Evaluation of CPT - based Correlation of Fines Content and Soil Behaviour Index for Groningen Soils

by

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to obtain the degree of Master of Science
Section Geo - Engineering,
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to be defended publicly on November 21, 2019 at 11.00 AM .

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Acknowledgement

This master thesis results from valuable contributions of many people, to whom I express my sincere gratitude. I am deeply thankful to my supervisor, *Dr.Mandy Korff* for offering this interesting topic to work on and being so patient with me throughout and my Graduation committee members, *Dr. Dominique Ngan-Tillard* and *Dr. Femke Vossepoel* for guiding me and for sharing their knowledge and timely feedback.

Special thanks to *Kees-Jan van der Made*, my supervisor at Wiertsema and Partners B.V., for encouraging me to find my strengths and to improve my coding skills in python during data collection process. I would also like to thank my colleagues *Alain Maas*, *Maria Palomeque* and other colleagues at Wiertsema and Partners B.V. for being very kind in helping me with the collection of the data and understanding of the database structure. I would also like to thank Deltares for providing me with CPT data.

My heartfelt thank you to all my friends who stood by me during this journey. I'm eternally grateful to *Madhu* and *Kavya*, for being my family here in Netherlands. *Neethu* and *Sushma*, my angels, for advising me and constantly pushing me to do better. Special thanks to *Vinay* and *Meghana* for assisting me with coding and being my saviours during homeless phase and otherwise. A huge shout out to my Sai family-*Ramchandra Rao & family, Nel, Audrey & Aniel, Kiran, Pavan* for having my back.

I am grateful to have parents and family members who believe in me and allow me to fly, no matter what. *Chandrashekhar Doddamani and Arpana Doddamani*, I love you and I am, because of you both. My grandparents, *FY,SF Doddamani and NK,VN Dhavale* for supporting me mentally, emotionally and financially during times of need. Without you all, this journey would not have been possible. Last, but not the least, *Swami*, Thank you for this journey, which has guided me to travel deep within and find the light at the end of the tunnel (literally!).

Chaitra Chandrashekhar Doddamani
Delft, November 2019

Abstract

Earthquakes in the past few decades has questioned the safety of people and infrastructure in Groningen region and its surroundings areas. The excessive gas extraction from the subsurface has led to human-induced earthquakes in this region. Liquefaction is a phenomenon that occurs as a result of earthquakes, reducing the soil shear strength to zero and the soil in turn behaving like a liquid. It has been observed in other parts of the world in case of natural and human-induced earthquakes alike.

Thus, it is necessary to identify the liquefaction prone regions and taking steps towards creating better designs, equipped to handle earthquake loads along with precautionary measures, to save existing building and infrastructure.

In order to do so, it is important to examine the existing the methods, various parameters and factors that influence the liquefaction potential analysis. In this project, the different factors that could influence Liquefaction Potential Analysis are studied based on the existing CPT-based correlations between Fines Content (FC) and Soil Behavior Index(IC).

The previously proposed correlation by Boulanger and Idriss (2014) is examined for Groningen Soils to evaluate if it needs any modifications. Depth of the sample, Distance between CPT and borehole, Grain Size Distribution and Geology of the sample are main factors considered for the study. Each of these factors are analysed by collecting laboratory samples of Grain size analysis test from Groningen region. The strength of the correlation between FC and IC is evaluated based on the factors.

This study would be beneficial for geo-technical software developers, construction and design engineers who highly depend on correlations and it gives insight of how different the onsite scenario can be from the predicted values using correlations. It contributes to the future research on creating a data base of the all samples in the Netherlands, to indicate high risk regions. It also helps in answering if IC is a good parameter to consider while evaluating liquefaction potential for Groningen Soils.

List of Symbols

Symbol	**Description**	**Units**
FS_L	Factor of Safety	$-$
CRR_z	Cyclic Resistance Ratio	$-$
CSR_z	Cyclic Shear Ratio	$-$
q_c or q_t	Cone Resistence	MPa
f_s	Sleeve Friction	MPa
σ'_{vo}	Effective stress	kPa
σ_{vo}	Total stress	kPa
u_2 and u_0	Pore water Pressures	$-$
Q_t	Normalised Cone Resistence	MPa
FC	Fines Content	%
I_c or IC	Soil Behavior Index	$-$
ϵ or CFC	Error term or Fitting parameter	$-$
I_{GS}	Grain Size Index	$-$
R^2	Coefficient of Determination	$-$
$D50, D60, D30, D10$	Percentage of soil particles finer than this size	%

List of Abbreviations

ASTM	American Standards for Testing Materials
BH	Bore Hole
BPT	Becker Penetration Test
Cc	Coefficient of Curvature
CPT	Cone Penetration Test
Cu	Coefficient of Uniformity
NAM	Nederlandse Aardolie Maatschappij BV
FC	Fines Content
GBase	Data Storage with location details
IBase	Data Storage without location details
IC	Soil Behaviour Index
NEN	National Standards accepted in Netherlands
PSD	Particle Size Distribution
SPT	Standard Penetration Test
SBT	Soil Behaviour Type
SQL	Structured Query Language
W&P	Wiertsema and Partners B.V.

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Introduction

1.1. General

Groningen region, northern part of Netherlands was identified to have the largest natural gas reserves in Europe. Since late 1950s, Nederlandse Aardolie Maatschappij BV (NAM) has been extracting natural gas. The exploitation of natural gas has resulted in "human-activity" induced earthquakes that has greatly affected the lives of the people and damaged existing properties. This study contributes to the prediction of liquefaction, triggered by earthquakes due to gas extraction, in the Groningen region in the near future.

As stated by Sladen et al (1985) "Liquefaction is a phenomenon where in a mass of soil loses a large percentage of its shear resistance when subjected to monotonic, cyclic or shock loading, and flows in a manner resembling a liquid until the shear stresses acting on the mass are as low as the reduced shear resistance." After 1964, Niigata Earthquake and Alaska Earthquake, liquefaction was identified as the major cause of damage. Over the last two decade, substantial amount of research has been done. Christchurch, New Zealand in 2010 and 2011 recorded earthquakes of 7.1 and 6.3 magnitude which also led to liquefaction. The highest magnitude recorded so far in Groningen is, 3.6 at Huizinge in 2012. Since earthquakes can lead to liquefaction, it would be ideal to have liquefaction prone sites identified to have minimum damage. It could lead to better infrastructure designs and economical solutions.

There are many contributing factors to susceptibility of soils to liquefaction such as history of the soil at location, composition, geological formation and natural state of the soil itself. Thus, understanding the properties of soil becomes an essential part of this study. Over the last five years a lot of construction companies have taken interest in investigating the effects of the induced earthquakes in the Groningen region as they've been involved in recovery of the damaged structures.

Cone penetration test (CPT) in the Netherlands is one of the most common, preliminary geotechnical tests to be made at any site. It forms the basis for calculating bearing capacity of the soil, determining the soil type and throws light on the different layers of soil present in sample. This would help in understanding the properties of soil and in determining whether the soil is capable of handling different kinds of loads, both static and dynamic. Depending on the different type of soil present, and the lab tests done on the samples collected, through boreholes (BH), it can be studied together to make detailed soil profile at a particular location. The Soil Behaviour Index (IC) is calculated using the parameters measured by CPT.

Particle Size Distribution or Grain size analysis (PSD) is geotechnical test, used to determine the percentage of various sizes of particles in a given dry soil sample. This is performed in two stages, sieve analysis (dry analysis) and sedimentation analysis (wet analysis) for coarser and finer soils respectively. A soil behaviour is studied based on the gradation of a soil, which is the particle size distribution curve, a graph plotted on a logarithmic scale with Percentage finer vs particle diameter. Fines Content (FC) percentage is calculated from PSD results.

In this project, the FC, IC and their correlation are of major interest, to determine triggering of the liquefaction potential, by analysing the various factors that influence them . Based on work done by Robertson and Wride (1998), IC is calculated from the CPT test which is a function of cone resistance (q_t) and Sleeve friction (f_s). According to Boulanger and Idriss (2014) study on CPT liquefaction triggering, it is discussed that the FC and IC have a correlation, as presence of fines influences the triggering of liquefaction.

1.2. Problem Definition

Groningen region recorded small earthquakes and tangible amount of damage and loss of property. To assure safety for the years to come by, detailed investigations are necessary. Liquefaction potential analysis is essential to identify the potential liquefiable layers. It requires the knowledge of the composition and properties of soil, geology, and location. CPT data can verfied using the BH samples to identify the soil profile with better precision. It is economical, most commonly used and efficient method for profiling of the subsurface soil layer.

The soil properties can be evaluated and calculated from the CPT data available, which aids in understanding the soil type, based on the soil behaviour. Accurate results are necessary from the field, by validating the bore hole data with the CPT data, to assure realistic estimates of correlations between parameters, leading to effective and economical design solutions. However, locations that are not exactly the same, in terms of location, geology, type and properties, would need a site specific correlation. At times, when the correlations need to be modified to a larger extent, it becomes mandatory to evaluate the parameters involved in the correlation and verify it based on the field results.

1.3. Research Objectives and Research Question

This research focuses mainly on the type of soil based on its geological formation, the particle sizes, and its influence on FC, IC correlation, which plays an important role in determination of Liquefaction Potential. Thus, the major research objective is:

”What is the correlation between Fines Content and Soil Behaviour Index for Groningen soils?”

This can be broken down into the following sub-questions:

1. What is FC verses IC for Groningen soils?
2. What are the factors that influence the correlation between FC and IC?

   Analysis based on the following factors:

   - Depth of the sample
   - Distance between CPT and borehole from which a sample has been collected
   - Gradation of the soil sample
   - Geology of the region/age of the soil
3. Boulanger and Idriss (2014) correlation between FC and IC is widely used.

   $$FC = 80(IC + CFC) - 137 \tag{1.1}$$

   To validate if the same correlation can be used for soils of Groningen safely.

   - Does this correlation accurately estimate FC value closer to true FC derived from laboratory tests ?
   - Is it necessary to modify the correlation when considering Groningen soils?

1.4. Research Approach

The following approach is being adopted for the study,

1. Collection of laboratory data and creating a database:
   - Selection of area for the study.
   - Identifying the projects having PSD test results.
   - Collection of laboratory PSD test results.
   - Creating a database with unique ID.
2. Processing of the collected data:

  - Calculation of FC based on the Dutch standards and ASTM from PSD.
  - Calculation of IC value based on Robertson (2009).
  - Extraction of pairs of CPT and BH based on distance between them.

3. Statistical Characterisation and Analysis:
  - Creating scatter plots based on the selected four factors.
  - Creating of subsets all samples based on the four factors.
  - Analysis bases on the Coefficient of Determination (R^2 value).
  - Calculations based on correlation proposed by Idriss and Boulanger(2014)
4. Results and Conclusions:
  - Results from analysis based on four select factors
  - Conclusions and recommendations.

2

Literature Review

This chapter presents the literature study for the chosen topic. Here is a general introduction to earthquakes, liquefaction, liquefaction potential analysis, and the basic geotechnical tests like cone penetration test(CPT), the grain size analysis(PSD). The background for the CPT-based correlations between the parameters selected for the study by other scientists and researchers is explained.

2.1. Earthquakes and Induced Earthquakes

Earthquake is a naturally occurring phenomenon, by the shearing of fault planes. Its defined as the shaking of the surface of the earth, resulting in the sudden release of energy created by seismic waves. This type of naturally earthquakes are caused by the movement of tectonic plates, fault mechanisms due to behaviour of rocks. It can also be triggered by tides or volcanic activity. This results in the loss of human life and damage to property. Humans have always been interested in understanding the nature better, to protect themselves from such natural disasters, to adapt and also to learn from previous experiences to create better safety measures for future. Thus, Earthquakes have been of interest to researchers all over the world.

First ever recorded earthquake was in China about 3000 years ago (Kramer, 1996). In the present times, an earthquake can result in the loss of millions of human lives and property damage running into billions. Due to the space constraints and growth in population, thousands are forced to live in the earthquake prone zones. Regions which are not earthquake prone zone naturally, are at a threat, due to human activity. These are known as human "induced earthquakes".

Human activities such as construction activities underground, or mining activities could be responsible for the triggering of fault plane failures. Injection of fluids into a fault zone, freezing and thawing technologies during construction of piles/tunnels causing temperature difference, altering the pore water pressure, excavations leading to re-adjusting of overburden pressures or a landfill construction changing the overburden pressures, etc can cause induced earthquakes. These are triggered by the effect of human activity. The earthquakes caused by human activity usually create a smaller strain energy release compared to those triggered by tectonic plate movements, nonetheless, causing severe damage. Induced earthquakes magnitude is comparable to that of natural earthquakes due to the stress change occurring from within the sub-surface layers of the ground.

Induced earthquakes occur at a shallow depth up to 3km. The duration of the such earthquakes are smaller compared to naturally occurring earthquakes. The soil strata comprises of mostly soft soil deposit at a shallow depth which transmit the seismic waves at a lower speed (50 to 300 m/s) than rocks or coarser material that transmit the wave at a higher rate of speed (up to 1500 m/s)(van Elk et al., 2013). Earthquakes at Groningen are induced earthquakes based on the above criteria. It is triggered due to the extraction of gases from the sub surface.

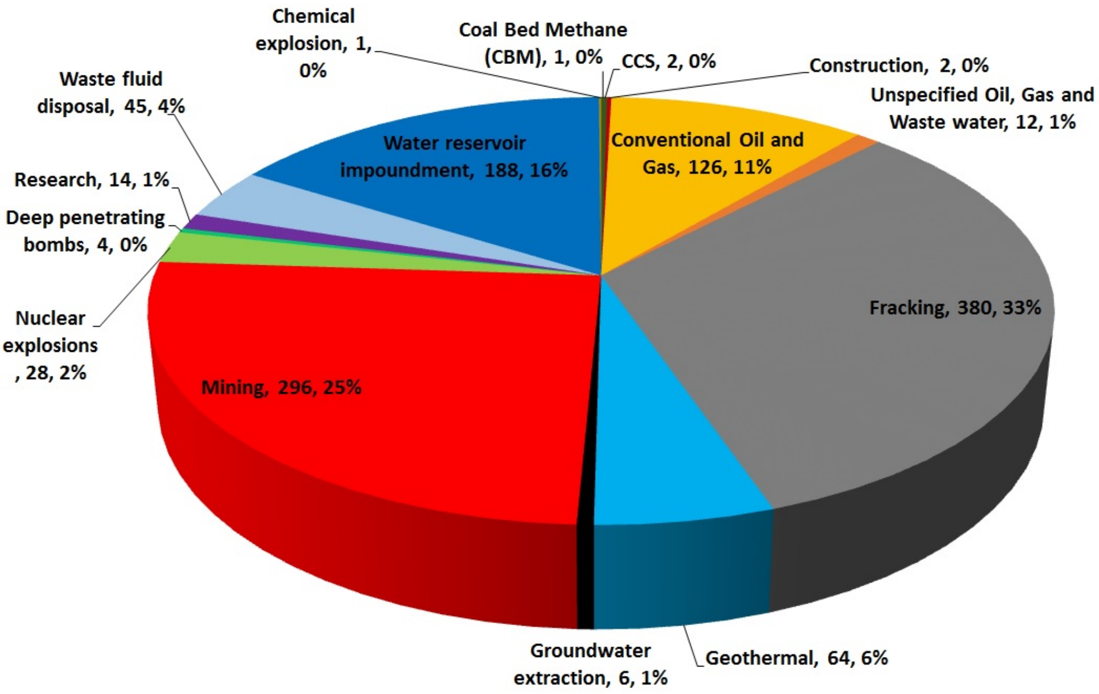

Figure 2.1: Various causes of Induced Seismicity and documented number of cases. Source:Wilson, M. P et al.(2017)

HiQuake – The Human-Induced Earthquake Database, is the most complete data base of anthropogenic projects proposed, on scientific grounds, to have induced earthquake sequences by Wilson, M. P et al.(2017). Figure 2.1 sheds light on the different human induced earthquakes and the number of earthquake cases registered as HiQuake. Differential ground subsidence and lateral spreading induced by liquefaction causes severe damage to infrastructure and lives within the city, requiring a large financial investment from the government for rehabilitation and restoration work.

2.2. Liquefaction

Soil is said to be liquefied when the effective stress of the soil becomes zero, under cyclic loading conditions. When a loosely packed, fully saturated soil is liquefied, the soil particles are in suspension and acts as a viscous fluid resulting in considerable deformations in the soil and severe damage to infrastructure. These suspended soil particles deposit at the ground surface as sand boils and/or quick sand, while excess pore water may cause surface flooding (Seed and Idriss, 1982).

Liquefaction develops suddenly and at a rapid rate , which could occur from either drained or undrained conditions. As long as the necessary triggering factor is acting, a sudden undrained behaviour could develop and generate failure under significant discharge of excess pore pressures (Kramer, 1988). The drainage of the excess pore water pressure leads to settlement of the soil after the dissipation of the vibrations of the dynamic load.

When a sample with loose sand particles is subjected to dynamic load, the particles tend to restructure themselves to pack tightly, however since the time span is short, the particles float in water. Once the dynamic loads have dissipated, drainage of the excess pore water occurs. In this study, liquefaction is considered only for the sands and the behavior on soft/organic soils like clay is disregarded. Soft soils also undergo a similar phenomena, which can seen in ”Quick Clay”. Earthquake propagation is slower through dense soils and it is faster through loose soils.

Drained behavior is said to occur when the loading is slow on a dense soil sample, resulting in volume increase due to dilation. If a loosely packed soil is subjected to same conditions, it results in contraction, leading to densification of the soil by decrease in volume. However, when the loading is rapid, leaving no time for the water to expel out, an undrained behavior is observed.

In a densely packed, saturated sample, under rapid loading conditions, there is no volume change as the dilation is not allowed by water in between soil particles, which is in-compressible. This leads to strengthening of soil. When a loosely packed soil is subjected to same conditions, there is no change in volume due to prevention of contraction causing the reduction in strength of the soil. In dense soils, there is a positive confinement causing increase in strength and in loose soils there is negative confinement leading to decrease in strength. This is shown in Figure 2.2 based on critical line approach.

Liquefaction may result in vertical (subsidence) and/or lateral (lateral spread-

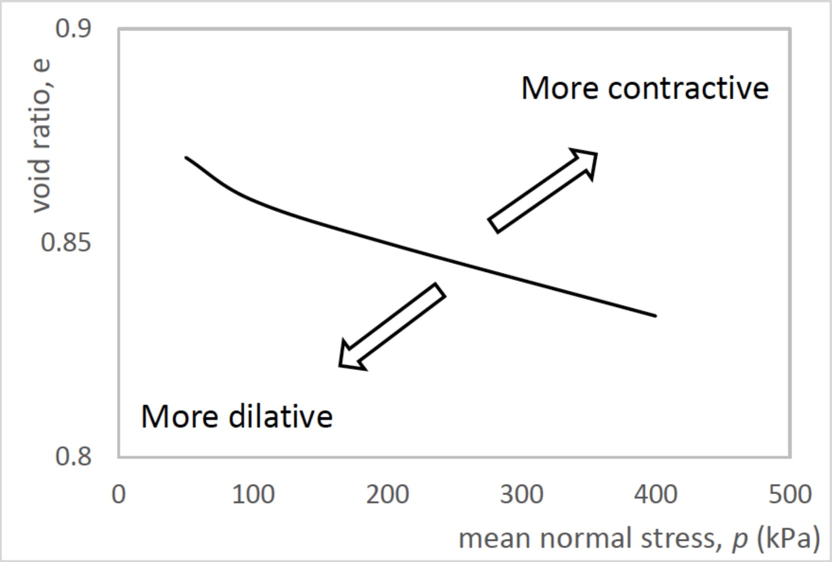

Figure 2.2: Critical state line approach

ing) deformation. Lateral spreading generally occurs in sloping ground conditions or gently-sloping ground leading to an open area, where liquefaction occurs. Suspended particles are carried along the slope and towards the open area, stretching the liquefied layer to expel the liquefied finer sediments along with excess pore water pressure. Unconsolidated, highly saturated fine grained soil particles ranging from sand to silt with a clay content of less than 15% at shallow depths, situated closer to the water table are highly susceptible, according to Youd et al., (2001). Holocene sands, fine to very fine sands, deposited within alluvial, deltaic, environments are considered to be highly susceptible to liquefaction (Youd and Hoose, 1977).

Secondary factors influencing the resistance to liquefaction include the spatial arrangement of the soil particles which affects the porosity, permeability and cohesion of the soil particles. Liquefaction potential of a soil mostly decreases with the age of the sedimentation deposit as the cementation of the particles would occur due to the increase in the confining overburden pressure by large deposit of sediments over the period.

Increase in number of subsidence cases due to liquefaction report the reduction in Liquefaction triggering thresholds (of IC value cut off at 2.6) following the 2010-2011 in Canterbury earthquakes (Tonkin and Taylor, 2015). Non-uniform surface subsidence and liquefaction due to lateral spreading is a major threat to human life and infrastructure. Earthquakes recorded in the recent past include 2010 Haiti (Madabhushi et al., 2013), and the 2010-2011 Canterbury Earthquakes (van Ballegooy et al., 2014a). Thus, it is understood that Liquefaction has some serious consequences such as loss of human lives and severe damage to infrastructure.

2.3. Liquefaction Potential Analysis

The potential for liquefaction is generally estimated from laboratory testing or in-situ geotechnical tests. Laboratory based methods include the application of horizontal cyclic loads to soil samples, to mimic the seismic waves as in an earthquake. The cyclic stresses generated are compared with the cyclic resistance of the soil to calculate a limiting value for liquefaction triggering (Idriss and Boulanger, 2014).

The Standard Penetration Test (SPT), Cone Penetration Test (CPT), and/or Shear Wave Velocity measurements are commonly used tests to assess sandy deposits, while the Becker Penetration Test (BPT) for gravels. Liquefaction Potential Analysis began as SPT-based correlations (Seed and Idriss (1982). In the recent times, this is being converted to CPT-based correlations, due to higher number of CPT investigations being preferred over SPT due to various reasons. The CPT measures the resistance of the soil strata, present at any given location, to a steel-rod driven at a constant rate and loaded vertically registered as qc for CPT. These values act as a proxy for grain size, porosity, and density of the strata deposit, which is a direct function of their resistance to liquefaction. The resistance of the soil strata deposit to liquefaction is determined using the stress-based approach derived by Seed and Idriss (1982), and later updated by Idriss and Boulanger (2008) and Boulanger and Idriss (2014).

This approach is based on ratio cyclic resistance ratios (CRR) of a soil to the earthquake-induced cyclic stress ratios (CSR) over the soil, to derive a Factor of Safety (FS) against liquefaction triggering. Thus, Liquefaction potential is expressed as :

$$FS_L = \frac{(CRR)_z}{(CSR)_z} \tag{2.1}$$

Where FS_L = factor or safety against liquefaction, CRR_Z = cyclic resistance ratio at a particular depth Z, CSR_Z = cyclic stress ratio at the same depth Z.

If FS<1,suggests the sample is liquefiable. Seed-Idriss simplified liquefaction procedure by considering correction coefficients to consider effective overburden pressures on the deposit, and the maximum horizontal acceleration as a function of gravity.

A stress reduction coefficient was also introduced to represent the dynamic response of the soil strata. The CRR is derived from the of CPT, respectively requires corrections for the over- burden stress and atmospheric pressure. The q_c needs a correction to account for the unequal area effects on the cone tip, including the area ratio and pore pressure. The CRR of the subsurface sediments is dependent on the duration of dynamic loading which is expressed through an earthquake magnitude scaling factor (MSF). Field observations from cases of historic earthquakes inducing liquefaction have been collected to constrain the CRR. These observations were corrected to a common reference condition of a moment magnitude 7.5 earthquake, effective vertical stress of 1 atmosphere, and level ground conditions. The MSF must therefore be applied to account for earthquakes and sites outside of these reference conditions. According to Boulanger and Idriss (2014), corrections are also necessary for the effect of fines content of the present in the deposit.

The following five screening criteria, for completing a liquefaction potential are:

1. **Geological age and origin:** If a soil layer is a fluvial, lacustrine or aeolian deposit of Holocene age, a greater potential for liquefaction exists than for till, residual deposits, or older deposits. (Youd and Hoose, (1977)

2. **Fines content and plasticity index:** Liquefaction potential in a soil layer increases with decreasing fines content and plasticity of the soil. Cohesionless soils having less than 15 percent (by weight) of particles smaller than 0.005 mm, a liquid limit less than 35 percent, and an in-situ water content greater than 0.9 times the liquid limit may be susceptible to liquefaction (Seed and Idriss, 1982).

3. **Saturation:** Although low water content soils have been reported to liquefy, at least 80 to 85 percent saturation is generally deemed to be a necessary condition for soil liquefaction. The highest anticipated temporal phreatic surface elevations should be considered when evaluating saturation. (Youd et al.,(2001)

4. **Depth below ground surface:** If a soil layer is within 15m of the ground surface, it is more likely to liquefy than deeper layers.

