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EFFECT OF WATER CONTENT AND SEA SALT ON SEISMOACOUSTIC WAVES IN BEACH SAND

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September 2001

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ABSTRACT

New findings are presented providing physical insight on the effect of moisture and sea salt on high-frequency seismoacoustic waves in beach sand. Quantitative results reveal that the velocity of high-frequency compressional waves *increases* by about 8 % as the water content is decreased by 18% from full saturation [1-3]. This increase in velocity is in contrast with the Biot-Gassmann theory which predicts that the velocity of low-frequency compressional waves *decreases* by 85% as the water content is decreased by only 1% from saturation [4]. Velocity plots as function of water saturation are compared for different sands and spherical glass beads. The effect of sea salt on grain to grain acoustic coupling is demonstrated. Salt crystallization and transport can lead to the formation of hard sand/salt layers with a compressional velocity increasing from 200 m/s to 2887 m/s, and a shear velocity increasing from 10 m/s to 1885 m/s [3]. A hypothesis is discussed with preliminary results on the potential existence of a suction-cup effect increasing the rigidity of unconsolidated compacted sediments, in the absence of roughness, due to the formation of cavitation microbubbles as the tensile strength of the thin capillary water film between compressed sand grains is exceeded [5].

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INTRODUCTION

The seismoacoustic properties of sand under various realistic conditions (underwater, beach, or desert) in the frequency range 1-100 KHz are not well understood. Reliable seismoacoustic detection of buried objects in sand requires developing fundamental physical understanding of the effect of water content, air bubbles, compaction, vibration, rain, and salt on acoustic properties. Sand is an unstable medium and can change from a liquefied state to a varying stiff matrix.

Several controversial acoustic problems are still unresolved regarding the seismoacoustic properties of sand [1-23]. In water-saturated sand, two types of compressional waves are known to exist according to Biot's theory, however the Biot wave has not yet been observed and identified in water-saturated sand. Hickey and Sabatier [18] reported on the dispersion of a slow compressional wave in air-filled sand. Boyle and Chotiros [9] observed an anomalous slow compressional wave (1200 m/s) in water-saturated sand. The value of the sand frame bulk modulus given by Chotiros [7] is more than 10x greater than the known value, and the bulk modulus of sand grains is 5x smaller than the typical value.

The compressional wave velocity in water-saturated sand is near 1700 m/s which is about 8x greater than in dry sand. Measurements by Velea [16] and Tavossi and Tittman [17] near 10 KHz revealed that the compressional velocity in drained sand is about 200 m/s. Smith et al [19] used 1620 m/s for the compressional wave velocity in partially-saturated beach sand. Shields et al. [20] determined the effect of water vapor on the compressional and shear wave velocities in Ottawa sand and glass beads. The vapor had little effect on the 10 KHz compressional wave in both materials and remained near 200 m/s.

The goal of the research is to achieve better physical understanding of fundamental littoral seismoacoustic phenomena on the interaction of underwater acoustic waves with marine sediments leading to accurate acoustic modeling of littoral surficial layer and reliable seismoacoustic detection of buried objects underwater and on the beach. New experimental results are presented on the effect of moisture and sea salt on high-frequency seismoacoustic waves in beach sand. Quantitative results reveal that the velocity of high-frequency compressional waves *increases* by about 8 % as the water content is decreased by 18% from full saturation [1-3]. This increase in velocity is in contrast with the Biot-Gassmann theory which predicts that the velocity of low-frequency compressional waves *decreases* by 85% as the water content is decreased by only 1% from saturation [4]. Velocity plots as function of water saturation are compared from different sands and spherical glass beads. The effect of sea salt on grain to grain acoustic coupling is demonstrated by inducing ultrasonic waves in a single grain of sand. Salt crystallization and transport can lead to the formation of hard sand/salt layers with decreased porosity, with a compressional velocity increasing from 200 m/s to 2887 m/s, and a shear velocity increasing from 10 m/s to 1885 m/s [3]. A hypothesis is given, supported with preliminary results using glass plates, demonstrating the potential existence of a suction-cup effect increasing the rigidity of unconsolidated compacted sediments in the absence of roughness, due to the formation of cavitation microbubbles as the tensile strength of the thin capillary water film between compressed sand grains is exceeded [5].

EFFECT OF WATER CONTENT ON COMPRESSIONAL WAVE VELOCITY

The compressional wave velocity in water-saturated sand is known to be between 1650-1750 m/s. The waveform of a compressional wave pulse in water-saturated sand is shown in Fig. 1. The horizontal time scale is 5 μs/div.. Two 2.5 cm diameter piezoelectric transducers were used to generate and detect the compressional waves. The distance between source and receiver was 4 cm.

Bachrach and Nur [4] calculated the compressional wave velocity as function of water saturation in sand based on the Biot-Gassmann low-frequency theory (Fig. 2). The calculated results show that starting with dry sand, the compressional wave velocity decreases slightly as the water content is increased, and then the velocity starts to increase above 85% water saturation. At 99% water saturation, the compressional wave velocity is still less than 200 m/s. According to the theoretical model, the last 1% of water to reach full saturation increases the compressional velocity by almost a factor of eight. Fig. 3 displays replotted and combined experimental results by Velea [16] on the effect of water

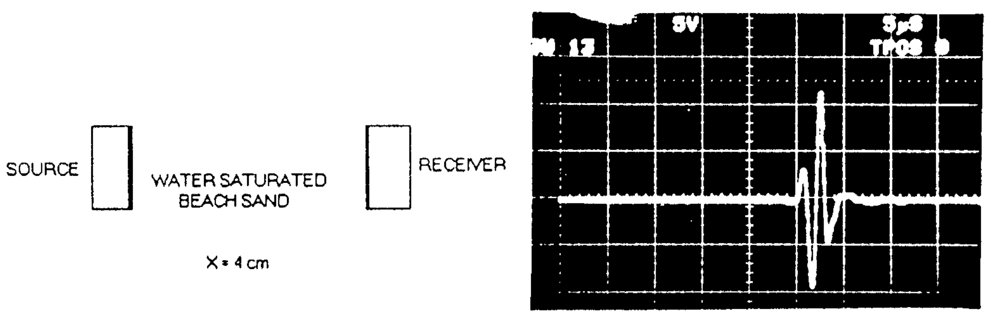


Fig. 1. Compressional wave in water-saturated sand. Measured compressional wave velocity c_p = 1702 m/s.

content and frequency on compressional wave velocity in Ottawa sand. Velea's experimental results show that the compressional wave velocity in partially saturated sand (97-98% water saturated) is about 200 m/s for frequencies below 10 KHz. No results were given for the partially-saturated sand at higher frequencies. The high-frequency compressional wave results for fully saturated sand had a compressional velocity around 1700 m/s as expected.

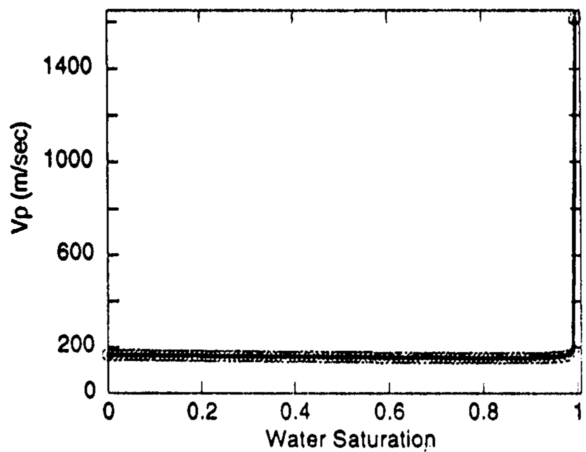


Fig. 2. Theoretical calculations by Bachrach and Nur [4] showing compressional wave velocity as function of water saturation in sand based on the Biot-Gassmann theory.

