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AN EVALUATION OF SHOCK WAVES IN UNSATURATED WET SNOW

by

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ABSTRACT

The propagation of shock waves in unsaturated wet snow is investigated, both analytically and experimentally.

The experimental program was carried out in the laboratory with an electromagnetic stress-wave generator. During each test, impact velocity was measured at the base of the specimen by means of a contacting wire system. Also, pressure was measured at the opposite end with a piezo-resistive pressure transducer with a flat response from below 0.5 to above 100 kHz.

Densities of snow samples in the range from 200 to 500 kg m^{-3} were tested. Impact velocities at the base were varied from 20 to as high as 100 ms^{-1}. Propagation distances (specimen lengths) were varied from 2 to 5 cm. Also, for each test, the free water moisture content in the test specimen was carefully measured so that the effect of this property could be evaluated. The test results are reported and the wave attenuation rates are characterized in terms of the parameters discussed above. In addition, these results are compared to test results for dry snow.

Finally, wave propagation theory is used to evaluate the material tangent modulus. The theory is also used to calculate particle velocity and density increases produced by the shock waves. The results are compared to those obtained earlier for dry snow.

1. INTRODUCTION

Even in dry snow, there has been little significant work on plastic shock waves. This problem was first investigated experimentally by Napadensky (1964); studies by Sato and Wakahama (1976) and Gubler (1977) followed. Brown (1980[a],[b],[c]) considered the theoretical behavior of shock waves in snow. Plastic waves in wet snow were examined by Wakahama and Sato (1977), but they restricted their work to the measurement of wave velocities.

It is well known that wet and dry snows behave in a very different manner. For instance, the compressive strength of snow immersed in water appears to be only several tenths that of dry snow (Kinosita 1963). Abele and Haynes (1979) also studied the effect of water content on the compressibility of snow and noted that water acts as a lubricant between ice particles.

There have been no experimental or theoretical measurements of pressure in plastic shock waves in wet snow. In order to investigate the effect of water content on plastic shock waves in wet snow, wave pressures were measured in snows of various water contents. On the basis of these measurements, several properties of plastic shock waves in wet snow are observed and discussed. Also, a comparison with dry snow is made.

2. EXPERIMENTAL PROCEDURE

(i) Sample preparation

The test samples were made of natural dry snow which was sieved into the sample containers. The containers were rectangular cylinders made of wood, with internal cross-sectional dimensions of 3.3 x 6.5 cm and with a height of 5.0 cm. The inside walls were lined with teflon. These samples were then placed in an insulated box which was kept at a constant temperature between +0.5 and +2.5°C. During the experimental period, which lasted for up to 24 h, the snow samples melted very gradually at the top surface, and water percolated through the sample naturally. Thus, wet snow samples with differing free water content could be obtained by changing the period of storage in the box. In no test was the bottom portion of the sample saturated before testing. However, the free water content could not be expected to be constant over the length of the sample, so the per cent water contents recorded here must be regarded as average values.

The free water content of each snow sample was measured by an improved version of the melt calorimeter designed by Akitaya (1978), which was based on the calorimetric method of Yosida (1959, 1960). Since temperatures were measured to within ±0.1°C and sample masses to within $\pm 1 \times 10^{-4}$ kg, accuracies were achieved which were better than those normally obtained with the melt calorimeter. Error analysis indicated maximum errors < ±2.9% water content. Densities of dry snow were also measured before the test samples were prepared.

(ii) Test equipment and procedure

The electromagnetic stress-wave generator used in these tests is described by Bowles and Brown (1981). It is capable of producing pressures ranging from a few kilopascals to as high as 10^4 kPa and load frequencies as high as 150 kHz. In these tests, three different voltages of 8, 10, and 12 kV were applied, which correspond to pressures ranging from 8×10^3 to 18×10^3 kPa.

The snow specimens were impacted from the bottom. Impact velocities were measured between the bottom of the sample and the loading strip by means of a contacting wire system.

A piezo-resistive pressure transducer was placed in contact with the top surface of the specimen. The sensor had a flat response from below 0.5 to above 100 kHz. The output of the sensor was amplified by a signal conditioner and was then recorded in a storage oscilloscope. The electric current in the stress-wave generator circuit was monitored by a Rogowski coil and recorded by another oscilloscope, in order to ascertain the applied pressure. For a more detailed discussion of the system, the paper by Bowles and Brown (1981) should be consulted.

