SMALL STRAIN STIFFNESS OF CEMENTED SAND

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Abstract. Determination of dynamic properties of soil is a difficult, complex and time consuming task but an essential and important aspect in Geotechnical Earthquake Engineering problems. Dynamic soil properties are important to predict the ground motion, site response and probability of seismic hazards in seismic zones. Seismically, shear wave velocity is the best indicator for site characterization and also to evaluate the liquefaction potential of soils. The piezoceramic bender element test was conducted to study the effect of artificial cementation on low strain dynamic properties of sand. Artificially cemented specimens were prepared using 10% of Portland pozzolana cement by weight. Then sample having dimension of 50mm ×100mm were prepared in relative densities of 30%, 50%, 85% and the samples were tested with the confining pressure of 100kPa, 200kPa, 300kPa, 400kPa after 7, 14 and 28 days of curing. It is determined that shear wave velocity and maximum shear modulus increases decreases with an increase in the density, confining pressure and curing periods.

Keywords: cemented sand, bender element, shear wave velocity, damping ratio, shear modulus, time domain.

1 Introduction

At lower strain levels (<0.001%) the soil exhibits higher stiffness and lower damping ratio, with stress strain behavior being relatively linear. At higher strain levels (>0.01%) the stress strain behaviour of the soil becomes nonlinear with higher damping ratio.. The shear stiffness of soils at low strain levels (<0.001%) denoted as G_0 or Gmax is a key parameter in major geotechnical applications involving deep excavations and tunnels, liquefaction evaluation or earthquake ground response analysis.. Dynamic properties of a soil are properties which are made manifest through movement of soil. The evaluation of dynamic properties of a soil deposit is of utmost importance in studying site response, prediction of ground motion, probability of seismic hazards and in design of machine foundation. The treatment of soils with cement is an attractive technique when a project requires improvement of the local soil for the construction of subgrade for rail tracks, for roads, as a support layer for foundation, and to prevent sand liquefaction. An understanding of the effect of low to moderate degrees of cementation on dynamic strength-deformation behaviour of sands is important in design and analysis of geotechnical engineering. The shear wave velocity is used to evaluate the dynamic soil properties such as dynamic shear modulus and damping ratio which are essential for computations of seismic site response, design of foundations subjected to dynamic loads and evaluation of liquefaction potential. The piezoelectric bender element test is relatively simple non-destructive test for the measurement of shear wave velocity and subsequent determination of maximum shear modulus. This study focuses on measurement of shear wave velocity to determine the small strain modulus of artificially cemented sand

2 Background

Extensive research has been carried out to study the small strain behaviour of cemented sands mainly through well controlled laboratory experiments using bender element tests and resonant column .Some concerns have been raised regarding problems associated with the coupling of the specimen to the end plattens of a torsional resonant column. Hence this study focuses on an alternative technique like piezoceramic bender element test for determining small strain stiffness. Some of the significant works using bender element testing are briefed in this section. This study will be useful to understand the influence of degree of cementation, age of cementation, depth of presence of cemented soil and density of the cemented soil in the field.