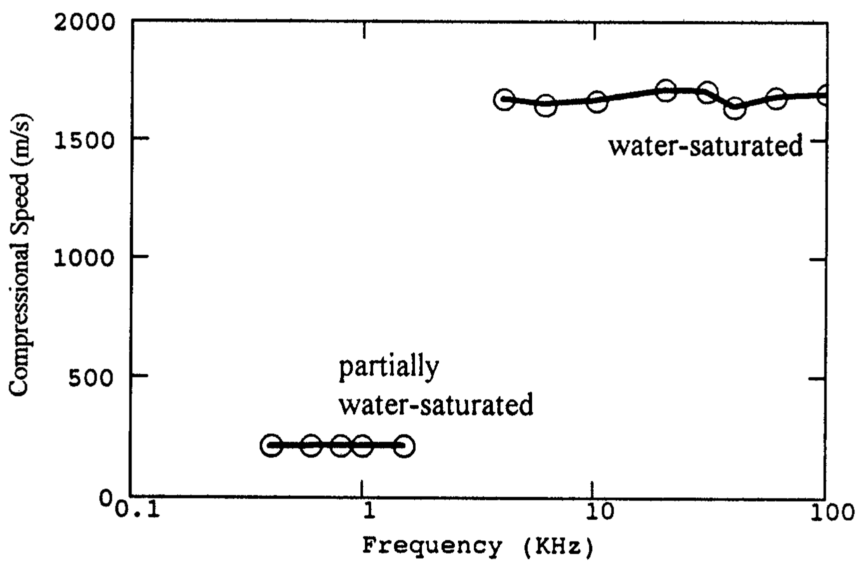


Fig. 3. Replotted and combined experimental results by Velea [16] showing the compressional wave speed as function of frequency in water-saturated and partially saturated sand.

Qualitative Results

A preliminary experiment (Fig. 4) was conducted to qualitatively study the effect of water content on high-frequency (~ 100 KHz) compressional waves in sand [1]. Source and receiver transducers were placed in a water tank. The distance between the transducers was fixed at 4 cm. Wet sand was slowly deposited in the water to form settled sand. The tank wall was tapped periodically to compact the sand until the tank was filled with water-saturated sand. The source was excited wih a broadband pulse. The received wave was displayed on an oscilloscope. The excess water on the sand surface was removed, and the sand was carved out from all the tank except for a rectangular wet sample 1 x 2 x 4 cm naturally held between the parallel faces of the transducers. During the carving process, the received fast compressional wave was monitored and it did not change. The sample was resaturated and the compressional waveform was recorded as shown in the top trace of Fig. 4. The measured compressional wave velocity was 1675 m/s. The second trace was obtained after sponge drying the sand sample. Notice that the compressional wave time of arrival remained almost unchanged. The sand sample was allowed to dry by blowing air on the sand. As the sample was evaporating, the received waveform was recorded periodically. The bottom trace in Fig. 4 was obtained from the "almost dry" sample as the sand bar crumbled. This qualitative experiment confirmed that the compressional wave velocity of high-frequency components above 80 KHz remained close to the water-saturated velocity and did not decrease by a factor of eight.

Quantitative Results

Different types of beach sand were collected to quantitatively determine the effect of water saturation on the compressional wave velocity. Laboratory silica white sand (450-850 μm and 150-425 μm) and spherical glass beads were also used in controlled experiments.

A precision experimental setup was made to simulatneously monitor the arrival time of the ultrasonic waves in the sand samples and measure the weight loss from the sample as water was evaporated from the sand.

A sand holder box (2x4x1.8 cm) was constructed having ultrasonic source and receiver transducers mounted at opposite ends of the box as shown in Fig. 5. The distance between the source and receiver was 4 cm. The box had a mesh bottom to allow wetting and drying the sand as needed. The setup was capable of measuring 1 milligram variation in the weight of the the sand box assembly. The results were calibrated in several ways to determine the weight loss due to water evaporation. The exact amount of water needed to reach 100% saturation for a given sand sample was determined. Experiments were first conducted on large samples of different sands to determine the porosity and Darcy's coefficient of permeability. Porosity and water saturation level were determined from the change in weight as water was evaporated. For porosity , the relation

