6.2. Dependence of compressional wave properties on geotechnical properties

The relationships between the compressional wave properties and geotechnical properties of marine sediments have typically been obtained either through the questionable amalgamation of data from a variety of sources or from the analysis of sediment samples under laboratory conditions for which the degree of sediment disturbance is unknown, *Section 3.1.* The approach adopted in this thesis allows *in situ* compressional wave properties for range of sediment types, which have been obtained through the use of a common device and methodology, to be compared to geotechnical properties measured on laboratory samples. The significance of the use of laboratory samples depends on the geotechnical property under examination, see *Section 4.4.3* for details.

The sediments examined within this project allow the dependence of velocity, attenuation coefficient and quality factor on geotechnical properties to be examined within medium to fine sands and medium to fine silts. The lack of data for the intermediate range, *i.e.* porosities from to 50.7 to 75.9 %, bulk densities from 1169 to 1789 kg·m^{-3}, mean grain diameters from 2.18 to 6.22 ϕ and percentages of sand sized particles from 21.8 to 97.6 %, prevents the application of empirical relationships which incorporate both sands and silts. Though the linear and quadratic trends favoured in the extant literature relationships were applied to sands and silts separately, the optimum trends produced unsatisfactory fits to the data, *i.e.* possessed confidence limits less than 80 %. This arises from the limited range of geotechnical properties present for each sediment type and the considerable spread in the compressional wave properties observed. The spread in compressional wave properties arises from the non-uniqueness of sediments and the effects of additional latent variables, *Section 2.4.1.* Hence, only qualitative relationships between compressional and geotechnical properties are be discussed in this section. In some cases, these will be compared to general relationships present in literature, while in other cases, the data presented in this report is the first such data.

The following sections will compare group velocity, effective attenuation coefficient and quality factor to the basic geotechnical properties of porosity, bulk density, mean grain diameter and the percentage of sand sized particles. Compressional wave properties from locations that are considered to be corrupted have been omitted (see *Appendix D*). In order to effectively span the frequency range examined, the dependence of attenuation coefficient and quality factor on geotechnical properties was investigated at central received frequencies of 19.8, 39, 58.2, 77.4 and 96.7 kHz, which correspond to emitted central frequencies of 20, 40, 60, 80 and 100 kHz. The confirmation that velocity is independent of frequency in *Section 6.1* justifies the examination of mean velocities only.

Velocities measured within this project are compared to the empirical relationships discussed in *Section 2.4, Table 2.3.* In order to obtain minimum and maximum sediment velocities, minimum and maximum pore water velocities are required (see *Section 2.4.1*). These were computed to be 1420 and 1476 m·s^{-1} respectively, from measured salinities and temperatures (see *Table 4.4, Section 4.4.3)* and standard empirical equations (see *Appendix A*). Constants of proportionality k_A are compared to values of Hamilton's parameter k_h obtained from published empirical relationships, which relate k_h to either porosity or mean grain diameter, *Section 2.5.1.*

6.2.1. Dependence on porosity

Mean velocities range from 1631 to 1782 m·s^{-1} for porosities from 39.5 to 50.7 %, and 1345 to 1455 m·s^{-1} for porosities of 75.9 to 91.9 %, *Figure 6.8*. Velocities are observed to be greater in the higher porosity range than the lower porosity range, with velocity decreasing as porosity increases from 39.5 to 50.7 %. No trends are observable within the spread of velocities for porosities greater than 80 %. Both the decrease in velocity as porosity increases from 39.5 to 50.7 % and the minimum in velocity at a porosity less than 80 % agree with the lower range of porosities which correspond to minimum velocities observed in the literature, *i.e.* 75 to 76 %, (Courtney and Mayer, 1993; Orsi and Dunn, 1990).

The empirical relationship (*Section 2.4.1*) overestimates velocities in silts and underestimates velocities in sands. This reflects the dependence of empirical relationships on sedimentary environment, with the empirical relationship derived from submerged sediments being inapplicable to inter-tidal sediments. Examination of *Equation 2.12* indicates that inter-tidal sands possess either higher bulk and shear moduli or lower densities than submerged sands, while the reverse is suggested for inter-tidal silts. As the hydrostatic pressure of the pore water acts in all directions the compaction of marine sediment depends on the sediment depth only and is independent of the height of the overlying water column (Craig, 1997). Therefore, as the inter-tidal sediment examined within this project and the submerged sediment from which the empirical relationship between velocity and porosity was derived both lie in the upper 1 m of the seabed, these sediments will possess the same effective pressure and degree of compaction. The discrepancies between the measured and empirical values may arise due to variations in mineralogy or sediment framework.

Velocities predicted by Wood's Equation (*Equation 2.13*, *Section 2.5.1*) were also computed, as these represent the lowest theoretical velocities that are allowed in marine sediment, *i.e.* Wood's Equation assumes that frame bulk modulus and shear modulus are both zero. In order to ensure that minimum velocities were obtained the additional parameters in the Wood's equation were set as follows:

- Grain bulk modulus was set to a minimum possible value of 32 GPa (see *Section 7.1.2*).
- Grain density was set to a maximum possible value of 2750 kg·m^{-3} (see *Section 7.1.2*).
- Fluid bulk modulus was set to a minimum possible value of 2.26 GPa (see *Section 7.1.1*).
- Fluid density was set to a maximum possible value of 1003 kg·m^{-3} (see *Section 7.1.1*).

The measured velocities in silts are lower than those predicted by the Wood's Equation. This indicates that either these measured velocities are suspect or that the considerable fraction of organic material observed at the silt sites (see *Section 4.4.3*) generates lower grain bulk moduli than exist for purely mineral aggregates.

The techniques used to measure porosity will over-estimate *in situ* values, with the degree of discrepancy more pronounced for silts than sands (see *Section 4.4.3*). Though a quantitative assessment of the discrepancy between measured and *in situ* porosities cannot be made, it is hypothesised that adjustment to *in situ* porosities will shift the measured velocities closer to the values predicted by the empirical equation for both sands and silts.

Attenuation coefficients vary from 3.6 to 51.2 dB·m^{-1} for porosities of 39.5 % to 50.7 % ($\pm$1.6 to $\pm$5.7 dB·m^{-1}) and 1.7 to 20.6 dB·m^{-1} ($\pm$0.7 to $\pm$4.6 dB·m^{-1}) for porosities greater than 75.9 %. Attenuation coefficients are greater over the low porosity range than the high porosity range. From 39.5 to 50.7 % attenuation coefficients generally increase with porosity. Though a trend between attenuation coefficient and porosity is less clear for porosities greater than 75.9 %, owing to the spread in attenuation coefficient, a decrease in attenuation coefficients is implied as porosity increases at the higher frequencies of 58.2, 77.4 and 96.6 kHz. These trends imply a maximum attenuation coefficient in the intermediate porosity range of 50.7 to 75.9 %, which broadly agrees with a peak in attenuation coefficient observed by previous workers for porosities from 45 % to 60 % (Hamilton, 1972; Shumway, 1960). Particular locations that consistently give attenuation coefficients greater than others include:

- the Saltern site, *i.e.* porosities of 92.5 to 92.7 %, which may arise from the presence of rubble at Saltern 2 and the observation of a stiff organic peaty layer lying 0.8 to 0.9 m deep at Saltern 1. These heterogeneities will cause additional scatter/reflection of compressional waves.
- Studland 1, *i.e.* a porosity of 39.1 %, where shells and pebbles with diameters up to 15 cm could act as additional scattering centres.

The constant of proportionality k_A varies from 0.14 to 0.52 dB·m^{-1}·kHz^{-1} in low porosity sands, with lower values of 0.06 to 0.20 dB·m^{-1}·kHz^{-1} in higher porosity silts, *Figure 6.9F*. An increase in k_A is observed as porosities increase from 39.5 to 50.7 %, with the value at 55.5 % less than that at lower porosities. No trends are observable within the spread and errors for porosities greater than 80.0 %, while the value at 75.9 % is consistently lower than at higher porosities. Measured constants of proportionality are less than or equal to those predicted by the empirical equation in sands, and greater than or equal to those predicted in silts. As the empirical relationship was developed from measurements on submerged sediment, the discrepancy between measured and predicted values highlights the inapplicability of the empirical fit to inter-tidal sediment and suggests that the frequency-dependence of attenuation coefficient may vary from the submerged to inter-tidal environments.