5. **Soil Penetration Resistance:** Seed and Idriss (1982), state that soil layers with a normalized SPT blow count [(N1)60] less than 22 have been known to liquefy. Marcuson et al (1990), suggest an SPT value of [(N1)60] less than 30 as the threshold to use for suspecting liquefaction potential. Liquefaction has also been shown to occur if the normalized CPT cone resistance q_c is less than 15 MPa, Shibata and Taparaska, (1988) If more than three of the above criteria are observed, then Liquefaction potential analysis needs to be undertaken. The first step to liquefaction analysis is to identify cases of liquefaction in the surrounding region. In the region of Groningen, majority of the sites were classified as **“No to Minor Surficial Liquefaction Manifestations”** based on R.A. Green, et all (2018) report for NAM. Owing to the earthquakes which have led to liquefaction in the other parts of the world, if the gas extraction continued in Groningen, there is a higher chance of liquefaction triggering.

2.4. CPT Interpretation and Soil Behavior Type and Index

A typical CPT profile along with the Soil Behaviour Index, IC, is shown in Figure2.3. Generally, CPT test measures the cone resistance (q_t) and sleeve friction (f_s) every 20mm. This is used to calculate the Friction Ratio (R_f). For every reading, the soil behavior index can be calculated. As per Boulanger and Idriss (2014), the correction for the cone resistance and sleeve friction are normalised. This is discussed in the next section.

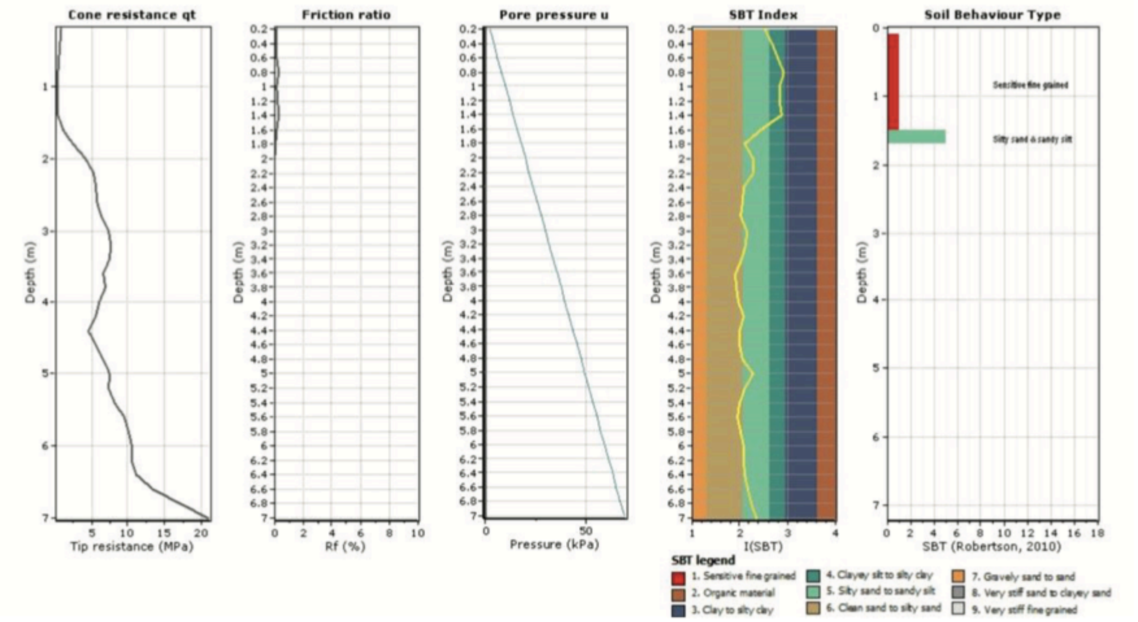

Figure 2.3: typical CPT profile along with the Soil Behaviour Index, IC

2.5. Soil Behaviour Type and Index (IC)

One of the major applications of the CPT is for soil profiling and soil type classification. Typically, the cone resistance, (q_t) is high in sands and low in clays, and the friction ratio ($R_f = f_s/q_t$) is low in sands and high in clays. The CPT cannot be expected to provide accurate predictions of soil type based on physical characteristics, such as, grain size distribution however provide a guide to the mechanical characteristics (strength, stiffness, compressibility) of the soil. CPT data provides a repeatable index of the aggregate behaviour of the in-situ soil in the immediate area of the probe. Hence, prediction of soil type based on CPT is referred to as Soil Behaviour Type (SBT).

Since both the penetration resistance and sleeve resistance increase with depth due to the increase in effective overburden stress, the CPT data requires normalization for overburden stress for very shallow and/or very deep soundings. A popular CPT soil behaviour chart based on normalized CPT data is that first proposed by

Robertson (1990). A zone has been identified in the plot which the CPT refers to most-young, un-cemented, less sensitive, normally consolidated soils. The chart identifies general trends in ground response, such as, increasing soil density, OCR, age and cementation for sandy soils, increasing stress history and soil sensitivity for cohesive soils. The chart is globally valid and provides only a guide to soil behaviour type (SBT). There may be overlap in some zones and it needs a correction based on the region (site specific correction).

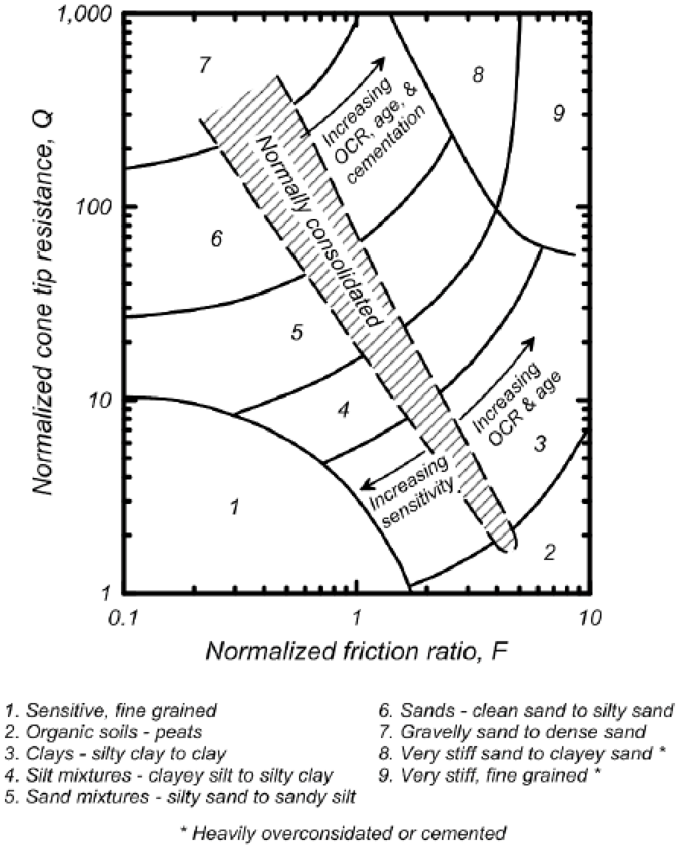

Figure 2.4: Soil behaviour type and soil behaviour index based on Robertson (1998)

Soil behaviour type can be improved if pore pressure measurements are also collected. In soft clays and silts the penetration pore pressures can be very large, whereas, in stiff heavily over-consolidated clays or dense silts and silty sands the penetration pore pressures (u_2) can be small and sometimes negative relative to the equilibrium pore pressures (u_0). The rate of pore pressure dissipation during a pause in penetration can also guide in the soil type. In sandy soils any excess pore pressures will dissipate very quickly, whereas, in clays the rate of dissipation can be very slow.

To simplify the application of the CPT SBTn chart, the normalized cone parameters Q_t and F can be combined into one Soil Behaviour Type index, IC, where IC is the radius of the essentially concentric circles that represent the boundaries between each SBTn zone as shown in Figure 2.4. The effective stresses are calculated as per Robertson and Cabal, (2010). Normalization was necessary to reduce the errors in the conversion from SPT based correlation to CPT based correlations. Thus, Q_t and F are defined as,

$$Q_t = \left(\frac{q_c - \sigma_{vc}}{P_a}\right)\left(\frac{P_a}{\sigma'_{vc}}\right)^{0.5} \tag{2.2}$$

$$F = \left(\frac{f_s}{q_c - \sigma_{vc}}\right) \cdot 100 \tag{2.3}$$

Thus, Soil Behaviour Index is calculated using,

$$I_c = [(3.47 - log(Q))^2 + (1.22 + log(F))^2]^{0.5} \tag{2.4}$$

According to Boulanger and Idriss (2014), for the liquefaction assessment, a fines correction may be used. For the fines correction, the FC from laboratory results can be used. In absence of laboratory results of FC, the FC can be obtained from a correlation with the soil behaviour index IC. From the liquefaction histories, cases are compiled into a data set and a correlation is proposed by regressing IC vs FC first and inversing the equation to estimate fines content. here, in this equation, error term is substituted by the fitting factor CFC by the standard deviation of the data set, i.e, 0 to -/+0.29. the CFC has an opposite sign as the positive CFC results in larger FC estimate.

$$IC = \frac{(FC + 137)}{80} + \epsilon \tag{2.5}$$

where ϵ is the error term

$$\Rightarrow \; FC = 80(IC + CFC) - 137 \tag{2.6}$$

where 0 ≤FC ≤100%

Similar studies were conducted after Christchurch earthquake in 2014 by Lee, J. et al, (2015). The results are as shown in Figure2.7. The data set proved the correlation to be true for the Christchurch dataset. Their assumptions include the maximum distance between CPT and BH is 5m and the samples below 20m depth is discarded.

Deltares conducted a study on FC vs IC, to find better correlations for the Groningen soils. Their finding consisted of 81 samples from the Groningen region and the plotting of FC vs IC graphs for the same. The analysis is based on IC value cut off at 2.6 and the samples are considered from the same region. Since there is a difference from the Boulanger and Idriss(2014) correlation, further investigation was necessary. Thus, other equations are proposed.

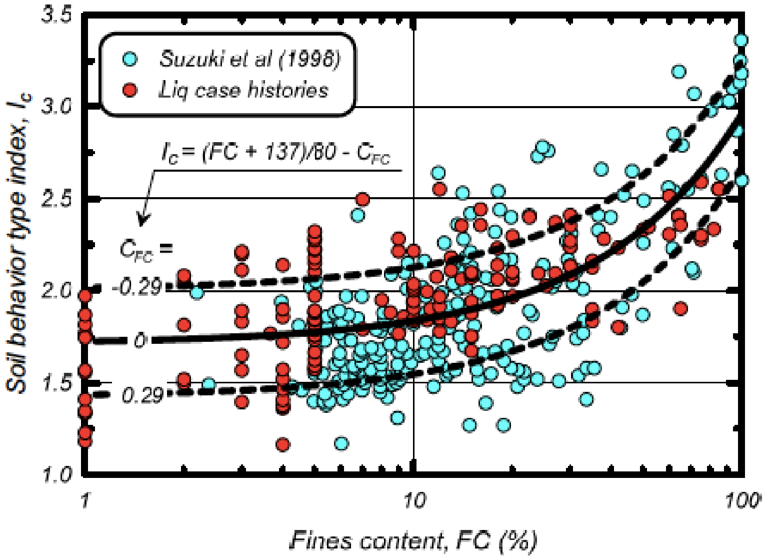

Figure 2.5: Soil behaviour type and soil behaviour index based on Robertson (1998). Source: Boulanger and Idriss (2014)

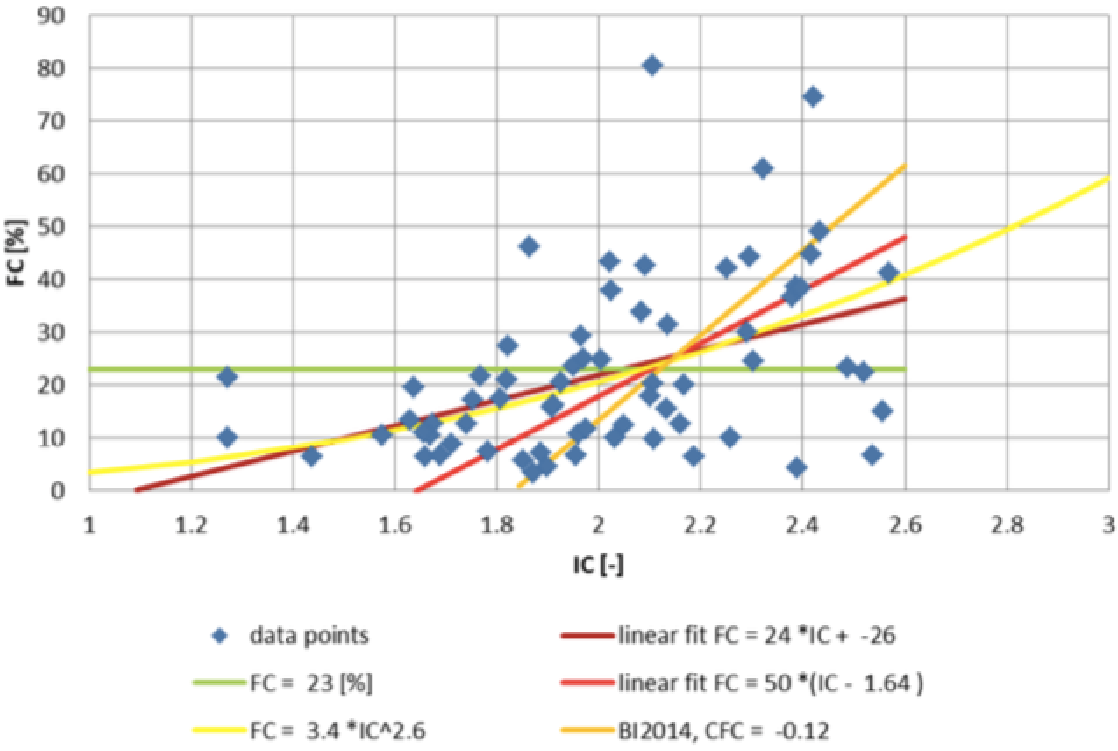

Figure 2.6: Comparison of various alternative FC vs IC correlations for estimating FC values. Source: Deltares Report (2017)

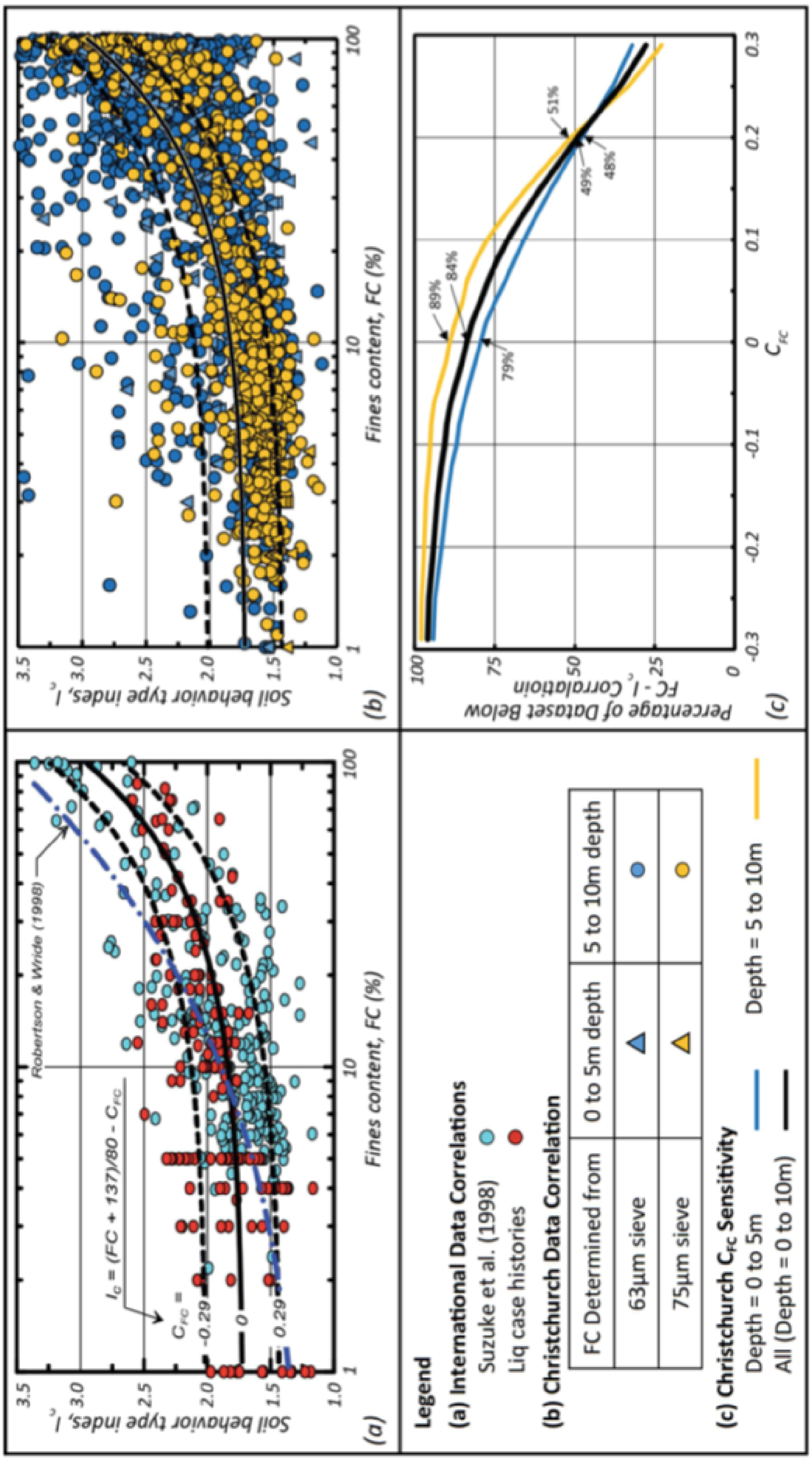

Figure 2.7: (a) Robertson and Wride (1998) and Boulanger and Idriss (2014) FC-Ic correlations overlain onto the international liquefaction case history database. (b) FC vs median IC for data in the Christchurch area with the Boulanger and Idriss (2014) FC-IC correlations using a CFC of -0.29, 0 and 0.29 overlaid. (c) Percentage of the FC-IC dataset below the Boulanger and Idriss (2014) FC-Ic correlation for a varying site specific fitting parameter, CFC. The conclusion consisted of reconsidering the cut-off for liquefaction susceptibility using IC thresholds with 2.4 and 2.8 as well. Source:Lee, J. et al, (2015)

2.6. Fines Content

Fines Content is defined as particles smaller than $75\mu m$ for ASTM D422 – 63 (Reapproved 2007). While the Dutch standards and British Standards define it as particles smaller than $63\mu m$ and $60\mu m$ respectively (NEN-EN-ISO 17892 part 4 2016; BIS 1377[3]). Indian Standard Soil classification system defines fines as particle smaller than $75\mu m$ (IS 2720-4).

The Grain Size distribution helps in calculating the fines content of soil samples. The Fines Content is the percentage of finer soil particles over the total dry weight of the soil samples. Effect of fines content is seen in earlier studies affecting the behaviour of the soil with respect to the cone tip resistance offered. IC is a function of FC. The fines content can be defined in two different ways.

1. Based on the soil classification described by the Standard of the country,i.e, ASTM, NEN, IS
2. Based on type of fines, i.e, Plastic Fines and Non Plastic fines

The fines content affects the CRR and overburden pressure corrections during the calculation of liquefaction potential analysis. The correction is applied for CRR for fines content equivalent as sand. It does not have a provision to consider the standards followed, that defines the size of the particle. This could explain the interesting behaviour of fines. A study at National Taiwan University by Tzou-Shin Ueng, Chia-Wen Sun and Chieh-Wen Chen, (2004), states the variation in the liquefaction resistance measured after the two soils with different fines are examined under cyclic triaxial loading. It is observed that the stress measured varies for different definitions of fines content. Hence, it is necessary to compare correlations according to one standard and using appropriate interpolations to estimate FC values.

2.7. Grain size Analysis

Grain size analysis can be defined as a commonly performed laboratory test that measures the percentages of the soil particles of different sizes present in any given soil sample. This analysis consists of Dry Analysis for coarser grained soils and Wet analysis for Finer soils. The following are the criteria for conducting dry and wet analysis on a soil sample as per specifications mentioned in NEN-EN-ISO 17892 part 4 2016 -

- If the sample has less that 10% of particles smaller than $63\mu m$, then the wet analysis is not necessary.
- If all of the sample is smaller than 2mm and has less than 10% of the particles larger than $63\mu m$, then a full sieve test (consisting of all the sieves) is not

normally required

- For all the other samples, a combination of dry (sieve test) and wet analysis (sedimentation test) is necessary in order to determine the full grain size distribution .

Results of the Grain size distribution are always reported as the fraction of soil particles that pass through the each sieve. The sieve sizes and classification is as shown in Figure 2.8.

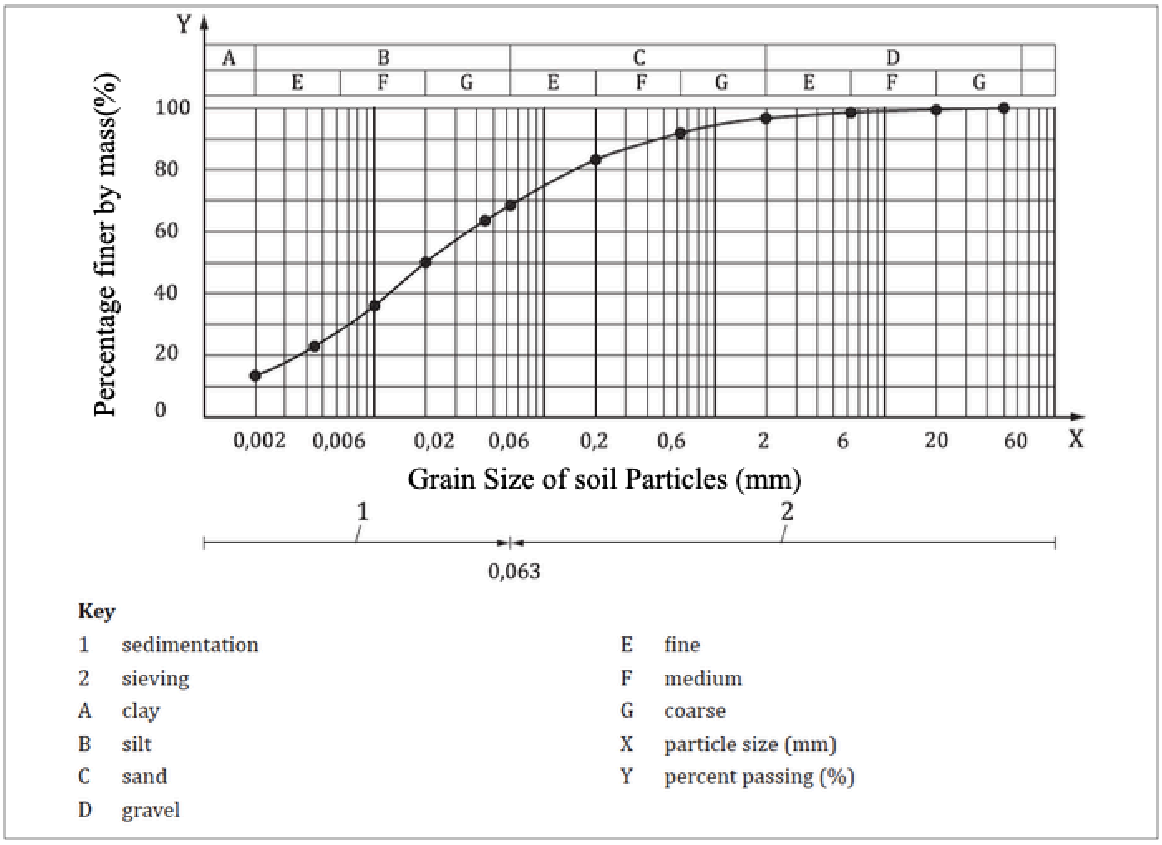

Figure 2.8: shows Soil Classification and Grain Size Distribution curve

Grain size distribution curve helps in understanding the overall soil structure and its composition. The proportion of the percentages of the different size particles differentiate the gradation of the soil. Grain Size Index (I_{GS}) is defined as an index representing the grain size distribution curves, can be used in the soil classifications for prediction of mechanical and physical properties of the soil. I_{GS} aids in facilitating a better understanding of the grain size dependency of the liquefaction potential and cyclic resistance ratio (CRR) of soil deposits as well as its strength and behaviour under dynamic loading conditions (Zeynal Abiddin Erguler, 2016) as shown in the Figure 2.9

$$I_{GS} = \frac{Areaunderthegrainsizedistributioncurve}{Totalareaencompassingboundaryconditions} \tag{2.7}$$

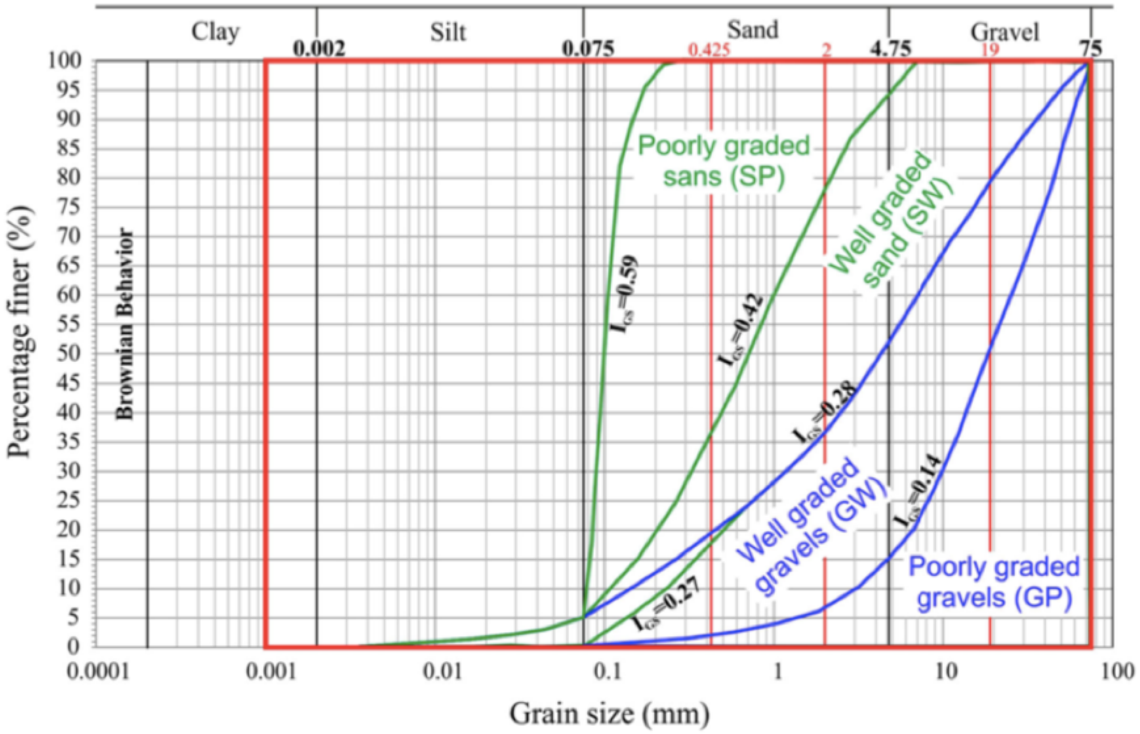

Figure 2.9: Illustrates the representative curves for the boundaries of well- and poorly-graded gravel and sand, and related I_{GS} values

Grain characteristics such as the grain size and angularity of the soil particles also influence liquefaction susceptibility, as do the ground conditions. This includes the depth to the water table, the saturation of the soil (it must be fully saturated to be liquefiable), the drainage conditions of the soil (i.e. whether pore water flow is impeded by impermeable soil layers), and the soil stratification. Furthermore, the depth to the liquefiable layers, also known as the crust thickness, relative to the thickness of the liquefiable layer will influence whether liquefaction is manifested on the surface and to what extent. Overall, the most susceptible soils are loose, non-plastic, young, thicker strata, fully saturated sandy deposits.