$$\text{porosity} = 1 - (\text{volume of grain})/(\text{bulk volume})$$

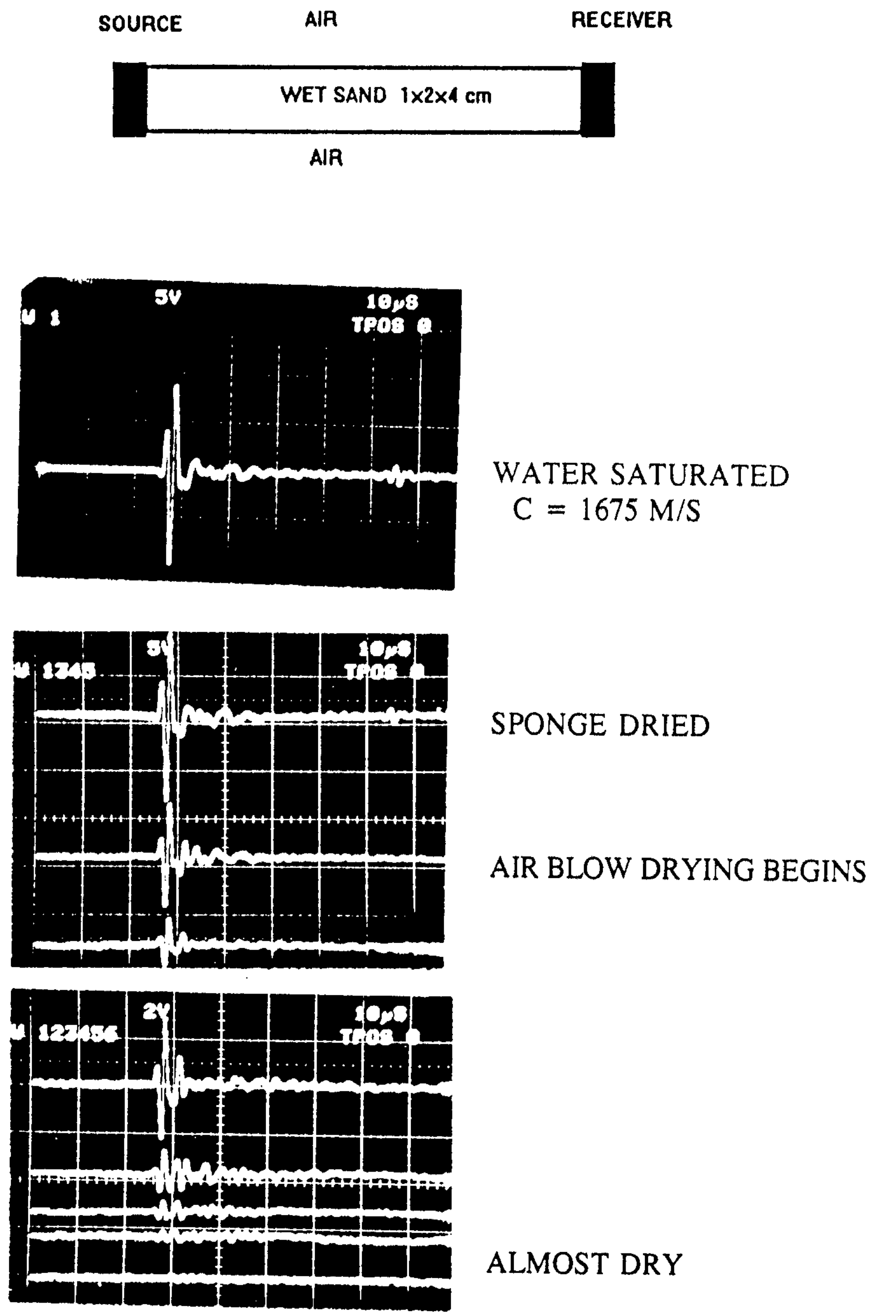


Fig. 4. Effect of water content on high-frequency compressional wave in beach sand. Waves propagated and detected in a wet sand block 1x2x4 cm carefully carved from naturally deposited sand. The compressional wave velocity remained almost constant as the water content decreased over a wide range of moisture content. Source-receiver distance 4 cm. Horizontal time scale 10 μs/div.

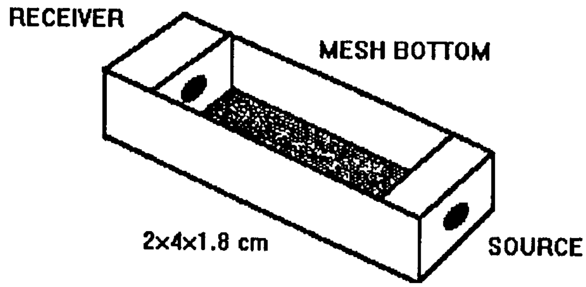


Fig. 5 . Diagram of sand holder with ultrasonic transducers.

was used. The saturation level was calculated from the ratio of water volume in pores divided by the total void volume. The measured porosity of the different sands is listed in Table 1. The porosity of fine to coarse beach sand varied between 31% and 34%. The porosity of laboratory fine to coarse silica white sand was between 36.8 % and 38 %. Darcy's coefficient of permeability K was determined using the falling head method and the relation

$$K = [\ln(L+h_1) - \ln(L+h_2)] / \Delta t$$

where L is the length of the sand core, h_1 the initial height of the water column above the sand, h_2 the final height of the water column, and Δt the time interval recorded for the water level to drop from h_1 to h_2.

A fine mesh was placed at the bottom end of a 4.15 cm diameter clear plastic tube. Pre-wet sand was allowed to settle in the water filled tube to form a sand core plug L = 10 cm at the bottom of the tube. The tube was initially filled to the top with water and time was recorded as the water level dropped from 68 cm to 28 cm. The experiment was repeated for different types of sand. The permeability results are presented in Table 2. Darcy's coefficient of permeability ranged from 1.71×10^{-3} for very fine sand to 30.13×10^{-3} for silica coarse white sand (0.85-1.5 mm).

The measured compressional wave velocity as function of water saturation for different sands is shown in Fig. 6. At 100% saturation, the spherical glass beads (430-600 μm) had a higher compressional wave velocity than the beach sand (fine, medium, and coarse). As saturation decreased, the compressional wave velocity increased in all the samples as shown. The amplitude of the compressional waves initially increased and then decreased as the water was evaporated from the samples. Magnified waveforms of the onset of a compressional waves in saturated and drained coarse sand are compared in Fig. 7. The effect of water saturation on the compressional wave velocity in laboratory coarse silica white sand (0.85-1.5 mm) is shown in Fig. 8. The velocity initially increased from 1735 m/s at full saturation to 1750 m/s at 92% saturation, then it decreased to 1720 m/s. Results from medium beach sand are included in Fig. 8 for comparison. In this experiment, the pulse peak frequency was 300 KHz.

TABLE 1. Measured Porosity (%)

FINE BEACH SAND (KENNEBUNK BEACH, MAINE)	33
VERY FINE BEACH SAND (NARRAGANSETT BEACH, RI)	34
MEDIUM BEACH SAND (PLAY SAND)	32
COARSE BEACH SAND (OLD ORCHARD BEACH, MAINE)	31
FINE SILICA (150-425 μm)	36.8
MEDIUM SILICA (425-850 μm)	37.3
COARSE SILICA (850-1500 μm)	38.0

TABLE 2. Measured Darcy's coefficient of permeability ($\times 10^{-3}$ cm)

VERY FINE BEACH SAND (NARRAGANSETT BEACH, RI)	2.32
FINE BEACH SAND (KENNEBUNK BEACH, MAINE)	1.71
MEDIUM BEACH SAND (PLAY SAND)	3.00
COARSE BEACH SAND (OLD ORCHARD BEACH, MAINE)	9.59
MEDIUM WHITE SAND (SILICA 425-850 μm)	10.53
COARSE WHITE SAND (SILICA 850-1500 μm)	30.13

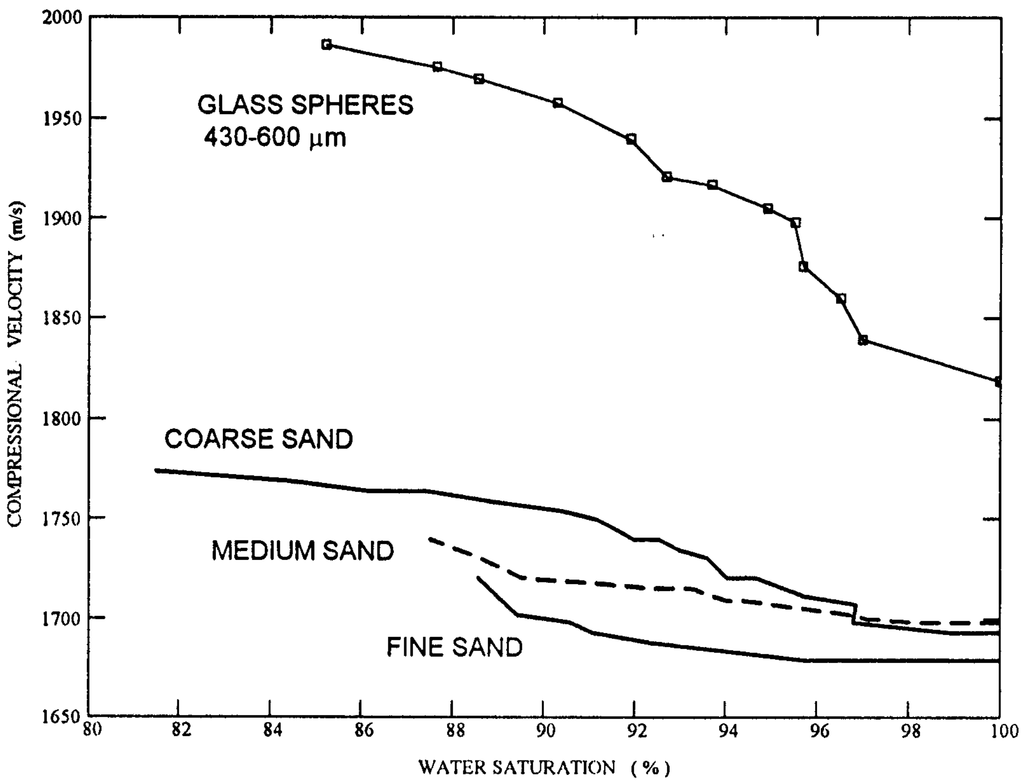
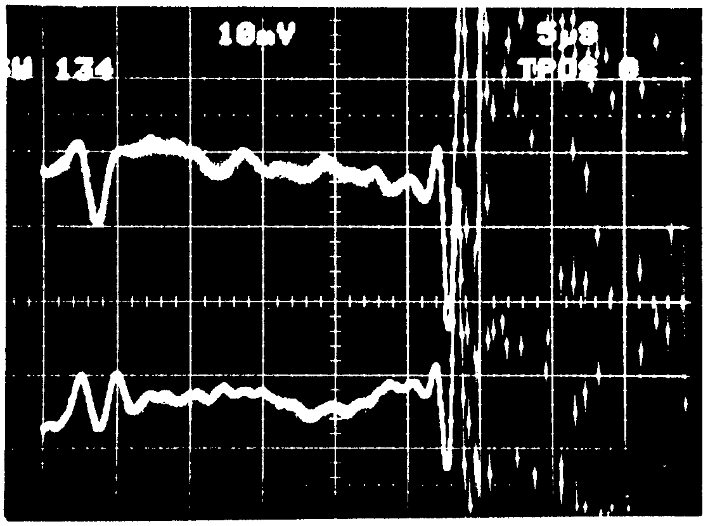