Quality factors are observed to be greater in high porosity silts than in lower porosity sands, with the difference more pronounced at the higher frequencies of 58.2, 77.4 and 96.6 kHz, *Figure 6.10.* Both this and the individual trends in the high porosity silts and lower porosity sands, *i.e.* quality factor decreases as porosity increases from 39.1 to 50.7% and increases as porosity increases from 75.9 to 91.9 %, reflect the trends observed between attenuation coefficient and porosity and the fact that attenuation coefficient is the dominant factor controlling quality factor, *i.e.* quality factor represents the inverse fractional energy loss per oscillation, *Section 2.1*.

No trends between the constant of proportionality Q_A and porosity are observable except that a larger degree of variability occurs over the higher porosity range than the lower porosity range, *Figure 6.10F*. This is attributed to the lower values of attenuation coefficient observed at low frequencies (16 to 30 kHz) in silts, which result in greater variations of quality factor over these frequencies in silts than in sands.

The observation of porosity dependent trends in velocity, attenuation coefficient and quality factor imply that porosity is one of the dominant factors controlling these compressional wave properties. With respect to the ultimate aim of sediment acoustics, which is the ability to determine the geotechnical properties of marine sediment from acoustic properties (*Section 1*) this research indicates that compressional wave velocity, attenuation coefficient and quality factor are useful properties from which porosity can be determined.

The trends in attenuation coefficient and quality factor indicate maximum energy losses for sediments with porosities from 50.7 to 75.9 %. This can be explained through sediment structure and heterogeneity (Stevenson *et al.*, 2002). Pure clays, with mean grain diameters greater than 8ϕ and porosities of approximately 80 %, possess a homogeneous structure that typically consists of packets of grains (*Section 2.2*). The inclusion of silt and sand particles, which decrease the porosity and increase the mean grain diameter, produce a more poorly-sorted, heterogeneous sediment, with a disrupted clay lattice. As the sand fraction further increases, the sediment eventually becomes more well-sorted, and more homogeneous, consisting of a few clay particles suspended in a sand/silt matrix. The increased heterogeneities within the more mixed sediments, which possess porosities from approximately 50 to 70 % (Hamilton, 1987) results in increased energy losses from either increased scatter or squirt flow.

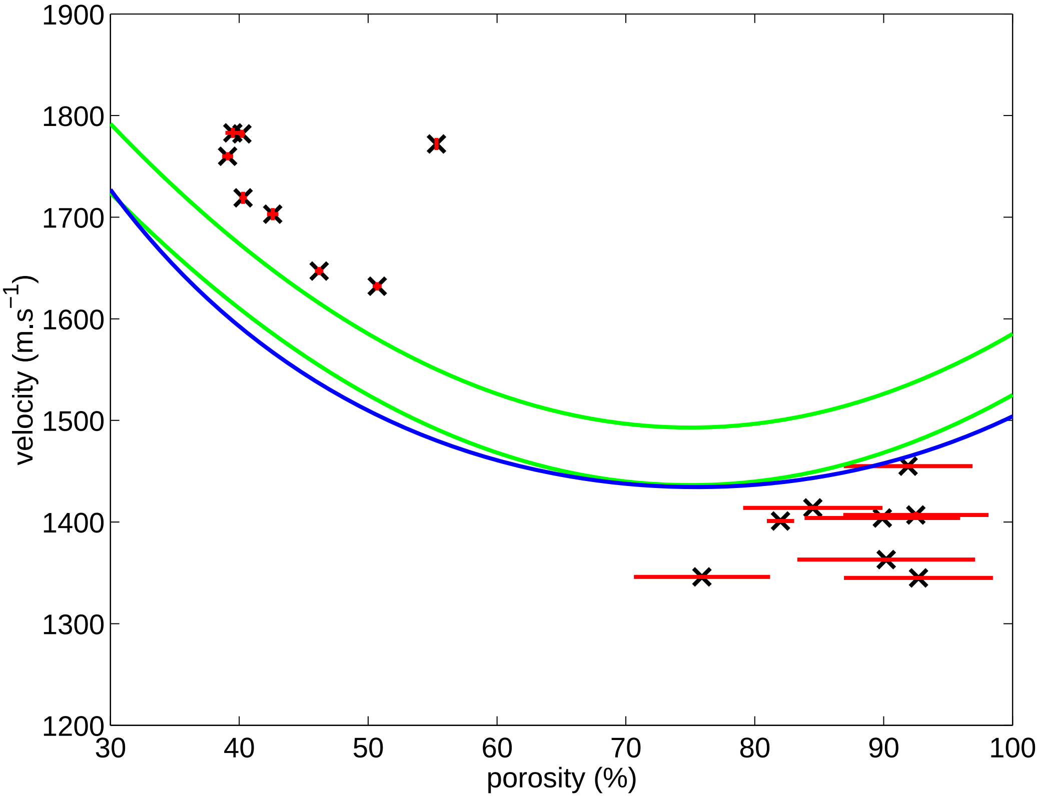


Figure 6.8. Mean velocity versus porosity, with mean values denoted by crosses and errors in porosity denoted by red lines. The minimum and maximum velocities predicted by the empirical fit of Richardson and Briggs (1993) are denoted by green lines, while the blue line denotes the lowest velocities predicted by Wood's Equation. No errors in velocity are plotted, as these are less than 6 m·s^{-1}.

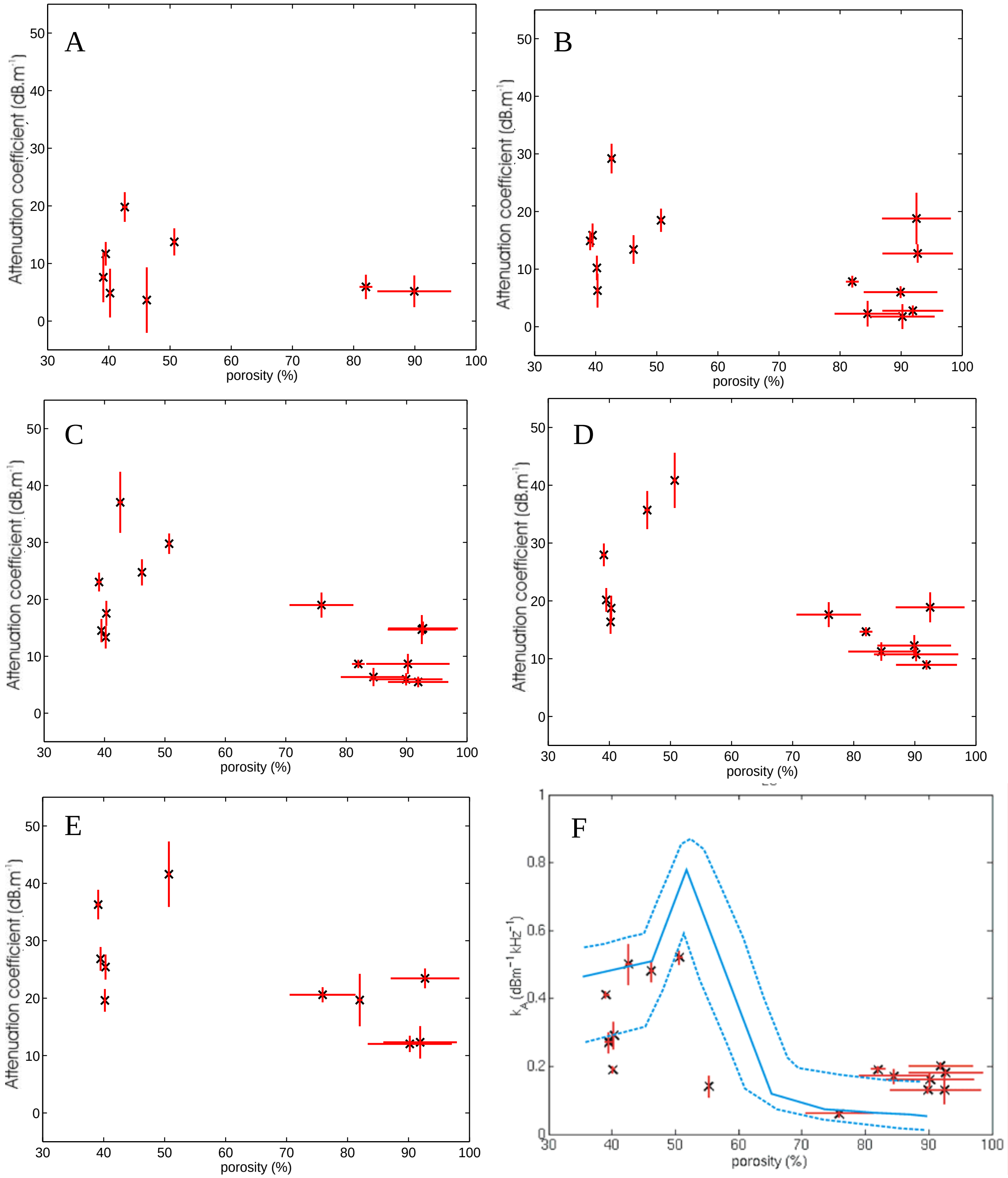


Figure 6.9. Dependence of attenuation coefficient on porosity including attenuation coefficients at received frequencies of (A) 19.8 kHz, (B) 39.0 kHz, (C) 58.2 kHz, (D) 77.4 kHz and (E) 96.6 kHz, and (F) constant of proportionality k_A. Measured values are plotted as crosses with errors as red lines, while the empirical fit of Hamilton (1972) is denoted by a blue solid line with errors denoted by blue dashed lines.

