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ELASTIC PROPERTIES OF THE LUNAR SURFACE FROM SURVEYOR SPACECRAFT DATA

Final Report

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Abstract

This report contains the scientific results obtained under Contract No. 952208 between the Jet Propulsion Laboratory, California Institute of Technology and Hawaii Institute of Geophysics, University of Hawaii; George H. Sutton, Principal Investigator. It provides estimates of the elastic properties and seismic velocities of the upper few centimeters of the moon from Surveyor data and compares these results with those from Apollo. The body of this report is being submitted to Journal of Geophysical Research for publication.

Data from the successful Surveyor spacecraft landings provided the first direct information on the elasticity of the lunar surface material (Choate _et al_., 1969). This data was obtained principally from strain gauges mounted in each of the spacecraft legs. The frequency and decay rate of the vertical oscillations upon landing of the spacecraft, measured by the strain gauges, are dependent on the elastic and damping properties of the spacecraft and of the lunar surface material. Analysis of this data suggested that the elastic properties of the lunar surface material are similar to those of a high porosity unconsolidated clay. These earlier results contained uncertainties principally related to the approximate values for spacecraft elastic parameters used in the analyses. This paper describes the results of subsequent tests on a duplicate spacecraft and additional analyses.

Oscillations of a spacecraft were studied in earth-based tests using a duplicate spacecraft (Gammell, 1968). Sample tracings of the strain gauge data from the tests and from the lunar landings are shown in Figure 1. During the tests lunar gravity was simulated using a spring support system having a negligible effect on the resonant mode being considered. Tests were made with footpads resting on a rigid concrete factory floor, on loosely packed (soft) fine grained rock dust, and on more tightly packed (hard) fine grained rock dust.

The test soil is a finely ground (within the clay size range) rock powder composed mostly of quartz (83%). The bulk density was 1.18 g/cm^3 for undisturbed "soft" soil; 1.20 g/cm^3 under a footpad after soft testing; 1.28 g/cm^3 for undisturbed "hard" soil; and 1.32 g/cm^3 under a footpad after "hard" testing. Using a grain density for quartz of 2.63 g/cm^3 this is equivalent to porosities (volume of voids/bulk volume) of 0.55 - 0.54 and 0.51 - 0.50 for the "soft" and "hard" soils respectively.

The tests clearly indicate a reduction in the oscillation frequency and changes in damping characteristics in going from rigid, to hard, to soft surfaces. Unfortunately, they also exhibit a frequency dispersion, frequency increasing with decreasing amplitude, which has made interpretation of the data difficult. Since the dispersion is most evident for tests on a rigid surface the source of the dispersion appears to be in the spacecraft.

For tests on the soft and hard surfaces the dispersion can be explained by variations in the spacecraft constants alone. Considering the test data as that for a simple linear system with no damping, i.e., spacecraft mass, in series with a spacecraft equivalent spring, in series with a soil equivalent spring, we can calculate the spring stiffnesses for the spacecraft from rigid surface data, using the formula (1) $K_1 = 4\pi^2 f_1^{\,2} M_1$ and the stiffness of the test soils using (2) $K_2 = 4\pi^2 M_1 f_1^{\,2} f_s^{\,2}/(f_1^{\,2} - f_s^{\,2})$ where

K_1 = Stiffness of one leg of spacecraft

K_2 = Stiffness of surface under one footpad

M_1 = 1/3 mass of spacecraft

f_1 = Frequency of oscillation of spacecraft on rigid surface

f_s = Frequency of oscillation of spacecraft-soil system

From Table I, which summarizes such calculations, it can be seen that the effective stiffness of the soil is relatively independent of amplitude while, as noted above, the spacecraft stiffness increases with decreasing amplitude.

Definite oscillations of the spacecraft were observed in Surveyor landings I, III, and VI. There appears to be no significant difference in the resonant frequencies observed at the different landing sites, and, since Surveyor VI data was the least noisy, it was used in this analysis. Plots of frequency vs. displacement for the test data and the lunar data are shown in Figure 2. Data from both the touchdown and the hop of Surveyor VI are shown.