Fig. 6. Measured compressional wave velocity as function of water saturation in fine sand and spherical glass beads. Fine sand (Kennebunk Beach, Maine), medium sand (Play beach sand), coarse sand (Old Orchard Beach, Maine), glass beads (430-600 μm).



SATURATED

DRAINED
(Velocity increased and
amplitude decreased)

Fig. 7. Magnified waveforms of compressional wave onset in saturated and drained coarse sand (Old Orchard Beach, Maine). Source-receiver distance x = 4 cm.

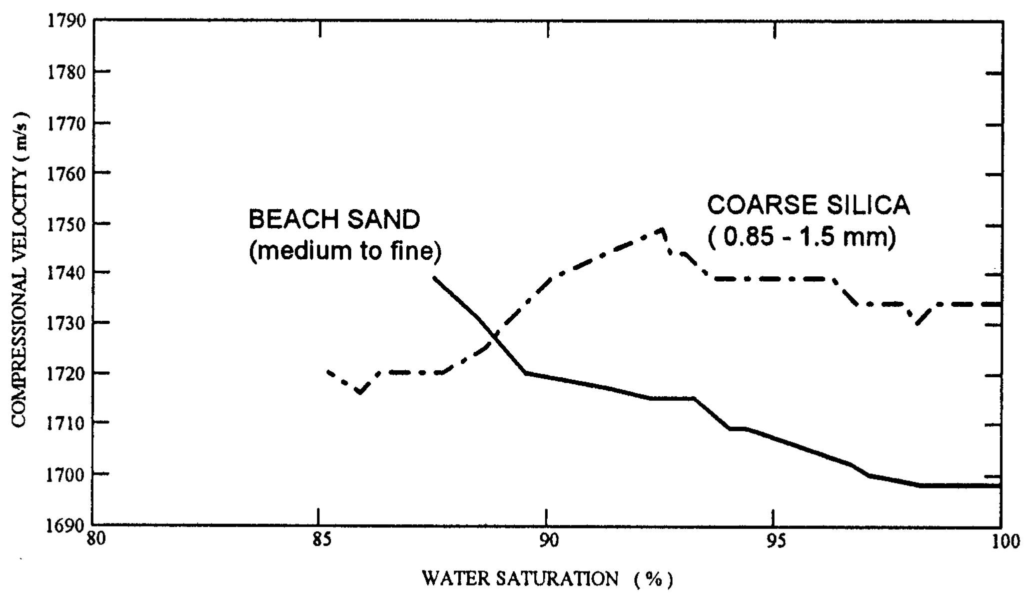
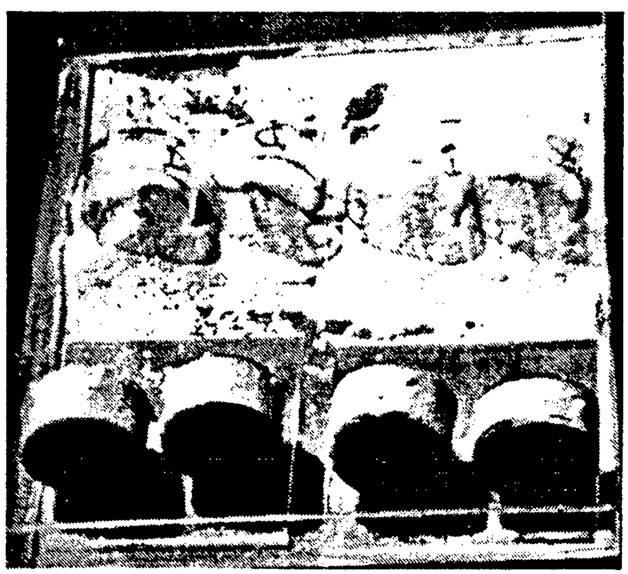


Fig. 8. Compressional wave velocity plotted as function of water saturation for beach sand and coarse silica (0.85-1.5 mm). Pulse peak frequency 300 KHz.

EFFECT OF SALT

About 97% of the water on earth is seawater with a salinity of 3.5%. When one liter of seawater is evaporated, 35 grams of the dissolved solids remain consisting of chlorine, sodium, magnesium, sulfur, potassium and calcium. The dominant component is sodium chloride (~ 77%). In porous materials, salt crystallization occurs in the pores. Crystallization occurs by concentrating seawater from evaporation or by cooling the saturated solution. Salt crystals have acoustic properties close to sand grains (compressional wave velocity 4.53 km/s, and density 2.165×10^3 kg/m^3) and can create a significant mechanical bond between sand grains. Experimental studies were conducted to investigate some aspects on the effect of sea salt on high-frequency seismoacoustic waves in beach sand leading to reliable detection of buried objects in sand under various realistic conditions.

In the process of preparing sand samples for acoustic characterization, it became evident that molded beach sand mixed with seawater retained its shape upon drying, while molded beach sand mixed with distilled water crumbled and did not retain its shape upon drying (Fig. 9). Eight molds were made from 2 cm long segments of a 4.2 cm diameter thin walled clear plastic tube. The four dry cylindrical samples shown at the bottom of the photograph were prepared in seawater and retained their shape upon drying. The top of the photograph shows dry crumbled sand and the corresponding four clear plastic molds prepared in distilled water. Fig. 10 compares the waveform of ultrasonic compressional



Distilled Water

Seawater

Fig. 9. Photograph showing dry beach sand retained its shape when compacted and molded in seawater. Dry beach sand molded in distilled water crumbled and did not retain its shape after drying.