3. EVALUATION AND DISCUSSION OF DATA

(i) Effect of water content on wave pressure

In order to discover the effect of water content on shock wave pressure, tests were run on wet snow samples with a wide range of water contents. Water content in snow is represented in terms of the ratio of weight of water in snow to weight of wet snow. The range of water content extended from zero to 26%. Zero water content means dry snow, which had a temperature between -1 and 0°C.

Applying a voltage of 10 kV yields pressures at the base of the sample in the range of 11×10^3 to 13×10^3 kPa. Figure 1 shows results of peak wave pressures in the case of application of 10 kV with a density of 330 to 430 kg m^{-3}. The tests were conducted on samples with three different heights of 20, 30, and 50 mm.

As shown in this figure, measured peak pressures decrease with increasing water content. The highest peak pressure of 380 kPa appears for dry snow with d = 20 mm. On the other hand, the lowest peak pressure of < 10 kPa was obtained for wet snow of about 20% water content with d = 50 mm.

These data can be fitted by exponential curves for each of the three groups:

$$P = 328.8\ e^{0.079W} \quad (d = 20\ \text{mm}),$$

$$P = 182.2\ e^{-0.086W} \quad (d = 30\ \text{mm}),$$

and $$P = 83.7\ e^{0.101W} \quad (d = 50\ \text{mm}),$$

where P and W are the peak wave pressure and the water content of the snow sample, respectively.

The scatter seen in Figure 1 has resulted from the poor contact between snow grains and the transducer. A small transducer with diameter 3.8 mm was used to pick up the high frequency of pressure waves. The diameter of this small transducer made good contact with the snow sample more difficult than would be the case with a larger transducer. Consequently there was more scatter than desirable, but the number of tests did allow the evaluation of statistically averaged results.

(ii) Effect of snow density

Since rapid densification of snow accompanies shock waves, the propagation of pressure waves in wet snow is strongly dependent upon initial snow density. This density effect is shown by Figure 2 for the case of a sample height of 30 mm. The results illustrated there are for water contents of 5 and 15%. Also, the data are augmented by using the relationship between pressure and water content, which was developed in the previous section, to convert data for various water contents to equivalent data for 5 and 15% water content.

In the density range of 200 to 460 kg m^{-3}, the wave pressure increases dramatically with increasing density. This tendency is more clearly seen for snow with 5% water content than snow with 15%.

This result indicates that a plastic shock wave in snow is a successive process of densification at the wave front. More wave energy is used in the compaction of low density snow than is used in the compaction of higher density snow. Snow compaction is

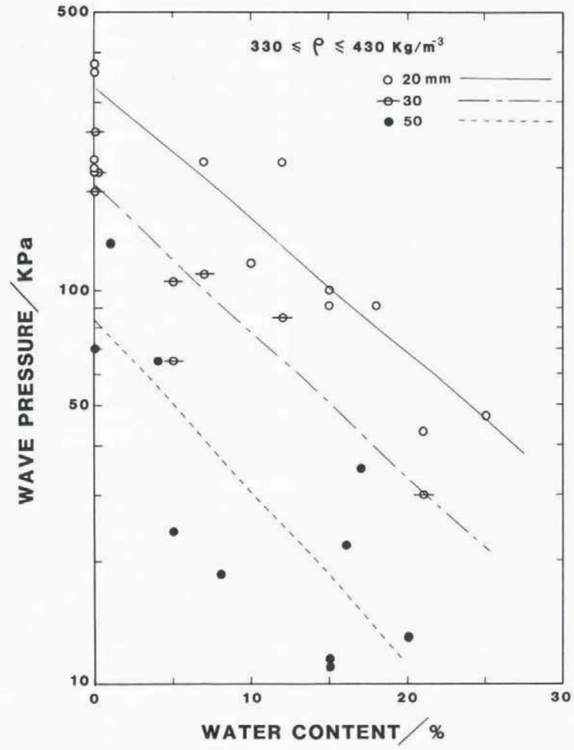

Fig.1. Effect of water content on wave pressure for three propagation distances.