Bender element test is used to determine the shear wave velocity with respect to relative density, cement content, confining pressure and curing periods. Yang and Salvati(2010), investigated the influence of the cement content and the type of cement, confining pressure and density on the small strain properties of cemented Ottawa, Monterey and Michiana sands by using bender element tests. Portland cement and gypsum with cementation level of 2.5%, 5%, 7.5% at 60%, 80% and 100% relative densities and curing period of 7,14 and 28 days were used in the study. The excitation frequencies ranging from 10 kHz to 80 kHz were used to measure the travel time of the soil sample and also calculate the shear modulus of cemented sand. The results showed that the density and confining pressure have the greatest effects on the small strain properties of uncemented sands, but their effects on the cemented sands were limited. Jaya et al. (2007) studied the estimation of maximum shear modulus of poorly graded sand from shear wave velocity measurements by bender element test. Samples were prepared by air pluviation technique at relative densities of 20%, 50%, 65% and 85%.G_{max} were obtained by using sinusoidal input voltage and travel time based on first deflection in the output signal. Based on the estimated values of G_{max} from bender element tests, a predictive relationship was developed for the poorly graded saturated sand. Baig et al. (1997) studied the dynamic properties of lightly cemented Ottawa sands using bender element tests and torsional column tests. Portland cement was used as cementing agent with 1% to 5% cementation at 0 to 50% relative density cured for 7 days in humid conditions. Since the cured cemented specimens were very hard it was not possible to insert the bender elements by pushing them in. To overcome this, the researchers made artificial slots of about twice the volume of bender elements were made on the top and bottom of the specimen. These slots were cut co planar in a vertical plane containing the axis of the specimen. Dry gypsum powder was used to fill these slots. At the time of testing, the bender elements were pushed inside these slots to ensure contact of the elements with specimens. The results obtained with piezoceramic bender elements were very close (ranging from 5% to 40% higher) to those obtained with a torsional resonant column, provided that the specimen was properly bonded to the end platens. The significant finding was that the bender elements and the torsional resonant column indicate a negligible effect of the confining pressure on the maximum shear modulus of the cemented sands. Consoli et al. (2012) studied about the key parameters for the control of strength and stiffness of cemented soils by uniform Osorio sand (SM) and well-graded Porto silty sand (SP) with different gradations. The authors quantified the influence of porosity/cement ratio on both initial shear modulus (G_0) and unconfined compressive strength (q_u). Portland cement was used as the cementing agent. Its gain of strength allowed the adoption of 7 days as the curing time. The results indicated that the shear waves were vertically propagated and horizontally polarized since the piezotransducers were vertically encastrated in base and top cap of triaxial specimens. Cristiana (2012) used bender element test for the seismic wave measurements. To overcome the limitation in applicability of this technique in compacted soils, naturally or artificially cemented soils and soft or weak rocks, the researchers made use of two accelerometers in conjunction with the bender element. The signal produced by the BE transmitter was acquired by the BE receiver and by the two accelerometers. The results of this research enabled to validate the interpretation methods used for Bender element testing.

The past researches indicate that the degree and type of cementation is the most influential parameter to determine the moduli of the specimens. Generally, Portland cement and gypsum were used for the studies in literature. They have significantly different strengths. The cube strength after 7 days is 50 MPa for Portland cement and 14 MPa for gypsum. It implies that cementing agent plays a significant role in the modulus of cemented sands. In literature, the cemented sand specimens were prepared with varying cement content of 1%, 2%, 5%, 8%. The maximum shear modulus values increases with increase in cement content. Stiffness of cemented sands increased with increase in relative density. The previous studies on shear modulus of cemented sands had used relative densities ranging from 0% to 80%. Stiffness of cemented sands increased with increase in relative density. Confining pressure has a significant effect on the small strain properties of uncemented sands, but their effects on highly cemented sands are limited. However, the small strain properties of cemented samples may be affected by the higher confining pressure and lower cement contents. Most of the literatures, the confining pressure were between the ranges of 100kPa to 600kPa. The curing process of cemented sand is strongly time-dependent. Most of the literature, the curing periods are considered for 7, 14, 28 and 60 days. At low relative densities, there being more voids, the exposed surface of the cement particles is much larger. So the cement hydrates faster than at higher relative densities, which have less exposed surface for a given period of time. The main objective of the present paper is to examine the shear wave velocity (V_s) and shear modulus (G) of cemented sands with 10% cement content at loose, medium dense states of 30%, 50%, 85% relative densities respectively using bender element tests. All the tests were conducted at confining pressures of 100kPa, 200kPa, 300kPa, 400 kPa for 7, 14 and 28 days curing periods.

3 Materials

The sand used for this study was collected from Palar river bed, Tamil Nadu,India. The cementing agent used for the study was Portland pozzolana cement. The sand consists of dominantly coarse fraction with D_{10} of 0. 54mm.The sand is classified as poorly graded sand (SP) according to unified classification system with uniformity co-efficient (c_u) of 3.81. The maximum and minimum dry density is 1.77 g/cc and 1.60 g/cc respectively. Their respective void ratios are 0.60 and 0.44 respectively. The specific gravity of cement and sand was 3.15 and 2.62 respectively. The grain size distribution of sand is shown in figure 1.