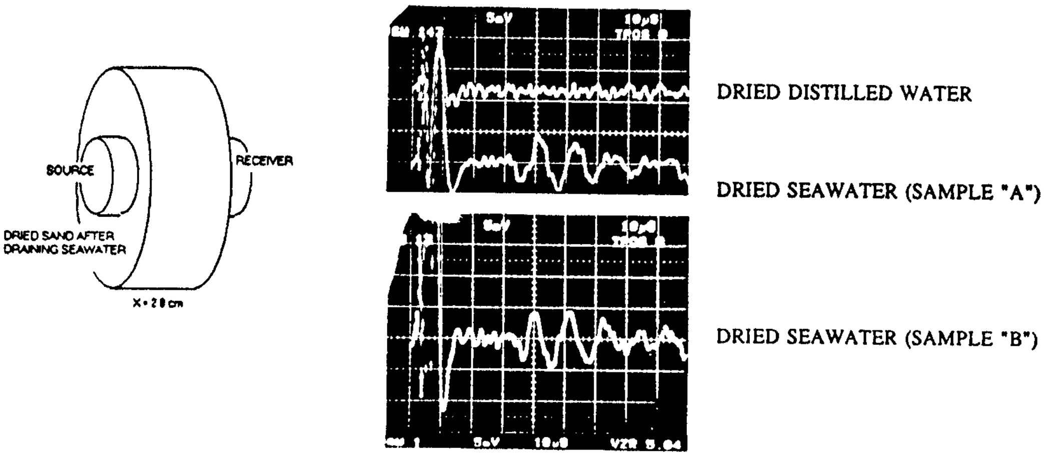


Fig. 10 . Comparing compressional waves in dry beach sand preformed in distilled water (top trace) and preformed in seawater (bottom two traces).

waves in a) dry beach sand rinsed in distilled water and b) waves in one of the dry cylindrical samples shown at the bottom of Fig. 9 containing sea salt. The waves were highly attenuated in the dry sand rinsed with distilled water, however, a measurable compressional wave was detected in the beach sand with salt. These cylindrical sand samples with salt were very fragile to handle.

In Fig. 11, ultrasonic results are presented demonstrating the effect of salt crystals on single sand grain to grain bonding and acoustic coupling. Ultrasonic waves were guided in a fine copper wire (0.25 mm) epoxied to one side of a sand grain under the microscope. The top trace shows a small compressional wave transmitted across dry grain to grain contact. A tiny drop of distilled water was placed between the sand grains to achieve wet contact (second trace). It was surprising to see little coupling with the wet grain to grain contact. This was repeated several times using different sand grains to verify the questionable signal level obtained from the wet condition. When the distilled water drop evaporated, the dry contact condition returned (third trace). Seawater wet contact produced similar results as the distilled water wet contact as shown in the fourth trace. A large compressional wave was detected when the seawater evaporated forming salt crystals coupling the ultrasonic waves between the sand grains. At the very top of Fig. 11, a sketch of the sand grain with the epoxied wire is included together with a photocopy of the actual sand grains with the copper wire.

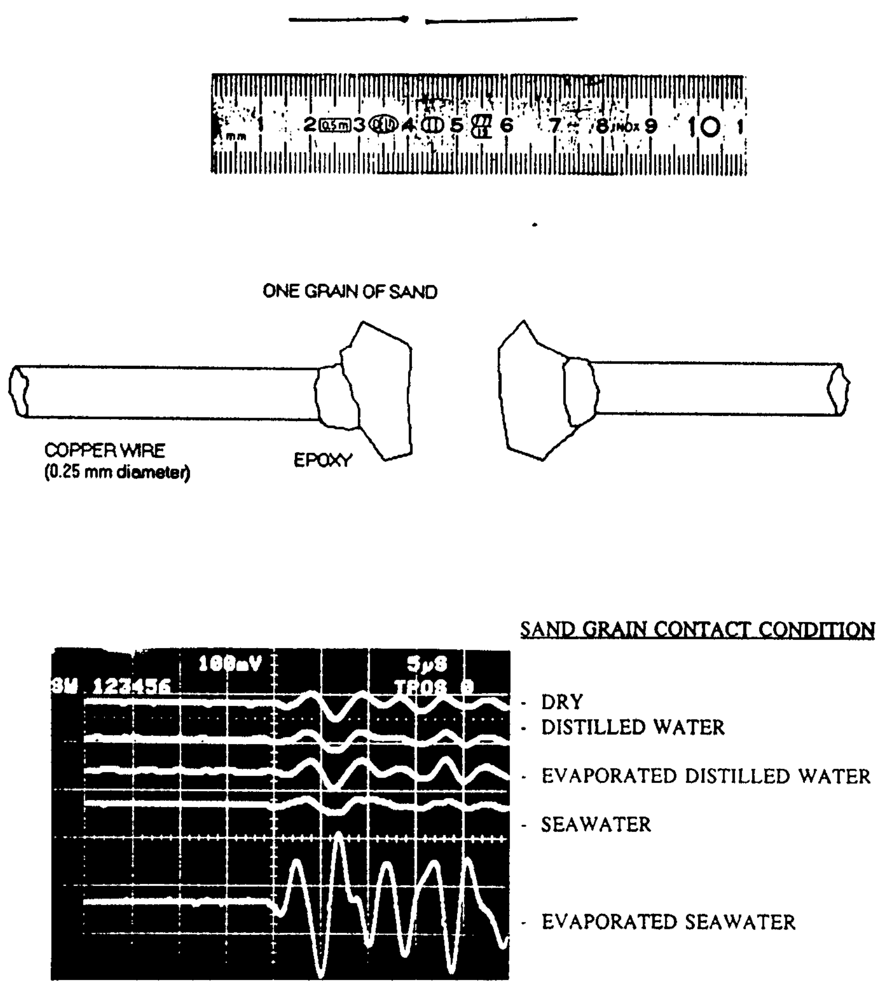


Fig. 11. Effect of salt from evaporated seawater on coupling high-frequency compressional waves in beach sand. Experiment on single grain to grain contact. Ultrasonic wave guided in thin copper wire epoxied to one side of a grain of sand under the microscope. Top trace: dry grain to grain contact. Second trace: wet contact made with drop of distilled water between grains. Third trace: evaporated the drop of distilled water and returned to dry contact condition. Fourth trace: wet contact made with drop of seawater.Bottom trace: evaporated the drop of seawater forming salt crystals significantly coupling the ultrasonic waves. Photocopy of actual sand grains with copper wire shown on top of the figure.

Salt crystals from evaporated seawater can bridge large air gaps between sand grains. A controlled experiment was carried out using two spherical glass beads separated by a 25 μm air gap (Fig. 12). Ultrasonic waves were coupled to the glass beads using a 0.25 mm diameter copper wire epoxied to one side of the bead. The top trace shows no signal transmission with the evaporated distilled water drop between the beads. A large compressional wave was detected as salt crystals from the evaporated seawater drop bridged the 25 μm air gap. The presence of sea salt alters the contact regions between sand grains. Even if sand grains were modeled as spheres, the contact between them cannot be represented as a point because of the formation of extended salt bonded regions as shown in Fig. 13. Coarse sand grains wet with seawater were placed on a microscope glass slide and were allowed to dry. A sketch of the salt crystals contact regions bonding the sand grains to the glass plate is presented in Fig. 13. Salt bonding of a spherical glass bead to the glass plate is included for comparison. Salt crystals make multiple contact regions bridging air gaps.