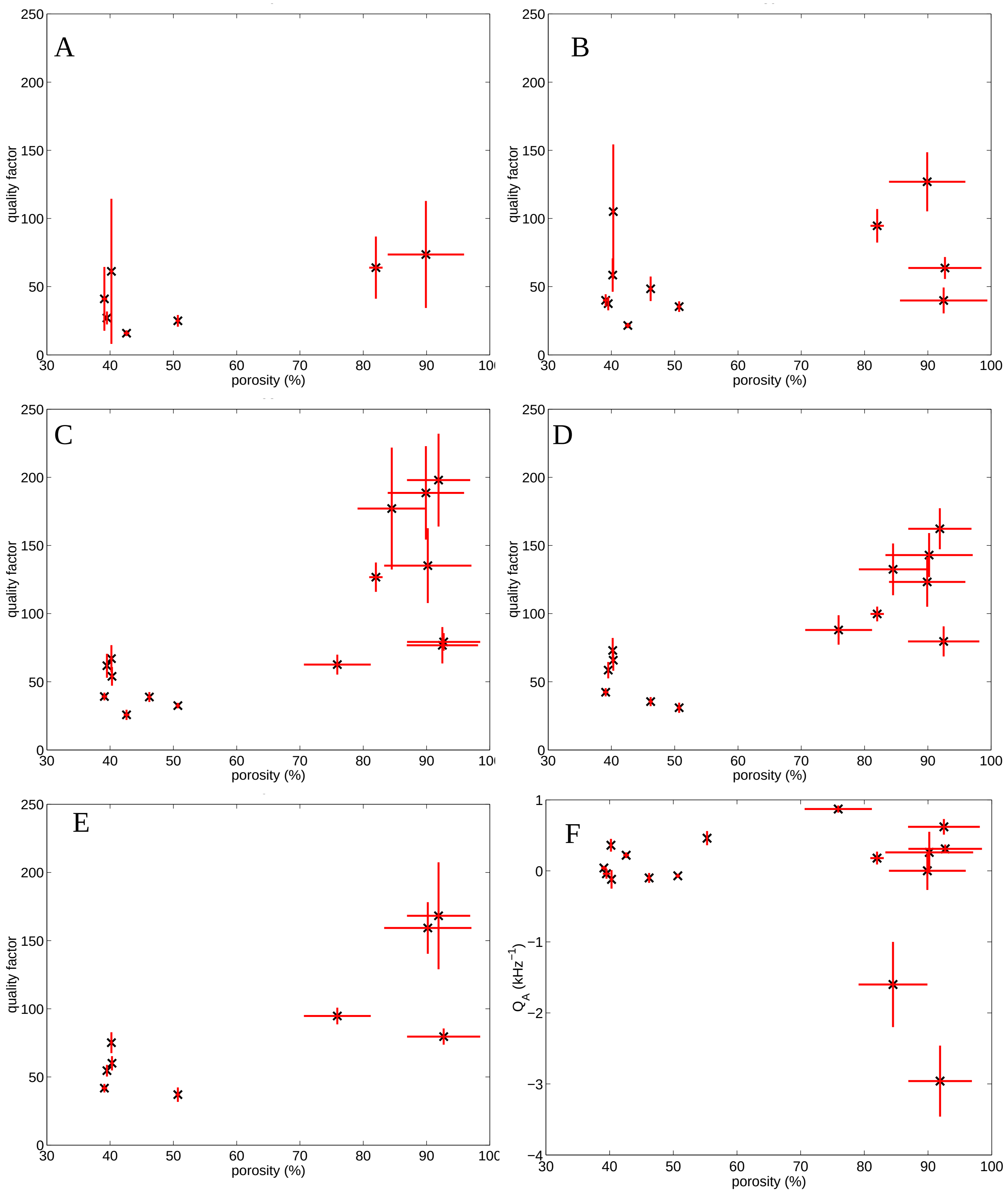


Figure 6.10. Dependence of quality factor on porosity including quality factors at received frequencies of (A) 19.8 kHz, (B) 39.0 kHz, (C) 58.2 kHz, (D) 77.4 kHz and (E) 96.6 kHz, and (F) constant of proportionality Q_A. Measured values are plotted as crosses with errors as red lines.

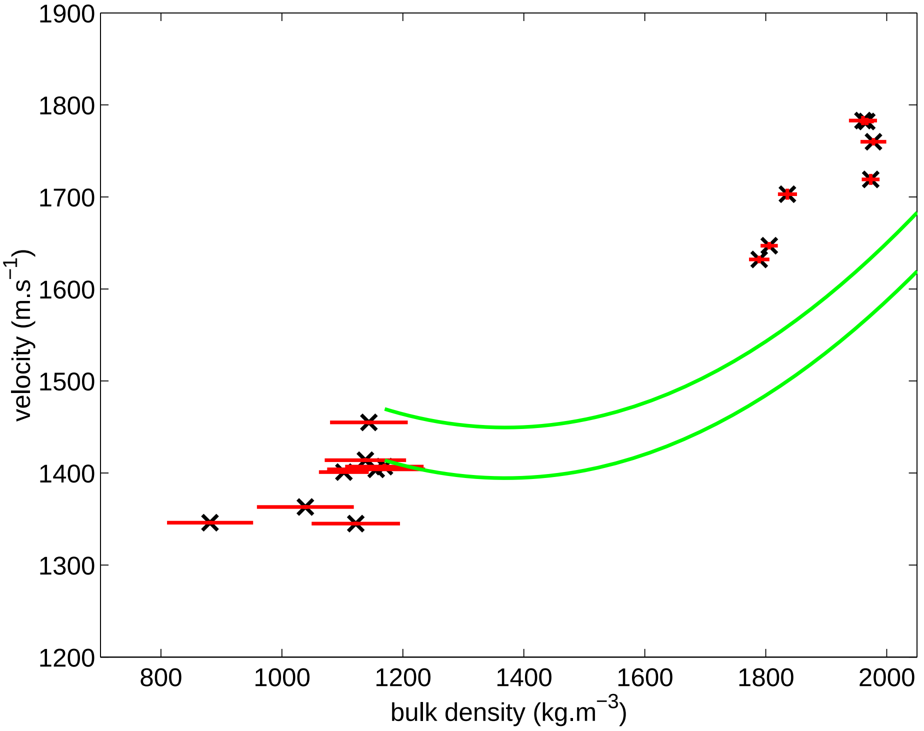
6.2.2. Dependence on bulk density

As discussed in *Section 2.2.2*, the density of sediment is primarily controlled by the porosity, with density decreasing as porosity increases. Hence the observation of an increase in mean velocity with bulk density, *Figure 6.11*, is expected. Velocity varies more dramatically with bulk density over the higher density range (1789 to 2238 kg·m^{-3}) than the lower range (881 to 1169 kg·m^{-3}). This broadly supports the quadratic relationship observed between velocity and bulk density in the literature, *Section 2.4.1*. However the observation of a minimum velocity over a density range of 1165 to 1445 kg·m^{-3} in the literature is not supported by this work. The empirical relationships under-predict velocities in high-density sands, with an extrapolation of the empirical fit below its lower limit of 1100 kg·m^{-3} resulting in an over-prediction of velocity in low density silts, the implications of which have been discussed in *Section 6.2.1*. The under-estimation of *in situ* bulk densities by the measurement techniques used within this project (see *Section 4.4.3*) will shift the measured velocities closer to the values predicted by the empirical equation.