Only few kinds of soils are susceptible to Liquefaction. A soil susceptible to liquefaction, generally falls between medium density to low density soils and the degree of saturation must be equal to 1. The low density soils liquefy easily compared to the higher density soils as the cohesion between the particles is less in a low density soil. High density soils can liquefy, however the deformations would be of lesser magnitude. Clayey Soils with high plasticity are not susceptible to liquefaction. These soils may undergo large deformations, however full liquefaction of the soil.

2.8. Geology in Groningen

The Figure 2.10 below depicts the different eras and the formations of the region formed during Paleozoic, Mesozoic and Cenozoic eras. The Slochteren layer in Groningen region consists of a thick 3000m sandstone layer carrying natural gas sandwiched between carboniferous and claystone deposits. In the topmost deposit during the Quaternary period, the Holocene and Pleistocene formations are found.

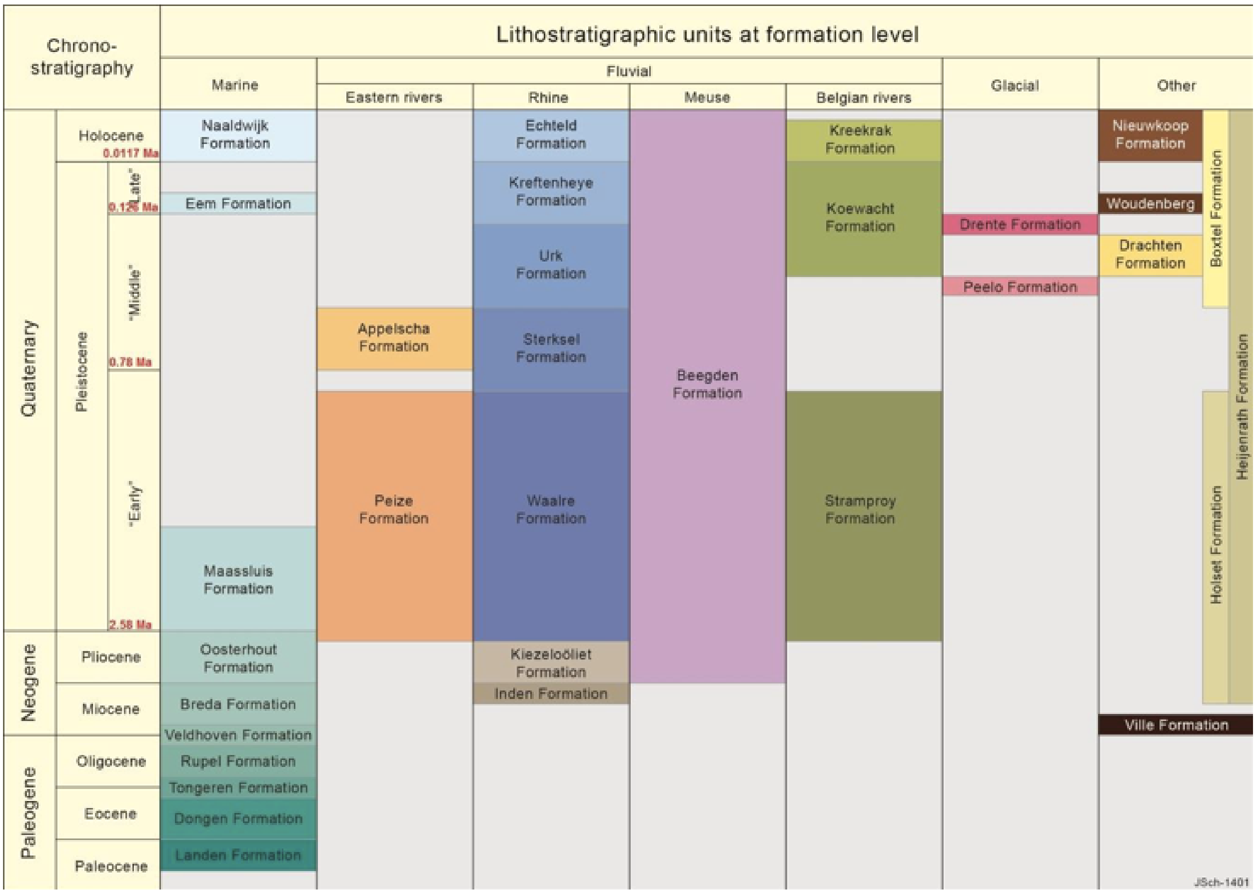

Figure 2.10: An overview of all formations of northern Netherlands based on TNO reports

The main geological formations in the Groningen region are based on information available on DINOloket and TNO 2016 reports:

1. **Naaldwijk Formation** It consists thin layers of deposits (1m-75m) of sands varying from fine to coarse, silts and clays. This is a Holocene formation, formed in an environment of marine, lagoon and beach with particle size of 105-210micron of fine grained sands to medium grained sands, with calcareous formations of low to high silty clays. Thin sand layers are embedded within clay deposits.

2. **Naaldwijk Formation** It consists thin layers of deposits (1m-75m) of sands varying from fine to coarse, silts and clays. This is a Holocene formation, formed in an environment of marine, lagoon and beach with particle size of 105-210micron

of fine grained sands to medium grained sands, with calcareous formations of low to high silty clays. Thin sand layers are embedded within clay deposits.

3. **Nieuwkoop Formation** This formation consists of extremely thin layers of deposit (0.5-0.4m), formed mostly by peat and clay deposits during Holocene sea level rise. It is mostly in brown colour with no minerals and low to high clay content.
4. **Peelo Formation** This formation results from the Glaciation of Elsterin with thickness of 10-30m layers. The ice formations over the northern part of Netherlands led to formation of deep subglacial valleys. Their thickness can vary up to 400m consisting of highly silty lacustrine and glacial clays, fine-coarse sand. Clay found here would be generally dense sometimes containing sand and gravel.
5. **Drente Formation** This formation is generally thin with thickness of 1m-10m consisting of majorly clays and loam (highly sandy/silty) formed during the Saalian glaciation. Also called boulder clay.
6. **Boxtel Formation** This formation consists of up to 30m thick layers, a combination of Aeolian sands and fluvial sediments formed during the periglacial period of Glaciation of Saalian and Weichselian. It ranges from low silty to high silty and loam with peat layers sandwiched sometimes in between, with particles of size 105-300micron.

The Holocene sands are vulnerable to liquefaction than the Pleistocene sands. Due to aging of the soil and better cementation of particles, Pleistocene is less prone to liquefaction. Boxtel does not belong to Pleistocene formations but for the purpose of this study, it will be considered along with other pleistocene formations. Example of a geological cross-section through the Holocene coastal deposits of the province of Groningen from North to South showing the full complexity of the Holocene and Late Pleistocene deposits relevant for the construction of the GSG-model, is shown as Figure 2.11

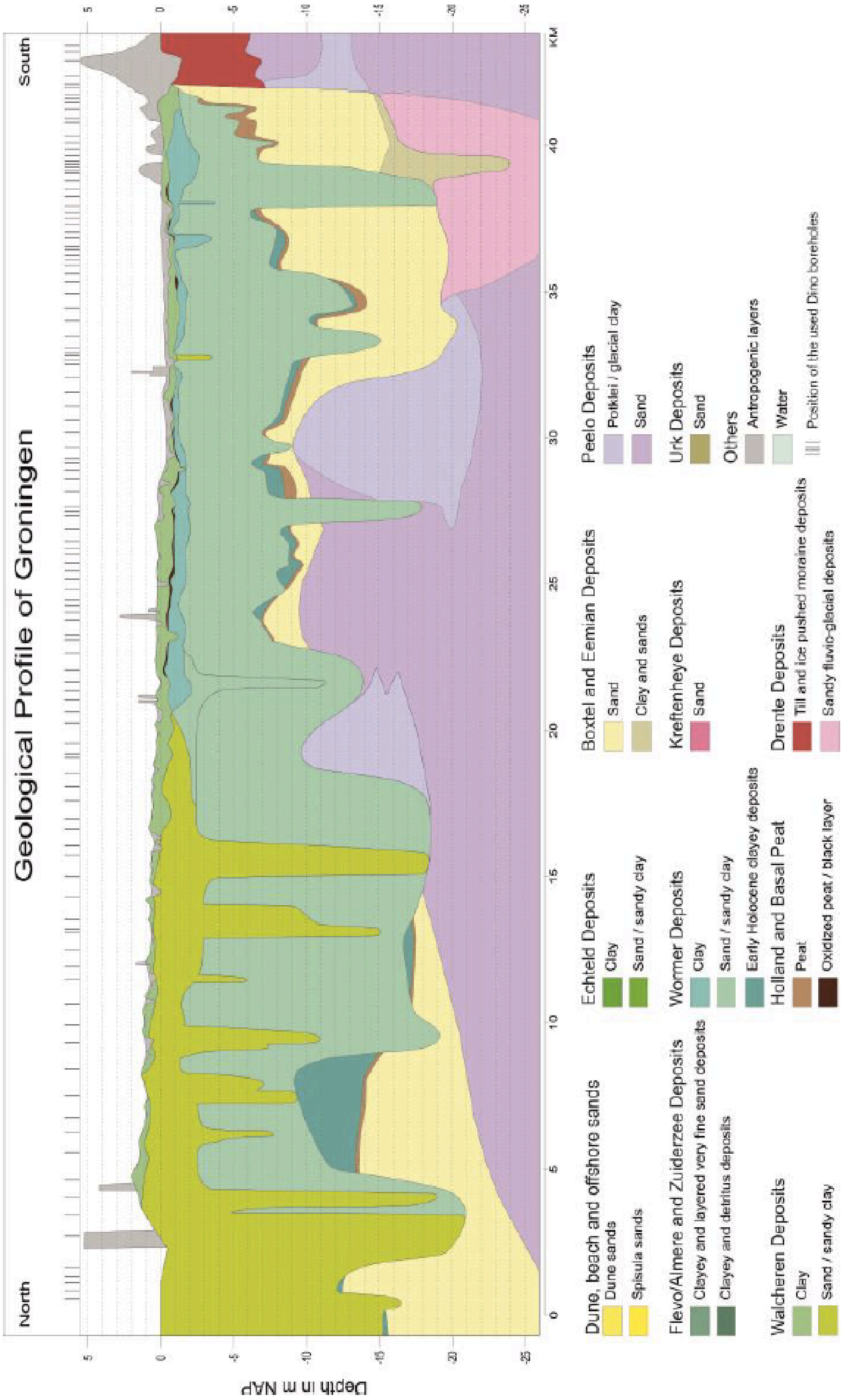

Figure 2.11: Example of a geological cross-section through the Holocene coastal deposits of the province of Groningen from North to South showing the full complexity of the Holocene and Late Pleistocene deposits relevant for the construction of the GSG-model.Source: Kruiver et al., 2015

2.9. Summary

Correlations are often used by design engineers to account for the complex behavior of the soil. With high technology softwares and design tools available at hand, the precision and validity of correlations is often forgotten as the calculation of all parameters would be a click away. Thus, it is necessary to evaluate if a correlation is eligible to be used, for a particular site. Hence, this is to summarize the available literature and to define the problem better.

- Idriss and Boulanger(2014), IC vs FC correlation is extensively used in Liquefaction triggering analysis. Recent Christchurch earthquake also added largely to the liquefaction case histories, which also confirmed the validity of the correlation for Christchurch samples. Along with a few minor modifications like the IC cutoff thresholds, it was concluded that the correlation was safe to be used. The error from the averaging of IC values over a certain height is explored by Lee. J et al.,(2015) for the Christchurch liquefaction studies.
- Deltares report found that the FC vs IC had scatter for Groningen soils, which is unexplained. An FC is estimated based on the Boulanger and Idriss (2014) correlation. It is found that this is not the best fit for the Groningen soil data. Hence, this report proposes alternative correlations that can be used in Groningen region. FC vs IC regression is considered. There is a certain error amounting from the difference in definition of fines content as per ASTM and NEN standards, which is disregarded. The effect of the distance between the CPT and BH in the Deltares report is also neglected.

This study is intended to validate and estimate the strength of the FC-IC correlation for Groningen specifically, along with consideration of the other factors that could be contributing to the scatter. These are based on the literature to consider the depth of the sample along with the geology while matching the lab results of FC with the estimated FC by Boulanger and Idriss (2014) correlation. Gradation defined by Grain size Index is included in predicting the soils liquefiable potential bands for Groningen soils.

3

Methodology

The methodology used in the thesis is schematically represented in the flowchart in Figure 3.1

3.1. Collection of Data

3.1.1. Understanding the structure of Data Storage at Wiertsema and Partners

The data used in this study are collected from Wiertsema and Partners B.V. (W&P), a soil consultancy in Tolbert, Netherlands. In Figure 3.2, the Phase 1 of the data collection is explained. It is essential to understand the storage of data, before data is extracted. The flowchart to the storage is attached in Appendix A. This gives an understanding of how the raw data is collected, it explains the necessity to convert the raw data to a processed data. Parameters required for this study are FC and IC. FC is determined from the Particle size distribution tests performed at the W&P laboratory. IC is calculated from the CPT .gef files. Any field test data is stored in IBase/GBase, a system of databases. IBase is an old database which may/may not have the information about latitudes, longitude and depth tagged to the raw data file of a given project. Over the last three decades, the data storage structure has also evolved at W&P, thus improving the accessibility to old files. GBase is a comparatively new database consisting of

- Old Project files that are tagged with XYZ information from IBase
- New Project files from recent times which already have XYZ information tagged during data entry.

This makes it easier to retrieve any data based on the geographical location of the project. So typically, every new project is given a Project number. To the Project

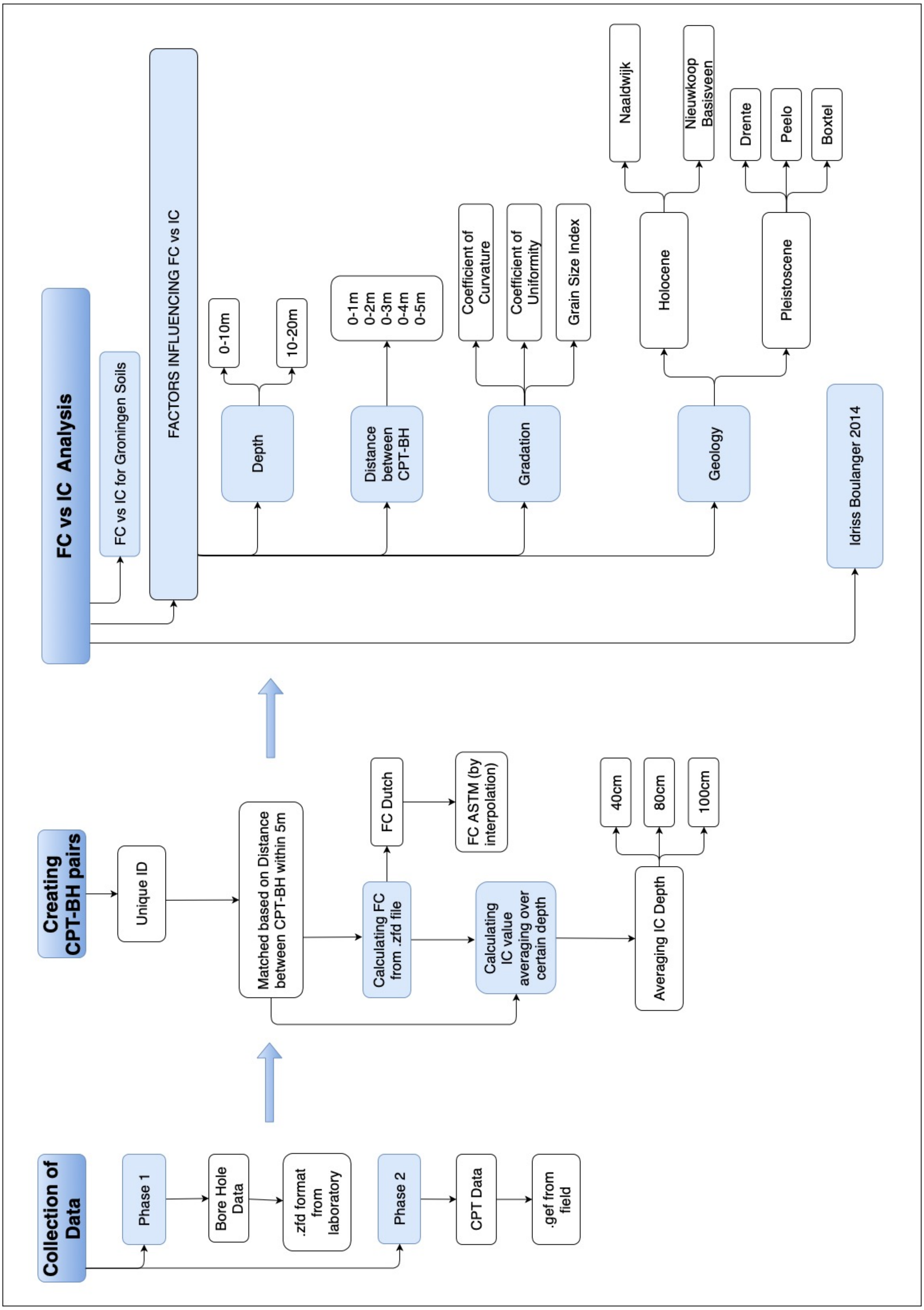

Figure 3.1: Schematic representation of the study

number, the XYZ information is also tagged. A BH sample collected now would ideally have a Project ID, Point ID (XY), Depth(Z), Specimen ID and Sample ID. But if there is inconsistency in this, then the data would be difficult to retrieve and also reduce the credibility of such data.

3.1.2. Sieve analysis laboratory results

When a sample is sent for PSD/grain size analysis/sieve analysis, the sample would have Project ID, Point ID, Depth, Sample ID and Specimen ID. Specimen ID is most important as one sample may have two or more specimens depending on the requirement of the lab test. Sieve Analysis would consist of wet and dry analysis depending on the location of soil sample collected and the contents of the soil itself. Coarser the soil, the more sandy it is in nature, would require dry analysis. More fine particles would mean the presence of clay and silt, wet analysis would be necessary. The detailed definition of this is given in Chapter 2, section of Grain Size Analysis. The results of the sieve analysis are stored in .zfd format and are tagged with Project ID, and if available, the XYZ information as well. The data collected is from over last decade, and the way the lab results are entered into the database has also improved. In case of missing link in the tags, such data is discarded.

3.1.3. Selection of Area of Interest

The selected area for the study is a radius of 30km with Loppersum (245,000;595,000) as centre in the northern region of Netherlands. Since one of the strongest earthquakes hit Loppersum area in 2018, this region was selected. It was also selected based on the number of important projects W&P had carried out in the Groningen Province. It consists of a few dike projects, meaning the safety of these dikes would be important in future. This area yielded in 200 Projects which had the PSD data. The below picture shows the selected area on a map.

3.1.4. Zeefprogramma and its function

The Laboratory at W&P uses a special, home built software called Zeefprogramma, a tool built based on Excel for the data entry of all test results from laboratory results of the Grain size analysis (wet and dry analysis). This started out as a very simple programme with columns for all the sieves based on Dutch standard and just a few columns to indicate the project number. As the number of projects and the complexity of numbering them increased, with increased services provided in a single project, a structure came into existence with many IDs to tag a single specimen and its results. Thus, the zeefprogramma also has evolved. For the selected area of 30km radius, about 200 projects with PSD data were found after a SQL (Structured Query Language) query. The data is chosen from the year 2009 till 2019 based on the availability of data digitally and its easy access with XYZ information. During

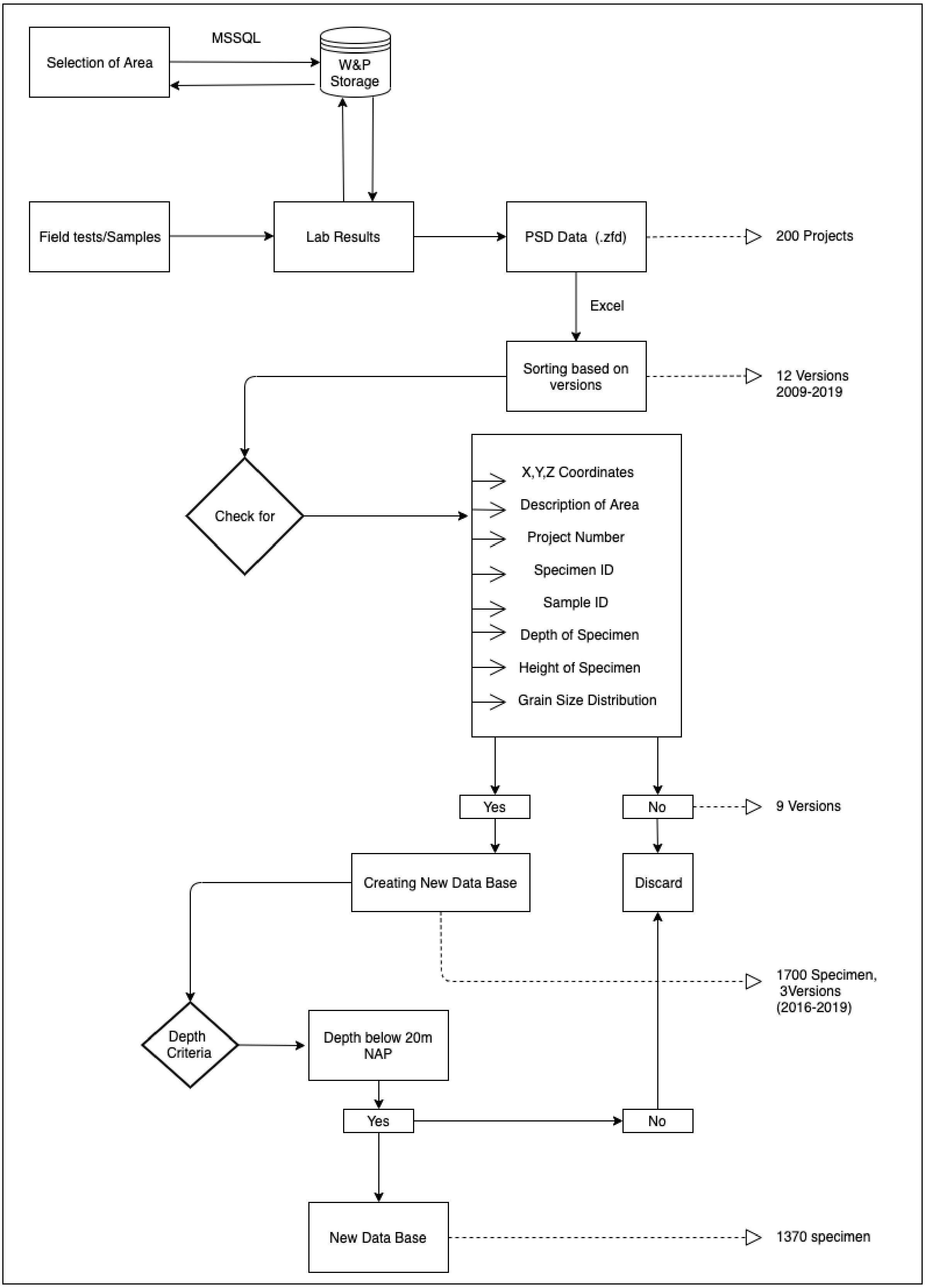

Figure 3.2: Flowchart of Phase 1 of Collection of Data

Figure 3.3: Area of interest for study; 30km radius with Lopersum as centre

this period, zeefprogramma if found to have 12 versions. Versions 16.3, 17.3, 18.3 have consistent number of columns and data entry has been very structured. Versions 1.3.02, 1.3, 10.2, 11.2, 12.2, 13.1, 13.2, 14.2, 15.2 have had many additions to precisely describe the location of a specimen, and the number of IDs tagged to each specimen increased. In the earlier versions, only a Project ID and name of the locality was made available. The zeefprogramma converts the excel format during data entry to be stored as a .zfd file. The .zfd file needs to be converted to excel for further analysis.

