in modified assemblies
q. Modification to the actuator mass to accept the new servovalve manifold, balance weight, side weights and air bag centering system

II. Comparison with Original Mertz M-9 Vibrator

	Original	Modified
a. Peak force, lb	21,900	34,650
b. Piston area, in.^{2}	7.30	11.55
c. Usable stroke, in.	4.0	3.5
d Reaction mass weight, lb	4550	7500
e. Displacement limited frequency, Hz	4.8	5.1
f. Flow at displacement limit, gpm	73	107
g. Baseplate area, in.^{2}	4488	4512
h. Servovalve	Atlas 10029-5	Atlas 8437
i. Servovalve pilot	Moog 73-232	Moog 73-232
j. Pump	Sundstrand 25	Reused
k. Vibrator engine	Detroit Diesel 6N71	Reused
l. Baseplate isolation	Air bags	Reused
m. Reaction mass centering	Cylinders	Air bags
n. Gross vehicle weight (approx.), lb	40,500	43,700
o. Weight on baseplate (approx.), lb	38,900	42,100

Table 3 - SUMMARY OF FINAL EQUIPMENT INVENTORY OF GRANT AFOSR-87-0056

Item Description	Cost	
• Mobile Vibrator with Trailer	$ 44,000.	*
• Modifications to Vibrator	27,735.	
• Additional Components to MASSCOMP Computer-Controlled Data Acquisition Unit	14,840.	
• Wavetek Filters for MASSCOMP	9,574.	
• Additional Channels to Hewlett-Packard N-Channel Analyzer	17,330.	
• 100-lb Shaker and Computer Control	16,471.	
• Contribution to Support Field Vehicle	4,000.	
• Two (2) Mark Products 1-Hz Geophones and Cables	2,050.	
TOTAL	$ 136,000.	**

* Mobile vibrator and trailer were purchased as used equipment. Their fair-market value was actually closer to $84,000. Therefore, the Teledyne Exploration, Corp. made a gift of about $40,000. to The University of Texas at Austin for which we are most grateful.

** Includes $10,000 matching funds from The University of Texas at Austin, BER Matching, 20-3030-2081.

3. INITIAL TESTS

To evaluate the performance of the vibrator, a series of initial tests was performed in Newkirk, Oklahoma after the modifications to the vibrator were complete (January, 1989). Two, vertical, 1-Hz geophones were placed at distances of 100 ft and 300 ft from the vibrator, with the vibrator and geophones forming a linear array. Various modes of excitation were created with the vibrator, and the output from the geophones was recorded with a Hewlett-Packard Model 3562A waveform analyzer.

Steady-state harmonic motion was the first mode of vibration tested. Frequencies from 1 Hz to above 100 Hz were used. Typical results are shown in Figs. 3 and 4. The vibrator performed well at frequencies of 10 Hz and above. However, at lower frequencies, the driving force was too large, and the baseplate began to lift off the ground which created rather complex motion as seen in Fig. 3. Unfortunately no lower loads were recorded. However, it was apparent that the vibrator had significant output at these frequencies. Also, it became apparent that it would be beneficial to add more mass to the baseplate to improve further the performance at frequencies below about 8 Hz. This option will be pursued in the future.

The second mode of vibration was an upward sweep. The motions monitored with each geophone for this type of excitation are shown in Fig. 5. The top two records represent the time histories of particle velocities while the bottom two records are the corresponding autospectra. From the autospectra, one can conclude that reasonable energy was generated in the 1 to 10 Hz range.

The cross-power spectrum was also determined from the upward-sweep measurements with two receivers, and these results are shown in Fig. 6. The time delay between receivers as a function of frequency , denoted as $\theta yx(f)$, can then be calculated using the phase of the cross power spectrum from:

$$t(f) = \theta yx(f)/2\pi f \qquad (1)$$

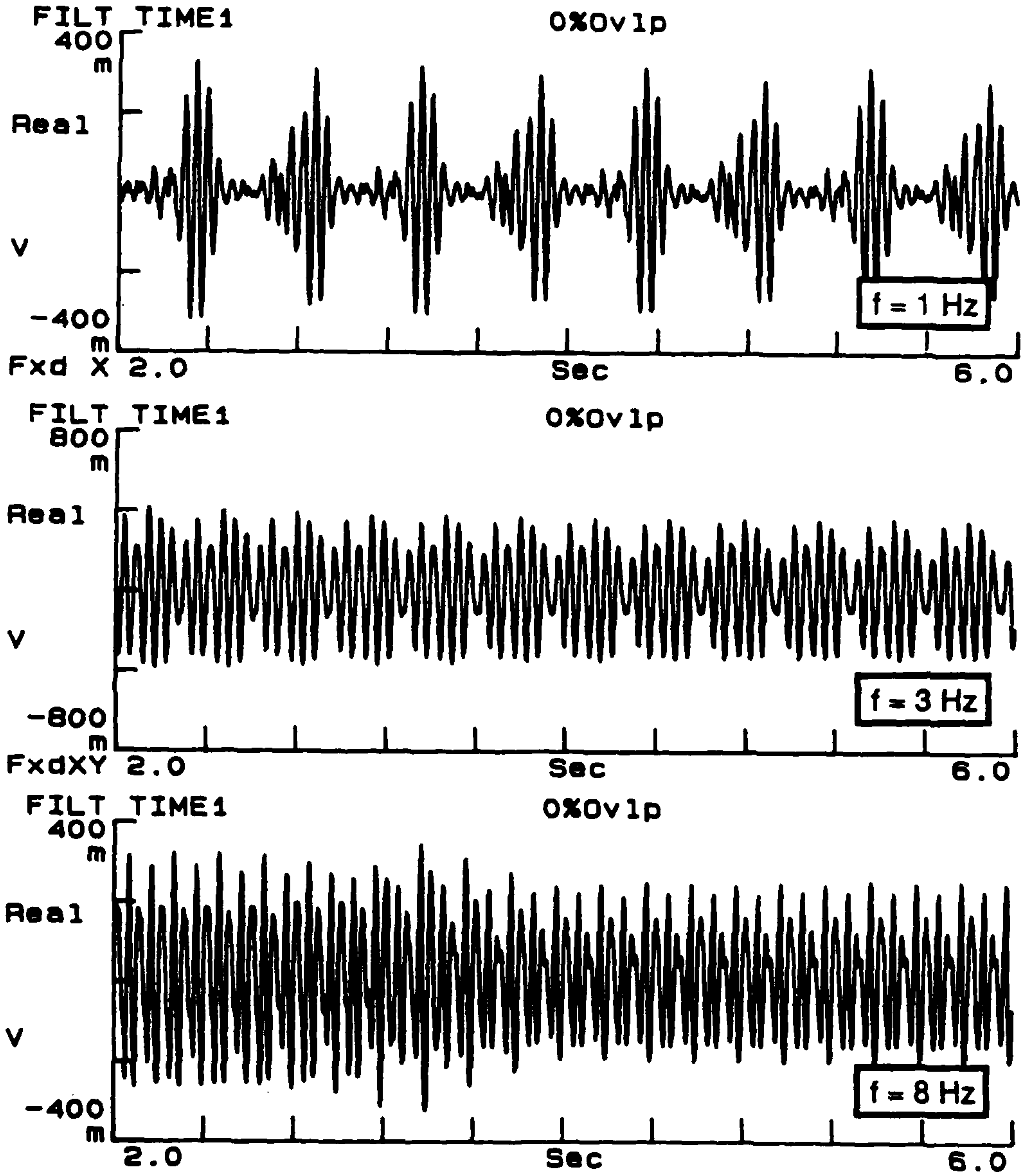


Fig. 3 - Low-Frequency Particle Velocities Measured with a 1-Hz Vertical Geophone at 100 ft from Vibrator Excited in Steady-State Mode