The relationship between attenuation coefficient and bulk density is less clear, *Figure 6.12,* with high density sands possessing greater attenuation coefficients than low density silts. Attenuation coefficients generally decrease as density increases across the high density sands, with the trend particularly clear at 39, 58.2, 77.4 and 96.7 kHz. Though a large degree of spread exists, trends at 39 and 77.4 kHz imply an increase in attenuation coefficient with density from 1000 to 1200 kg·m^{-3}. Reduced confidence is placed in the attenuation coefficient corresponding to 881 kg·m^{-3}, due to the doubt in a sediment density less than that of water (999 to 1003 kg·m^{-3} from *Table 7.1*). The constant of proportionality k_A is greater in the higher density range than the lower density range, and is observed to increase with bulk density from 881 to 1169 kg·m^{-3} and a decrease as bulk density increases from 1789 to 2238 kg·m^{-3}. This implies that k_A reaches a maximum value in the intermediate density range of 1169 to 1789 kg·m^{-3}.

As expected the relationship between quality factor and bulk density displays reciprocal trends to those observed for attenuation coefficient and bulk density, *Figure 6.13*. Quality factor is greater in low density silts than in high density sands and displays an increase as bulk density increases from 1789 to 2238 kg·m^{-3}, with no trends clear across the low density range examined. The lack of a trend across the low density range probably results from the large degree of variability in attenuation coefficient obscuring underlying trends. This variability is a consequence of differing amounts of energy loss from sediment heterogeneities, examples of which include variable grain size distributions, shells with diameters less than 5 mm at Needs Ore 3 and rubble at the Universe and Saltern sites (see *Appendix B* for details). No trends between the constant of proportionality Q_A and bulk density are observable within the scatter of the data, which agrees with a similar lack of trends between constant of proportionality and porosity, *Section 6.2.1*.

The observed trends in k_A and attenuation coefficient indicate that energy losses are maximum for sediments with bulk densities within the intermediate range of 1169 to 1789 kg·m^{-3}, the implications of which have been discussed in *Section 6.2.1*. The clear dependence of both mean velocity and k_A on bulk density indicates that the bulk density of the sediment can be more reliably obtained from these compressional wave properties than from attenuation coefficients or quality factors.



F*igure 6.11. Mean velocity versus bulk density, with mean values denoted by crosses, errors in bulk density denoted by red lines and the green lines denoting the minimum and maximum velocities predicted by the empirical fit of Richardson and Briggs (1993). No errors in velocity are plotted, as these are less than 6 m·s^{-1}.*

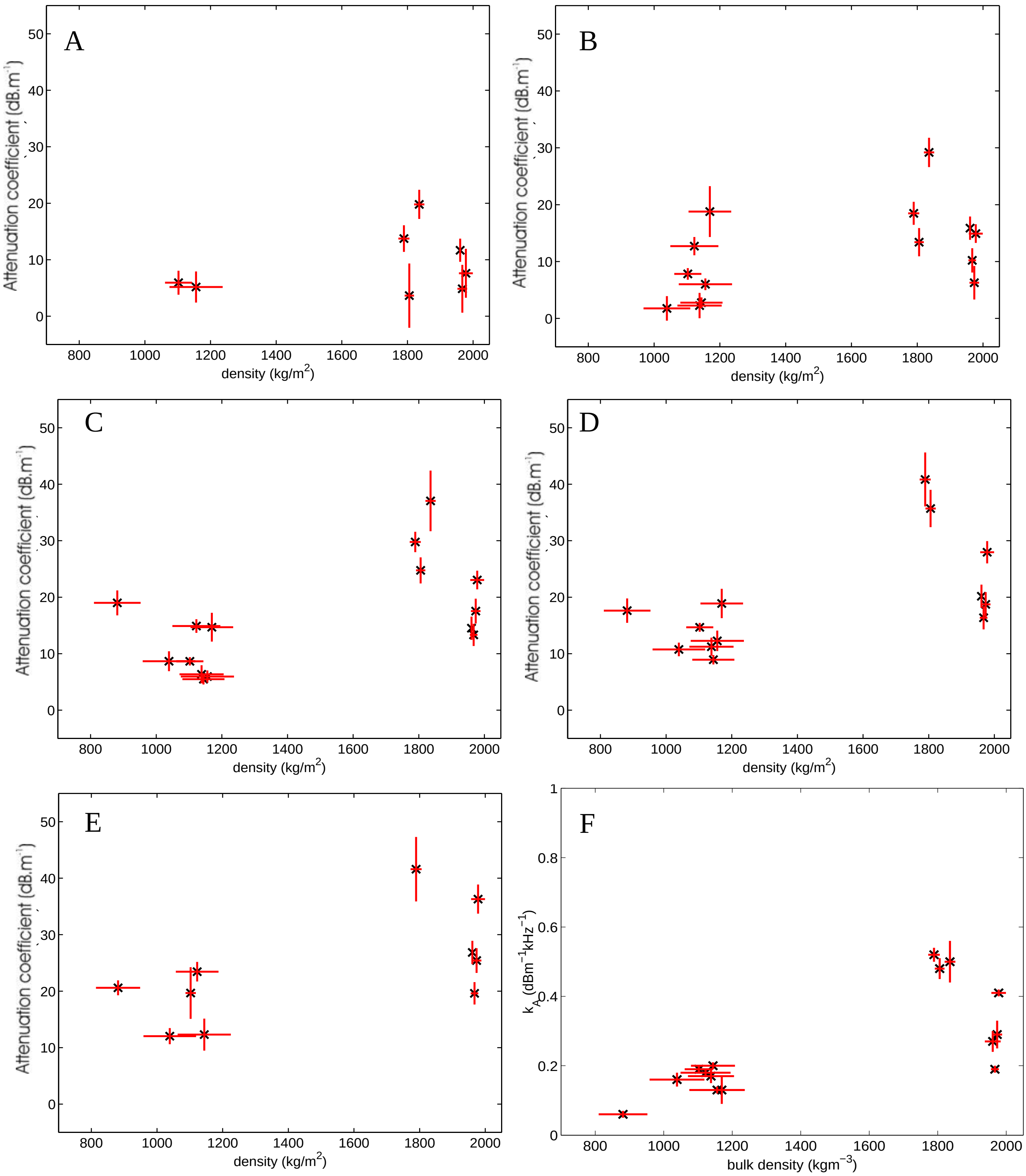


Figure 6.12. Dependence of attenuation coefficient on bulk density including attenuation coefficients at received frequencies of (A) 19.8 kHz, (B) 39.0 kHz, (C) 58.2 kHz, (D) 77.4 kHz and (E) 96.6 kHz, and (F) constant of proportionality k_A. Measured values are plotted as crosses with errors as red lines.