There is a considerable amount of scatter for the lunar data. We believe this is mainly the result of a large amount of noise in the original telemetry data. The strain gauges were not designed to produce reliable information at such low load levels. The points shown are the result of analysis of carefully filtered records and it is unlikely that much further improvement can be obtained. For amplitudes larger than about 9.8×10^7 dyne (peak-to-peak) the footpads should jump free of the surface during part of the oscillation and such data is not reliable for this study. The solid triangle and solid circle for initial touchdown and hop respectively indicate the first half cycle for which the spacecraft did not come free of the surface as determined from examination of unfiltered data. For the touchdown the indicated amplitude of 6.7×10^7 dyne suggests a possible error in calibration of about -2.2×10^7 dyne; at this level. More or less arbitrarily increasing the amplitudes for the touchdown data by 2.2×10^7 dyne would bring the two sets of lunar data into close agreement between about 8.9×10^7 dyne (peak-to-peak) and 4.5×10^7 dyne. Below 4.5×10^7 dyne it is probable that the data is unreliable because of noise. An amplitude near 6.7×10^7 dyne (peak-to-peak) appears to be the most reliable for estimating lunar properties. All analyses are made using parameters appropriate for this amplitude.

Equation 2 is accurate only for small damping (R_1 and R_2). In an attempt to obtain more accurate values for K_2, solutions were sought to equations of motion in which the damping terms were not ignored. This approach could also provide information on the damping characteristics of the lunar surface material. The model used is shown in Figure 3. It consists of a mass M_1 (the spacecraft) coupled by a spring-dashpot system, K_1 and R_1 (spacecraft legs), to another mass M_2 (the lunar surface material) which is coupled to the body of the moon by its mechanical characteristics (K_2 and R_2). The equations of motion are:

$$(3)\quad \ddot{X}_1 = -g - \ddot{X}_2 - \frac{R_1}{M_1}\dot{X}_1 - \frac{K_1}{M_1}X_1$$

$$(4)\quad \ddot{X}_2 = -\frac{M_1}{M_1+M_2}g - \frac{M_1}{M_1+M_2}\ddot{X}_1 - \frac{R_2}{M_1+M_2}\dot{X}_2 - \frac{K_2}{M_1+M_2}X_2$$

where g is lunar gravity; X_1 and X_2 are defined in Figure 3. The spring and damping constants of the spacecraft (K_1 = 2.14×10^8 dyne/cm and $R_1 = 2.7 \times 10^5$ dyne sec/cm) were computed, using Equation 3 with $\ddot{X}_2 = 0$, from the spacecraft tests on a rigid surface at an amplitude level of 6.7×10^7 dyne (peak-to-peak). Using Equations 3 and 4 an electronic analog computer was then employed to obtain values for the stiffness and damping parameters of the surface material (K_2 and R_2).

The parameters K_2 and R_2 were adjusted until the oscillations of the model closely matched those observed in the lunar landings and spacecraft tests. The parameter M_2, the effective mass of the surface material, was approximated as zero after determining that variation of this parameter within reasonable limits ($M_2 < 0.1\ M_1$) did not significantly affect the results. The values of stiffness (K_2) obtained from the analog computer model are presented in Table II along with values calculated under the assumption of negligible damping using Equation 2. Differences between the two sets of results are not considered to be meaningful.

The analog model was not exact in two noticeable aspects. First, the spacecraft oscillations are dispersive while those of the analog model are not. The dispersion of the spacecraft oscillations is probably caused by some non-linearity in the landing gear of the spacecraft. This difference, while making interpretation more difficult, was not considered serious enough to warrant the use of a non-linear model. Secondly, the model could not quite match the low damping observed in the records from the spacecraft tests on the hard soil (without reducing R_1). In this case, with R_2 set equal to zero (no damping in the surface material) the oscillations of the analog model decayed more quickly than those of the spacecraft. This may be the result of non-linearities not considered in the model or may be related to changes in lateral stresses on the footpads in going from rigid to compliant surfaces. For the small damping observed, values of K_2 are relatively insensitive to variations in R_2. As indicated in Table II, K_2 is also insensitive to changes in R_1.

As a check on the reliability of the parameters measured, loading experiments were run at the Hawaii Institute of Geophysics on the test soils used in the spacecraft tests. A rigid disk, evenly weighted to give a known loading, was placed on a smoothed soil surface. A step of acceleration was applied to the disk by lifting another weight quickly from the disk while the vibrations were measured by a geophone of negligible mass rigidly attached to the center of the disk. The loading tests differ from the spacecraft tests in that the oscillations measured in the loading tests should be influenced by the elasticity of the soil and the mass and radius of the disk only.