Dune sand may contain up to 31 % salt. Beach sand contains salt from evaporated seawater and under certain conditions may form a porous solid sand/salt crust. The presence of salt can increase the compressional wave velocity from 200 m/s to 2887 m/s as shown in Fig. 14. The shear wave velocity also increased from near 10 m/s to 1885 m/s. The porosity of the sand/salt crust was 12 %. Salt crystallization decreases sand porosity affecting the slow compressional wave.

Sand is a difficult granular material to work with ultrasonically to achieve adequate signal levels and repeatable experimental results. The relative signal levels obtained from various ultrasonic coupling methods to a sand/salt hard crust are shown in Fig. 15. Coupled compressional waveforms using ultrasonic gel, grease, putty, viscous uncured epoxy, and hard cured epoxy are compared. The best acoustic coupling was achieved with epoxy cured between the ultrasonic transducer and the sand/salt sample.

In order to study on the effect of water salinity "S" on grain to grain acoustic coupling, an experiment was carried out using the edge of two microscope glass slides as shown in Fig. 16. Coupling between the plate edges was altered as water with different salinity was allowed to dry along the contact line. The top trace shows dry coupling condition producing negligible acoustic coupling. A large signal was obtained when distilled water coupling was used as expected (unlike the surprising results of Fig. 11). By evaporating the distilled water, a negligible compressional wave was transmitted as the setup returned to the dry coupling condition. The experiment was repeated with diluted seawater with different salinities. Evaporated seawater (salinity S = 3.5%) generated a significant acoustic coupling. The bottom two traces in Fig. 16 show the decrease in acoustic coupling as seawater was diluted (S = 1.2% and 0.625%).

Rain can transport sea salt from the beach surface to deeper sand resulting in large variations in acoustic properties. A laboratory experiment was conducted to demonstrate the potential effect of rain on transporting salt affecting the seismoacoustic properties of sand (Fig. 17). A negligible compressional wave was detected in the dry sand previously

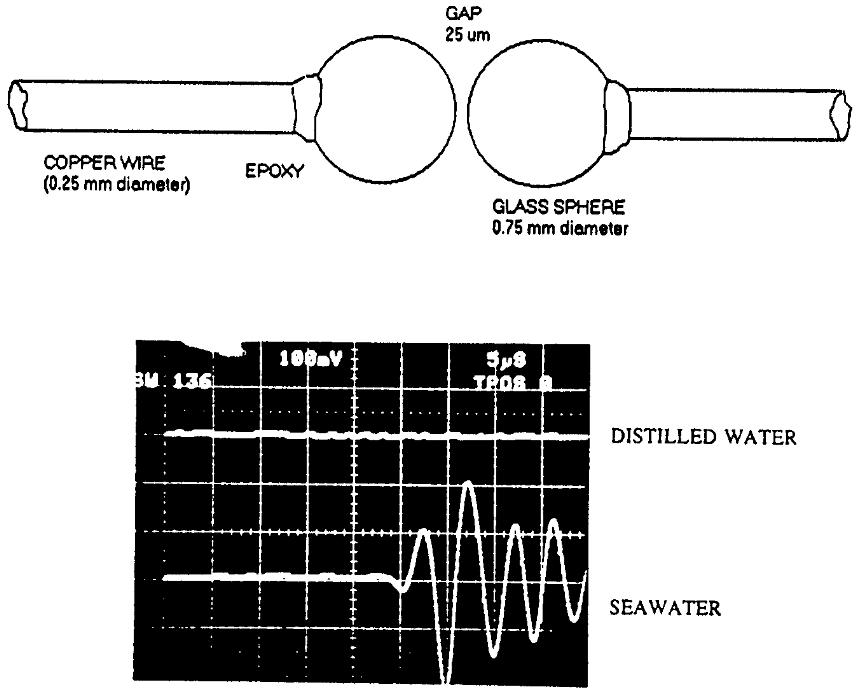


Fig. 12. Controlled experiment using spherical glass beads demonstrating effect of salt crystals from seawater evaporation on bridging a 25 μm gap and coupling acoustic waves. Dry sand porosity is greatly affect by salt content. Dune sand may contain up to 31 % salt. Reliability of detecting buried object using air speakers may be affect by crystallized and transported salt in sand.

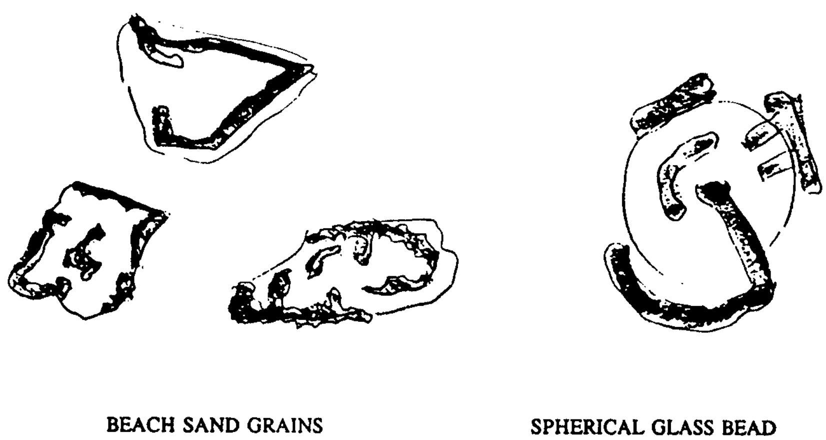
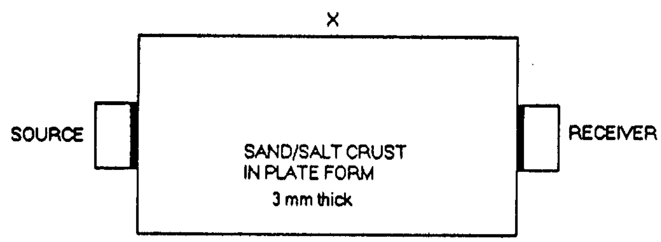
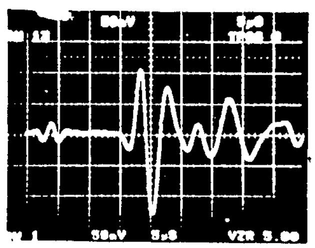


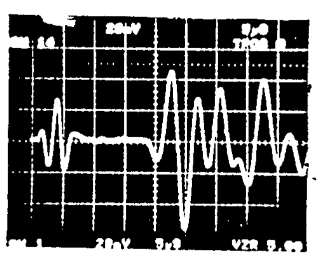
Fig. 13. Diagram of salt crystals contact regions formed upon evaporation of seawater between coarse sand grains (0.7 mm) and a microscope glass slide. One spherical glass bead (bottom right) is included for comparison. Salt crystals make multiple contact regions bridging air gaps.

rinsed with rained distilled water. A significant compressional wave was detected in the dry sand from the bottom region of a 4 cm diameter sand core containing excess salt transported by "rain" from the top sand region. The presence of salt also affected the electrical conductivity of the sand core as indicated by the amplitude of the electrical conductivity pulse observed at the beginning of each trace.





X = 4.2 cm
C_p = 2887 m/s
C_s = 1885 m/s
SAMPLE #1



X = 5.3 cm
SAMPLE #2

Fig. 14. Compressional waves in hard sand/salt crust sample formed on surface of dried beach sand previously saturated with seawater. The compressional wave velocity increased from 200 m/s to 2887 ms due to the presence of the salt. The shear wave velocity increased from about 10 m/s to 1885 m/s.