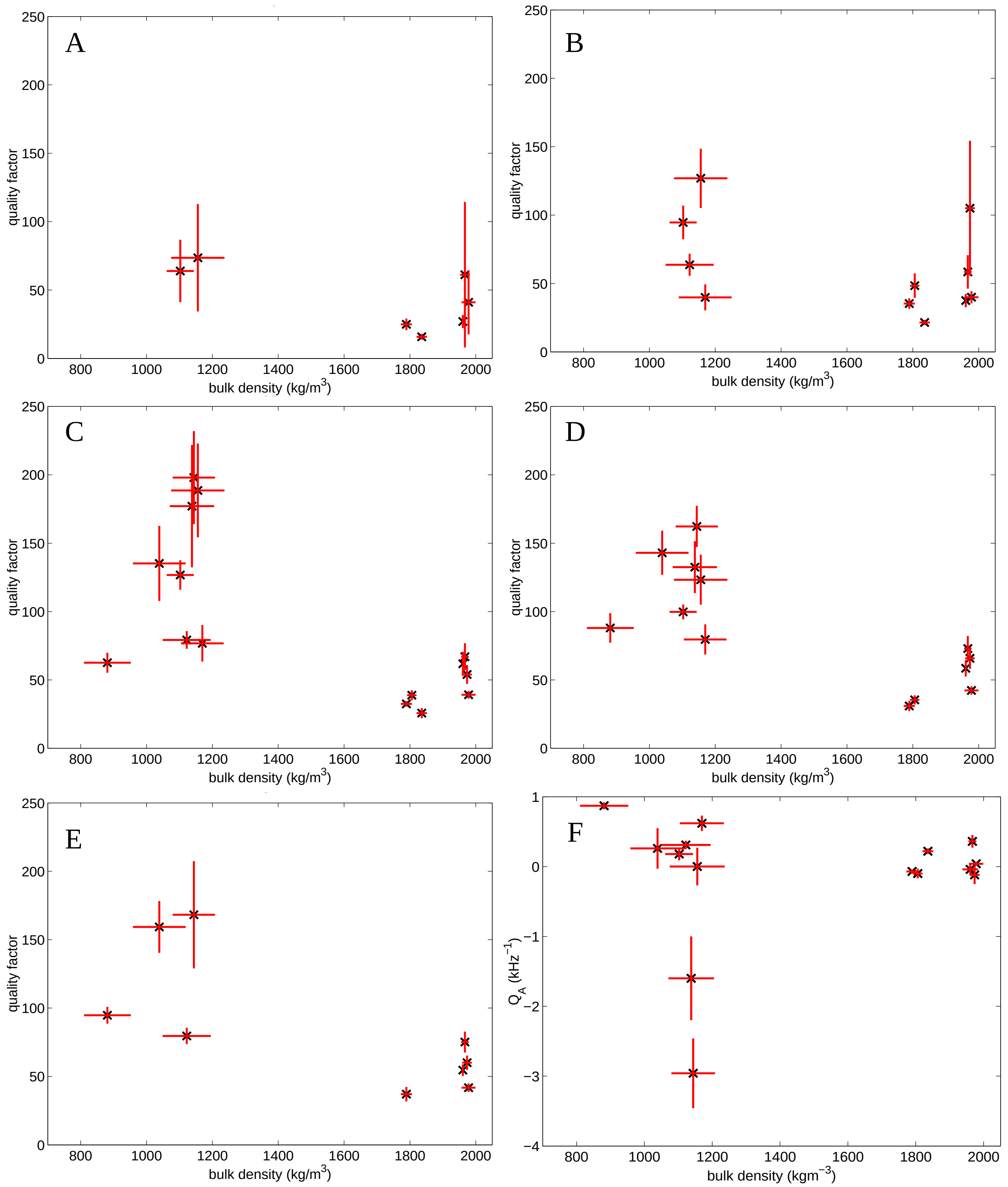


Figure 6.13. Dependence of quality factor on bulk density including quality factors at received frequencies of (A) 19.8 kHz, (B) 39.0 kHz, (C) 58.2 kHz, (D) 77.4 kHz and (E) 96.6 kHz, and (F) constant of proportionality Q_A. Measured values are plotted as crosses with errors as red lines.

6.2.3. Dependence on mean grain diameter

The mean grain diameter of the sediment is the most frequently measured geotechnical property and so the property to which compressional wave properties are traditionally compared. Unlike the geotechnical properties previously discussed in this section, the techniques used to measure both mean grain diameter and sand fraction are unaffected by the disturbance of the sample. Hence the measured values of both mean grain diameter and sand fraction are representative of *in situ* values. As observed in *Section 6.2.1* and *6.2.2* velocities are greater in sands than in silts, *Figure 6.14*. Velocities corresponding to mean grain diameters from 1.24 to 2.18 ϕ display a peak at 2 ϕ, an observation which is contradicted by a wide suite of literature and hence attributed to variability within the data. The spread of velocities for mean grain diameters of 6.22 to 7.89 ϕ prevents any trends being observed for silts. The lack of observation of published trends between velocity and mean grain diameter contrasts with the agreement of observed relationships between velocity and porosity, *Section 6.2.1*, and velocity and bulk density, *Section 6.2.2*. This supports the hypothesis that the dominant factor controlling both velocity and bulk density is porosity rather than mean grain diameter, as discussed in *Section 2.4.1*.

Greater attenuation coefficients occur in sands than in silts, *Figure 6.15*, with no relationship observed between attenuation coefficient and mean grain diameter from 1.24 to 2.18 ϕ. For mean grain diameters from 6.26 to 7.89 ϕ, the relationship between attenuation coefficient and mean grain diameter depends on frequency, with attenuation coefficient decreasing as mean grain diameter decreases at 58.2 kHz and 77.4 kHz and no trend visible for 19.8, 39, 96.6 kHz. This agrees with previous literature, which presents a decrease in attenuation coefficient as mean grain diameter decreases from 4 to 10 ϕ (see *Section* 2.*4.2* for details). No trends are observed between the constant of proportionality k_A and mean grain diameter in either sands or silts, although the agreement between the observed and predicted values are better than displayed in *Section 6.2.1*.

As observed in *Sections 6.2.1* and *6.2.2*, changes in quality factor are dominated by changes in attenuation coefficient and quality factor is greater in sands than in silts, *Figure 6.16*, with the difference between quality factor in sands and silts more pronounced at the higher frequencies of 58.2, 77.4 and 96.6 kHz. Trends between quality factor and mean grain diameter can be observed within both silts and sands at certain frequencies. The majority of the quality factors from 1.24 to 2.18 ϕ imply a decrease in quality factor as mean grain diameter decreases, while quality factor is observed to increase as mean grain diameter decreases from 6.27 to 7.89 ϕ. This implies that a minimum value of quality factor occurs between 2.18 and 6.27 ϕ, and so attenuation coefficient peaks in this intermediate range. The persistent anomaly of the quality factor at 1.24 ϕ, is attributed to large attenuation coefficients observed at the corresponding location (Studland 1) which arise from additional scattering losses from shells and pebbles. The scatter in the constant of proportionality Q_A prevents any relationships being identified with mean grain diameter, *Figure 6.16F*.

The obscuration of observable trends between all compressional wave properties, barr attenuation coefficient, and mean grain diameter highlights the secondary effect this geotechnical property has on compressional wave properties. Hence the large degree of variability introduced by additional properties, *e.g.* the porosity, sorting and modality of the sediment, will inhibit the reliable determination of mean grain diameter from compressional wave properties.

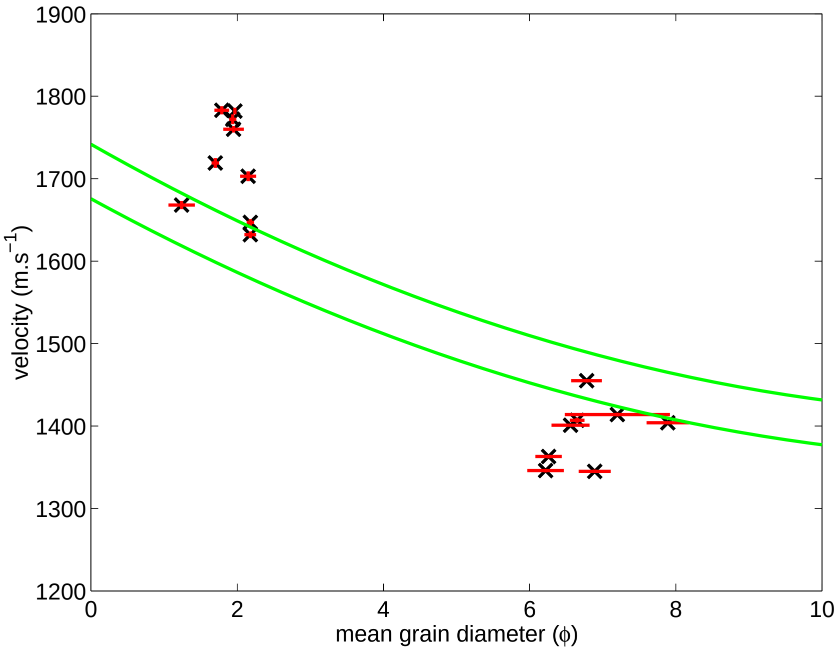


Figure 6.14. Mean velocities versus mean grain diameter, with mean values denoted by crosses and errors in mean grain diameter denoted by red lines. The minimum and maximum velocities predicted by the empirical fit of Richardson and Briggs (1993) are denoted by green lines. No errors in velocity are plotted, as these are less than 6 m·s^{-1}.