3.1.5. Selection of Data and Uniqiue ID

The selected area of 30km radius resulted in 200 W&P projects. Each .zfd file includes many specimens tested for a project. An example of the data from .zfd files after conversion is shown in Appendix. It consists of the Project ID, Sample ID, Specimen ID, the XYZ coordinates, a small description about the soil classification, the weight of the soil particles retained on each sieve. The location of Specimens from the earlier versions 1.3.02-15.2 was not available due to missing links mostly. Since the number of specimens recorded happened to be comparatively less from those versions, it was neglected. Data from versions 16.3-18.3 consisted of 82 projects carried out within the selected area radius. A small python code was written to convert .zfd files to excel. From 82 projects, 1370 specimens were yielded, after eliminating all the missing columns in each specimens' data and after filtering it based on the prerequisites for the each of the factor considered. Each of these specimens were given a different ID to simplify the problem of having many IDs. "Chai ID" is a unique ID assigned to each of the specimens that would be able to give other information such as Project IDs, Sample and Specimen IDs, Location, Location description, etc. For further calculations and analysis, only Chai ID is used. It also facilitates tagging of the data from CPT to BH depending on the distance between them.

3.1.6. Programming towards creating a big network of data using gINT

Initially, the usage of gINT was considered, as it would simplify the analysis. gINT is a Bentley systems geotechnical tool which is used for different geotechnical calculations. Main advantage of using gINT is that it can work effortlessly with the database. Also the conversion from .gef of CPT files would be eliminated. Collection of data is a two phased process in this study. Phase 1 is collection of test results of PSD data from BH samples , Phase 2 is collection of CPT data. As indicated in figure 3.2, all the data needs to be compatible with each other to make sure it can be worked with, on one single platform or tool. So conversions from .zfd to excel/ .gef to excel was necessary. Since gINT application would have made it easier to access the CPT data and in calculation of IC and its variants, it was a valid argument to consider it. gINT accepts .zfd data in a particular template that was time consuming to program, and it would also require a lot of other information from W&P database. Any missing link in the information would result in unsuccessful attempt of retrieving data. Python with Panda was attempted to programme for the conversion of .zfd files to the required template.

3.1.7. Complextities and opting to work with Excel

By considering gINT, the complexities increased with the extraction of data from data base than reducing it. After a lot of time invested in programming the complex template, it was decided to eliminate gINT and manually extract the .zfd files to excel (ta small python code was used to extract .zfd file for each of the 82 projects to excel) to simplify the process and to focus on creation of a smaller data base, for this study alone. Since excel is proficient in handling the small data set with just a few thousand points, it was the best tool to work with. A sample of the Data set of all the results of the PSD test on 1370 specimens together, with the Chai ID and XYZ coordinates is considered as the final data set. This is the Phase 1 of the Collection of the Data. A sample of this can be seen in the Appendix A.

3.2. Creation of CPT - BH sets

The CPT data is provided by Deltares based on the exact location of the BHs selected for the study. The CPTs considered are within the range of 5m distance from any given BH, to start with. This reduced the number of BH considered for the study. The closer the CPT to the BH, the higher the probability that the CPT measured is similar to the soil sampled in BH. If the strata of soil being identified accurately is higher, owing to much better quality of results with less variance.

3.2.1. CPT and BH matching using ID

The collected CPT data is tagged with the closest BH data using the Chai ID. The analysis begins from here onward with the plotting of the FC vs IC graphs. For each of the different factors used in the study, a separate sub-data set is created with the CPT-BH pairs. With Depth and Distance, the IC value varies as the distance or depth considered to calculate IC value increases. Thus, it is necessary to maintain a database with the matched CPT-BH sets with the ID. Hence, the number of CPT-BH pairs created were 167. This means each of these 167 samples from BH have CPT within 5m distance.

Figure 3.4: Selected area consisting of CPT-BH pairs

3.2.2. Calculation of FC based on ASTM and Dutch Standards

Fines content can be measured using the PSD test or the Grain size analysis. Fines content definition are slightly different on the basis of the standard followed. For this study, the Fines Content percentage is the soil particles passing through the sieve size of $63\mu m$ over the total weight. as per the NEN ISO 13317-1, ISO 3310-1 and ISO 3310-2. ASTM standard defines the fines content as percentage of the soil particles passing through the sieve size $75\mu m$ divided by the total weight. Since the laboratory tests are done only using the Dutch standards, it is important to also calculate the FC based on ASTM standards. For this, the weight of the soil particles passing through $75\mu m$ is interpolated between $90\mu m$ and $63\mu m$ from the lab test results. Following formula are used to calculate the FC values:

$$FC(NEN) = 1 - \frac{Mass(gm) of soil fraction passing through 63 micron sieve}{Total dry mass of the sample} \tag{3.1}$$

$$FC(ASTM) = 1 - \frac{Mass(gm) of soil fraction passing through 75 micron sieve}{Total dry mass of the sample} \tag{3.2}$$

3.2.3. Calculation of Soil Behavior Index

Soil behaviour Index IC is calculated based on the correlation given by the Robertson (1998) as suggested in the section 2.5.

3.2.4. Averaging of Soil Behavior Index

The depth over which IC is calculated is necessary as the IC value can be calculated for every measured cone resistance and sleeve friction reading. Considering a sample of 40cm, would have about 40 readings if it is measured per centimetre. Since the sample would consist of 40cm, it would be ideal to average the IC values. The IC values are averaged over the height of sample. The IC value at 20cm (mid-height of the sample) cannot be considered as the sample height is 40cm and the soil particles within that height needs to be accounted for, in case there are different layers of soil. So, to evaluate if there is any effect, the IC values were also averaged over 80cm, twice the height of the sample and over 1m for each of the sample.

3.3. Factors for FC vs IC Analysis

The major four factors considered for the analysis to study the influence of these factors on the FC calculation or the calculation of the IC, in turn effecting the correlation between FC vs IC are :

- Depth of the sample
- Distance between the CPT and BH
- Geology of the region and history of the soil
- Gradation of the Soil

Figure 3.5 shows the variation of FC vs IC. Generally, when the FC is proportional to IC. Thus, it can be expected that the values would start from the left bottom quadrant and end in top right quadrant. Low FC,IC shows the presence of Gravels and High FC,IC corresponds to clayey/organic soils. Samples belonging to low FC, high IC quadrant are mostly prone to liquefaction.

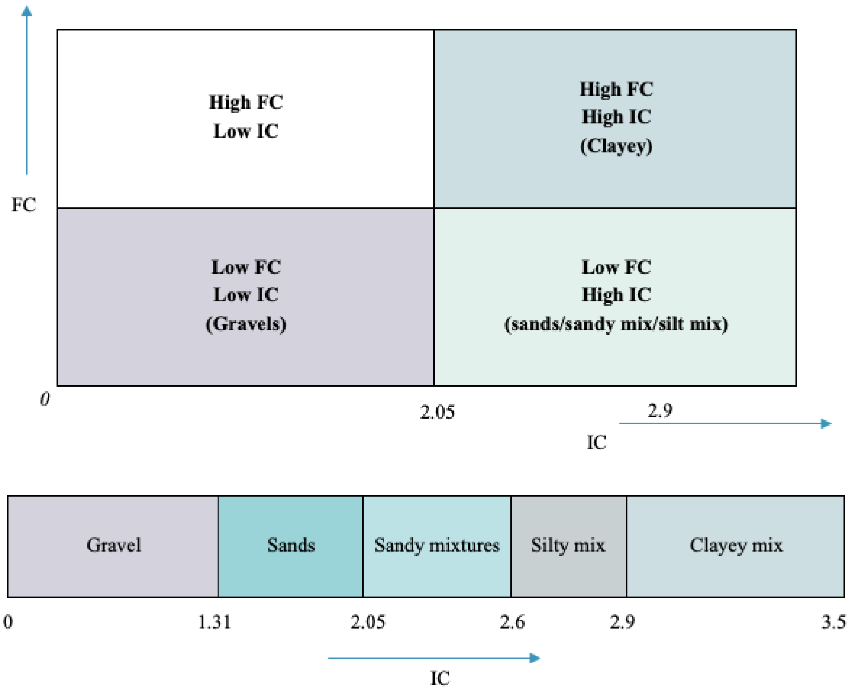

Figure 3.5: Representation of FC vs IC along with soil types

3.3.1. Depth

The depth at which the sample collected is one such factor that can affect the fines content and the Soil behaviour index. With the different layers of formation present, the depth at which soil is collected becomes important. It facilitates to register depth to identify the Geology of the region. It is used to determine if the samples found at shallow depths have an influence.

3.3.2. Distance

The set of CPT samples are collected in such a way that the distance between the CPT and a borehole is not more than 5m. Soil variability is an important factor when sampling procedures are in question. The soil variability needs to be accounted for. The closer the CPT to the borehole, more accurately the soil profile can be described and it would reduce errors in identifying the type of soil and the geology. Here, it is validated if the distance between the CPT and borehole has any effect over the soil behaviour index or the fines content. Correlation between the distance between CPT and Borehole is studied.

3.3.3. Grain Size Distribution curve

Grain size distribution curve is an important aspect which is to be studied in relation with the fines content and soil behaviour index. Soil behaviour is dependent on the size of the particles present and their quantity. If there are particles of the same size in larger quantity, then the soil sample is said to be poorly graded soil unlike the sample which contains all sizes of the soil particles in proportion, then it is said to be an well graded soil. Depending on the size of the particle that is dominant, it is classified into silt/clay/sand/gravel type of soil. If the soil is well graded, then the soil is less likely to liquefy, while poorly graded soils are highly susceptible to liquefaction. Since the presence of fines largely decides the behaviour of soil, it is also essential to check if the entire samples grain size distribution curve has any effect on the FC or IC.

3.3.4. Geology

Geology is essential for recognising the history of the soil. The history helps in understanding the pressure the soil has been subjected to in the past, the origin of the soil from type of soils, the environmental/chemical/biological factors it is been subjected to, that has resulted in weathering of the rocks to form soil, the loading over the period of time. This effects the soil behavior based on the formations and the depth along with it accounts for its influence. Hence, the different formations and their influence on FC vs IC are studied in this section.

4

Analysis and Results

This chapter summarizes the analysis and the result of the study. It deals with the evaluation of all the factors selected for the study. Comparison is based on the value of coefficient of determination, which describes the strength of a correlation. The relationship between FC and IC is shown by the scatter plot below by linear regression. According to the Dutch standard, the fines content is defined by the percentage of the particles below the size of $63\mu m$. The graph is expected to have an exponential increase in IC when there is increase in FC. Rather in this case, there is a scatter. The R^2 is found to be **0.32**. There are total of 167 samples selected for the study. Since the FC based on Dutch standards cannot be used to directly compare with other research studies in this field, conversion to ASTM standard is carried out

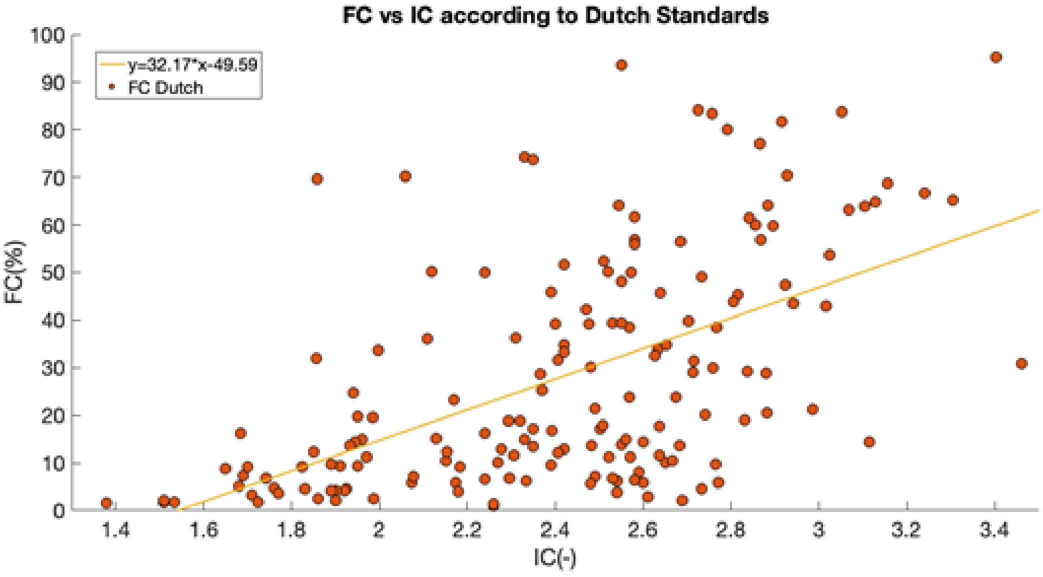

Figure 4.1: FC vs IC for Dutch standard

by interpolation. Both FC Dutch and FC ASTM are plotted against the IC. The R^2 is found to be **0.32** for Dutch and **0.35** for ASTM. From this step onwards, the FC Dutch is disregarded. This is used as a foundation to compare the influence of the various factors has on FC vs IC.

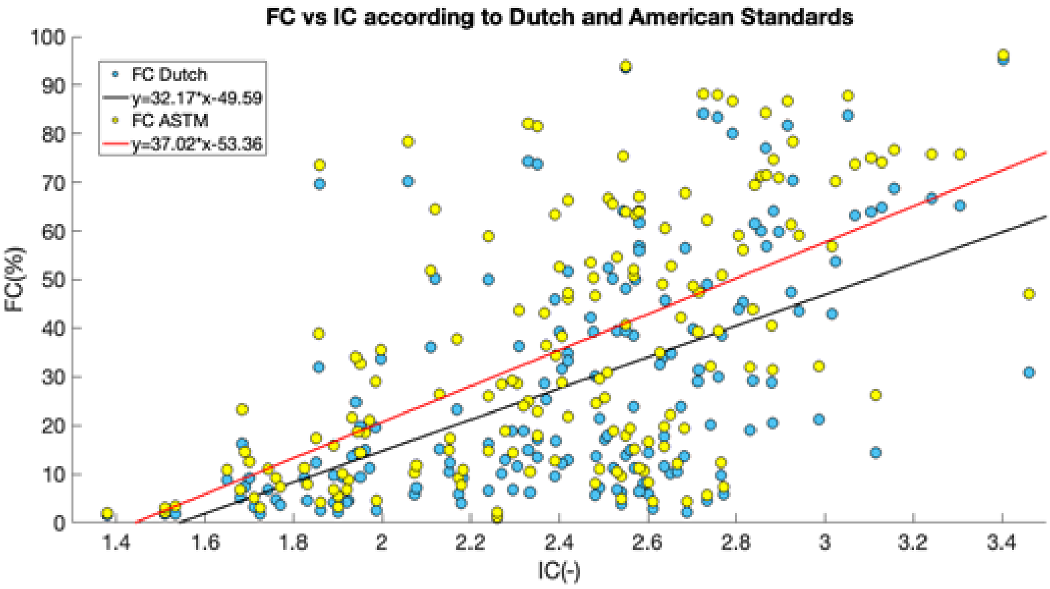

Figure 4.2: FC vs IC for the Dutch standard and ASTM standard

4.1. Averaging the IC value

The analysis carried out to understand the effect of the depth considered to average the IC value. In Figure 4.3, different cases averaging of IC can be seen. Generally, the sample height is 40cm. Thus, the IC value is averaged over the same height. The IC value at 20cm mid-height of the sample cannot be considered as the sample height is 40cm and the soil particles within that height needs to be accounted for, in case there are different layers of soil. Thus, the IC value is averaged for the entire height of sample. Now, considering the reverse case, if the averaging height is considered as 80cm or 1m, beyond the height of the sample, it is observed that the scatter plot shows a digressing pattern. For further study, the IC value averaged over the height of sample is considered. It explains that the IC values can be overestimated if its averaged over larger depth, reducing the reliability.Figures for IC avergaing over 80cm, 1m are attached in Appendix B

The R^2 values for the different cases of IC averaging are:

0.35- for averaging over 40cm (height of the sample)

0.20- for averaging over 80cm (over the height of sample

0.18- for averaging over 1m (well over the height of sample)

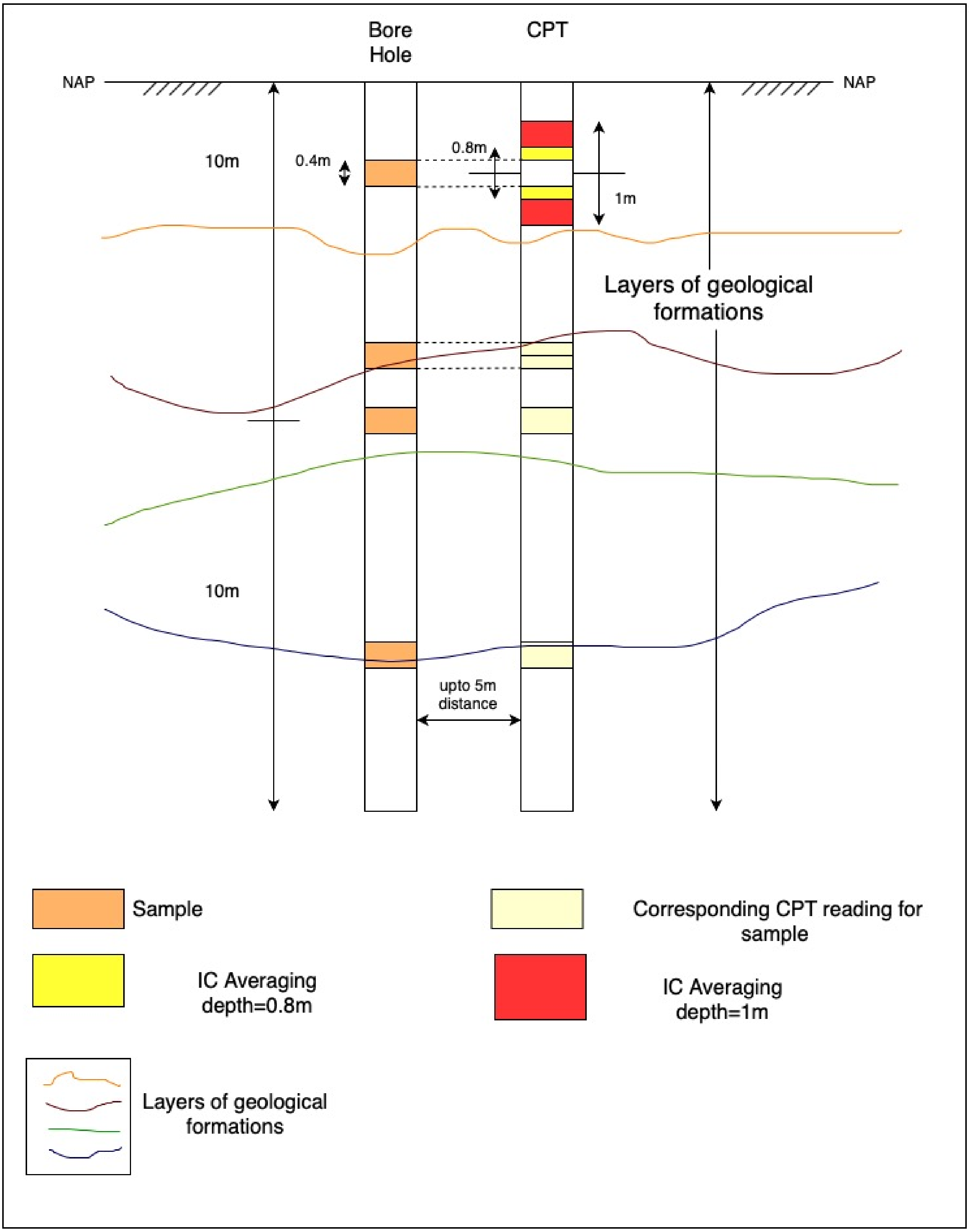

Figure 4.3: Representation of the Averaging IC values and Prerequisites for factors in consideration

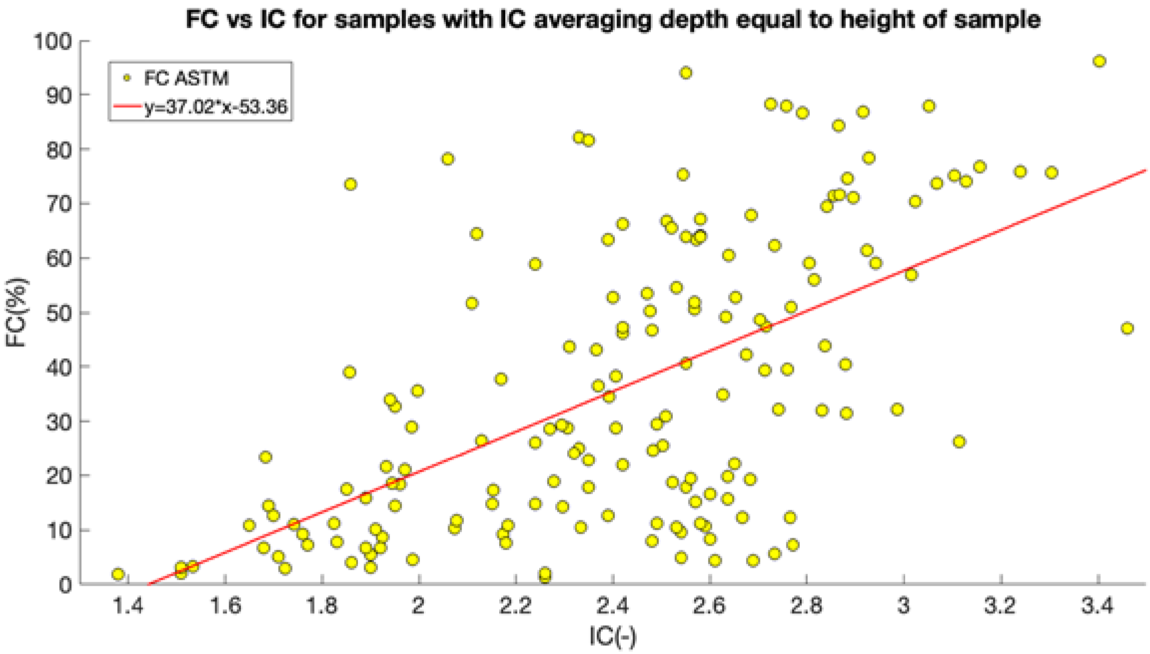

Figure 4.4: FC vs IC for samples with IC averaging depth equal to height of sample

4.2. Analysis based on Different factors considered

4.2.1. Depth of the soil sample

In this case, the depth at which the soil sample is collected becomes the criteria for study. The total depth of up to 20m is considered and further is divided in two, 0 to 10m and 10m-20m to see if there is any pattern which explains the scatter. One observation from figure 4.5 is, the samples from top layer, have very less FC and their IC varies between 1.3- 2.6.

The R^2 values:

0.33 for 0-10m depth.

0.59 for 10m-20m depth.

This shows an interesting pattern, the samples at deeper depth show better correlation than the ones found at 0 to -10m. The reason for such behaviour would be explained better when the geology of the soil is considered. The entire depth of the study is restricted to 20m because the liquefaction is known to occur within shallow depths.