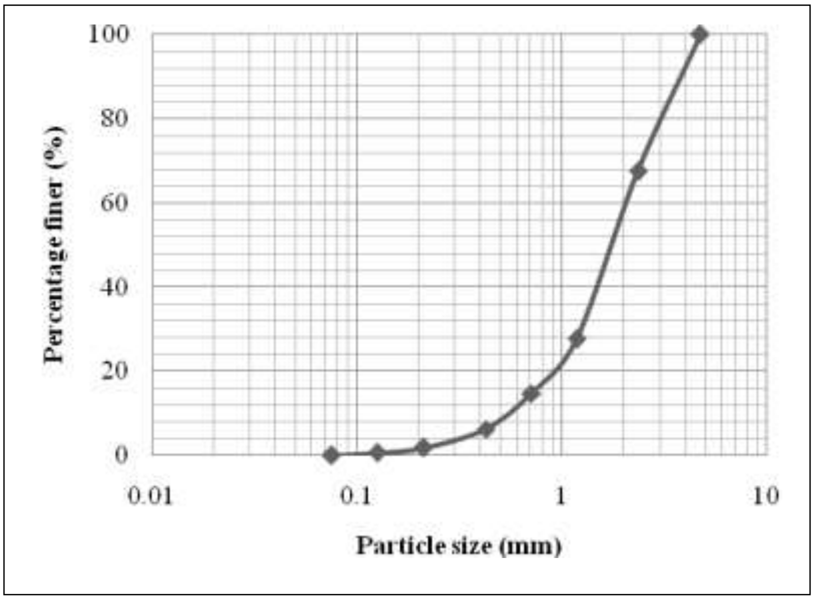

Fig. 1. Grain size distribution curve of sand

3.1 Specimen Preparation for bender element testing

The amounts of sand and cement needed for a relative density of the sand skeleton and degree of cementation were first mixed in a bowl by using spatula. Then, water was added. The mix was divided into six equal parts. Each part was compacted separately with the same number of blows using a heavy, large-diameter rod in a (PVC) mold. The mold had a slit along its side and was held together by using O - ring. After compaction, the top of each layer was scarified to ensure proper bonding of each lift with the underlying layer. The compacted specimens were then cured inside the moulds. Due to difficulty in insertion of bender element into the cured cemented sand specimens two different methods were adopted as trial procedures for insertion of bender element in this study. In the first method, molds in the size of the bender element were inserted on the top and bottom surface of the cemented specimens during the preparation stage itself. But difficulty in maintaining the density of the specimens was observed in this kind of insertion. In the second method, slots in size of the bender element were made on top and bottom surface of the cemented specimen after an hour or two before curing. This method maintained proper density of the cemented sand in addition to providing ease in the insertion of bender element before testing. All the cemented sand specimens in this study were inserted with bender element using the second method.

4 Test Program

A Bender Element system supports its operation in the piezoelectric property, which allows for the generation and detection of small shear waves travelling in a soil specimen. Electronic peripherals permit the generation, acquisition, and storing of input and output signals. Bender element test was performed in the laboratory in the soil specimen having dimensions 50 mm diameter and 100 mm height. Peizoceramic bender elements of size 13×10×0.6 mm were used.The bender element were placed in such a way that two third of their length was cantilevered inside the cemented sand specimen. An input voltage of 20 volts was applied for all the tests. The bender element mounted on the bottom pedestal worked as a transmitter and the top element worked as a receiver. The transmitter element converts the input voltage as a mechanical energy (shear movement in the soil). The shear wave travelled through the soil and that was received by the receiver element as a mechanical energy and the mechanical energy converted as an output voltage. Function generator was used to give input such as type of wave, amplitude, no of cycles, frequency and period of wave etc. Oscilloscope shows the transmitted and received signal as a waveform as shown in fig 2. So that the time difference between the two waves were obtained from oscilloscope. From the tip to tip distance between two elements and the obtained time difference, shear wave velocity was determined.