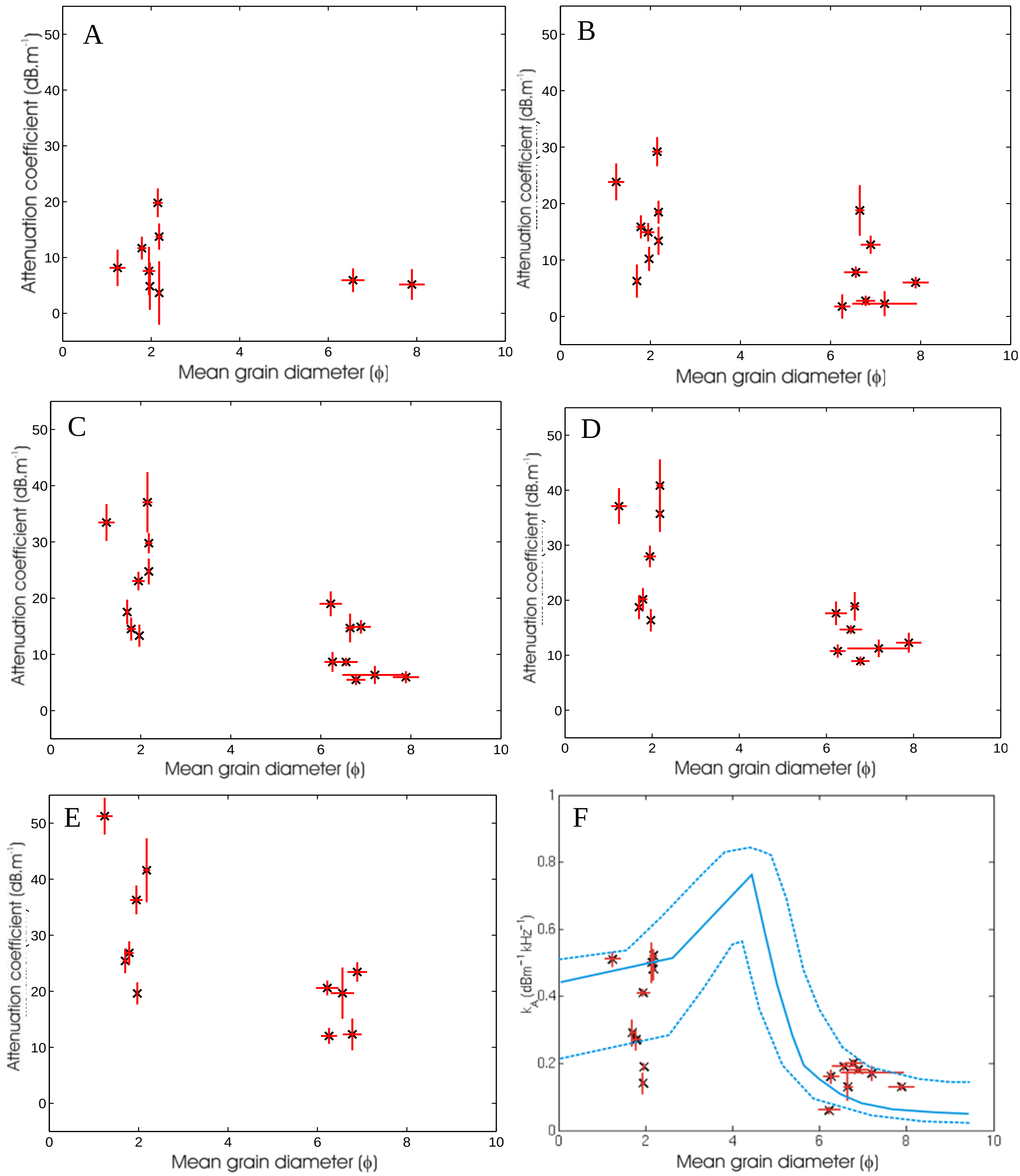


Figure 6.15. Dependence of attenuation coefficient on mean grain diameter including attenuation coefficients at received frequencies of (A) 19.8 kHz, (B) 39.0 kHz, (C) 58.2 kHz, (D) 77.4 kHz and (E) 96.6 kHz, and (F) constant of proportionality k_A. Measured values are plotted as crosses with errors as red lines, while empirical fit of Hamilton (1972) is denoted by blue solid line with errors denoted by blue dashed line.

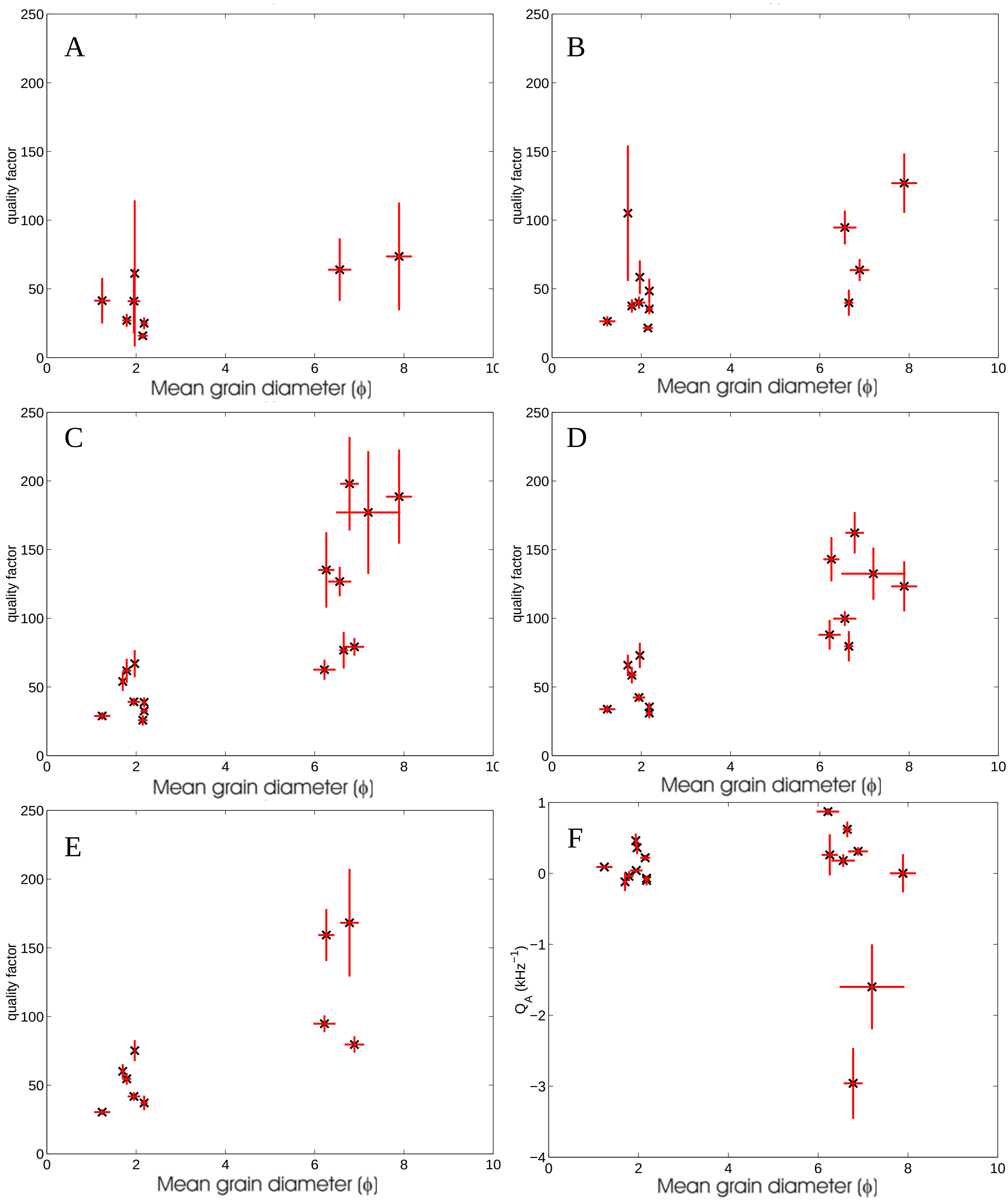


Figure 6.16. Dependence of quality factor on mean grain diameter including quality factors at received frequencies of (A) 19.8 kHz, (B) 39.0 kHz, (C) 58.2 kHz, (D) 77.4 kHz and (E) 96.6 kHz, and (F) constant of proportionality Q_A. Measured values are plotted as crosses with errors as red lines.