4.2.2. Distance

The distance between CPT and BH is set for 5m as it is presumed that the closer the CPT to BH, the better the soil profiling would be, and much accurately the soil layers can be identified. Thus, 5 different cases are considered to validate this. Five different cases of samples with CPT-BH pairs between 0-1m, up to 0-5m are considered. It can be seen that the closer the CPT to BH, the better the R^2 value. The R^2 values are:

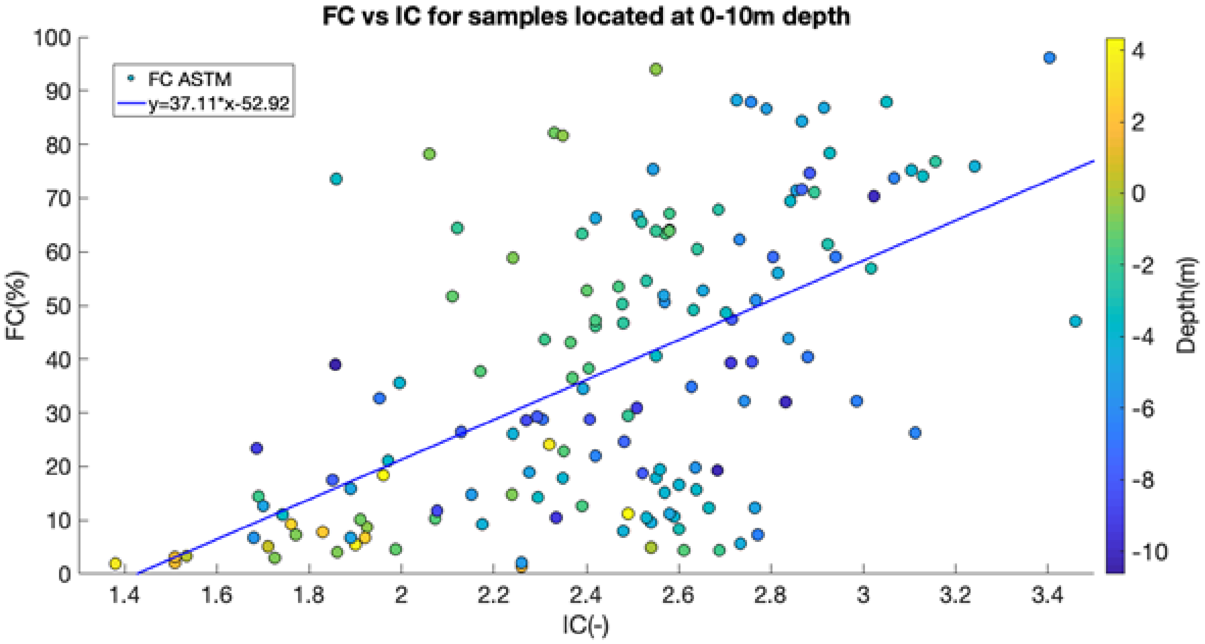

Figure 4.5: FC vs IC for samples based on the depths of the sample collected between 0-10m NAP

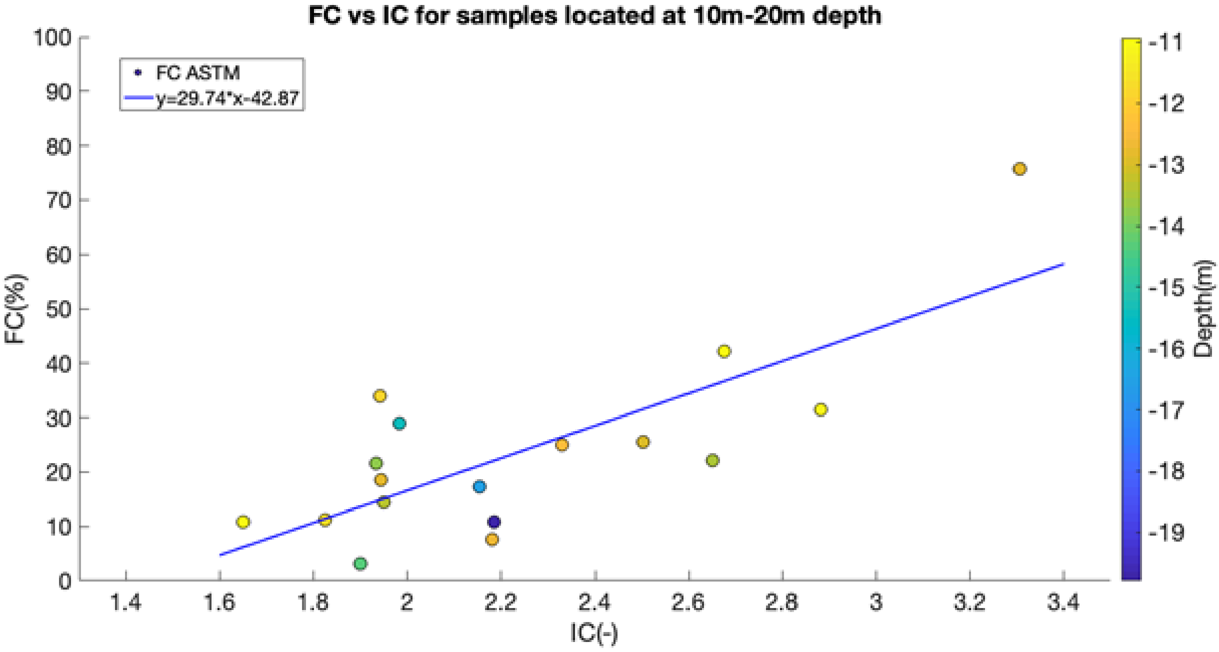

Figure 4.6: FC vs IC for samples based on the depths of the sample collected between 10m-20m NAP

0.44 for 0-1m
0.40 for 0-2m
0.40 for 0-3m
0.35 for 0-4m
0.35 for 0-5m. Thus, the distance between the CPT-BH also has influence on the FC and IC correlation. From this stage onwards, samples with CPT-BH distances 0-1m

are considered.

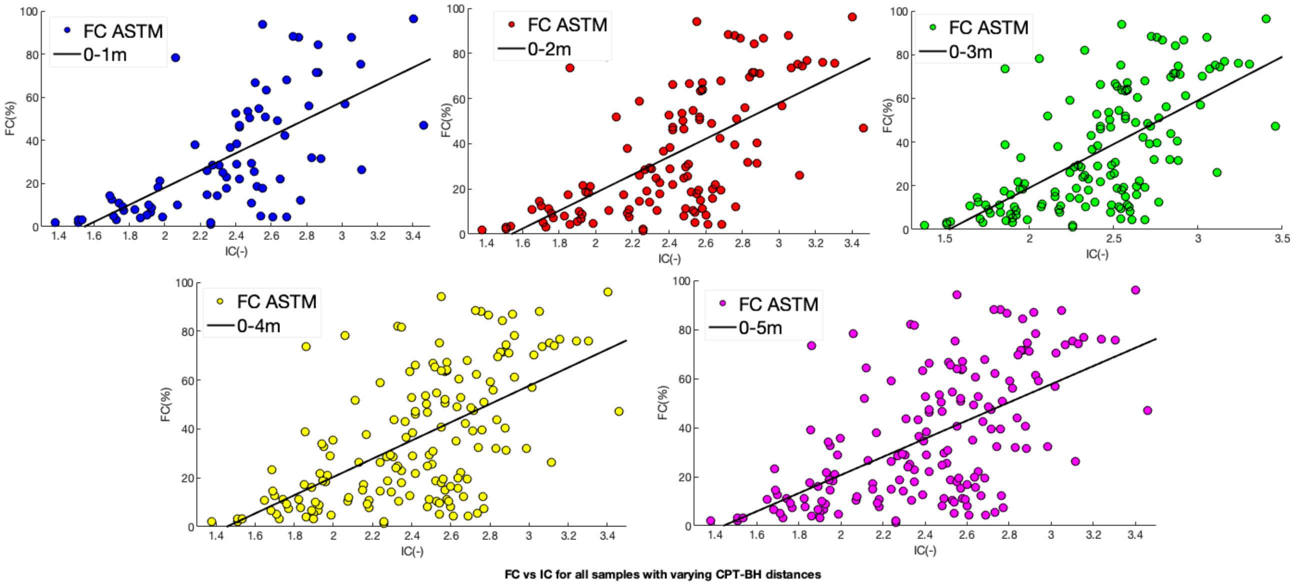

Figure 4.7: FC vs IC for all samples with varying CPT-BH distances (left to right)

4.2.3. Gradation

Grain size distribution for all the samples are plotted on a logarithmic scale as shown in Figure 4.8. Grain size Index (I_{GS}) is calculated to classify the soil gradation as well graded or poorly graded apart from the Coefficient of curvature and Coefficient of Uniformity which would give the overview of the amount of the particles present under a particular size. According to Erguler, Z., A., (2016), for well-graded sand, the values of I_{GS} is between 0.27–0.42 and for poorly graded sand, I_{GS} is between 0.42–0.59. In this case, most of the samples fall under the category of poorly graded soils. In terms of the boundaries for preliminary assessment of liquefaction of poorly graded soils, the I_{GS} values define a range between **0.74** and **0.34** for soil potentially liquefiable, and between **0.62** and **0.43** for the most liquefiable soil. 86% of the data set falls into the category of potentially liquefiable soils as they are mostly poorly graded soils.

From figure 4.9, Grain size index is directly proportional to the FC of the soil, which means that the higher the fines content, higher the grain size index. But the FC vs IC plot has an R^2 value equal to **0.35**. Figures attached in Appendix B show the variation with the Coefficient of uniformity and Coefficient of curvature.

$$Coefficient\ \ of\ \ Uniformity = \frac{D60}{D10} \tag{4.1}$$

$$Coefficient\ \ of\ \ Curvature = \frac{D30^2}{D60 * D10} \tag{4.2}$$

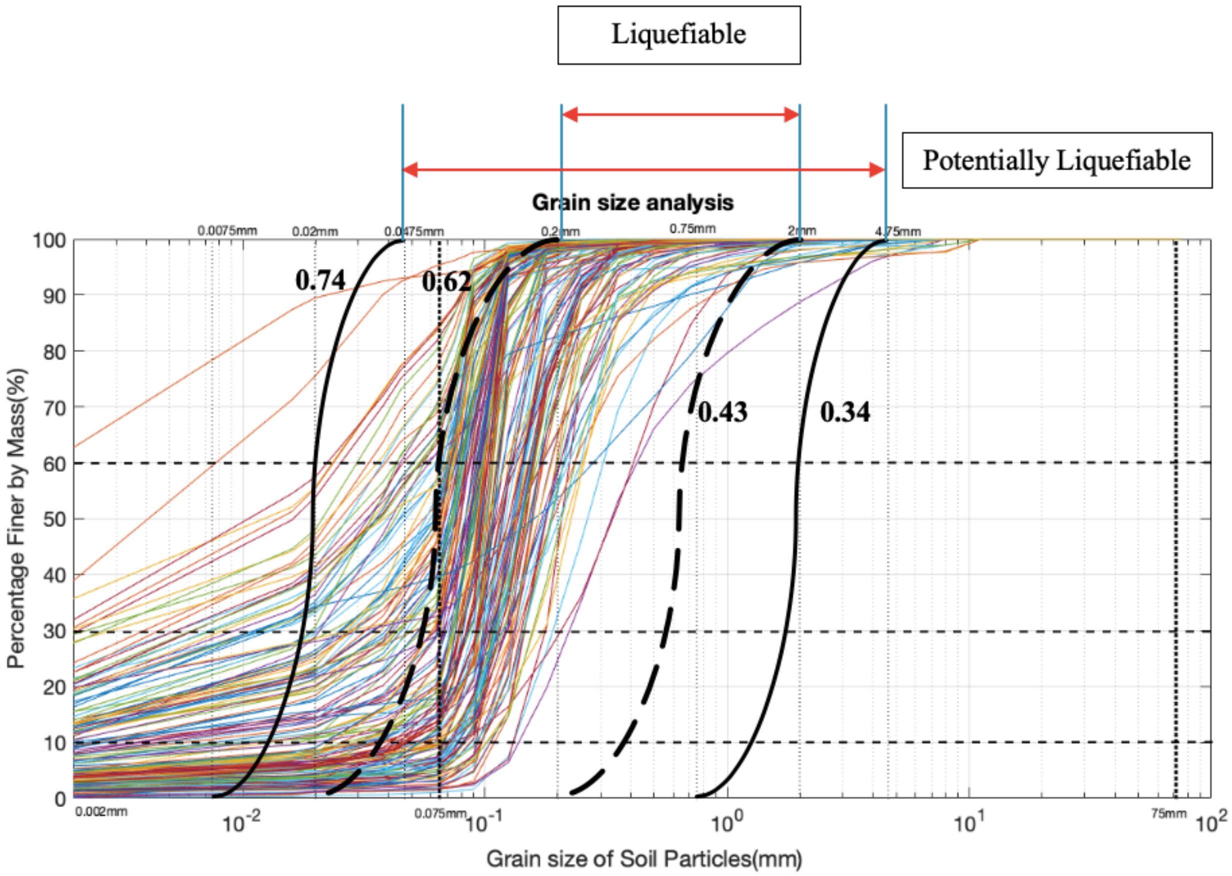

Figure 4.8: Grain size distribution curve for all the samples along with bands indicating potentially liquefiable and liquefiable ranges of I_{GS} for all samples

The terms D60, D30,D10 and D50 are defined as:

D60 - 60% of the soil particles are finer than this size.
D30 - 30% of the Soil particles are finer than this size.
D10 - 10% of the Soil particles are finer than this size.
D50 - 50% of the soil particles are finer than this size.

Since the soils are poorly graded, the values of Cc and Cu are abnormally high. Samples with CPT-BH distances between 0-1m are considered, the R^2 value raises to **0.44** for plots with FC vs IC with grain size index. Therefore, D50 is calculated. D50 is directly proportional to FC vs IC. The regression of D50 vs FC and D50 vs IC results in R^2 about 0.82 and 0.71 respectively. This is higher than in case of Cu and Cc. I_{GS} alone would not be sufficient as the area under the curve could be same for two different samples with different fines content and steepness. Since this cannot be used individually, it is to be used in combination with D50 to determine the effect. Highest value of D50 in the data set is 0.3mm. Higher the D50, lower is the fines content. Along with it, if the sample's I_{GS} value falls between 0.62-0.43, then it is said to be liquefiable or if it falls between 0.74-0.34, then it is said to be potentially liquefiable for Groningen soils. Since Cu and Cc values are ratios, it is possible that

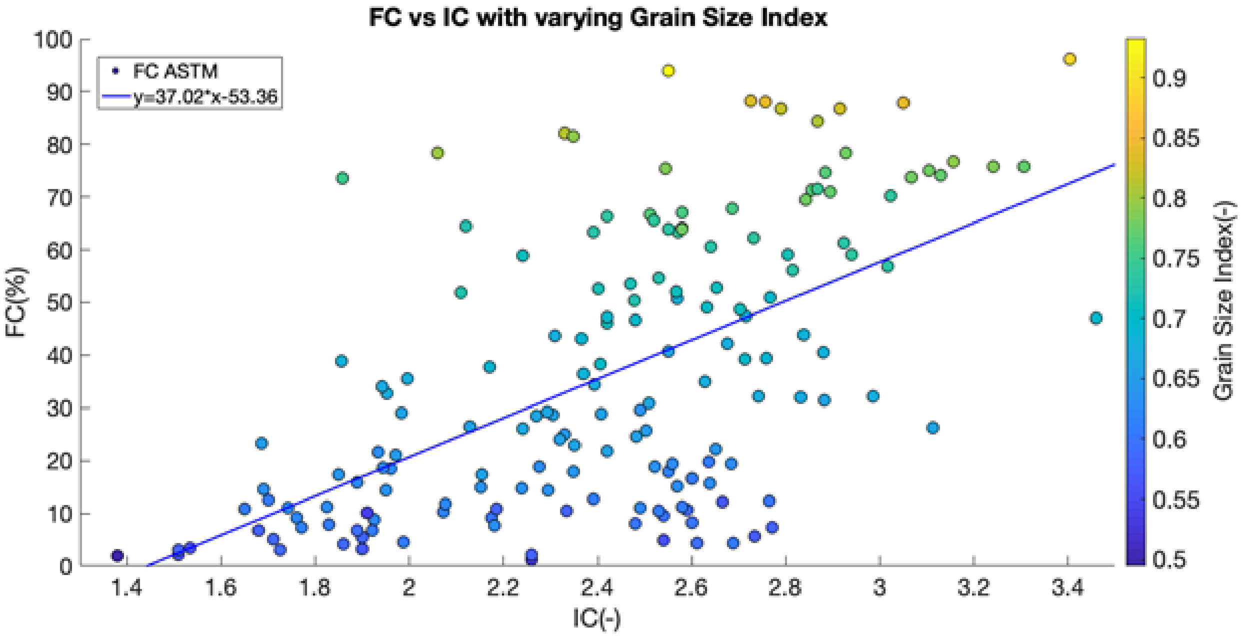

Figure 4.9: FC vs IC with varying grain size index

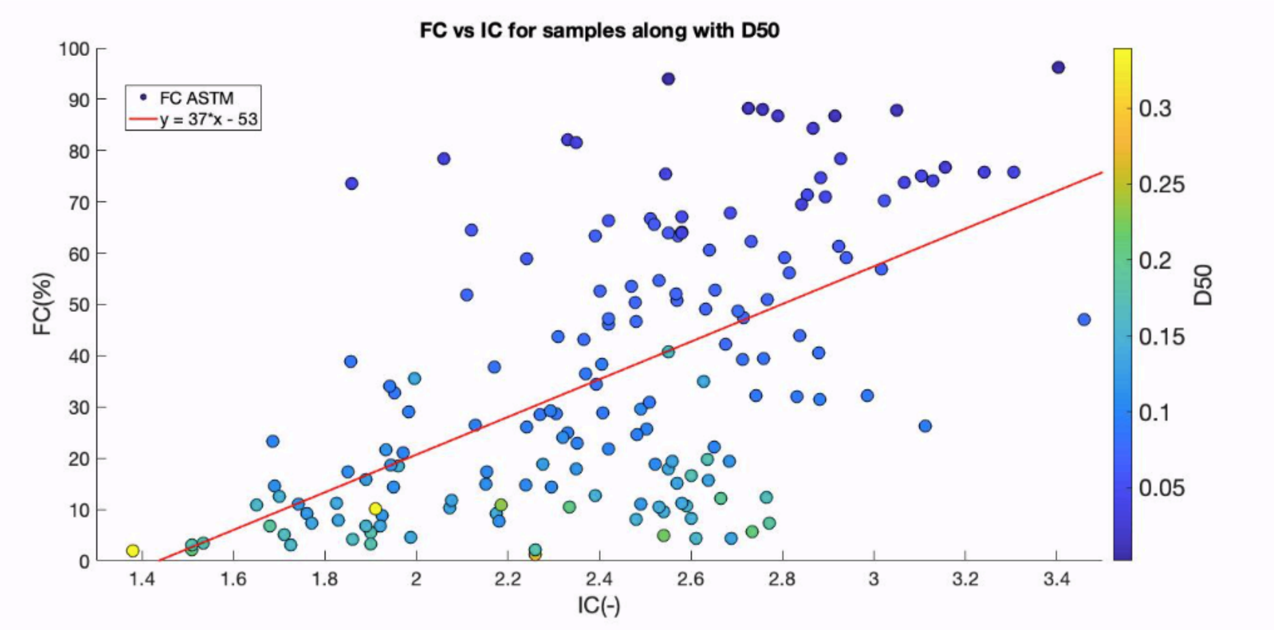

Figure 4.10: FC vs IC for all the samples along with D50

the range could be relative.

4.2.4. Geology

The geology of Groningen divided into two major groups- Holocene and Pleistocene formations. Since the younger soils are more susceptible to liquefaction, the Holocene

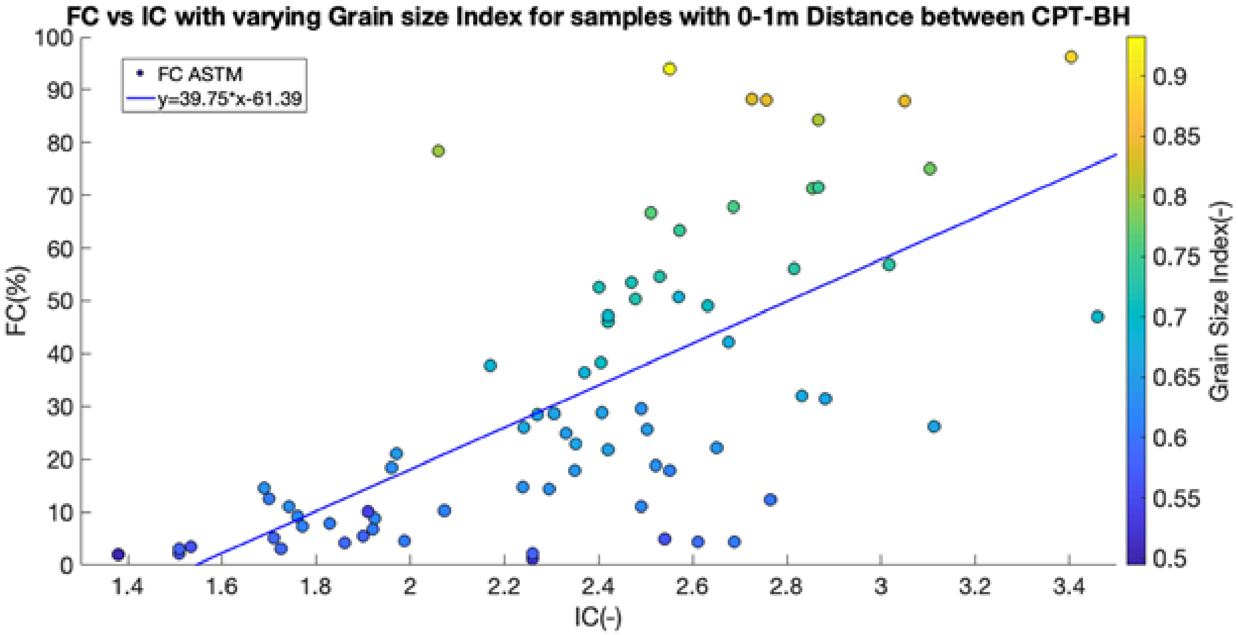

Figure 4.11: FC vs IC with varying grain size index for samples with CPT-BH distance between 0-1m

soils are expected to have some interesting correlation. The R^2 for Holocene formations is **0.33**, thus describing very less variance of FC with variance of IC. The correlation is poor when Holocene is considered entirely. The R^2 values are as follows:
0.52 for Naaldwijk Walcheren,
0.27 for Naaldwijk Wormerveer,
0.41 for Naaldwijk Undifferentiated,
0.62 for Nieuwkoop Basisveen.

This shows that the Naaldwijk formations has a good correlation. Nieuwkoop Basisveen is ignored hereafter as it is a peat formation and very few samples are of this soil type.

The R^2 value for Pleistocene formations is **0.05**. Pleistocene formations have far less influence than the Holocene, from the above. The R^2 values are :
0.01 for Peelo,
0.41for Drente,
0.03 for Boxtel. This data set is insufficient to draw conclusions from the above graph. Though Boxtel does not belong to the Holocene and Pleistocene entirely, here it is considered as a part of Pleistocene formation, for convenience.