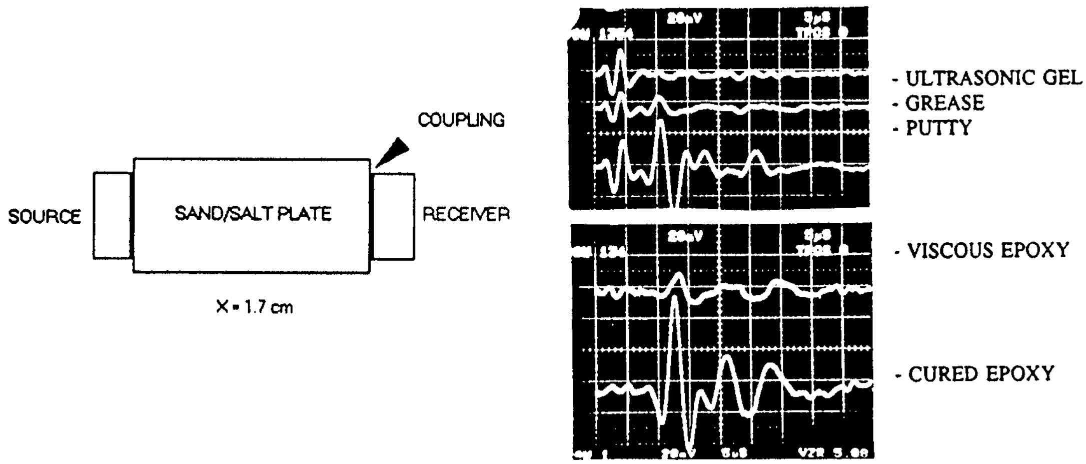


Fig. 15. Relative signal levels obtained from various ultrasonic coupling methods to sand/salt hard crust. The compressional waveforms were obtained using (from top to bottom traces) ultrasonic gel, grease, putty, viscous uncured epoxy, and hard cured epoxy.

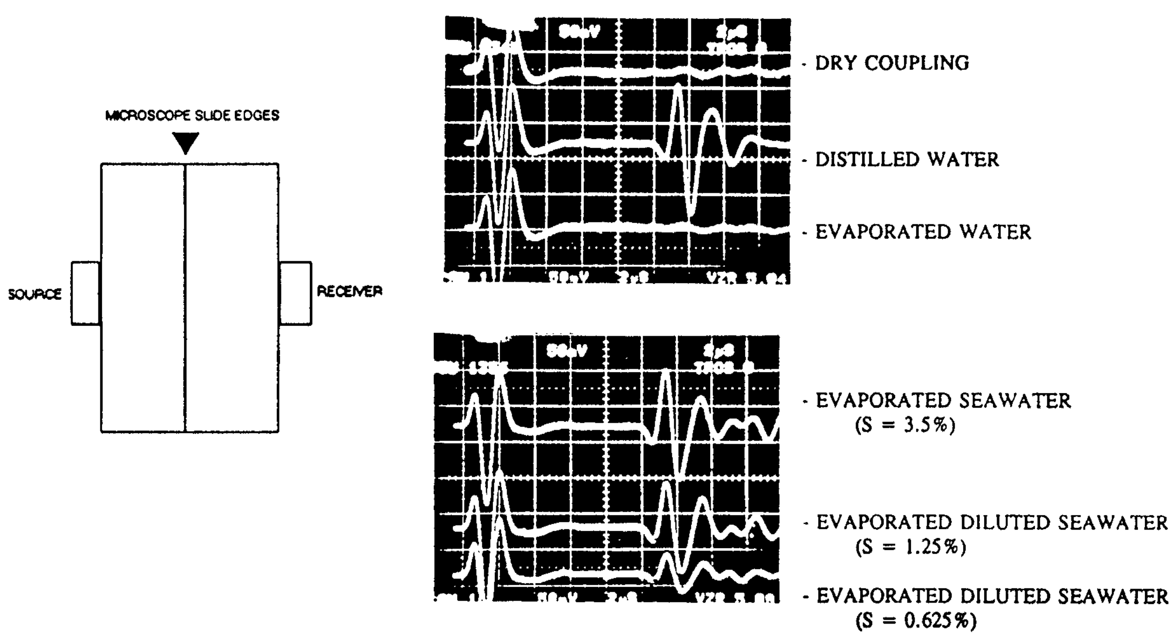


Fig. 16. Study on the effect of water salinity "S" on grain to grain acoustic coupling with formed crystallized salt as water is evaporated.

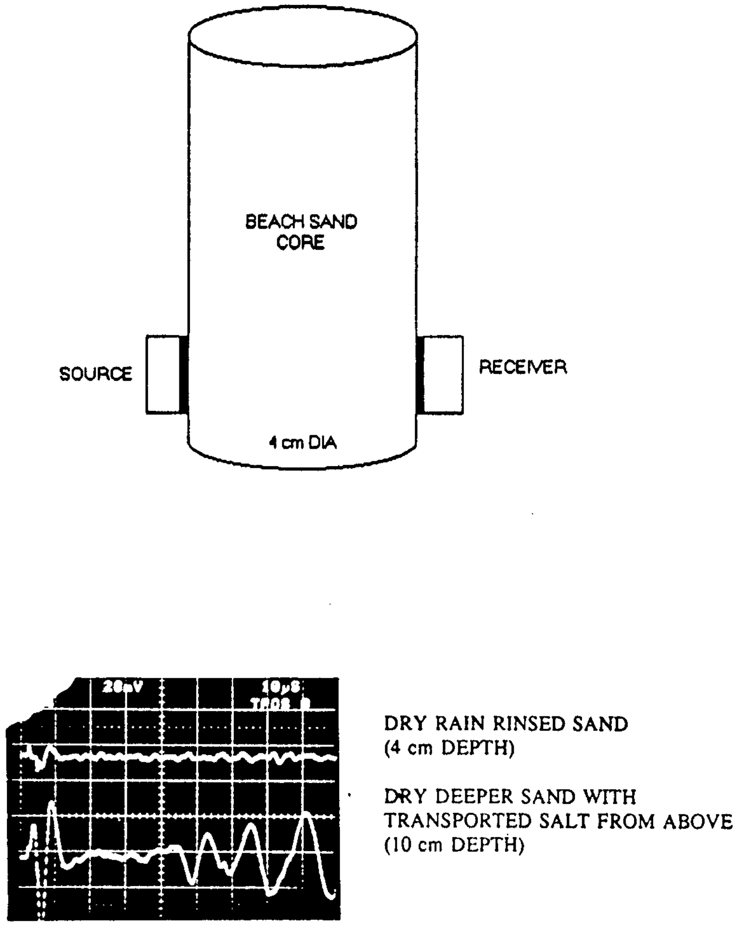


Fig. 17. Laboratory experiment demonstrating effect of rain on transporting salt from top layer to deeper sand region affecting acoustic properties of sand. Top Trace: compressional waveform from dry sand rinsed previously with rained distilled water. Bottom trace: significant compressional waves detected in dry sand from bottom region of sand core containing excess salt transported by rain from the top sand region. Presence of salt also affected the electrical conductivity of the sand core as indicated by the amplitude of the electrical conductivity pulse observed at the beginning of each trace.