The formulas used in interpreting the loading test data are:

(1) $K = 4\pi^2 mf^2$

(5) $L = mg/\pi r^2$

(6) $K/r = 0.5\pi^2 \mu/(1-\sigma)$ (Timoshenko and Goodier, 1951)

where m = mass of disk system
L = loading
r = radius of disk
μ = rigidity modulus
σ = Poisson's ratio

From these equations it is noticed that K/r is a constant of the soil independent of loading, and that the resonant frequency for constant loading should be proportional to $1/\sqrt{r}$.

Tests were run using three different disks and three different loadings corresponding to 1/2, 1, and 2 spacecraft footpad radii (12.7 cm) and 1/2, 1, and 2 times the loading per footpad on the moon (3.32×10^{11} dyne/cm^2). Because of resonances of the soil container (55 gallon drum) reliable data was obtained only for tests on soft soil using the small disks. The resulting values of K for the soft soil and 6 cm disk are 3.09×10^8, 2.66×10^8, and 2.71×10^8 dyne/cm for loading of 1/2, 1, and 2 spacecraft footpad loadings respectively, giving an average value of $(K)_{6\ \mathrm{cm}} = 2.82 \times 10^8$ dyne/cm. Since K/r is a constant, K for a 12.7 cm disk can be extrapolated from data for the 6 cm disk yielding $(K)_{12.7\ \mathrm{cm}} = 5.95 \times 10^8$ dyne/cm. Comparison of this value with that obtained from the analog model for the spacecraft test on soft soil ($K_2 = 9.0 \times 10^8$ dyne/cm) provides reasonable confidence in the results.

The determination of other elastic parameters from the soil stiffness depends upon the relationships:

(6) $\mu = 2K(1-\sigma)/\pi^2 r$

(7) $\beta^2 = \mu/\rho$

(8) $\alpha^2 = (2-2\sigma)\beta^2/(1-2\sigma)$

where

ρ = bulk density

α = compressional wave velocity

β = shear wave velocity

From Equation 6 it is seen that if K and r are known, μ can be determined to within a factor of 2 since σ is restricted to values between 0 and 1/2 by the physical properties of materials. From Equations 6 and 7, β can be determined to within $2^{1/2}$ if K, r, and ρ are known. From Equation 8, if σ is unknown, a minimum value for α can be determined, $\alpha_{\min} = 2^{1/2}\beta$. Figure 4 shows the relationships among K_2, α, β, and σ for two values of ρ appropriate for the test soils.

Compressional wave velocity near the lunar surface was measured over a distance of 130 m during the Apollo 12 lunar mission by timing the signal from an LM thruster recorded on the seismometer of the Passive Seismic Experiment (Latham _et_ _al_., 1970). This velocity, 108 m/sec, can be considered as an upper limit for α at the surface.

Table III is a summary of elastic properties of the lunar surface material and the two test soils. The density for the lunar material, 1.5 g/cm^3, is that obtained from Surveyor (Jaffe _et_ _al_., 1969). Laboratory measurements on lunar soil from Apollo 11 give bulk densities ranging from 1.4 to 1.6 g/cm^3 for the upper few centimeters (Costes _et_ _al_., 1970). The grain density of the lunar soil is 3.1 g/cm^3 (Costes _et_ _al_., 1970) and that for the test soils is 2.63 g/cm^3. A test soil having the same porosity as lunar material with bulk density 1.5 g/cm^3 would have a bulk density of 1.3 g/cm^3.

If the lunar surface material has a Poisson ratio similar to that for the test soil, $\sigma = 0.33$, then, using $K_2 = 7.3 \times 10^8$ dyne/cm and $\rho = 1.5$ g/cm^3, we obtain $\mu = 8 \times 10^6$ dyne/cm^2, $\beta = 23$ m/sec and $\alpha = 45$ m/sec as an estimate for the **elastic** properties of the upper few centimeters of the Moon.

The compliance of the lunar material can effect the response of a seismometer resting on the surface. As an example, the seismometer of the Apollo Passive Seismic Experiment having a total mass of 11.5 kg and diameter of 23 cm, would have a resonant frequency of about 40 hz if the surface were evenly loaded under the package (neglecting effect of coupling of the inertial masses of the seismometer); the resonant frequency would decrease as $r^{1/2}$ for smaller loaded areas. The response of such a seismometer will be degraded for frequencies near and above this frequency.

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TABLE I.

DEPENDENCE OF SPRING STIFFNESS ON AMPLITUDE

Amplitude (dyne p-p)	Spring Stiffness (dyne/cm)		
	Spacecraft	Hard Soil	Soft Soil
6.7×10^7	2.14×10^8	1.8×10^9	1.0×10^9
1.8×10^7	2.9	1.6	1.1
1.8×10^6	3.4	1.5	1.1

TABLE II.