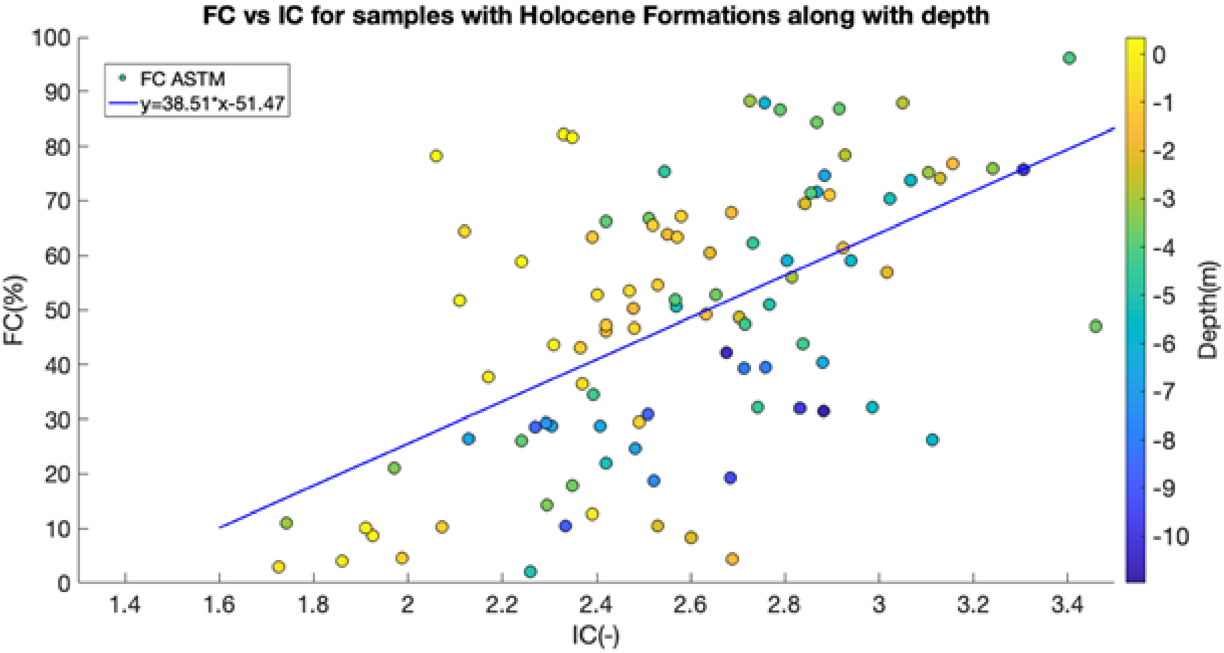

Figure 4.12: FC vs IC with varying depth for Holocene formations

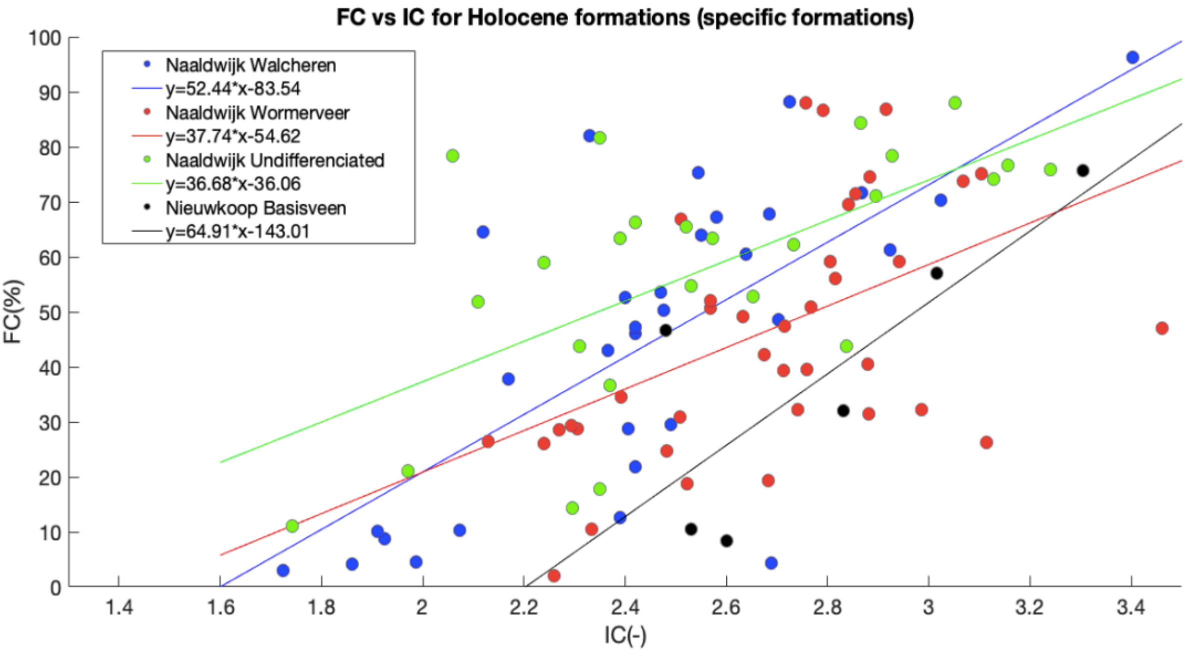

Figure 4.13: FC vs IC with varying depth for Holocene formations showing specific formations

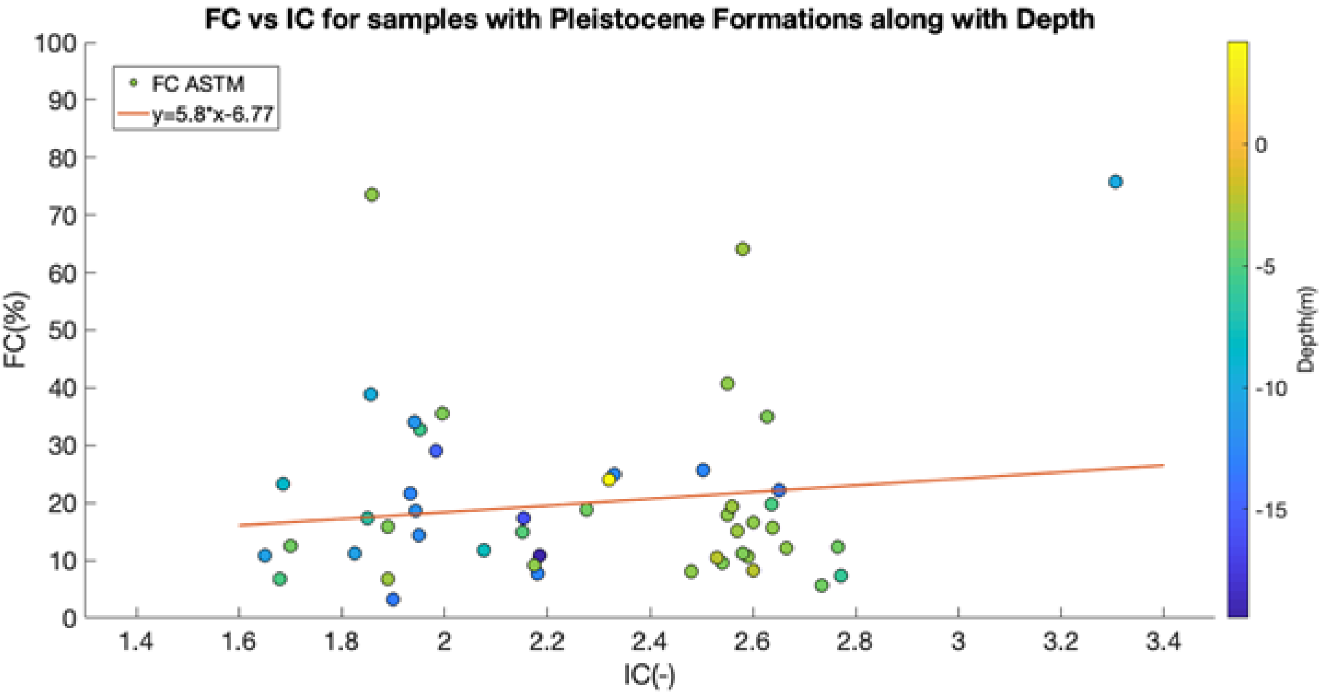

Figure 4.14: FC vs IC with varying depth for Pleistocene formations

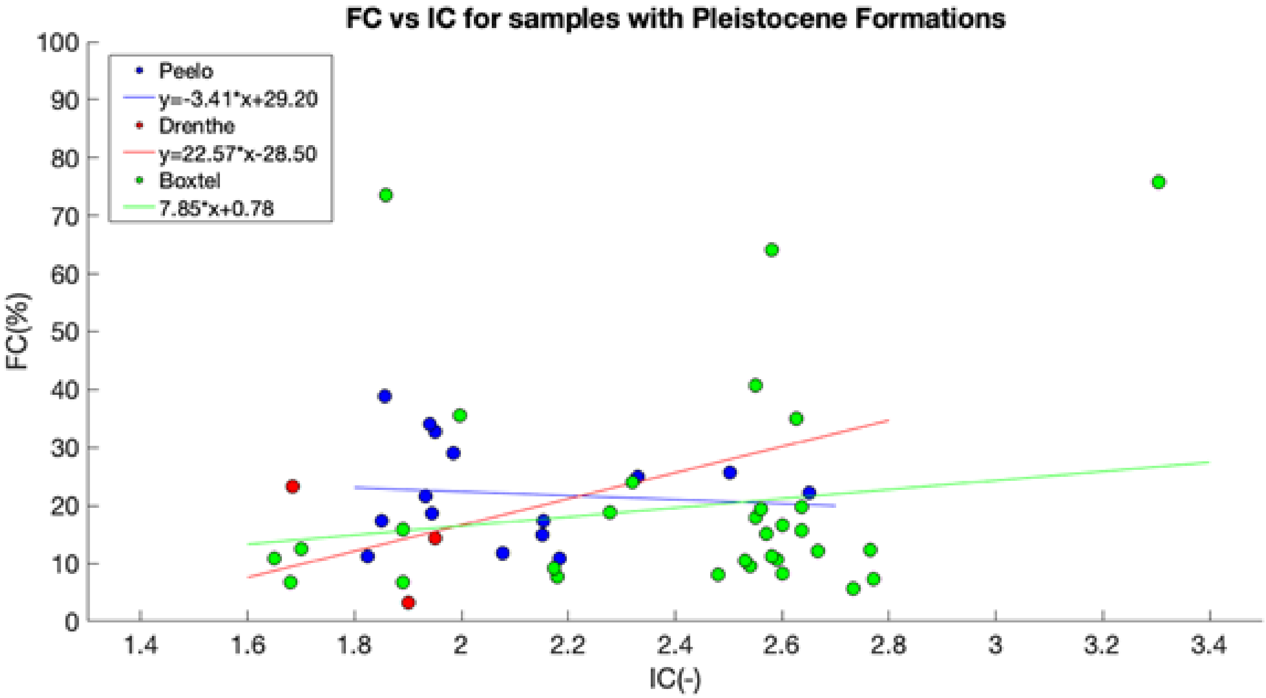

Figure 4.15: FC vs IC with varying depth for Pleistocene formations with specific formations

4.3. Boulanger and Idriss (2014) correlation

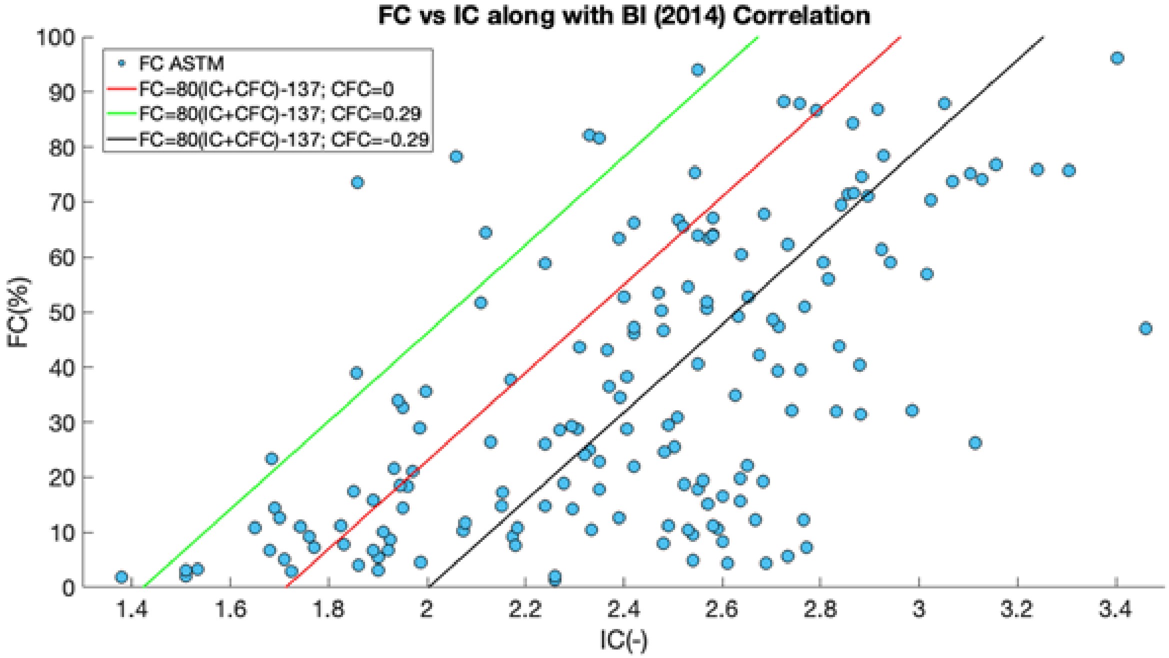

Figure 4.16: FC vs IC with Boulanger and Idriss (2014) correlation

According to Boulanger and Idriss (2014), $2/3^{rd}$ of their data set was between the range of 0.29 to -0.29 based on the standard deviation of the error term used in the equation. After removal of the outliers, the standard deviation drops from 0.41 to 0.31 for the data set of Groningen soils. The equation can be used with CFC=-0.29, but not recommended. Further investigation is necessary with higher number of samples as the scattered, increasing the standard deviation. If the standard deviation for the data set from Groningen is beyond +/-0.29, then it would be unsuitable to use this correlation. This equation is based on the data set from USA and hence, site specific.

A new equation is proposed, based on these 167 samples from Groningen, which is site specific. Provision can be made for accounting the factors that influence the FC vs IC correlation as well. Since the R^2 value is low, the extent of the influence of the selected factors over FC vs IC is low. Further study needs to be done based on other factors affecting liquefaction. Otherwise, when using the Boulanger and Idriss (2014) equation, it should be noted that the correlation is may be underestimating or overestimating the values of FC. Without the removal of the outliers, the equation is $FC = 37.02 * IC - 53.36$, with R^2=0.35. This equation improves to $FC = 40.58 * IC - 62.60$ with $R^2 = 0.43$ (with 158 samples out of 167 samples from original set of samples considered for all analysis). In comparison with Boulanger and Idriss (2014), IC vs

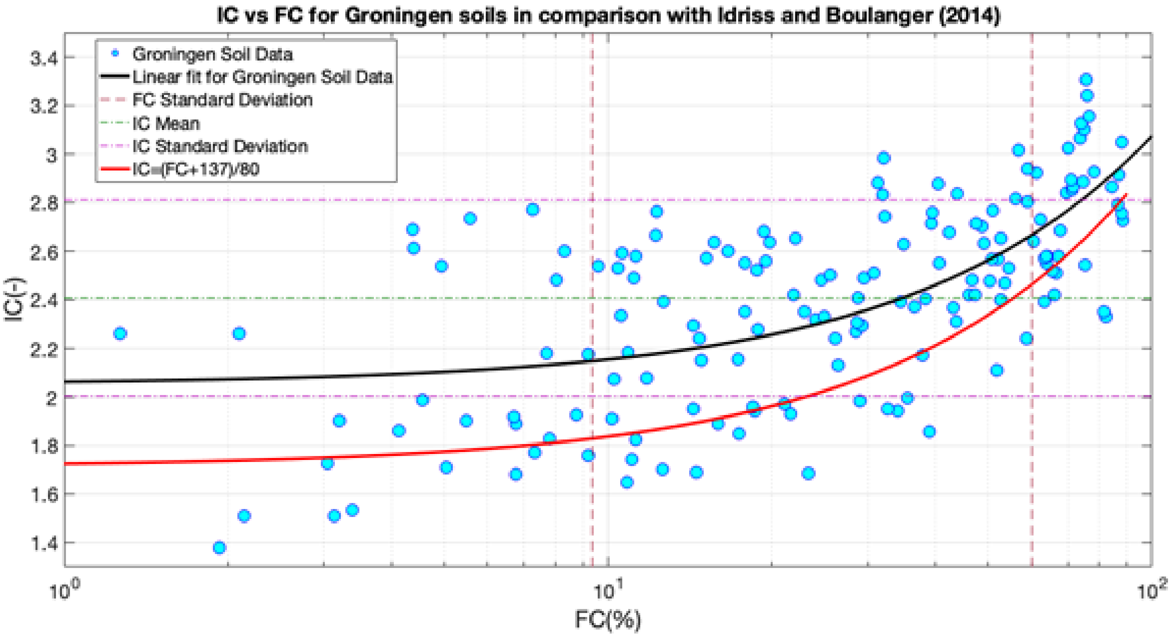

Figure 4.17: FC vs IC with Boulanger and Idriss (2014) correlation

FC regression is done for the Groningen soils.

$$IC = 0.27(\frac{FC - 34}{25}) + 2.4 + \epsilon \tag{4.3}$$

$$FC = 92.6(IC - CFC) - 256.2 \tag{4.4}$$

Where ϵ is the error term, fluctuating between +/-0.27, the standard deviation for the sample set, by normalising the mean. The error term is substituted with CFC, a fitting parameter, to facilitate site specific correlation. CFC is the same sign as the error term, positive CFC corresponding to larger FC value and vice versa. FC lies between 0 to 100% and IC is calculated based on Robertson,(1998). For the purpose of extensive study, the IC value has not been cut-off at 2.6 (to filter out the clayey soils) since it varies depending on the soil variability and location. It may be relevant to consider 2.4 or 2.8 as well. Thus, this study includes IC values up to 3.5. Figure 4.18 suggests the new correlation for Groningen soils.

The results of such analyses are play an important role in the site-specific sampling and testing, instead of completely relying on the correlations. Site specific sampling is a must considering the risk/ consequences of every project.

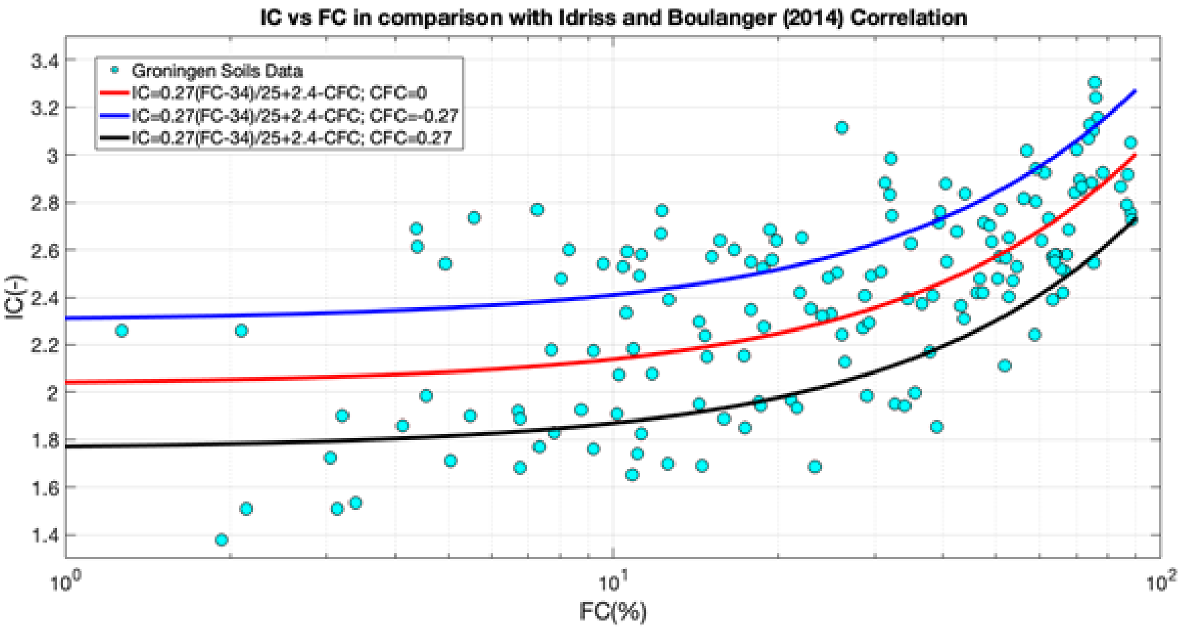

Figure 4.18: FC vs IC regression suggesting a new correlation, specific to Groningen soils

4.4. Further Analysis on Geological layer

4.4.1. Naaldwijk

Naaldwijk consists of three different subsets of formations, namely, Naaldwijk Walcheren, Naaldwijk Wormerveer, Naaldwijk undifferentiated.

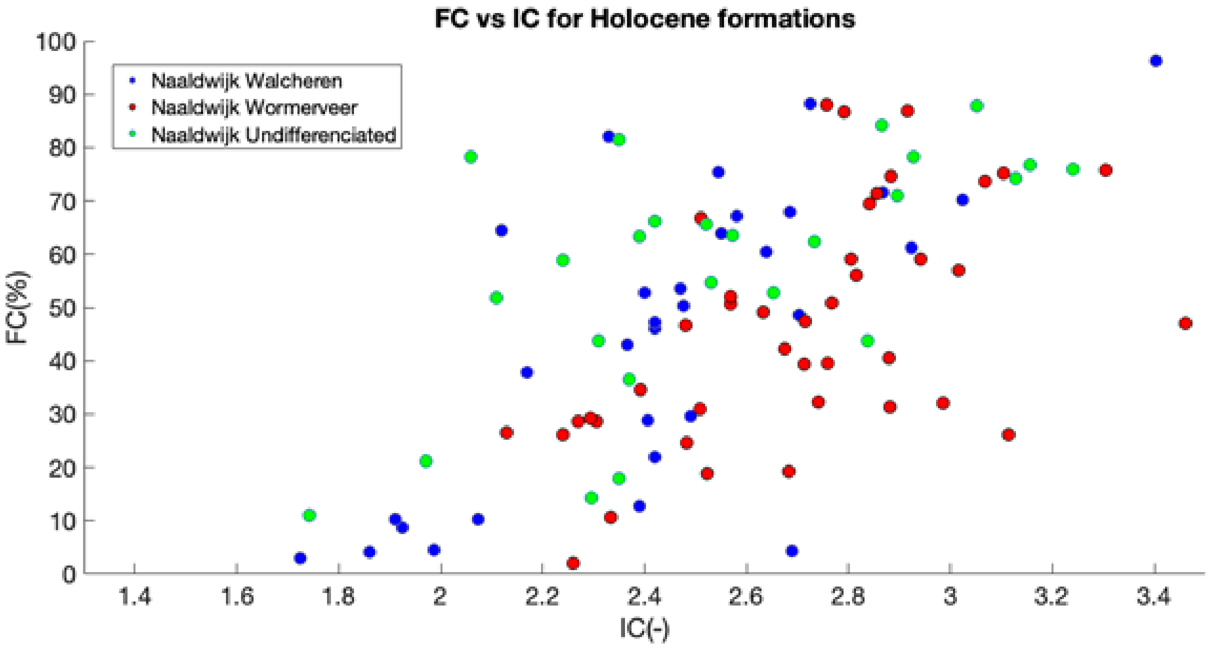

Figure 4.19: FC vs IC for Naaldwijk formations

1. **Effect of Depth**
   Initially, the data set is divided into 4 sets based on 5m interval up to -15m. An interesting pattern is found, but to improve the data set, it is sorted as 0-5m depth and 5m-15m. The R^2 values are:
   0.37 for the depth between 0 to 5m
   0.42 for the depth between 5m to 15m.
   Here, the depth is considered at 0-5m and 5m-15m, like the initial case, just to see if the correlation improved. This case of considering 5m as the mid interval depth seems to be better than 3m (dividing the set into groups of almost equal samples). But overall, the R^2 value is not sufficiently good for a strong correlation. Samples between 0-5m depth tend to have higher FC with IC ranging from 1.7-3.4. Samples from 5m-15m depth tend to have lower FC with lower IC than top layer. This accounts for the silty mix.

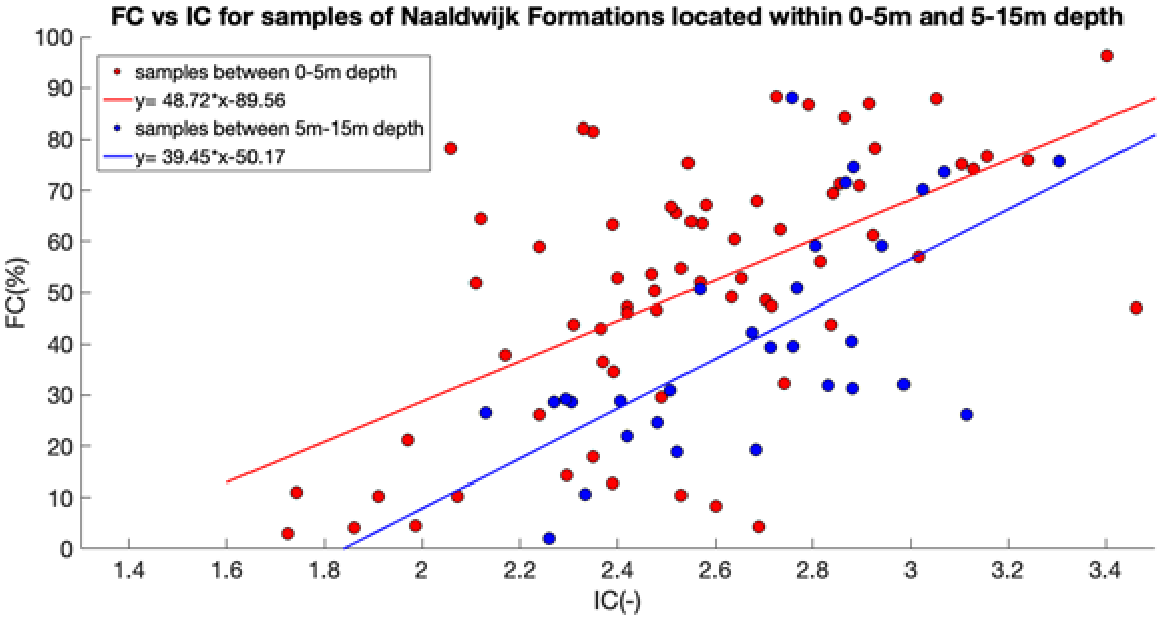

Figure 4.20: FC vs IC with varying depth for Naaldwijk formations

2. **Effect of Distance**
   R^2 value is **0.42** for samples of Naaldwijk formation with the CPT-BH distance of 0-1m.