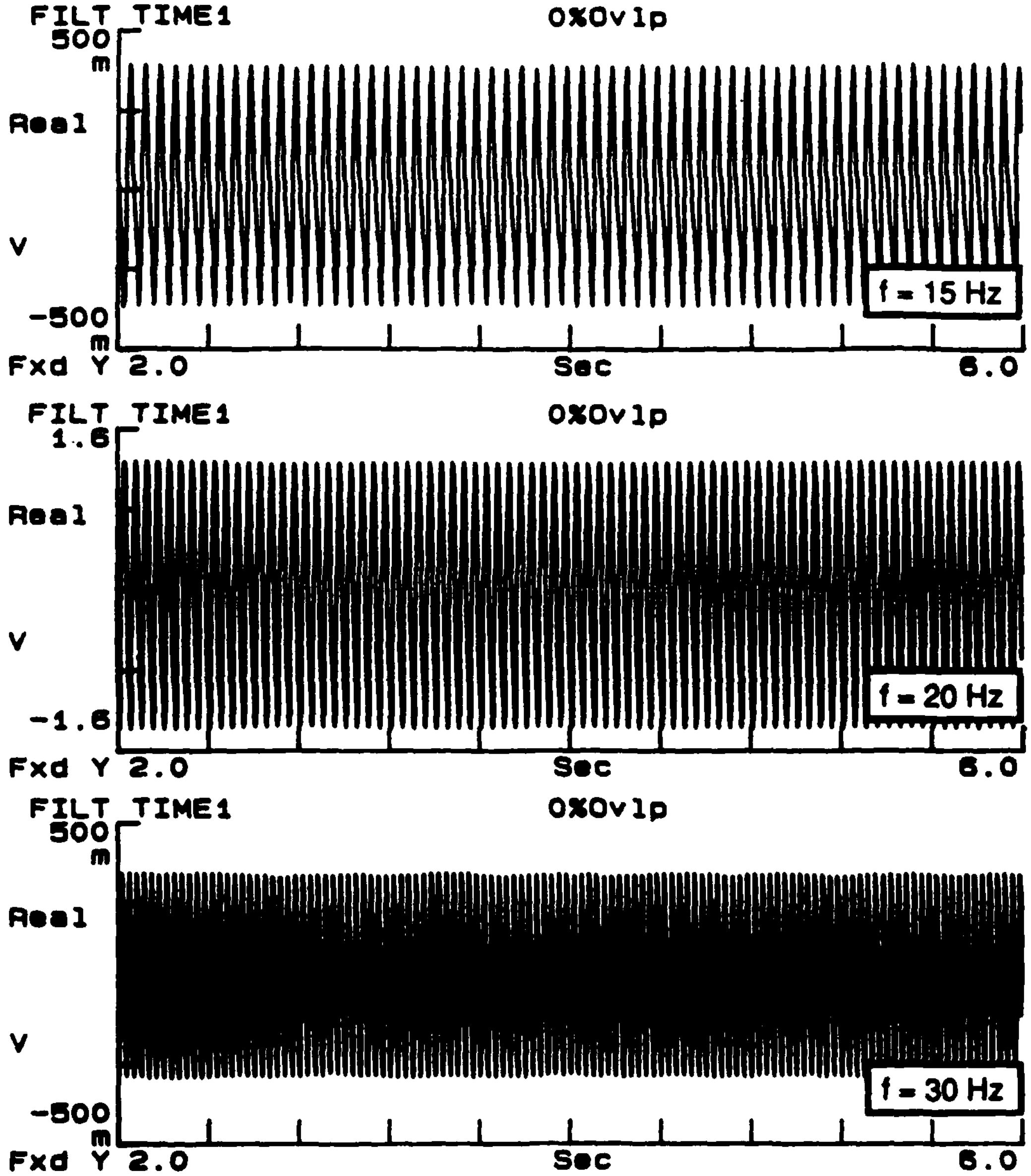


Fig. 4 - Intermediate-Frequency Particle Velocities Measured with a 1-Hz Vertical Geophone at 100 ft from Vibrator Excited in Steady-State Mode