SURFACE STIFFNESS

Surface	Frequency	Stiffness (K_2) A	Stiffness (K_2) B
Rigid	7.3 hz	∞	∞
Test Hard Soil	6.9	18×10^8 dyne/cm	23×10^8 dyne/cm
Test Soft Soil	6.6	9.6	9.0
Lunar Soil (Most probable)	6.4	7.2	7.3
Lunar Soil (Minimum)	6.0	4.7	4.2

A - Stiffness calculated from frequency assuming no damping. (Eq. 2)
B - Stiffness obtained from analog model including damping.

TABLE III.

ELASTIC PROPERTIES

	K_2 (a) 10^8 dyne/cm	ρ g/cm^3	μ 10^7dyne/cm^2	σ	β m/sec	α m/sec
Soft Soil	9.0	1.1	1.0	.32	30	58
Hard Soil	23.0	1.3	2.4	.35	43	90
Lunar Surface	7.3	1.5	1.2 - 0.6	0 - .48	28 - 20	40 - 108 (b)

(a) for r = 12.7 cm

(b) 108 m/sec from Apollo 12 at 130 m range

Figure Captions

Fig. 1. Tracings of strain gauge data (broad-band) from Surveyor Spacecraft: A - Rigid surface test; B - soft soil test; C - initial landing of Surveyor VI; D - hop of Surveyor VI. In tests, the spacecraft was initially depressed producing maximum force at the beginning. Zero force occurs when the spacecraft footpads are off the surface. The traces are aligned so that equal amplitudes occur at about the same time near the beginning of the trace. The bar to the right of each trace represents force from zero to 10^8 dyne.

Fig. 2. Amplitude vs. frequency for Surveyor VI lunar data and test soils. The solid data points represent the first points for which the spacecraft did not leave the surface. Note that the touchdown and hop data would agree quite well if the touchdown data were increased by 2×10^7 dyne.

Fig. 3. Dynamic model of spacecraft sitting on compliant surface.

Fig. 4. Relationships among stiffness, shear wave velocity, compressional wave velocity, and Poisson's ratio: A for $\rho = 1.1$ g/cm^3; B for $\rho = 1.3$ g/cm^3.