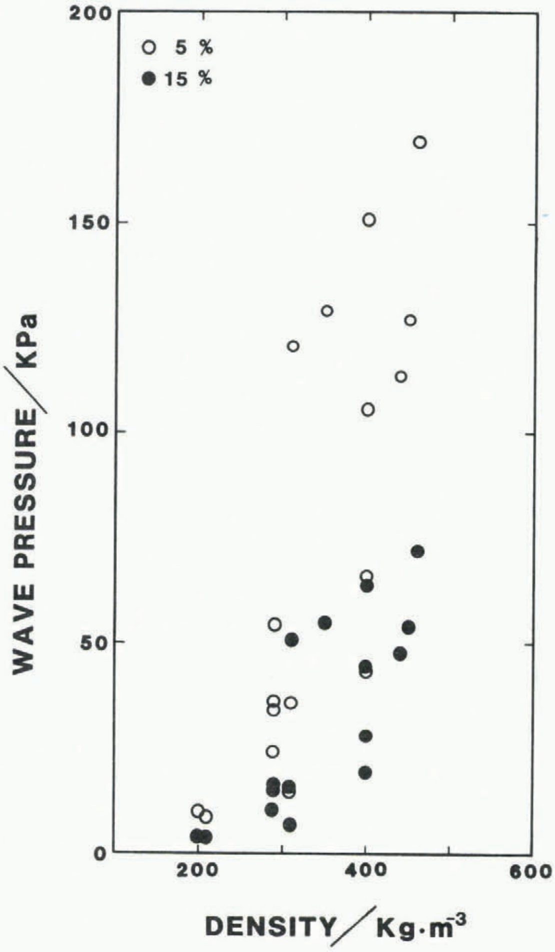

Fig.2. Effect of density on wave pressure at a propation distance of 30 mm.

evident until the critical density of 600 to 700 kg m^{-3} is reached (Sato unpublished). This density is achieved at the wave front. According to this, the pressure in the snow decreases as the density decreases. And further, the lower wave pressures for snow of higher water contents correspond to the fact that wetter snow can be more easily compacted than dry snow (Abele and Haynes 1979). In other words, wetter snow is mechanically weaker and so absorbs more wave energy than dry snow.

(iii) Attenuation (rates) of wave pressures

Shock wave amplitude attenuates during propagation in a snowpack. Figure 3 shows attenuation of wave pressure with distance for snow with three different water contents. As mentioned before, snow of zero water content shows the highest pressure, and as the water content increases, the pressure decreases.

Each data group can be represented by a simple power law:

$P \propto d^{-1.26}$ (zero water content),

$P \propto d^{-1.59}$ (5% water content),

$P \propto d^{-1.83}$ (15% water content),

where d is the sample height in millimeters, which is the distance from the origin of the shock wave in snow and the position of the pressure transducer at the surface.

It can be concluded that as snow acquires a higher water content, the wave pressure decreases and the attenuation rate increases.

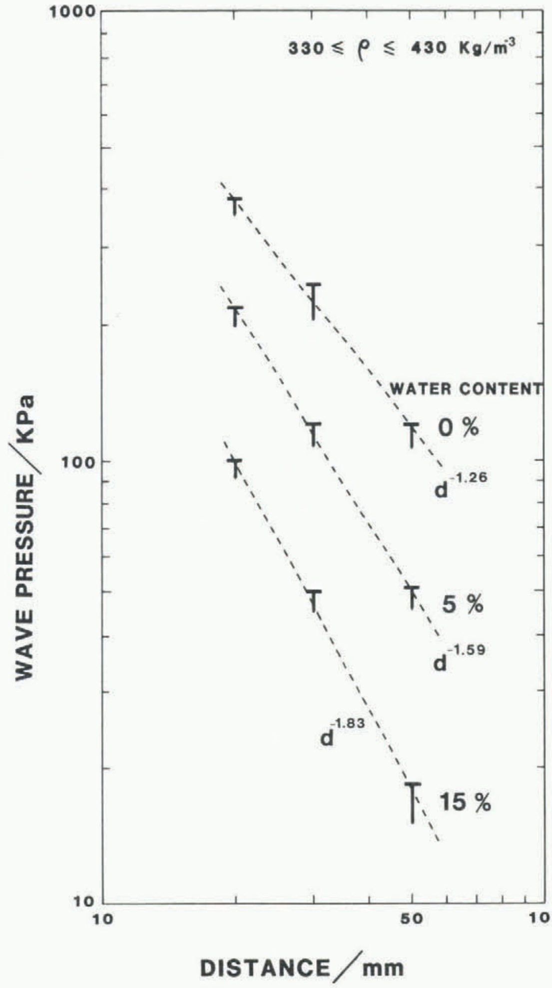

Fig.3. Attenuation of wave pressure with propagation distance. τ represents the data range.