Fig. 2. Bender element test on cemented specimen

4.1 Setup and connections

The test setup developed for measuring Vs in sands. On both ends of the soil sample, bender elements (the pair of a transmitter and a receiver) is fitted. The transmitter is excited with a single cycle sine wave or with a step function of certain amplitude, which is generated from a function generator. The receiver is connected to a filter/ amplifier circuitry, which in turn is connected to a digital oscilloscope, which also receives a direct sine wave or a step signal from the function generator. The sine waves recorded by the oscilloscope can be processed to determine the travel time of the shear wave (t).

4.2 Testing procedure

Once all the connections were made and the proper power supply was given, the power button in electronic unit, function generator and oscilloscope was switched on. In the function generator the inputs such as amplitude is 20 Vpp , time period for next wave generation is 10 ms and frequency of wave is such that the near field effect to be avoided were given to generate a single sinusoidal wave. Once the inputs were given, the channel 2 output button was pressed. The transmitted and received waves were shown in oscilloscope. Then the output wave was filtered out by band pass filter. The upper limit and lower limit of filter was selected such that the given input frequency was within the range and noise was avoided. The horizontal and vertical control in the oscilloscope was used to relocate and rescale the waves and clear waves were obtained. The time difference displayed in oscilloscope was noted. The horizontal and vertical control in the oscilloscope was used to relocate and rescale the waves and clear waves were obtained. The time difference displayed in oscilloscope was noted.

The peak points of the input and output waves were chosen. In order to reduce the near field effect on the results, two precautions were adopted. One is that the transmitter and the receiver bender elements were kept as far apart as possible. The frequency of the waves was taken as high as possible. Increasing the frequency resulted in decreasing the wave length, thus increasing the ratio L/λ. The shear wave velocity and shear modulus were calculated from Equation 1 and 2 respectively.

$$V_s = (L_{tt}/ \Delta x) \tag{1}$$

where Vs is the Shear wave velocity (m/s) , Ltt is the tip to tip distance (m), Δx is the Time difference (ms)

$$G = \rho V_s^2 \tag{2}$$

Where G – Shear Modulus (MPa) ,ρ – Mass Density of the soil in the specimen (kg/ m^3) and V_s - Shear wave velocity (m/s)

5 Results and discussion

The results obtained from bender element test for dry and cemented sand with the cement content of 10% and curing periods of 7, 14, 28 days with the relative densities of 30%(loose state), 50%(medium dense) and 85%(dense state) are discussed in this section. The shear wave velocity for the dry sand at relative density of 30%, 50% and 85% and different confining pressure of 100kPa, 200kPa, 300kPa and 400kPa is presented in table 1.

Table 1. Shear wave velocity and shear modulus of dry sand

Confining pressure (kPa)	Rd = 30%			Rd = 50%			Rd = 85%		
	V_s (m/s)	G (MPa)	L/λ	V_s (m/s)	G (MPa)	L/λ	V_s (m/s)	G (MPa)	L/λ
100	51.47	4.42	12.2	59.32	6.07	10.6	92.10	15.17	6.84
200	54.68	4.99	11.5	64.81	7.24	9.72	145.8	38.05	4.32
300	60.34	6.08	10.4	73.68	9.36	8.55	198.5	85.6	3.17
400	71.43	8.52	8.82	82.35	11.69	7.65	233.3	111.8	2.70

The shear wave velocity and shear modulus for the cemented sand at relative densities of 30%, 50% and 85% at different confining pressure of 100 kPa, 200 kPa, 300 kPa and 400 kPa for different curing periods of 7, 14 and 28 days for cement contents of, 10% are listed in table 2. The variation of shear wave velocity and shear modulus with respect to confining pressure for relative density of 30%, 50% and 85% are shown in figures 2, 3 and 4 respectively.