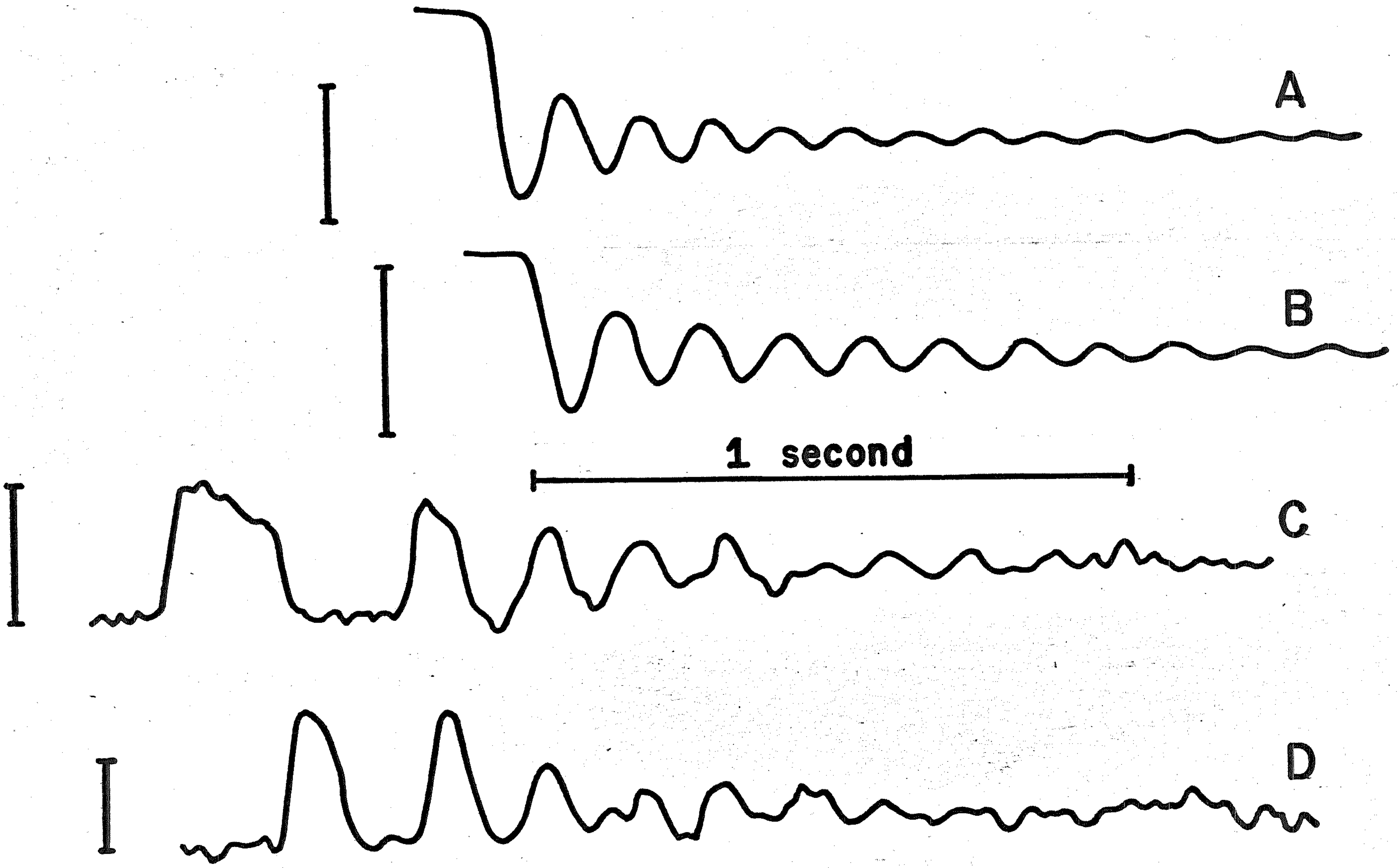


FIG 1

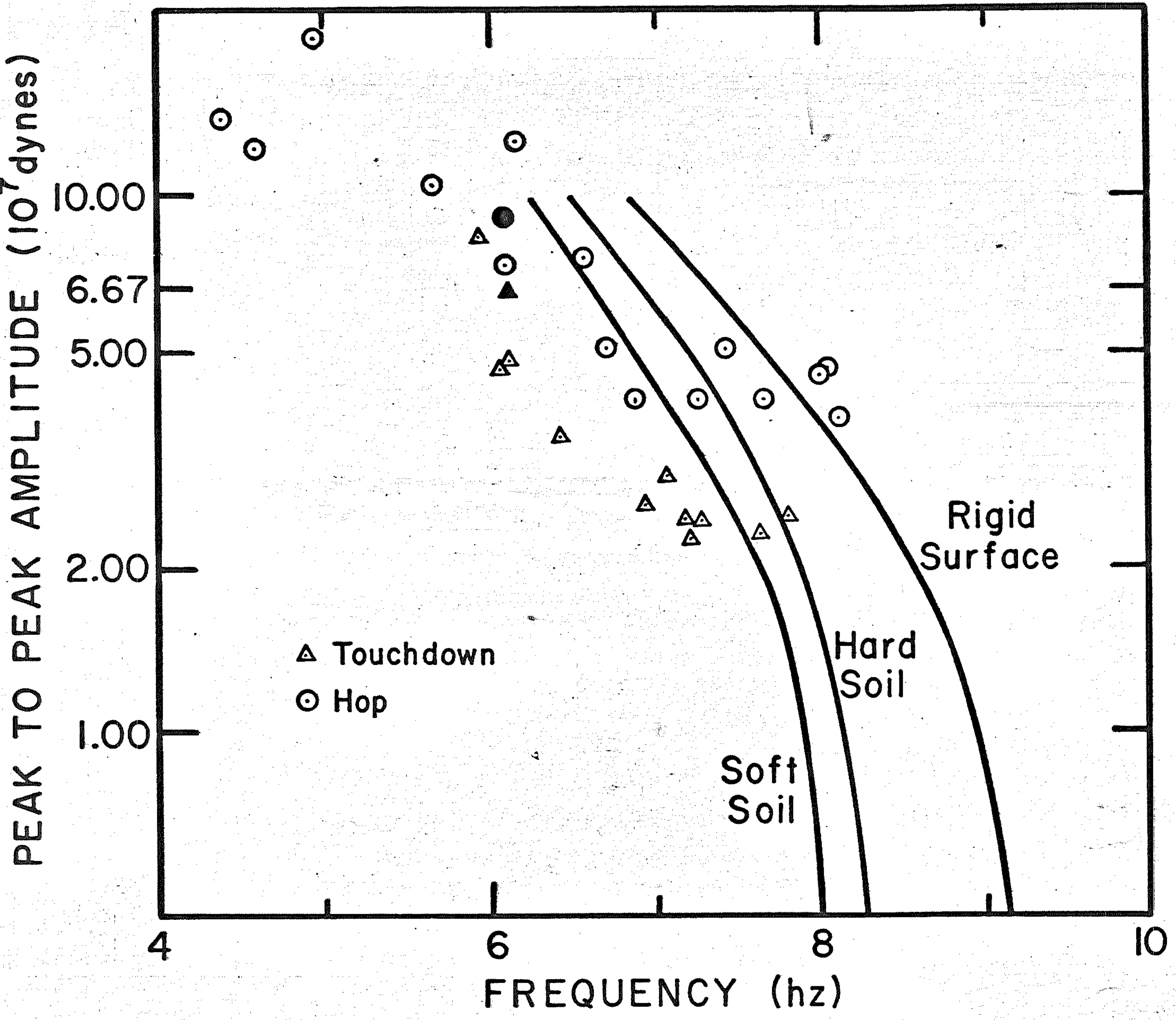

PEAK TO PEAK AMPLITUDE (10^7 dynes)
10.00
6.67
5.00
2.00
1.00
4
6
8
10
FREQUENCY (hz)
Δ Touchdown
⊙ Hop
Rigid Surface
Hard Soil
Soft Soil