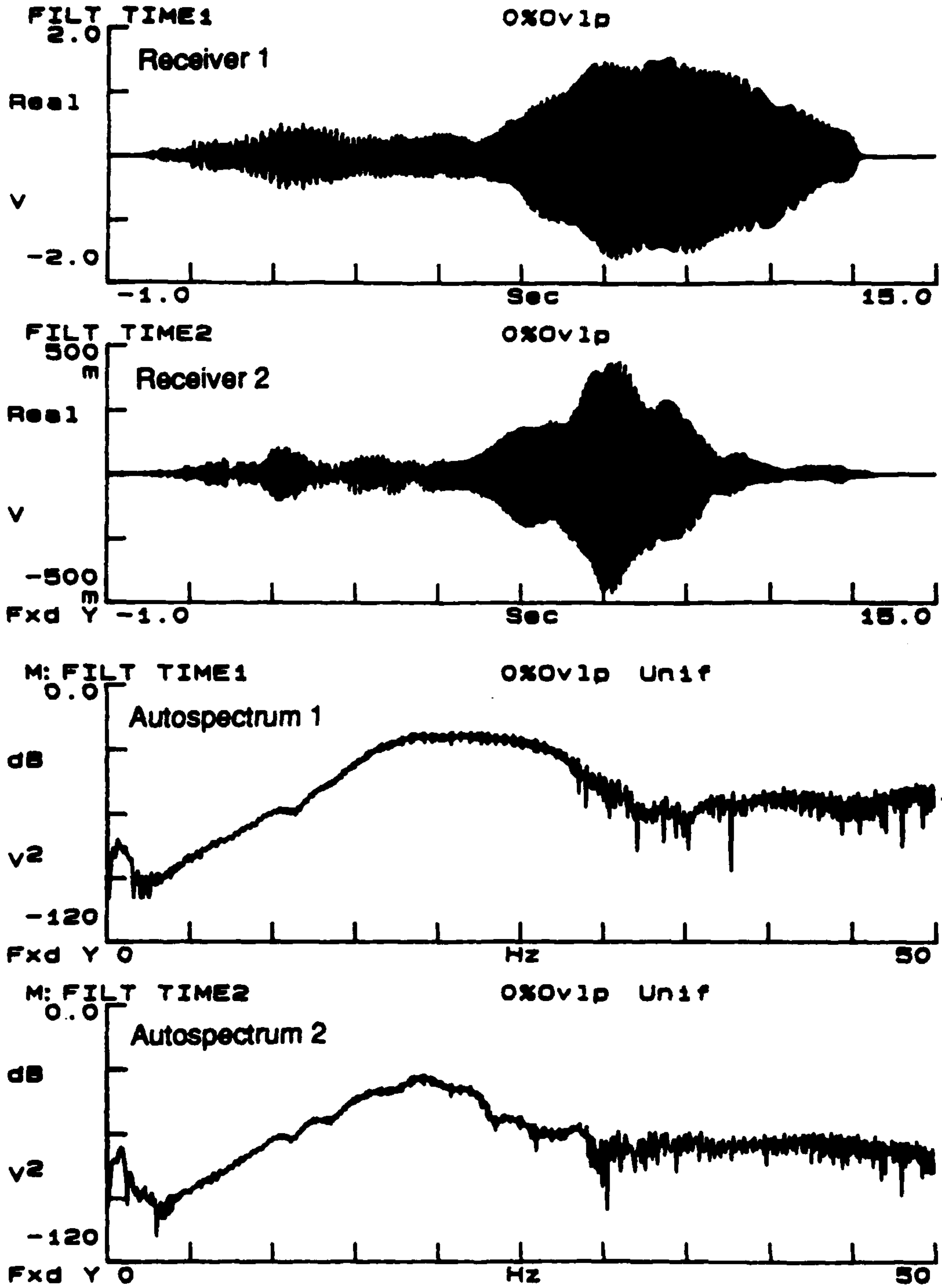
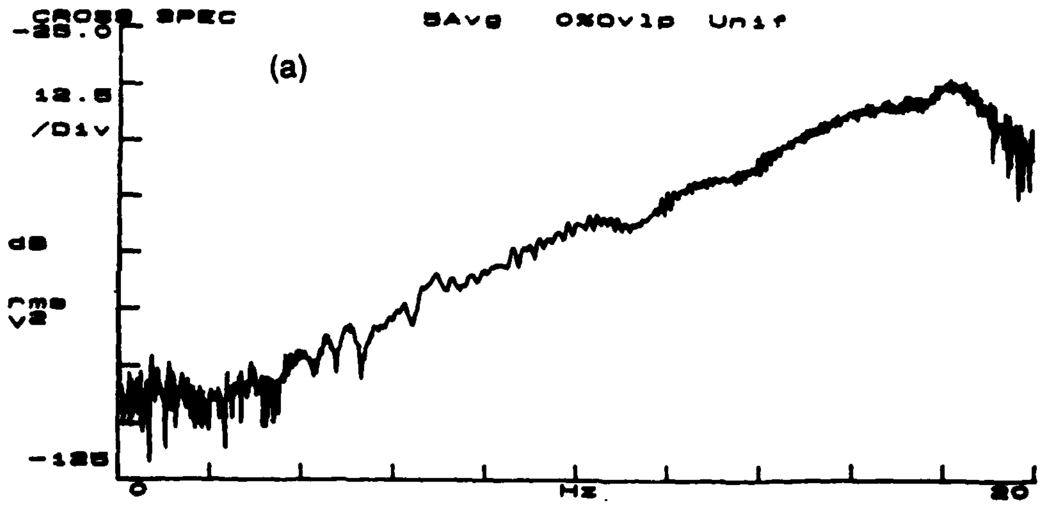