3. **Effect of Gradation**
   The figure 4.22 shows the Grain size distributions for the Naaldwijk formations with CPT-BH distance of 1m. About 70% of the samples fall under the category of potentially liquefiable soils with an average grain size index value of 0.69. The R^2 value for FC vs IC with varying grain size index is **0.42**.

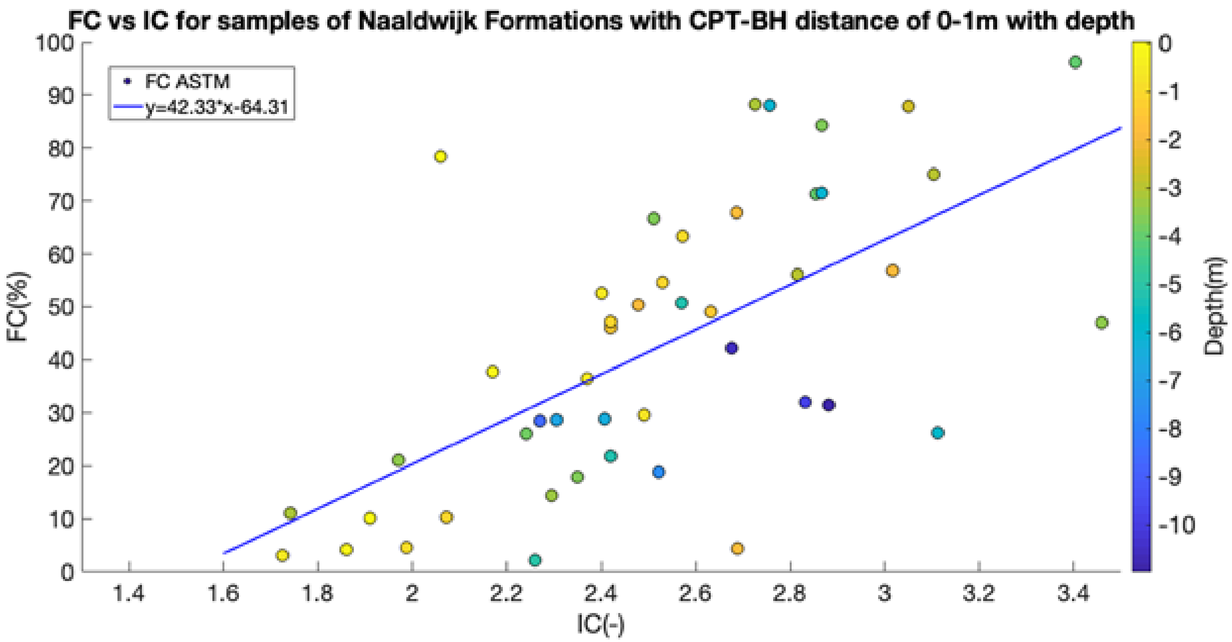

Figure 4.21: FC vs IC with varying depth for Naaldwijk formations for samples found within 0-1m CPT-BH distance

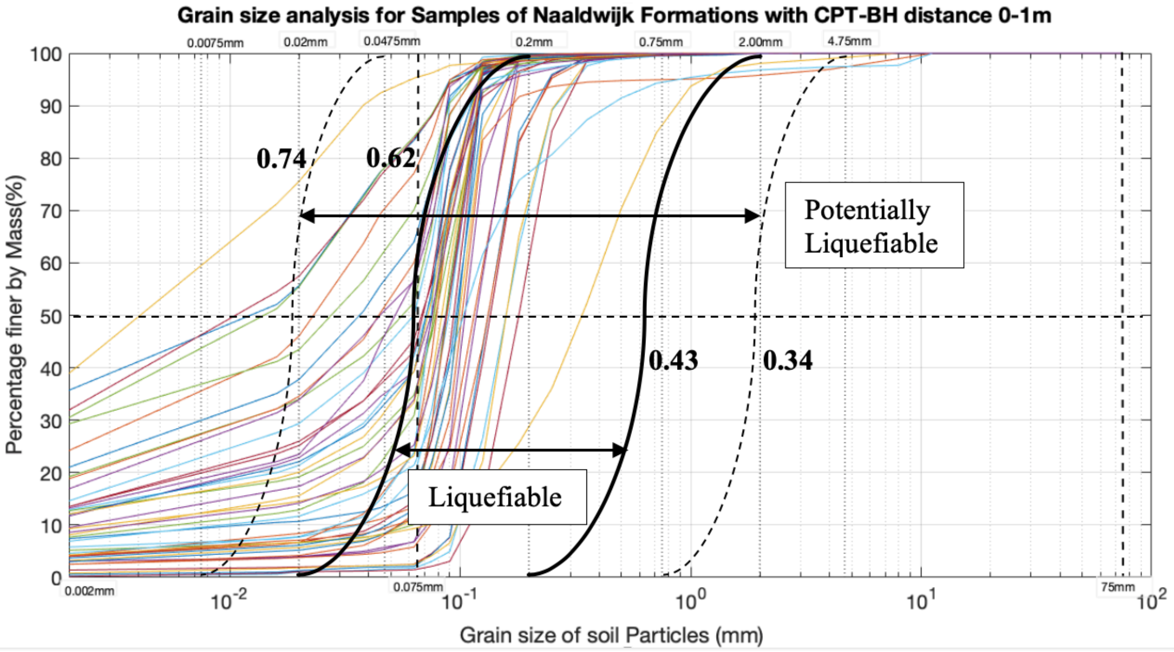

Figure 4.22: Grain size distribution curve for all the Naaldwijk samples along with band ranges indicating potentially liquefiable and liquefiable samples

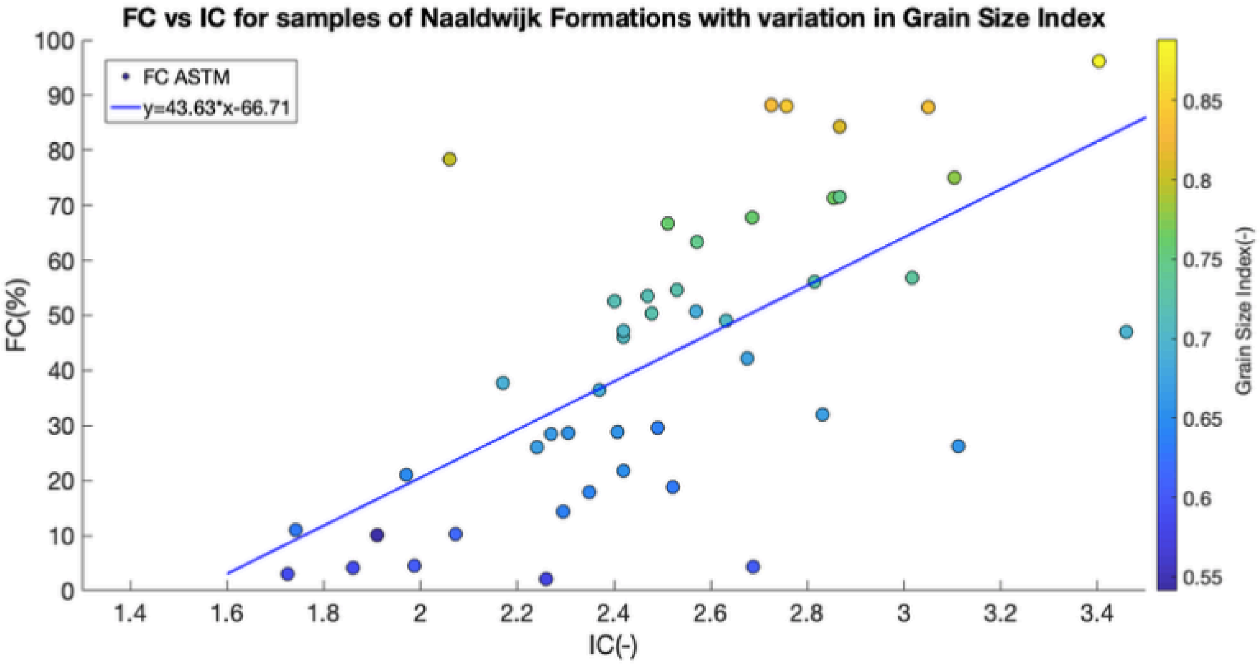

Figure 4.23: FC vs IC along with grain size index for Naaldwijk formations

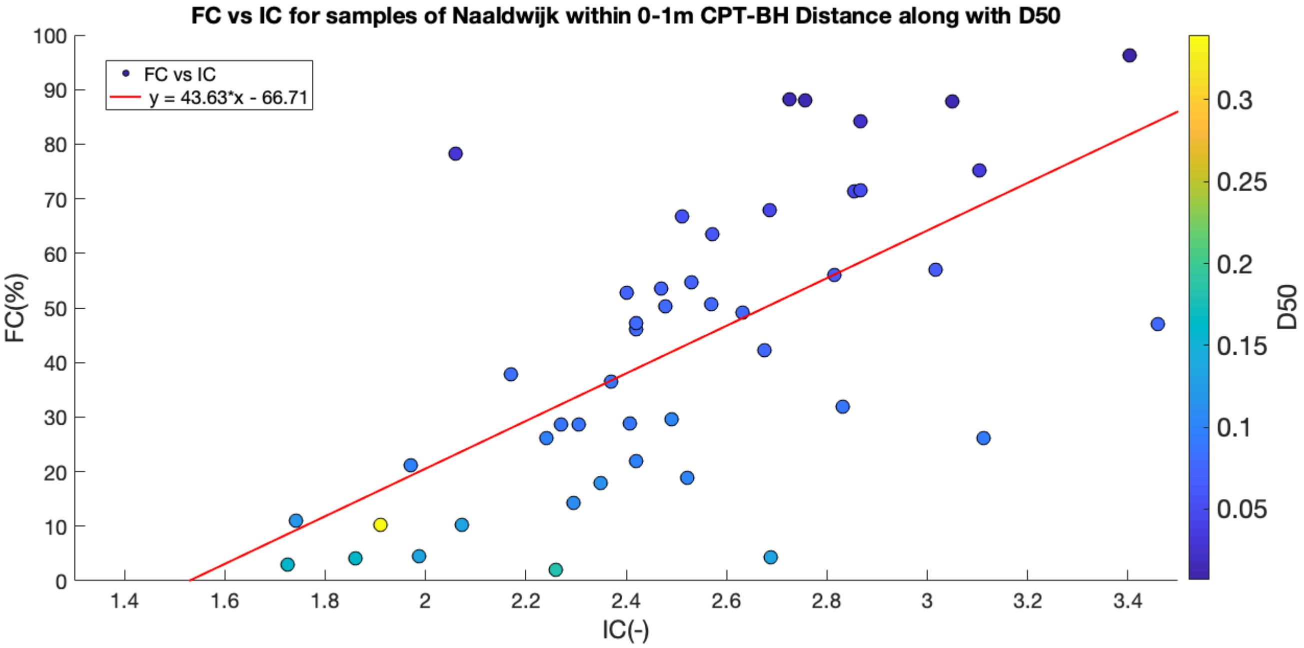

Figure 4.24: FC vs IC along with D50 for Naaldwijk formations

4. **Boulanger and Idriss (2014) Correlation**
   In this case, the Boulanger and Idriss (2014) correlation manages to encompass almost 2/3rd of the data set. It could be safer to use a better fit.

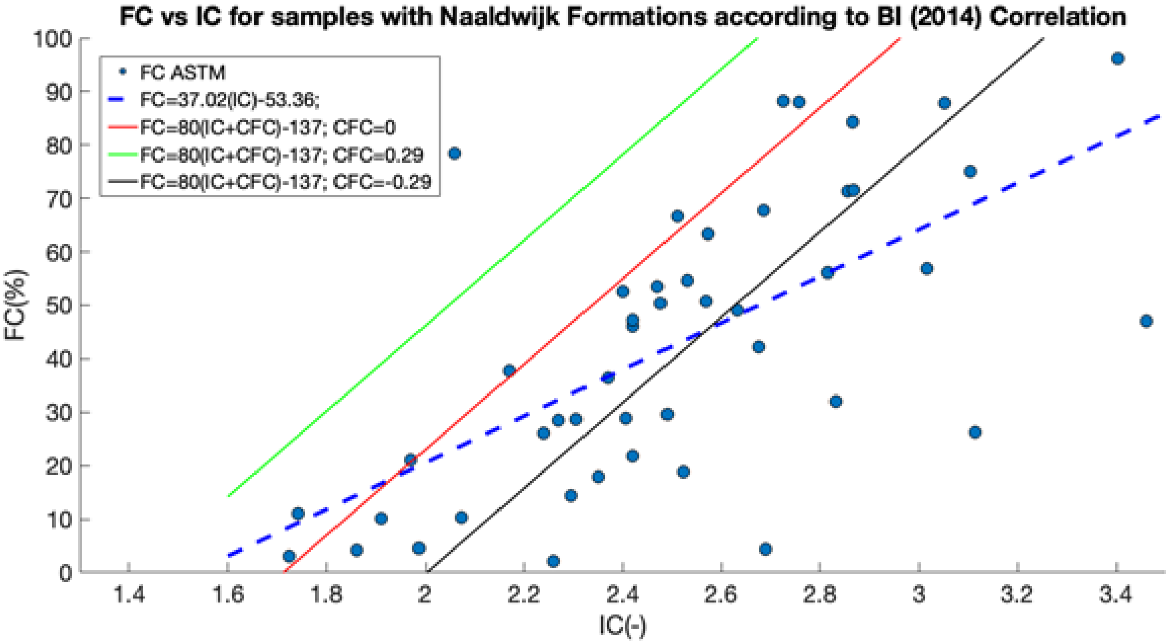

Figure 4.25: FC vs IC with Idriss and Boulanger(2014) Correlation for Naaldwijk formations

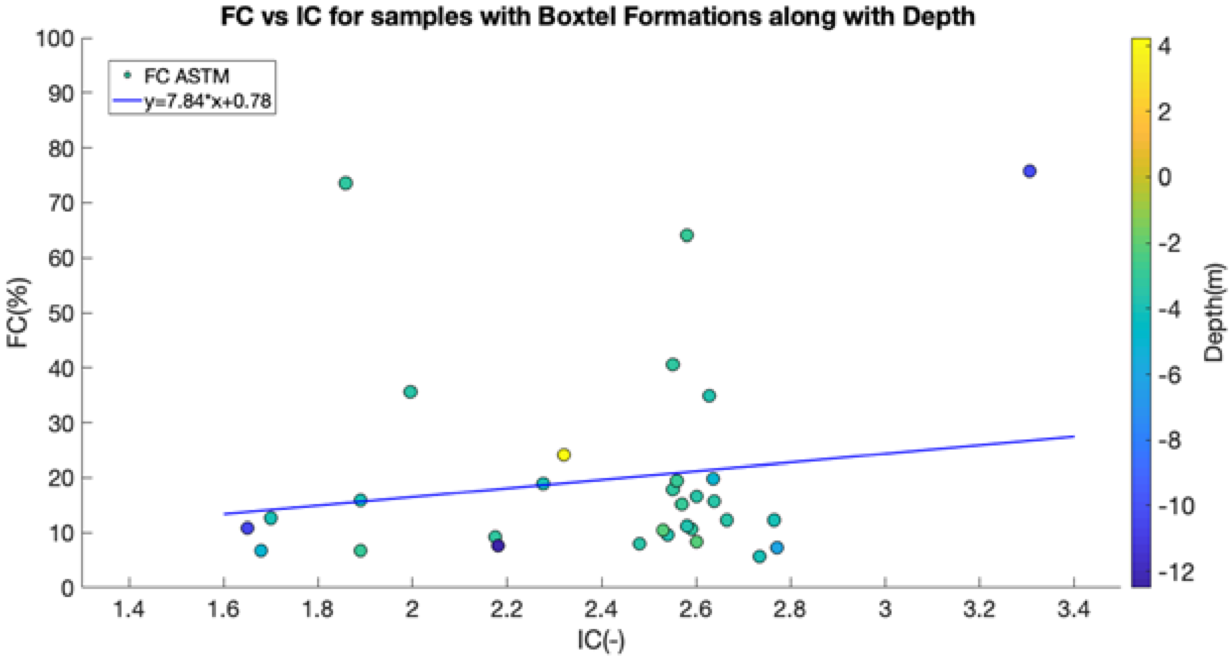

Figure 4.26: FC vs IC for Boxtel formations

4.4.2. Boxtel

It is interesting to see that there is a high concentration of the Boxtel from 0 to -5m at around 2.5 to 2.8 IC values, with fines content no more than 30%. These samples are not from the same bore hole or same project site. Further investigation is needed to justify this behaviour. The R^2 value is **0.03**. It is true that the data set is insufficient to draw conclusions. Further analysis was not carried out due to small sample set. In general, the correlation can be improved for Groningen soils based on the inclusion of depth of sample, gradation and geology. The coefficient of determination is weak in general for FC vs IC for Groningen soils.

4.5. Improving R^2 value using other functions

Using other than linear fit, different trend-lines are attempted using MATLAB curve fitting tool. A Sigmoid Fit is supposed to give a S-shaped curve, which is why it is important for the data set considered (with samples of CPT-BH distance is between 0-1m). A Polynomial Fit and a Fourier fit are the best among other trend-lines used. The R^2 value increases to **0.45** while using the Fourier Fit and further to **0.47** when using a Robust Regression with Polynomial trend-line.

The Equations used for the different fits are:

- Sigmoid Funtion:

$$y = \frac{\mathrm{a}}{1 + e^{-}bx}$$

  where a and b are 95% confidence interval coefficients

- Fourier Funtion:

$$y = a0 + a1 \cos(xw) + b1 \sin(xw)$$

  where $a0, a1, b1, w$ are 95% confidence interval coefficients and x is normalised.

- Polynomial Funtion:

$$y = p1 * x^3 + p2 * x^2 + p3 * x + p4$$

  where $p1, p2, p3, p4$ are 95% confidence interval coefficients and x is normalised.

The graphs for both Sigmoid Fit, Fourier Fit, and Polynomial Fit are shown in figures 4.27, 4.28 and 4.29 respectively. R^2 value for the Sigmoid Fit is **0.08**, Fourier Fit is **0.45** and Polynomial Fit is **0.47**. Samples with 0-1m CPT-BH distances are considered for this particular analysis. Thus, it can be concluded that the Polynomial Fit would be better than Linear Fit to increase the R^2 value for the data set, but it does not increase the value significantly.

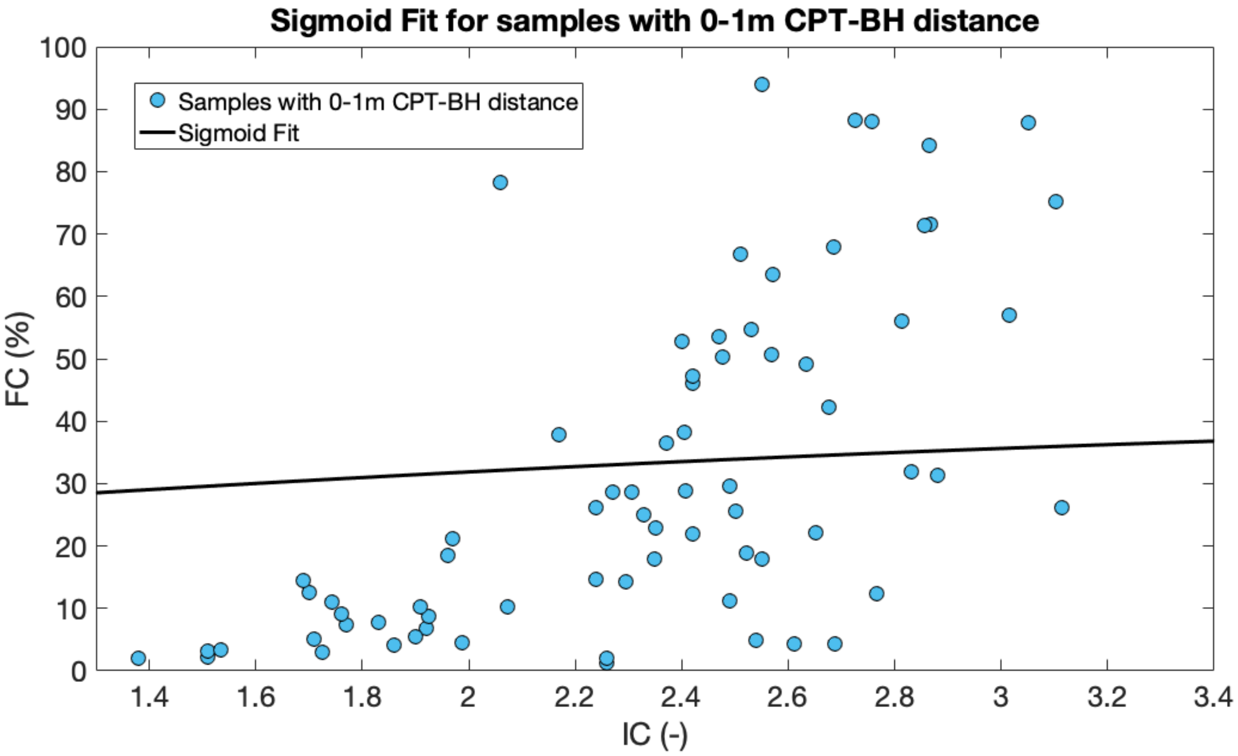

Figure 4.27: FC vs IC with Sigmoid Function

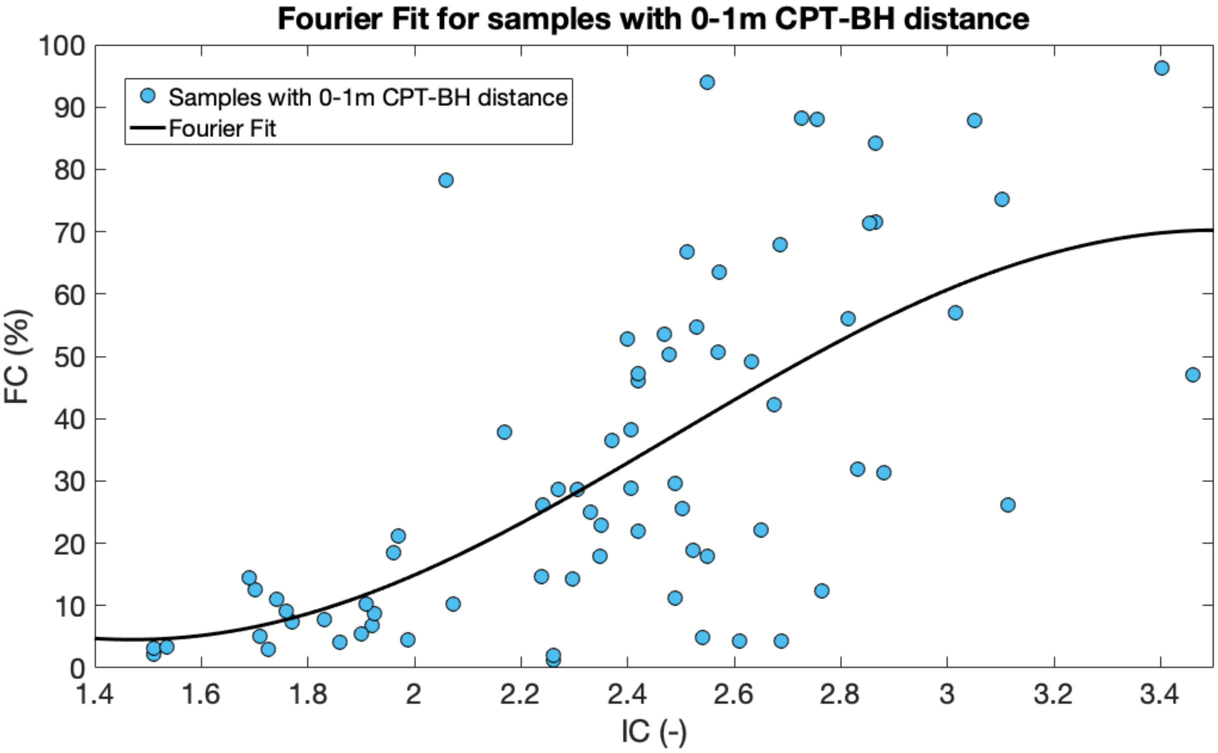

Figure 4.28: FC vs IC with Fourier Function

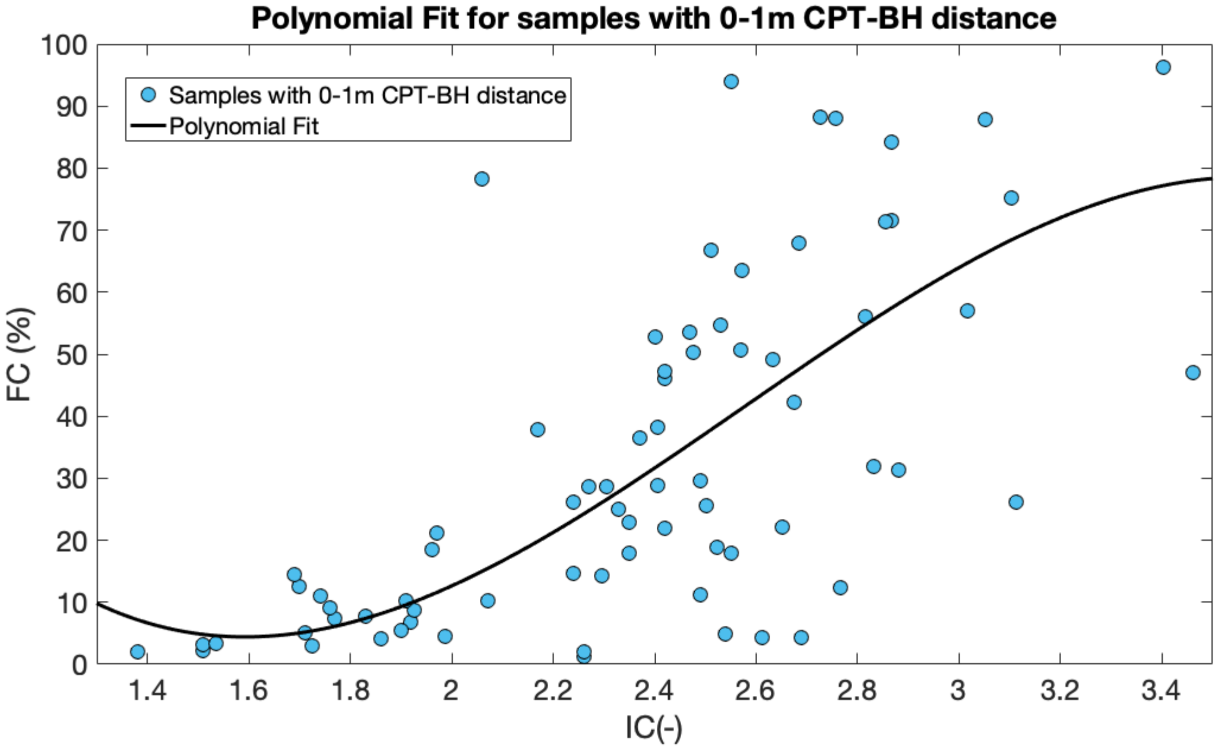

Figure 4.29: FC vs IC with Fourier Function

4.6. Summary of Analysis

The 4.1 below shows a summary, i.e, the Figure number of the graphs with the number of samples analysed based on factors, for R^2 value.