Gubler (1977) reported that peak wave pressure obeys the power law $P \propto d^{-1.12}$, which was derived from a field test where the explosive was placed 1 m above the snow and the pressure was measured at the snow surface. It is thought that this law describes the attenuation in the air rather than in the snow cover. Our result shows that the attenuation rate in snow is higher than that in the air, and that this rate of attenuation is even larger in wet snow.

A comparison of attenuation in snow and air has been made by Mellor (1977). He reported rather high attenuation rates in snow, which ranged from a decay proportional to d^{-4} to one proportional to d^{-3}. His results, however, included the effects of geometric spreading present in wave fronts that are not flat. In our results, attenuation rates range from $d^{-1.26}$ for dry snow to $d^{-1.83}$ for wet snow.

(iv) Stress wave velocity

The stress wave velocity was determined from the oscilloscope traces. Normally, the elastic precursor wave was detected before the slower plastic wave arrived at the pressure transducer. The elastic wave speed was found to lie between 250 and 660 m s^{-1}. The plastic wave speeds were strongly affected by free water content, density, and pressure. Since the pressures attenuated very quickly, the wave speed was found to change dramatically with propagation distance.

Figure 4 shows how the plastic wave speed is affected by water content and propagation distance. In spite of the considerable scatter, three trends indicated by the lines can be seen. Wave speed decreases with increasing free water content, and increases with propagation distance. In these tests, impact pressures of approximately 10 MPa were developed. By 20 mm, pressures had normally decreased to <0.4 MPa. By 50 mm, pressures were between 0.02 and 0.15 MPa, depending on the free water content. These are extremely large attenuation rates, much larger than in dry snow. The three points shown for zero water content represent results for snow at -1°C. For snow at -10°C, wave speeds between 150 and 200 m s^{-1} were calculated for densities and pressures comparable to these tests. These calculations were made with a constitutive equation developed earlier (Brown 1980[a]).

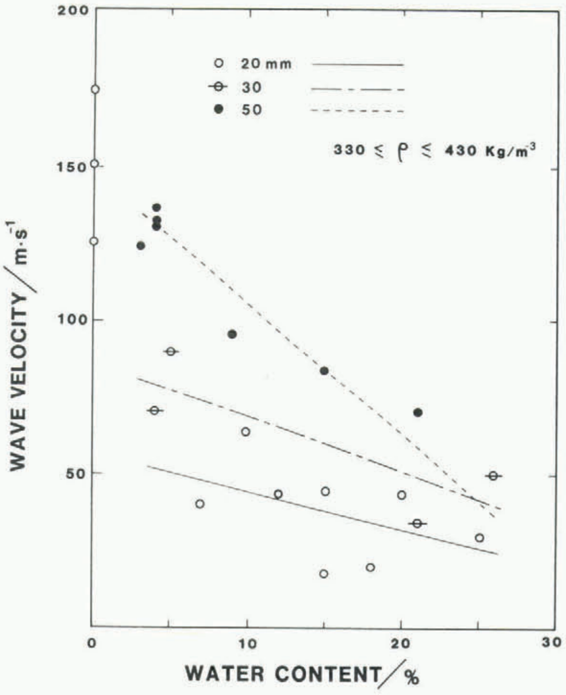

Fig.4. Stress wave velocity.

Sato and Wakahama (1976) showed that plastic wave velocity for wet snow is, in general, smaller than that for dry snow of the same density. In Figure 4, this tendency is clearly seen for 20 mm, and there is a weak correlation with water content.

On the other hand, for 50 mm, wave velocity decreases drastically with increase of water content. In this case, these detected waves might possibly be pressure waves which traveled through the air space among the snow grains rather than plastic shock waves.