For 10% cement content, the shear wave velocity and shear modulus for 7 days curing lies within a range of146m/s to 206m/s and 36MPa to 72MPa respectively. For 14 days curing, the shear wave velocity lies within a range of 152m/s to 226m/s and 39MPa to 85MPa respectively. Similarly, for 28 days curing the shear wave velocity and shear modulus lies within a range of 163m/s to 250m/s and 44MPa to 104MPa respectively for confining pressure of 100kPa to 400kPa. For 50% relative density, , the shear wave velocity and shear modulus of 10% cemented sands for 7 days curing lies within a range of 160m/s to 233m/s and 44MPa to 94MPa respectively. For 14 days curing, the shear wave velocity lies within a range of 167m/s to 267m/s 56MPa to 108MPa respectively. Similarly, for 28 days curing, the shear wave velocity lies within a range of 184 m/s to 350m/s and 59MPa to 211MPa respectively for confining pressure range of 100kPa to 400kPa. For 85% relative density , the shear wave velocity and shear modulus for 7 days curing lies within a range of 184 m/s to 318 m/s and 61MPa to 181MPa respectively. For 14 days curing, the shear wave velocity lies within a range of 206 m/s to 345m/s and 76MPa to 213MPa respectively. Similarly, for 28 days curing, the shear wave velocity lies within a range of 233m/s to 436m/s and 97MPa to 340MPa respectively for confining pressure of 100kPa to 400kPa. Irrespective of the density, the shear wave velocity and shear wave modulus of the 10% cemented sands increases with increase in curing period for all confining pressures. While increasing the density of the cemented sand specimen the travel time decreases and hence the shear waves velocity and the shear modulus increases. This is due to the increase in interparticular contact as the density increases and travel time decreases

Table 2. Shear wave velocities of 10% cemented sand at different relative densities

Curing periods (days)	Confining pressure (kPa)	30% Relative density			50% Relative density			85% Relative density		
		Vs(m/s)	G(MPa)	L/λ	Vs (m/s)	G (MPa)	L/λ	Vs (m/s)	G (MPa)	L/λ
7	100	145.8	35.9	4.3	159.0	43.6	3.96	184.2	60.6	3.4
	200	166.6	46.9	3.7	175	52.7	3.60	218.7	85.6	2.8
	300	184.2	57.3	3.4	212.1	77.5	2.97	250	111.8	2.5
	400	205.8	71.6	3.0	233.3	93.8	2.70	318.1	181.1	1.9
14	100	152.1	38.6	4.1	166.6	47.8	3.78	205.8	75.82	3.0
	200	175.0	51.1	3.6	184.2	58.5	3.51	233.3	97.39	2.7
	300	200.0	66.8	3.1	232.5	93.1	2.70	291.6	152.1	2.1
	400	225.8	85.1	2.7	267.2	122.9	2.52	345.2	213.2	1.8

	100	162.7	44.2	3.8	184.2	58.5	3.42	233.3	97.40	2.7
28	200	184.2	56.6	3.4	194.4	65.1	3.24	259.2	120.2	2.4
	300	218.7	79.9	2.8	259.2	115.8	2.43	350	219.1	1.8
	400	250	104.3	2.5	350	211.19	1.8	436.4	340.7	1.0

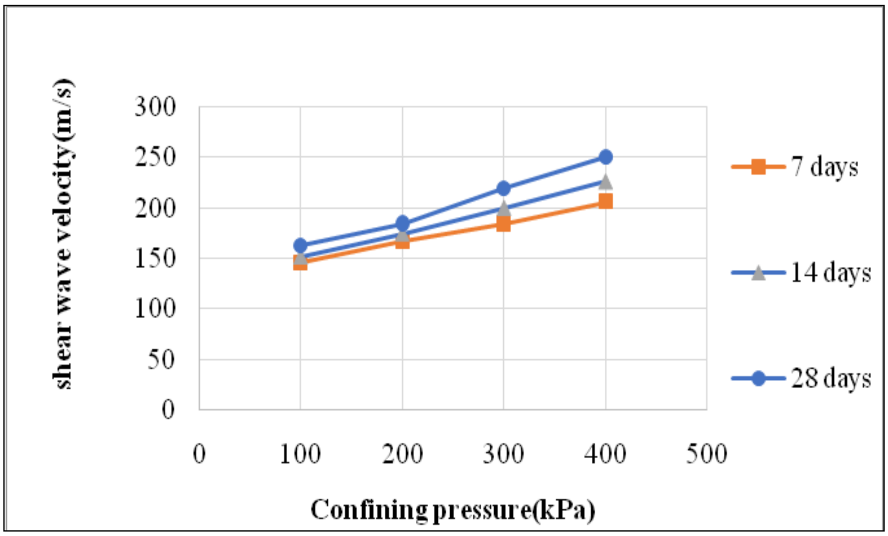

Fig. 3. Variation of shear wave velocity of 10% cement content at 30% relative density.