Fig 5 - Particle Velocities and Autospectra Measured with Two, 1 Hz Vertical Geophones at Distances of 100 and 300 ft from Vibrator Excited in Upward-Sweep Mode



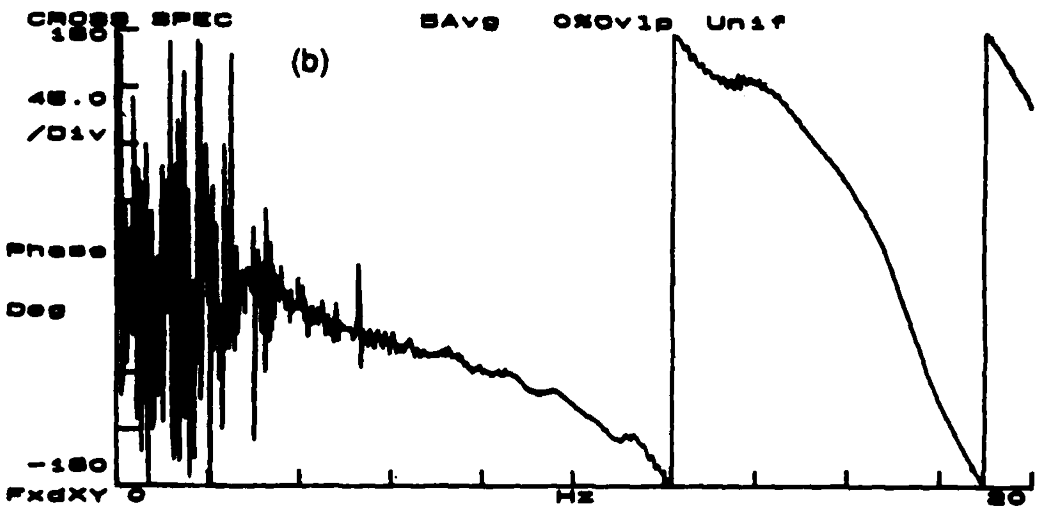


Fig. 6 - Magnitude (a) and Phase (b) of Cross Power Spectrum Measured with Geophones at Distances of 100 and 300 ft from Vibrator Excited in Upward-Sweep Mode

where the phase angle is in radians and the frequency, f, is in Hertz. Because a vertical vibrating source generates mainly surface (Rayleigh) waves under these conditions, the surface wave phase velocity, V_R, can be determined using:

$$V_R(f) = (d_2 - d_1)/t(f) \tag{2}$$

where d_1 and d_2 are the distances to receivers 1 and 2, respectively. The corresponding wavelength of the surface wave is calculated from:

$$L_R = V_R/f. \tag{3}$$

The result of these calculations is a dispersion curve (V_R versus L_R) for the 200-ft receiver spacing which is shown in Fig. 7. The results are for the frequency range of about 12 to 20 Hz in Fig. 6. The results seem quite reasonable and show that the vibrator can be used very effectively at low frequencies (to about 3 Hz in Fig. 6 even though no calculations were performed because of near-field effects in this case). In addition, the results indicate that the site in Newkirk, Oklahoma is very stiff, appearing to be rock-like at depths greater than about 50 ft.