6.2.4. Dependences on percentage of sand sized particles

The percentage of sand sized particles represents an alternative measure of grain size distribution to mean grain diameter, which allows the relative proportions of coarse and fine grains to be assessed. As expected from *Section 6.4.3,* velocity is greater for higher percentages of sand sized particles (98.8 to 99.9 %) than for the lower range (2.5 to 21.8 %*) Figure 6.17*. Despite the variability, velocity is observed to increased with sand fraction from 98.8 to 99.9 % and decrease as sand fraction increases from 3.2 to12.6 %. Over the higher range of sand fractions, the observed trend agrees with previous research while over the lower range, the observed trend contradicts previous research (*Section 2.4.1*). However, owing to the spread of velocities values and presence of significant proportions of organic and shell material in the sand fractions of the medium to fine silts (*Section 4.4.3*) no conclusions can be drawn concerning the validity of previous research. The use of clay fraction rather than sand fraction prevents comparison with the micro-geometrical model, *Section 2.5.3*.

As expected attenuation coefficient is greater for the upper range of percentage sand sized particles than the lower range, *Figure, 6.18.* Though the upper region spans a range of less than 3 %, a consistent decrease is observed as percentage of sand sized particles increases. Over the lower range, certain frequencies display an increase in attenuation coefficient as the percentage of sand sized particles increases, while other frequencies display a decrease in attenuation as percentage of sand sized particles increases. The constant of proportionality k_A is also observed to decrease as the percentage of sand sized particles increases, *Figure 6.18F.*

As expected from *Sections 6.1.1* to *6.1.3* quality factor is greater in the lower range than the higher range, with the effect more pronounced at the higher frequencies of 58.2, 77.4 and 96.6 kHz, *Figure 6.19*. Over the lower range, no clear trends between quality factor and percentage of sand sized particles can be observed, while an increase in quality factor is observed as percentage sand increases from 98.8 % to 99.9 %. No relationship is observable between the constant of proportionality Q_A and percentage of sand sized particles, *Figure 6.19F.*

Despite the presence of shell material (calcite), organic material and quartz grains in the sand fraction, the present research indicates that predictions of the sand fraction from compressional wave properties will be more reliable than predictions of mean grain diameter, *i.e.* the relative proportions of coarse to fine particles has a more pronounced effect on compressional wave properties than mean grain diameter. Hence, if a research project intends to examine the relationship between the geoacoustic and geotechnical properties of marine sediment, the geotechnical analysis undertaken should retain all materials that affect the propagation of acoustic waves in marine sediments. The decrease of attenuation coefficient, and increase in quality factor, as percentage of sand sized material increases from 98.8 % to 99.9 % is of particular interest, as the variation of these properties over this high range have not been previously examined.

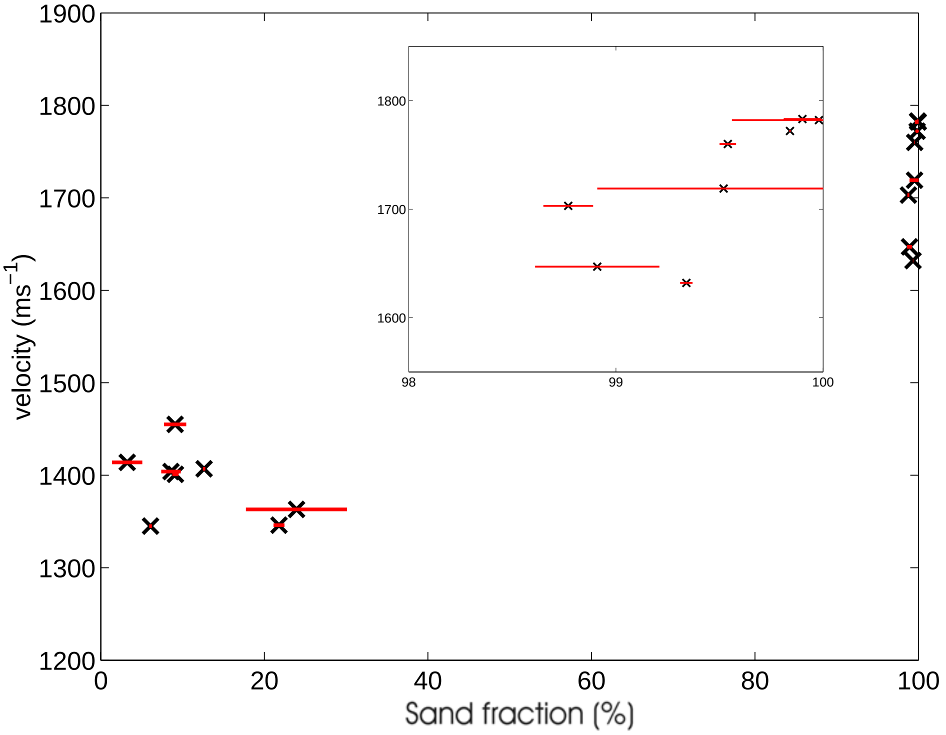


Figure 6.17. Mean velocity versus percentage of sand sized particles with mean values denoted by crosses and errors in mean grain diameter denoted by red lines. No errors in velocity are plotted as these are less than 6 m·s^{-1}, while inset displays zoomed image for sand fractions greater than 98 %.

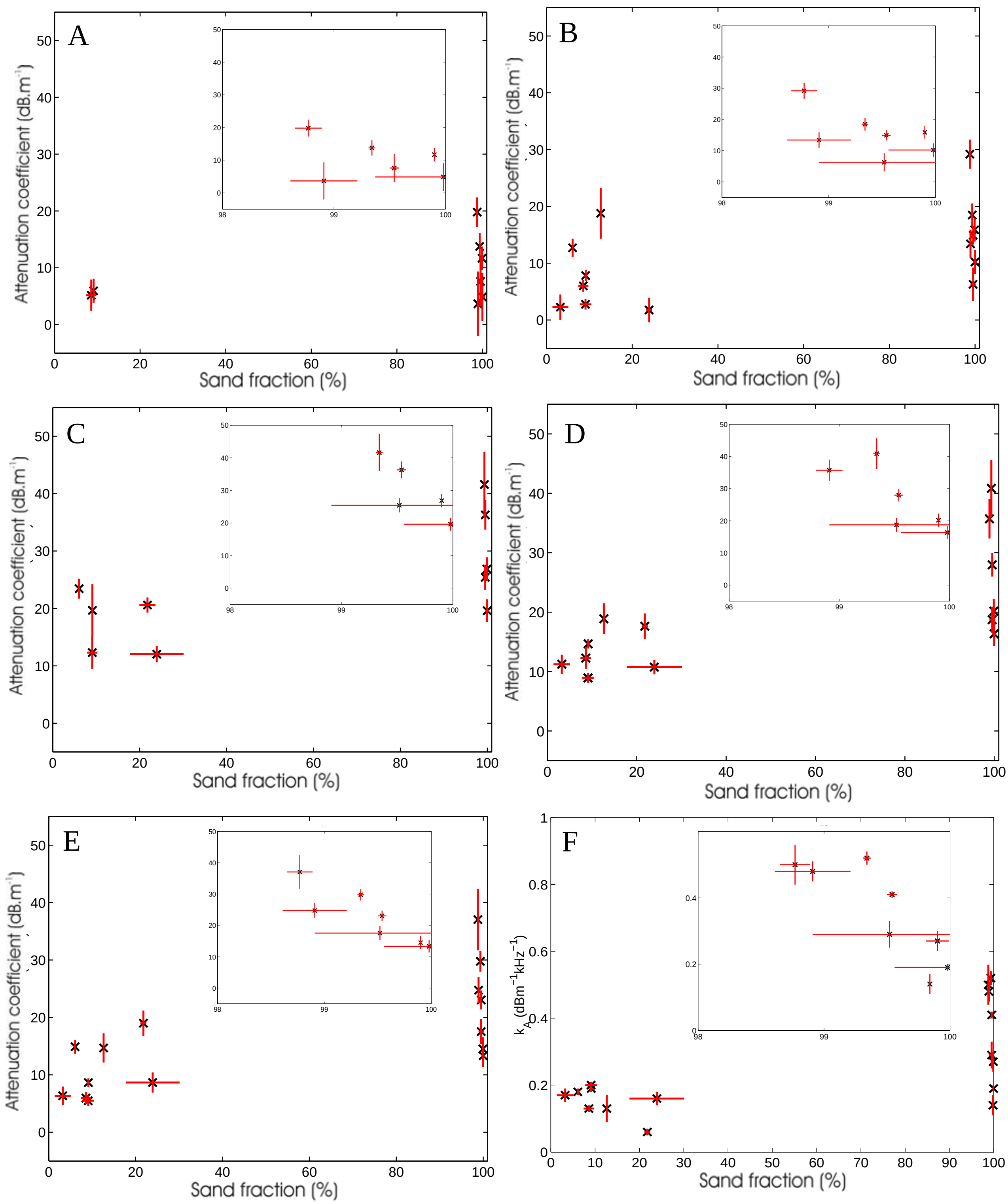


Figure 6.18. Dependence of attenuation coefficient on percentage of sand sized material including attenuation coefficients at received frequencies of (A) 19.8 kHz, (B) 39.0 kHz, (C) 58.2 kHz, (D) 77.4 kHz and (E) 96.6 kHz, and (F) constant of proportionality k_A. Measured values are plotted as crosses with errors as red lines. Insets display zoomed images for sand fractions greater than 98 %.