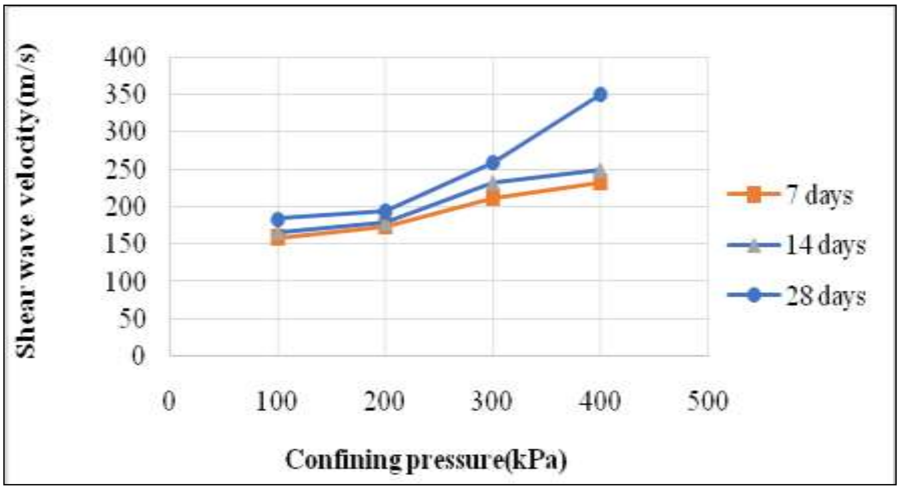

Fig. 4. Variation of shear wave velocity of 10% cement content at 50% relative density

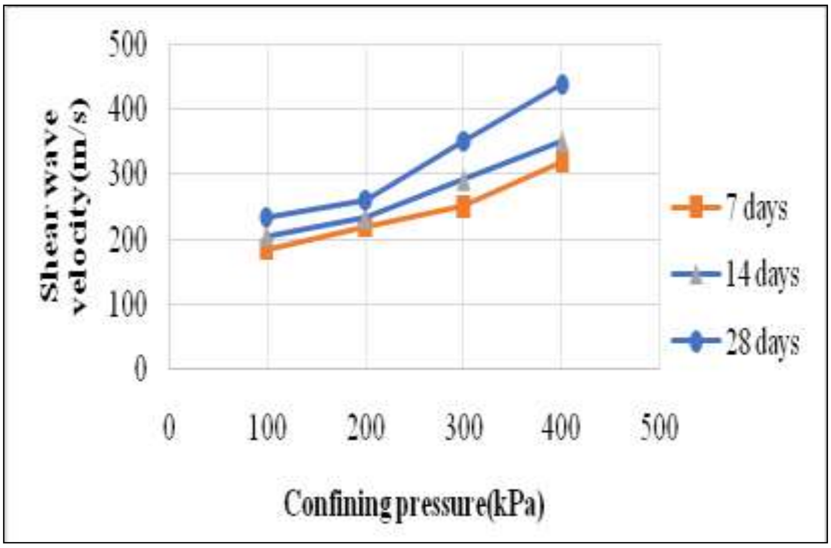

Fig. 5. Variation of shear wave velocity of 10% cement content at 85% relative density

The rate of increment of shear wave velocity is higher for cemented sands, than dry uncemented sand with the confining pressure of 100kPa to 400kPa. Figures 2 to 4 and table 1, it is observed that irrespective of confining pressures, curing period and relative densities, the travel time decreases compared to dry uncemented sand and hence the shear wave velocity and corresponding shear modulus increases and near field effect(L/λ ratio) decreases for studied cement percentage. The variation in shear wave velocity and shear modulus for relatively loose sand and relatively medium sand is less when compared to dense state. The shear wave velocity and shear modulus increases with increases in confining pressure but the increment is more for dense state than medium and loose state.