4. CONCLUSIONS

A high-energy mobile vibrator has been developed which represents a valuable new resource in the area of in situ seismic measurements. First, the equipment will permit field studies of wave propagation in soils at large strains to be conducted. This potentially represents a significant advance in an area essentially devoid of research (except for blast studies). Understanding of such behavior is necessary for proper constitutive modeling of problems such as: amplitude and attenuation characteristics from shock loading, liquefaction of granular soils, degradation of cohesive soils, pavement and runway performance, and hardening of underground structures. Second, the equipment will permit field research in the area of pavement and runway design and performance. With this equipment it is possible to mimic all presently used pavement evaluation equipment such as the falling weight deflectometer, the dynaflect and the roadrater. In addition, the equipment can be employed in field research with the new spectral analysis work with surface waves. Surface waves can be used in rapid and accurate evaluations of: stiffness profiles of soil sites, integrity of earthen and concrete dams, and stiffness profiles and long-term monitoring of flexible and rigid pavement system.

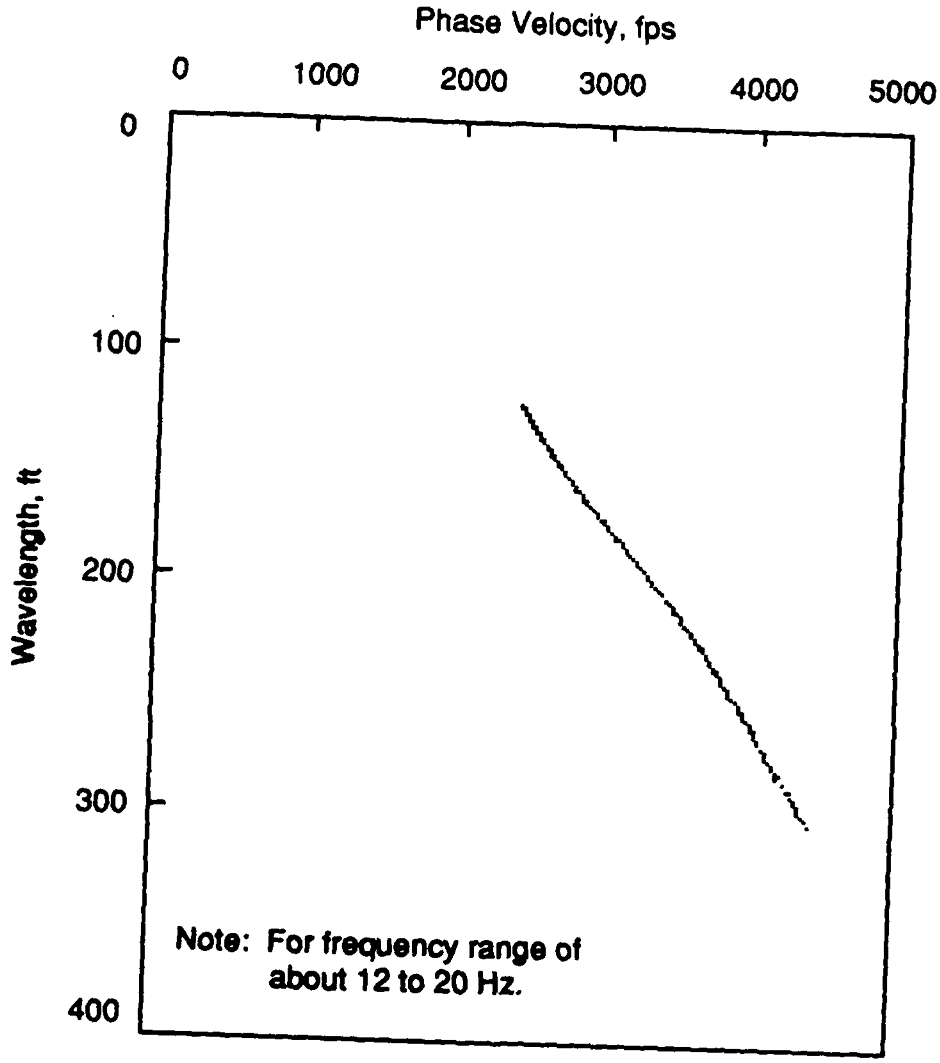


Fig. 7 - Dispersion Curve Generated from Phase Plot Shown in Fig. 6