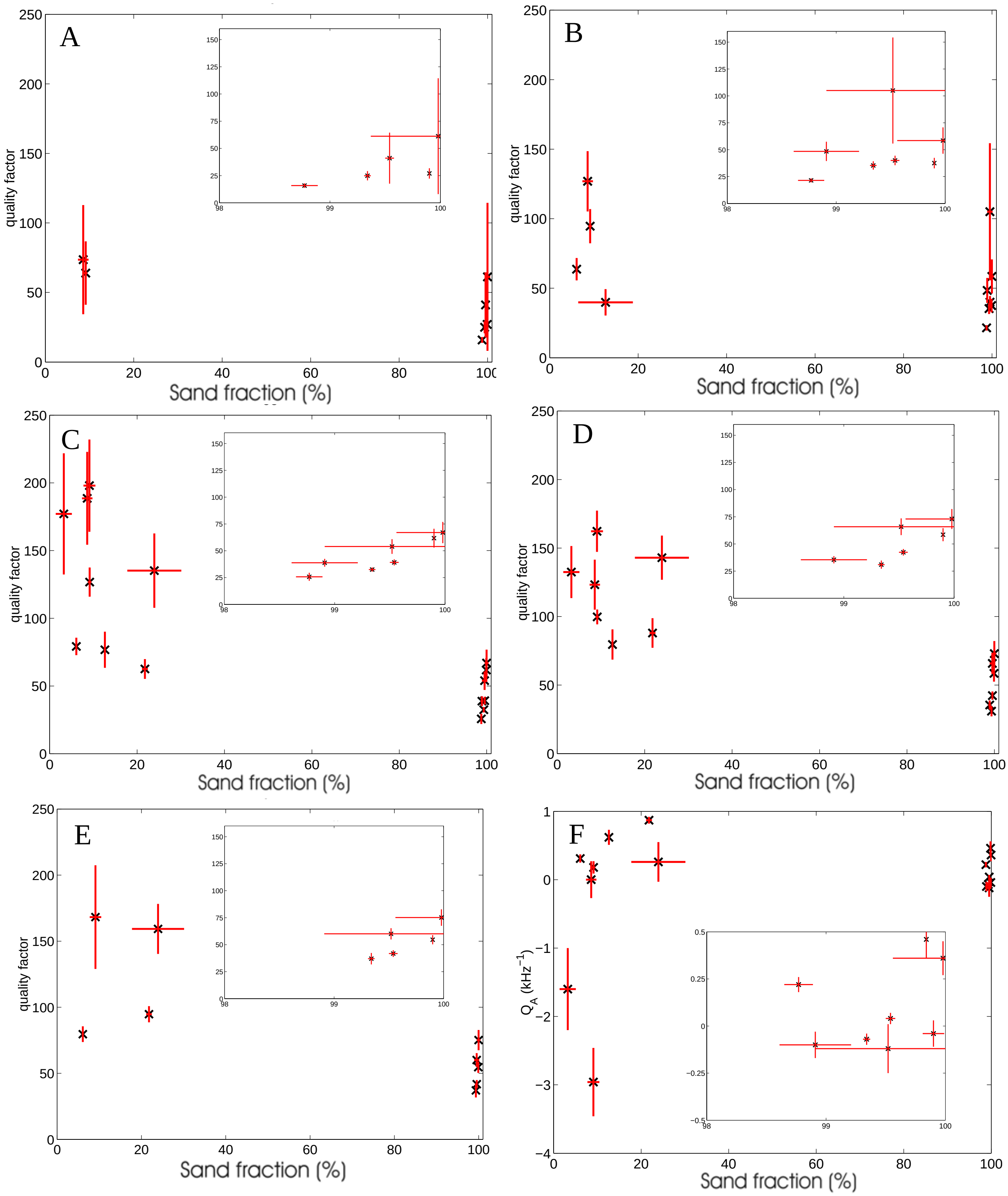


Figure 6.19. Dependence of quality factors on percentage of sand sized material including quality factor at received frequencies of (A) 19.8 kHz, (B) 39.0 kHz, (C) 58.2 kHz, (D) 77.4 kHz and (E) 96.6 kHz, and (F) constant of proportionality Q_A. Measured values are plotted as crosses with errors as red lines, with insets displaying zoomed mage for sand fractions greater than 98 %.

6.3. Summary

In this chapter the compressional wave properties from a range of inter-tidal sand and silts sites examined are presented. Group velocities were greater in sands (1590 to 1880 $m \cdot s^{-1}$) than in silts (1260 to 1472 ms^{-1}), with measured values greater than those previously presented for sands. The observation of velocities less than that of pore water in silts is supported by the extant literature. Attenuation coefficient ranged from 2 to 52 $dB \cdot m^{-1}$ in sands and 1 to 23 $dB \cdot m^{-1}$ in silts, with values in sands broadly agreeing with previous research and values in silts exceeding those from previous research. Quality factors were less in sands (14 to 120) than in silts (66 to 400). Despite measured values being considerably greater than those previously published for medium to fine silts, the omission of errors from the published values prevents the significance of this discrepancy from being determined.

Within the sand sites, the variability of compressional wave properties agreed with spread of the geotechnical properties over each site, with significant variation introduced owing to the non-unique nature of marine sediment. Within the silt sites, no direct link could be made between the observed spread of geotechnical and compressional wave properties, implying that geotechnical properties can be more reliably obtained from compressional wave properties in sands than in silts.

Statistical analysis confirmed that, within the errors observed, velocity was independent of frequency for sandy sediments. However within the reduced velocity errors observed for silts, neither the hypotheses that velocity is independent of frequency or is proportional to frequency are acceptable. An attenuation coefficient which was proportional to frequency was confirmed for the majority of the sand and silt locations examined, with constants of proportionality k_A greater in sands (0.19 to 0.52 $dB \cdot m^{-1} \cdot kHz^{-1}$) than in silts (0.06 to 0.2 $dB \cdot m^{-1} \cdot kHz^{-1}$). No conclusions could be drawn concerning the frequency-dependence of quality factor in either sands or silts.

Qualitative trends between compressional wave properties and geotechnical properties were also examined. These confirmed that porosity is one of the dominant factors controlling compressional wave properties, and hence a geotechnical property that can be relatively reliably determined from compressional wave properties. Observed trends also indicate that compressional wave properties can be used to determine bulk density and sand fraction, while the large degree of variability observed in plots of compressional wave properties against mean grain diameter will inhibit the reliable determination of mean grain diameter from these acoustic properties. Measured velocities in silts are generally less than those predicted by the Wood’s equation. This implies that either these measured velocities are suspect or that organic material within the silts produces lower grain bulk modulii than present for purely mineral aggregates.

Despite the presence of shell material (calcite), organic material and quartz grains in the sand fraction, the present research indicates that the sand fraction more accurately describes the grain size distribution than mean grain diameter does. Hence, if a research project intends to examine the relationship between the geoacoustic and geotechnical properties of marine sediment the geotechnical analysis undertaken should retain all materials that affect the propagation of acoustic waves in marine sediments.

The trends in attenuation coefficient and quality factor indicate that maximum energy losses occur for sediments with porosities from 50.7 to 75.9 %. This can be explained through a higher level of heterogeneities in the mixed sediment which possess these porosities, which results in increased energy losses from either increased scatter or squirt flow.