6 Damping ratio of tested dry sand

Damping is a phenomenon that makes any vibrating body or structure to decay in amplitude of motion gradually by means of energy dissipation through various mechanisms. The damping ratio is a dimensionless measure describing how oscillations in a system decay after a disturbance. The application of piezoceramic bender elements (BE) for the measurement of the material damping ratio Ds in a triaxial cell under isotropic confinement at shear strains below the elastic threshold shear strain of 10-5. BE show a bending displacement when a voltage is applied and generate a voltage when they are forced to bend. They can therefore be used to transmit and receive shear waves in soil specimens. The damping ratio value for dry sand at relative densities of 30% with confining pressure of 100kPa and input frequencies ranges from 1 kHz to 15 kHz with constant amplitude at the transmitter are listed in table 3. The variation of damping ratio with respect to input frquencies for relative density of 30% with confining pressure of 100kPa are shown in fig 5. The material damping ratio is caluclated using equation 3 and found to be 13.8% for dry sand at 30% relative density using equation 3.

$$D_s = \omega_2 - \omega_1 / 2\omega_{re} \quad (3)$$

Ds = Material damping ratio, ω_1 = Initial frequency (kHz), ω_2 = Final frequency (kHz)

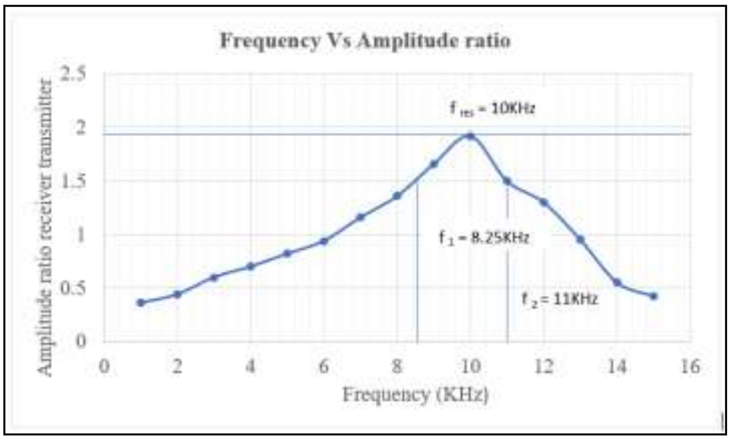

Fig. 6. Determination of Material damping ratio of dry sand at 30% relative density

Table 3. Determination of damping ratio for dry sand

Input frequency (kHz)	Amplitude at the transmitter (mV)	Amplitude at the receiver (mV)	Amplitude ratio receiver transmitter
1	10	3.60	0.36
2	10	4.40	0.44
3	10	6.00	0.60
4	10	7.00	0.70
5	10	8.20	0.82
6	10	9.40	0.94
7	10	11.6	1.16
8	10	13.6	1.36
9	10	16.6	1.66
10	10	19.2	1.92

11	10	15.0	1.50
12	10	13.0	1.30
13	10	9.50	0.95
14	10	5.50	0.55
15	10	4.20	0.42

7 Conclusions

The influence of, relative density, confining pressure and curing periods in shear wave velocity and shear modulus of cemented sand have been studied using bender element test. The important conclusions drawn from the study are briefed below.

1. The variation in shear wave velocity and shear modulus for relatively loose sand and relatively medium sand is less when compared to dense state. The shear wave velocity and shear modulus increase with increases in confining pressure, but the increment is more for dense state than medium and loose state.
2. Increase in the density of cemented sand the travel time decreases and hence the shear wave velocity and the shear modulus increase. This is due to the increase in interparticular contact as the density increases and travel time decreases.
3. The increment in shear wave velocity for 7 and 14 days curing period is less when compared to 28 days of curing for 10% cement content at relative density of 30% for all confining pressures. At low relative densities, there being more voids, the exposed surface of the cement particles was much larger. So, the cement hydrates faster than at higher relative densities, which have less exposed surface for a given period of time.
4. Irrespective of, confining pressures, curing period and relative densities, the travel time for decreases compared to dry uncemented sand and hence the shear wave velocity and corresponding shear modulus increases and near field effect(L/λ ratio) decreases for the studied cement percentage.
5. The material damping ratio of 30% relative density dry coarse sand is 13.8% at the bender element test strain level.

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