FIG 2

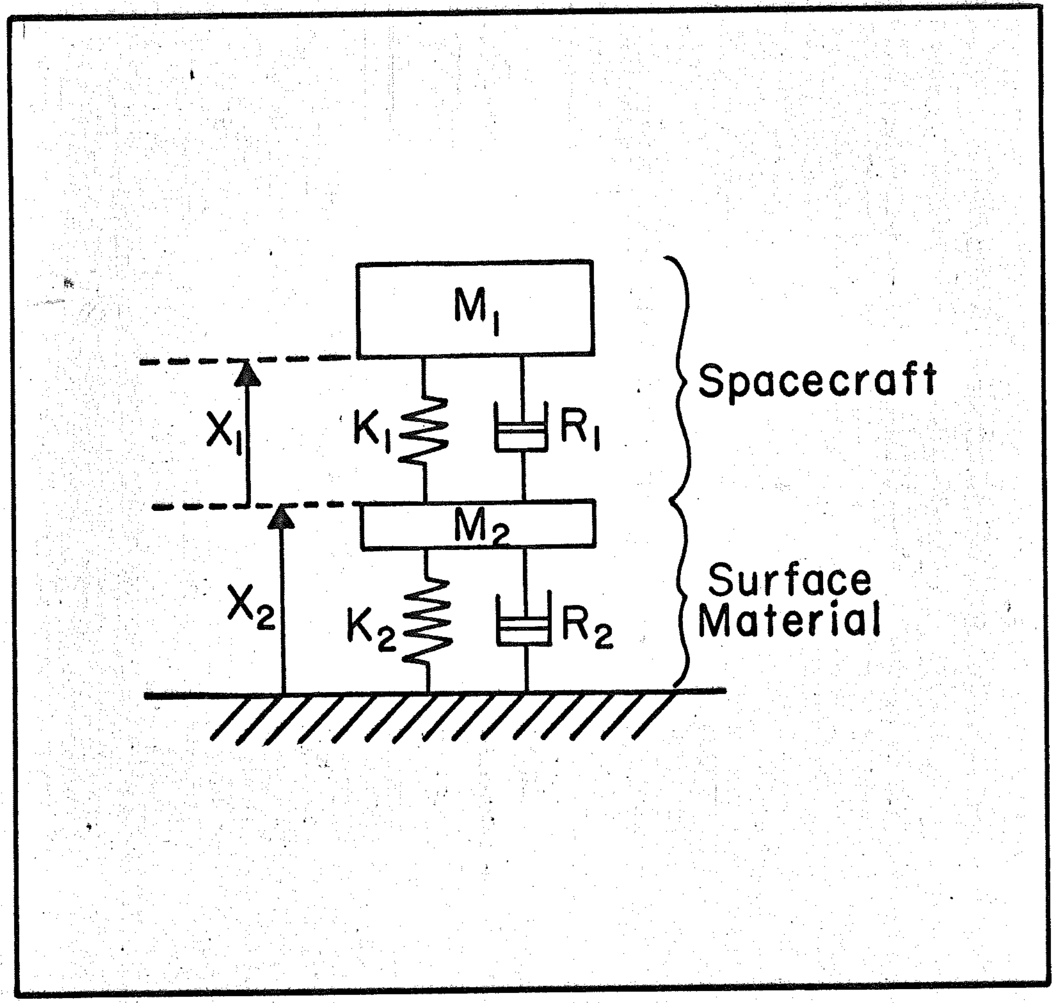
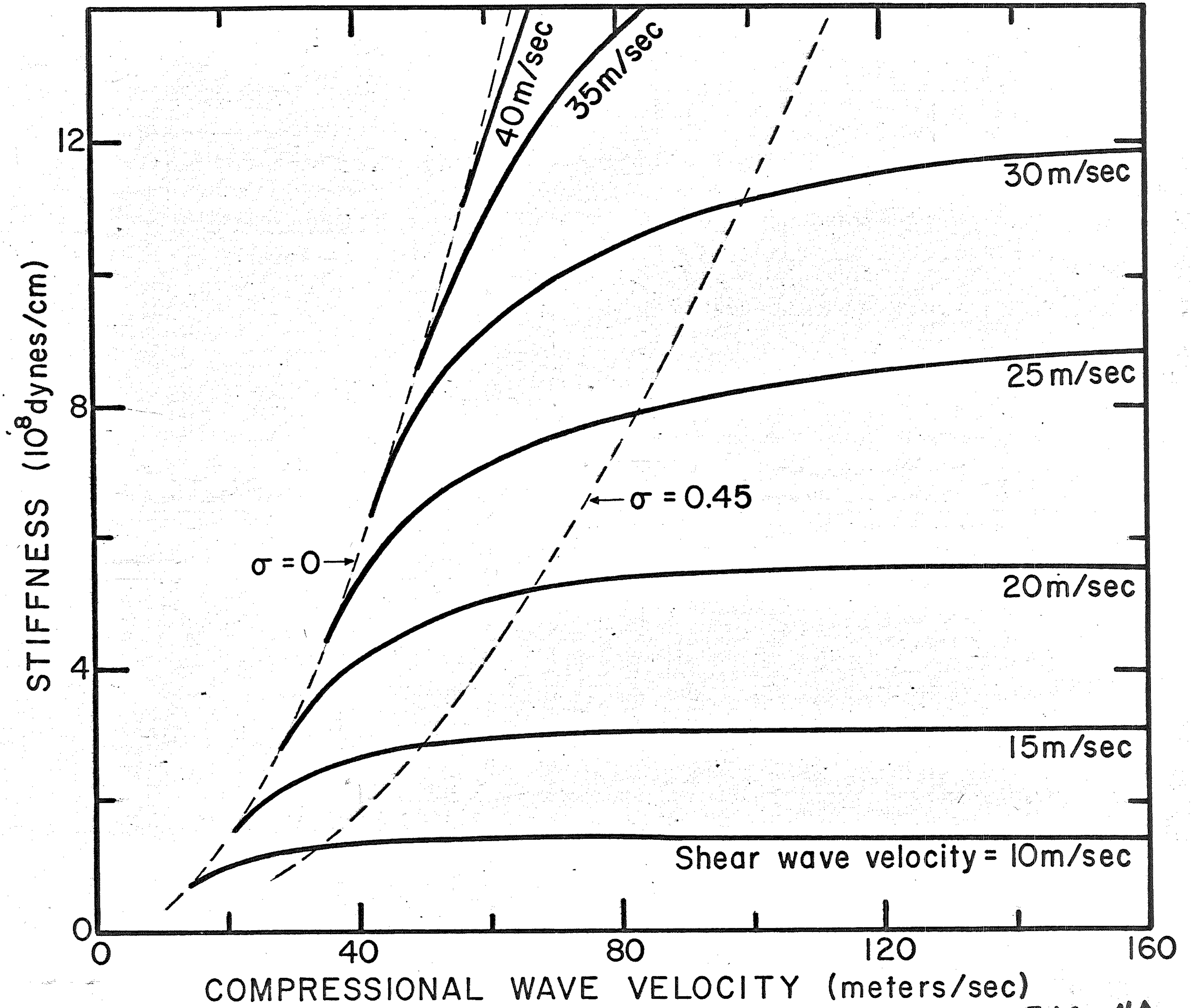