STRESS WAVE ANALYSIS

The theory of stress wave propagation may be used to obtain some additional information from the data just illustrated. For instance, stress wave theory (Brown 1981) may be used to obtain the following relations:

$$E_s = \frac{\rho_o^2}{\rho_m} V^2 , \qquad (1)$$

$$[v] = \frac{[p]}{\rho_o V} , \qquad (2)$$

$$[a] = -\alpha_o [v]/V. \qquad (3)$$

E_s is the secant modulus defined by

$$E_s = \frac{[p]}{[\alpha]} . \qquad (4)$$

α is the density ratio ρ_m/ρ, where ρ is the density and ρ_m is the density of ice [p], [α], and [v] represent the changes or jumps in the pressure p, density ratio α, and particle velocity v due to the shock wave. For instance, [α] is simply the difference in the density ratio of the snow just behind and in front of the shock wave. V is the shock wave speed. Equation (1) may then be used to calculate the effect of free water content on the secant modulus. This gives a direct measure of how free water content affects the material stiffness.

The secant modulus as found with Equation (1) is illustrated in Figure 5. Here again, trends are discernible. Free water content has a very significant effect on the material stiffness as measured by secant modulus. Also, the smaller propagation distances (higher pressures) have smaller values of secant modulus. This implies that, for the pressures experienced at the three distances, 20, 30 and 50 mm, the material experiences a definite softening with increasing pressure. Work hardening effects associated with densification are apparently not significant in comparison to the flow mechanisms within the material. This is a somewhat different result than is observed in dry snow (-10°C or colder).

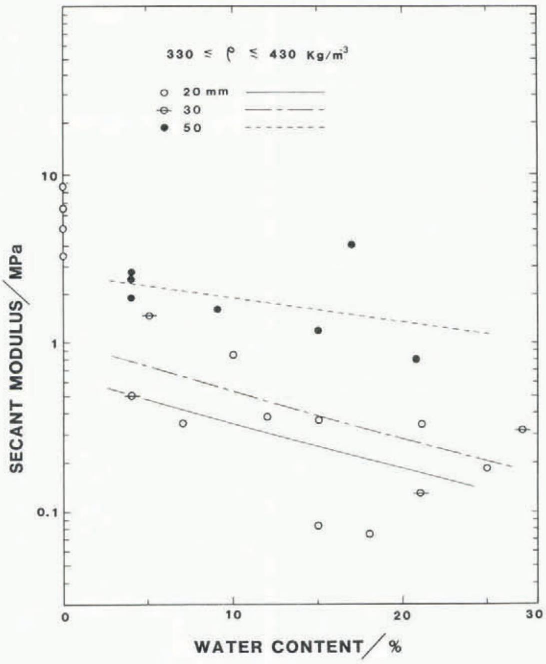

Fig.5. Variation of material secant modulus with water content and propagation distance.

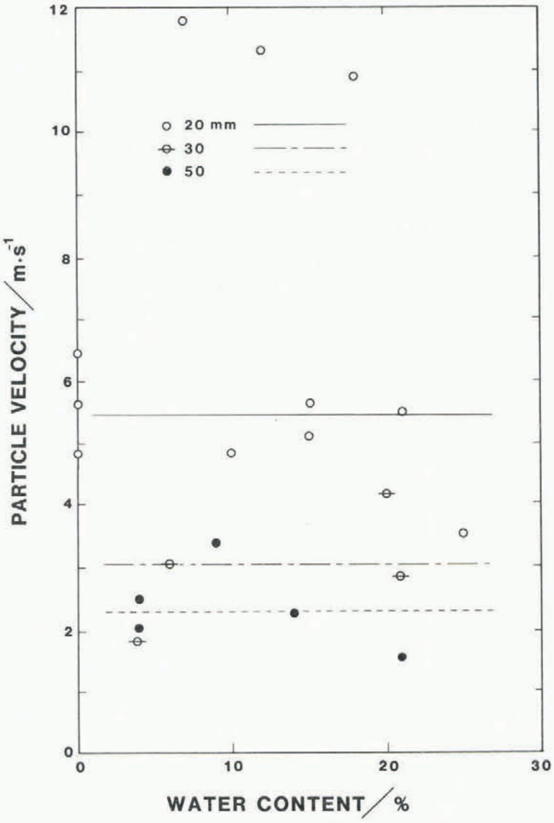

Fig.6. Calculated values of particle velocity produced by stress waves in wet snow.

Finally, Figure 6 shows the particle velocities produced by the shock wave loading. These were found with Equation (2). Surprisingly, there was very little variation with free water content. Aside from the three anomalous data points for 20 mm, one could say that particle velocity is not radically affected by free water content. As expected, particle velocity shows a decrease with propagation distance, since the wave attenuates as it propagates through the material.