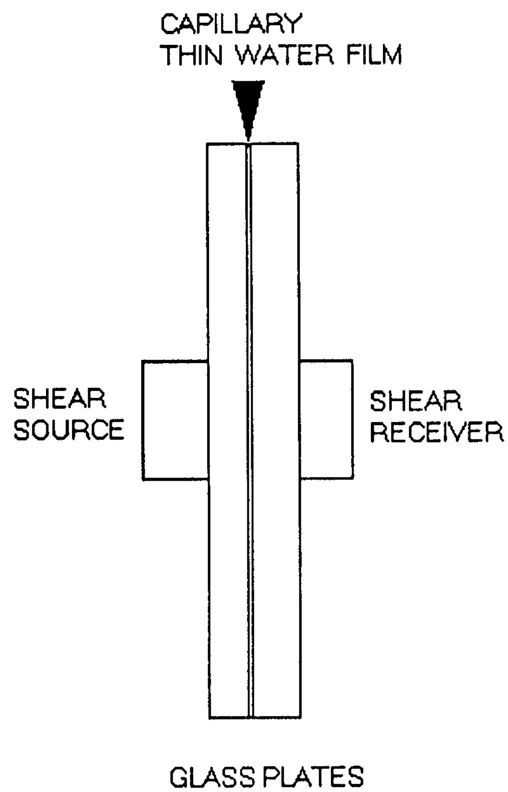
PRELIMINARY RESULTS ON SUCTION-CUP EFFECT

Preliminary results are discussed on a possible mechanisms affecting the rigidity of underwater or partially-saturated unconsolidated sediments. In partially saturated sand, capillary forces are present. The thin water film existing between sand grains has a dramatic effect on the acoustic properties of sand. The author hypothesized [5] that in addition to the capillary forces, there may be another force due to a suction-cup effect between sand grains under certain conditions as described below.

When two parallel glass plates are immersed in water, interfacial surface tension is not present and little force is needed to pull them apart. If the two wet plates are removed from the water, a capillary water film exists between the two plates and an interfacial surface tension plays an important role at the water/air/glass interfaces. Now a greater force is needed to pull the plates apart to overcome the interfacial surface tension, however, the plates are still free to slide against each other and shear waves cannot be transmitted across these parallel plates as shown in Fig. 18. By squeezing the two plates and exerting a slight sliding motion, a suction-cup effect is created between the two plates and shear waves now can be transmitted as shown in the top trace of Fig. 18. Cavitation microbubbles are formed as the tensile strength of the thin capillary water film is exceeded resulting in a suction-cup effect strongly bonding the two plates preventing them from sliding. Newton fringes can be observed at localized spots on the glass plates. In some experiments, a hermetic seal was naturally formed trapping localized thin water films between two glass plates for a period of several months. The exact nature of the hermetic capillary seal is not known, it is postulated that it was probably formed from silica gel particles, salt, and other impurities in the water. Can water be trapped between sand grains for a long time?

This preliminary experiment was conducted using two smooth microscope glass slides (1x25x76 mm) and a thin capillary film of distilled water. The glass plates remained stuck together when the applied force was removed. The theory of elastic waves in unconsolidated sediments by Buckingham [8] depends on grain roughness, where the shear speed goes to zero as the losses vanish. These preliminary results [5] indicate that in the absence of roughness, a very large rigidity modulus and shear coupling can be created when two smooth solids separated by a capillary thin water film are pressed against each other, due to the formation of cavitation microbubbles and a "suction-cup" effect.

The London-van der Waals force of interaction between two parallel plates in vacuum follows the inverse third-power law according to the London-Hamaker theory [24], where the force is proportional to $1/d^3$ and d is the distance between the plates. Howe et al. [25] describes the London-van der Waals force for the interaction of a sphere and a plate as proportional to $1/d^2$. Howe et al. calculated the interaction of a 1mm diameter glass bead and a plate. The force is in the order of 1 dyne for $d > 25$ angstroms, and increase rapidly as d is increased. At a separation of 5 angstroms, the force is about 80 dynes. Glass is hygroscopic and silica gel particles form on its surface. Water impurities determine the ease of cavitation and formation of microbubbles. Gay and Leibler [26] described the role of the suction-cup effect in the theory of tackiness of adhesive polymer films increasing the bonding strength by up to 10,000 times. Future work is needed to assess the potential seismoacoustic role of the "suction-cup" effect in compacted sediments.



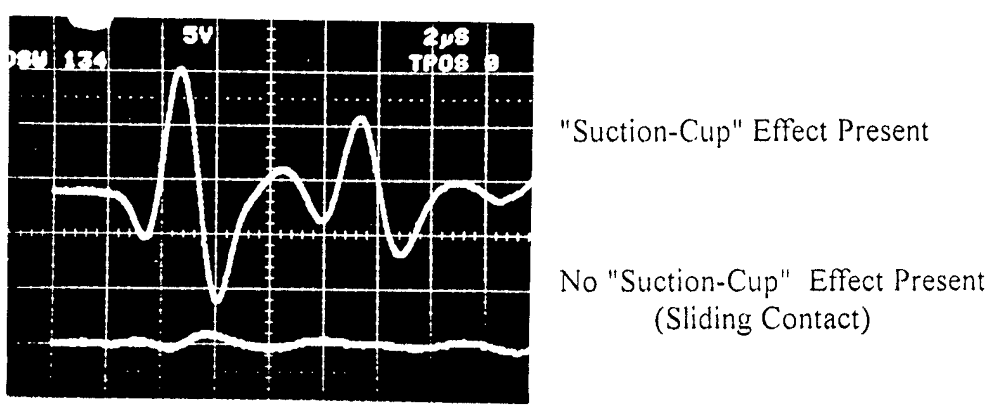


Fig. 18. Basic experiment demonstrating shear wave coupling between two microscope slides glass plates when suction-cup effect is present.

CONCLUSIONS

Under controlled laboratory conditions, the following new findings were obtained providing physical insight on the effect of moisture and sea salt on high-frequency seismoacoustic waves in beach sand:

1. The velocity of high-frequency compressional waves in beach sand *increases* by about 8 % as the water content is decreased by 18% from full saturation [1-3]. This increase in velocity is in contrast with the Biot-Gassmann theory which predicts that the velocity of low-frequency compressional waves *decreases* by 85% as the water content is decreased by only 1% from saturation [4].

2. Sea salt crystallization increased the grain to grain acoustic coupling. Acoustic coupling increased as the water salinity was increased.

3. Form retention was observed in seawater dried sand.

4. Salt crystallization can form hard sand/salt layers with a compressional velocity increasing from 200 m/s to 2887 m/s, and a shear velocity increasing from 10 m/s to 1885 m/s [3].

5. Demonstrated potential role of rain on transporting salt to deeper regions drastically altering the acoustic properties of sand.

6. Salt crystallization decreases sand porosity.

7. Preliminary results using glass plates supported a new hypothesis on the potential existence of a suction-cup effect increasing the rigidity of unconsolidated compacted sediments, in the absence of roughness, due to the formation of cavitation microbubbles as the tensile strength of the thin capillary water film between compressed sand grains is exceeded [5].

The research outcome provides basic physical understanding needed to develop theoretical models for predicting the acoustic properties of seabed leading to accurate ocean bottom characterization and reliable high-frequency seismoacoustic detection of buried objects in saturated, moist, and dry marine sediments. Further future work is needed to study micromechanisms on grain to grain acoustic coupling.

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