FIG 3



STIFFNESS (10^8 dynes/cm)
0
4
8
12
0
40
80
120
160
COMPRESSIONAL WAVE VELOCITY (meters/sec)
40m/sec
35m/sec
30m/sec
25m/sec
20m/sec
15m/sec
Shear wave velocity = 10m/sec
σ = 0
σ = 0.45

FIG 4A

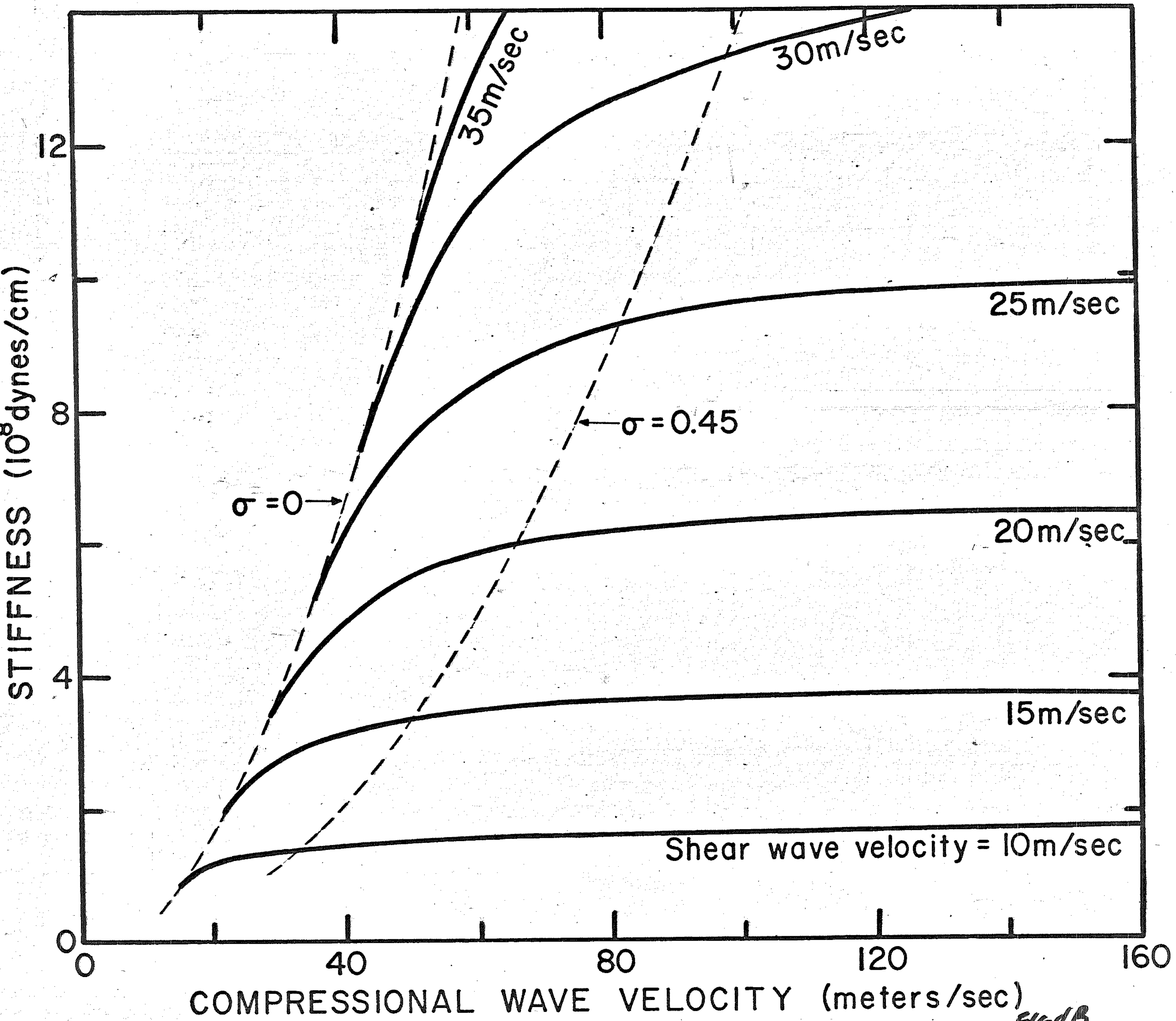

STIFFNESS (10^8 dynes/cm)
0
4
8
12
0
40
80
120
160
COMPRESSIONAL WAVE VELOCITY (meters/sec)
35m/sec
30m/sec
25m/sec
20m/sec
15m/sec
Shear wave velocity = 10m/sec
σ = 0
σ = 0.45

FIG 4B