The density increase due to the shock wave may be calculated with either Equation (3) or (4). In this case, Equation (3) was used, and the results are displayed in Figure 7 for the density range used in Figures 3 to 6. At 20 mm, the scatter was too large to show a definite trend with water content. However, the results for 30 and 50 mm showed much less scatter and the water content caused increased compaction.

It would have been preferable to have been able to calculate the tangent modulus E_T and the rate modulus E_1 from the shock wave data, where

$$E_T = -dp/d\alpha \qquad (5)$$

and

$$E_1 = dp/d\dot{\alpha} \qquad (6)$$

These could possibly be obtained from the following jump equations (Brown 1981):

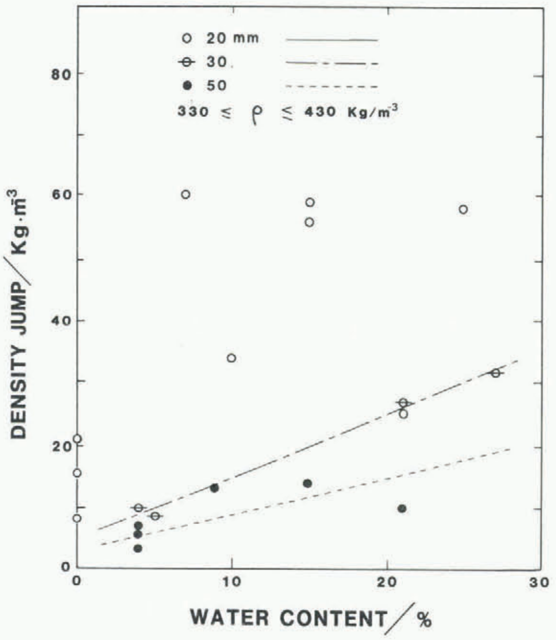

Fig.7. Density jump produced by stress waves.

$$\dot{V}[\alpha] + V[\alpha]_t = \alpha_0[v]_t, \tag{7}$$

$$[p]_t = - E_T[\alpha]_t + E_1[\dot{\alpha}]_t, \tag{8}$$

$$\frac{1}{2}(3\,E_T + E_s)\,[\alpha]_t - \frac{3}{2}\,E_1[\dot{\alpha}]_t = - E_s[\dot{\alpha}]. \tag{9}$$

However, in order to use these equations, $\dot{V}$, $[p]_t$, and $[v]_t$ would have to be determined experimentally to a high degree of accuracy. A numerical procedure for calculating these when there is considerable data scatter would yield poor values. Since there was some scatter in the results, this was not attempted.

5. CONCLUSIONS

The results obtained here form a basis for comparing shock wave propagation in wet snow with that in dry snow. It has been found that wet snow is more compliant to shock wave propagation than dry snow is and shows much more attenuation than dry snow does. As can be seen in the figure for pressure, the wave pressure decays to only 15% of its initial pressure in less than 3 cm. This rate of attenuation is significantly greater than in dry snow. The material modulus was also found to be smaller than in dry snow, indicating that it will also compact somewhat more than dry snow under the influences of a shock wave. This statement, of course, is restricted to dry snow which has the same density as wet snow. Since wet snow in the field normally has densities in excess of 300 kg m^{-3}, most of the analysis was restricted to densities between 300 and 400 kg m^{-3}.

As the free water content is increased, the snow definitely shows a softening effect. As a consequence, the material modulus decreases with increasing water content. Material compaction and wave attenuation rates show marked increases with increasing water content. The only variable which did not show an obvious change with water content was particle velocity.

As with any testing program involving shock waves, the experimental scatter was significant. Part of the problem was associated with the pressure transducers. They have a small cross-sectional area, and this produced most of the scatter. The stress-wave generator (Bowles and Brown 1981) was found to function satisfactorily, and there was not much scatter associated with this instrument.

In conclusion, new data on stress wave propagation in snow are now becoming available. While this information is still incomplete, many aspects of the problem are being addressed. This includes plastic waves, acoustic waves, evaluation of material properties for wave propagation, and theories which treat snow as a multiphase material. The next few years should result in an even better understanding of the topic of stress wave propagation in porous materials such as snow.

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