Table 4.1: Summary of R^2 values obtained during analysis for the factors considered

Figure No.	FC vs IC Analysis based on	No. of Samples	R^2 Value
1	Overall- FC Dutch	167	0.32
2	Overall- FC ASTM	167	0.35
4	Averaging IC Values- 40cm	167	0.35
	Averaging IC Values- 80cm	167	0.20
	Averaging IC Values- 100cm	167	0.18
5	Depth- 0-10m below NAP	150	0.33
6	Depth- 10-20m below NAP	17	0.59
7	Distance 0-1m	75	0.44
	Distance 0-2m	119	0.40
	Distance 0-3m	144	0.40
	Distance 0-4m	164	0.35
	Distance 0-5m	167	0.35
8	Gradation (Grain Size Index)	167	0.35
12	Geology- Holocene overall	113	0.33
13	Geology- Holocene Specific-Walcheren	36	0.52
	Geology- Holocene Specific-Wormerveer	45	0.27
	Geology- Holocene Specific-Undifferentiated	25	0.41
	Geology- Holocene Specific-Nieuwkoop Basisveen	6	0.62
14	Geology- Pleistocene	55	0.05
15	Geology- Pleistocene Specific- Peelo	15	0.01
	Geology- Pleistocene Specific- Drenthe	6	0.41
	Geology- Pleistocene Specific- Boxtel	34	0.03
20	Depth- Naaldwijk- 0-5m below NAP	78	0.37
	Depth- Naaldwijk-5-15m below NAP	31	0.42
21	Distance- Naaldwijk(0-1m)	46	0.42
23	Gradation- Grain Size Index- Naaldwijk	46	0.42
26	Boxtel Overall	34	0.03
27	Sigmoid Fit	75	0.08
28	Fourier Fit	75	0.45
29	Polynomial Fit	75	0.47

5

Conclusions and Recommendations

5.1. Conclusions

The conclusions of this study are summarized below: FC verses IC for Groningen soils has a scattered pattern when plotted. The equation by the least squares approach for Groningen soils is $y = 37.02x - 53.36$. The overall R^2 value for all the samples is 0.35, which shows that the strength of the correlation is low. Using a correlation without the understanding the limits of the equation would lead to unrealistic estimates than the field scenario. The usage of correlations would be beneficial in building geotechnical software and application based tools. But it is necessary to identify if the correlations can be specifically used for the locations across the globe. Hence, it is recommended to use the Boulanger and Idriss (2014) correlation with modifications.

The scatter in the pattern of FC vs IC is evident, agreeing with the Deltares report. Hence, the factors were selected to evaluate the scattered pattern. From the results, it can be concluded that all the four factors have an influence on the FC vs IC correlation. But influence is very low as the R^2 values are as low as 0.03 to 0.35. Discarding the outliers, the general equation can be improved to 0.41 as the equation would become $y = 40.3x - 62.3$, which is not very high. From the R^2 values studied for all the factors, the summary is:

- **Depth**: The samples found at 10m-20m have a higher influence on the correlation than samples found at the top 10m.
- **Distance:** The samples within 0-1m CPT-BH distance have higher value than the ones up to 5m distance, hence it is concluded that the BH samples closer to CPT have a higher influence on the correlation of FC vs IC

- **Gradation**: The coefficient of uniformity and curvature do not provide much information other than suggesting if they are poorly graded or well graded. With grain size index, the samples could be classified as potentially liquefiable or liquefiable along with D50 value. Most of the samples are potentially liquefiable in Groningen region, around 82% of the samples. It is seen that samples with lower D50 value has higher Grain size index value.R^2 is still very low
- **Geology**: It was observed that the holocene formations have a higher R^2 value than the pleistocene affirming the potential of holocene sands to liquefy than pleistocene sands. Naaldwijk has the highest R^2 values, confirming that it would be the most susceptible among all other formations. Samples at 5-15m depth are to be dealt with carefully. But, Boxtel has low FC for low IC values meaning it could also have an influence in the liquefaction triggering, and due to low number of samples, probably R^2 value is very low.

Thus, it can be concluded that the CPT closer to BH would give better results. The geology of the sample and depth of the sample together have a high influence on FC vs IC correlation. The deeper samples 5m-15m consists mostly of Naaldwijk samples that have higher probability of liquefying. The D50 in combination with I_{GS} has a good correlation with FC vs IC than I_{GS} in combination with Cu and Cc. But the influence is not high enough for the strength of correlation to be close to 1.

To improve the R^2 values, other functions such as Sigmoid Function, Polynomial Function and Fourier functions can be used. Significant increase in the R^2 value is not observed, but it increases to 0.47.

Boulanger and Idriss (2014) CPT-based correlations are used world-wide. But, as we have seen with the Groningen soil data set, the equation overestimates FC values. The CFC value, fitting factor for Groningen soils is higher than (|0.31|) maximum values that can be used according to Boulanger and Idriss (2014) of |0.29|. Though it can be used, but it could be overestimating higher FC values and underestimating lower FC values.

This suggests that it needs further investigation. In case of more samples included for the study, it could differ by a larger standard deviation. Thus, a new equation is derived as an attempt to find a better fit. The equation is better than Boulanger and Idriss (2014) for Groningen soils, but not by a substantial amount. Even though IC is a function of FC, it can be inferred that IC may not be the most suitable parameter for correlation with FC, for Groningen soils.

Thus, it can be concluded that the FC vs IC correlation is very weak for the selected area in Groningen. The factors do play an important role in the relationship as it is seen that they improve slightly when each of the factors are considered separately and evaluated. But, overall, the relationship remains weak (not more than 50%). The correlation proposed by Boulanger and Idriss (2014) needs modification according to the requirements of Groningen Soils. Hence, a new equation is proposed. The research questions intended to be examined are answered.

The correlation FC vs IC cannot be used directly to study the Liquefaction Potential Analysis. It shows that the relationship to be weak, meaning that if used, it can lead to wrong conclusions of whether a sample is prone to liquefaction or not. Hence, more study is needed in this area as to identify a better parameter of Liquefaction Potential analysis for Groningen soils. This also suggests that the correlation needs to be used with caution, specially during design phases of construction. Engineers would have to use it carefully, after modifications to be sure of safe designs.

5.2. Limitations

There are a few limitations that confine the results and conclusions to this study.

- Lab test Results from only Wiertsema and Partners are considered within the selected area over only last decade.
- The data set is very small due to which the results may be skewed.
- The CPT-BH pairs created are within the select area. Possibility of finding closer CPT to a BH adjacent to the selected area than within the radius.
- Human error during the PSD test or CPT tests.
- The consideration of factors coupled with other parameters like relative density
- Other functions could be suitable as best fit curves if the data set increases

5.3. Recommendations

Inclusion of more number of samples for the study would help in understanding if IC is a suitable robust correlation parameter. Further research is necessary to evaluate other factors in combination with the selected factors, which contribute to liquefaction triggering like the relative density and the pore water pressures which could have the potential to correlate better. Results from the tri-axial testing of Groningen soils could be evaluated to comment on the correlation. Further study can be extended to the classification of fines content plastic and non-plastic fines in Groningen region.

6

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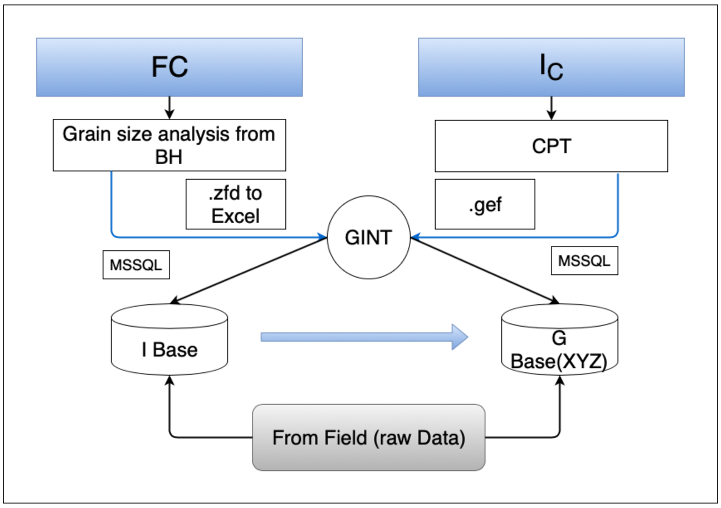
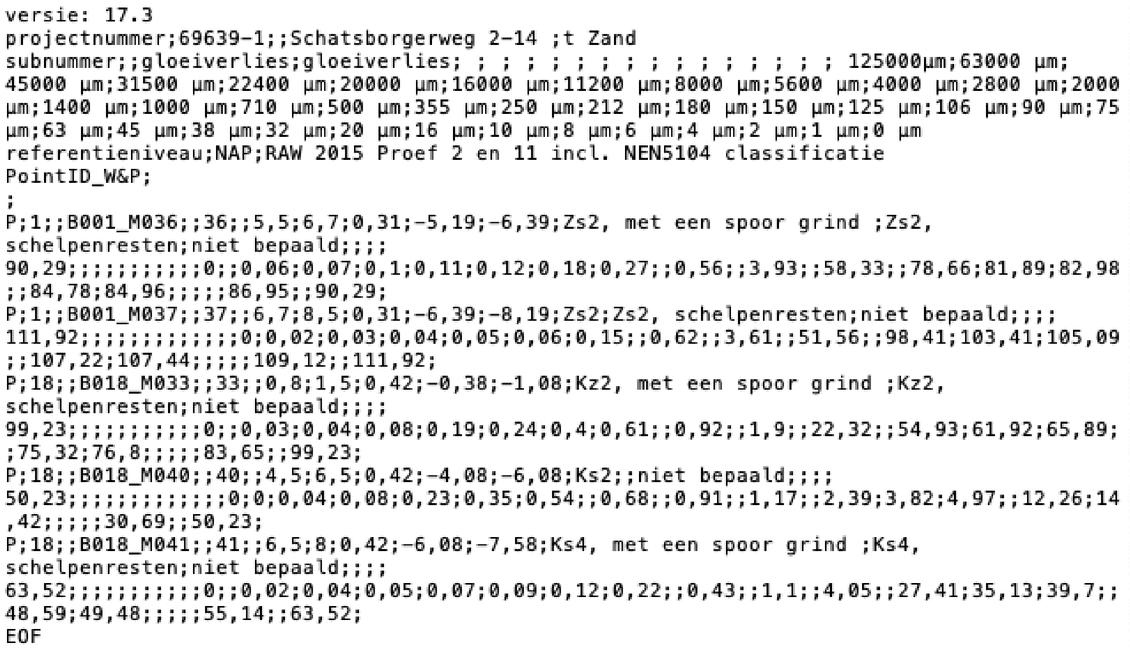
Appendix A

Flowchart explaining the storage of data at W&P is show in figure below. A sample of .zfd file is shown.



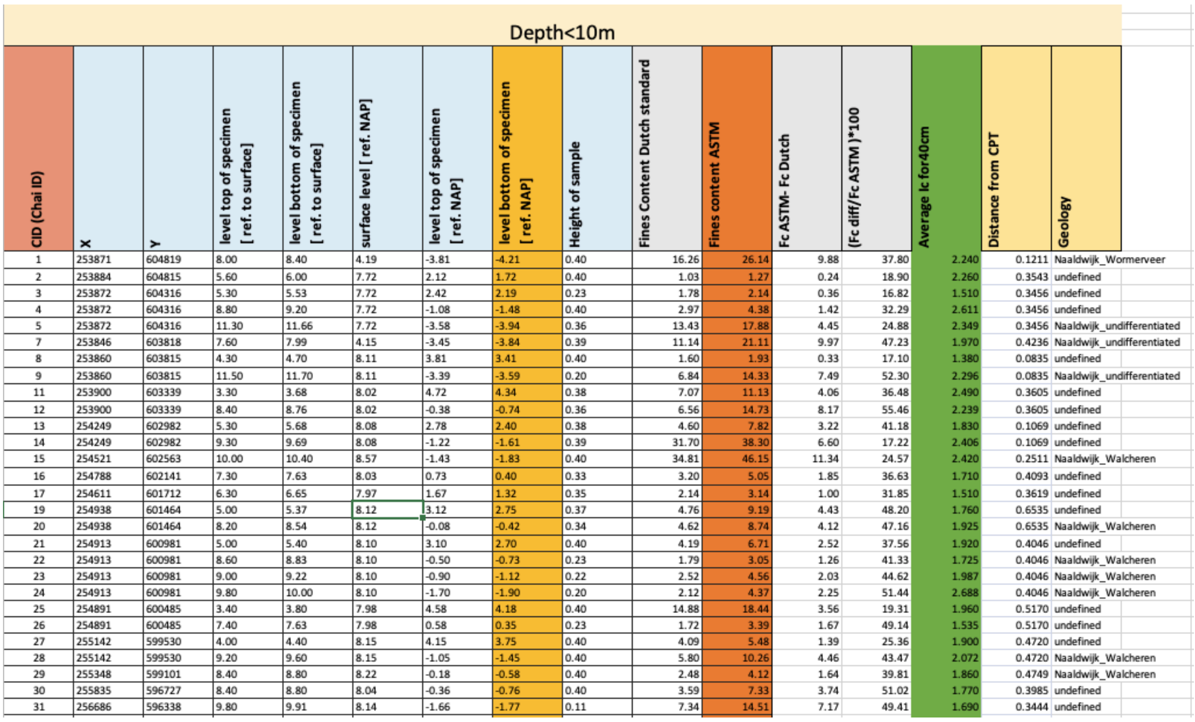
Schematic representation of Storage of data at WP



```
versie: 17.3
projectnummer;69639-1;;Schatsborgerweg 2-14 ;t Zand
subnummer;;gloeiverlies;gloeiverlies; ; ; ; ; ; ; ; ; ; ; ; ; ; ; ; 125000µm;63000 µm;
45000 µm;31500 µm;22400 µm;20000 µm;16000 µm;11200 µm;8000 µm;5600 µm;4000 µm;2800 µm;2000
µm;1400 µm;1000 µm;710 µm;500 µm;355 µm;250 µm;212 µm;180 µm;150 µm;125 µm;106 µm;90 µm;75
µm;63 µm;45 µm;38 µm;32 µm;20 µm;16 µm;10 µm;8 µm;6 µm;4 µm;2 µm;1 µm;0 µm
referentieniveau;NAP;RAW 2015 Proef 2 en 11 incl. NEN5104 classificatie
PointID_W&P;
;
P;1;;B001_M036;;36;;5,5;6,7;0,31;-5,19;-6,39;Zs2, met een spoor grind ;Zs2,
schelpenresten;niet bepaald;;;;
90,29;;;;;;;;;;;0;;0,06;0,07;0,1;0,11;0,12;0,18;0,27;;0,56;;3,93;;58,33;;78,66;81,89;82,98
;;84,78;84,96;;;;;86,95;;90,29;
P;1;;B001_M037;;37;;6,7;8,5;0,31;-6,39;-8,19;Zs2;Zs2, schelpenresten;niet bepaald;;;;
111,92;;;;;;;;;;;;;0;0,02;0,03;0,04;0,05;0,06;0,15;;0,62;;3,61;;51,56;;98,41;103,41;105,09
;;107,22;107,44;;;;;109,12;;111,92;
P;18;;B018_M033;;33;;0,8;1,5;0,42;-0,38;-1,08;Kz2, met een spoor grind ;Kz2,
schelpenresten;niet bepaald;;;;
99,23;;;;;;;;;;;0;;0,03;0,04;0,08;0,19;0,24;0,4;0,61;;0,92;;1,9;;22,32;;54,93;61,92;65,89;
;75,32;76,8;;;;;83,65;;99,23;
P;18;;B018_M040;;40;;4,5;6,5;0,42;-4,08;-6,08;Ks2;;niet bepaald;;;;
50,23;;;;;;;;;;;;;0;0;0,04;0,08;0,23;0,35;0,54;;0,68;;0,91;;1,17;;2,39;3,82;4,97;;12,26;14
,42;;;;;30,69;;50,23;
P;18;;B018_M041;;41;;6,5;8;0,42;-6,08;-7,58;Ks4, met een spoor grind ;Ks4,
schelpenresten;niet bepaald;;;;
63,52;;;;;;;;;;;0;;0,02;0,04;0,05;0,07;0,09;0,12;0,22;;0,43;;1,1;;4,05;;27,41;35,13;39,7;;
48,59;49,48;;;;;55,14;;63,52;
EOF
```

Sample of .zfd file

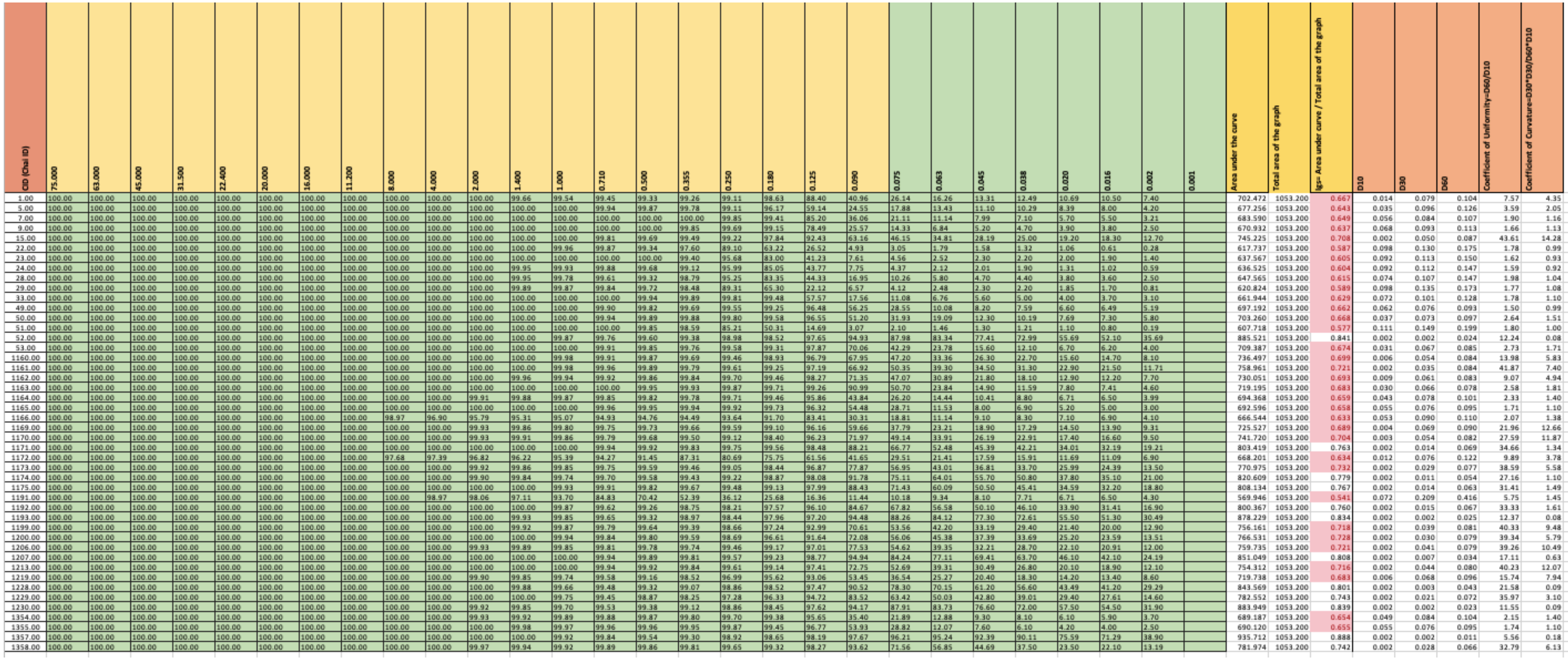
Sample of Excel Database with Unique ID is represented in the next two figures. In the example, it shows the processed version of the .zfd files and after making the sets using unique ID called ”Chai ID”. The first column shows the Chai ID, the average IC value is carried over from another source file consisting of CPT reading for every cm of the depth penetrated by the tip. Further on, at each step, the data set was sorted per factor, creating a new set in order to use the factor in question efficiently.



Depth<10m

CID (Chai ID)	X	Y	level top of specimen [ref. to surface]	level bottom of specimen [ref. to surface]	surface level [ref. NAP]	level top of specimen [ref. NAP]	level bottom of specimen [ref. NAP]	Height of sample	Fines Content Dutch standard	Fines content ASTM	Fc ASTM- Fc Dutch	(Fc diff/Fc ASTM)*100	Average Ic for40cm	Distance from CPT	Geology
1	253871	604819	8.00	8.40	4.19	-3.81	-4.21	0.40	16.26	26.14	9.88	37.80	2.240	0.1211	Naaldwijk_Wormerveer
2	253884	604815	5.60	6.00	7.72	2.12	1.72	0.40	1.03	1.27	0.24	18.90	2.260	0.3543	undefined
3	253872	604316	5.30	5.53	7.72	2.42	2.19	0.23	1.78	2.14	0.36	16.82	1.510	0.3456	undefined
4	253872	604316	8.80	9.20	7.72	-1.08	-1.48	0.40	2.97	4.38	1.42	32.29	2.611	0.3456	undefined
5	253872	604316	11.30	11.66	7.72	-3.58	-3.94	0.36	13.43	17.88	4.45	24.88	2.349	0.3456	Naaldwijk_undifferentiated
7	253846	603818	7.60	7.99	4.15	-3.45	-3.84	0.39	11.14	21.11	9.97	47.23	1.970	0.4236	Naaldwijk_undifferentiated
8	253860	603815	4.30	4.70	8.11	3.81	3.41	0.40	1.60	1.93	0.33	17.10	1.380	0.0835	undefined
9	253860	603815	11.50	11.70	8.11	-3.39	-3.59	0.20	6.84	14.33	7.49	52.30	2.296	0.0835	Naaldwijk_undifferentiated
11	253900	603339	3.30	3.68	8.02	4.72	4.34	0.38	7.07	11.13	4.06	36.48	2.490	0.3605	undefined
12	253900	603339	8.40	8.76	8.02	-0.38	-0.74	0.36	6.56	14.73	8.17	55.46	2.239	0.3605	undefined
13	254249	602982	5.30	5.68	8.08	2.78	2.40	0.38	4.60	7.82	3.22	41.18	1.830	0.1069	undefined
14	254249	602982	9.30	9.69	8.08	-1.22	-1.61	0.39	31.70	38.30	6.60	17.22	2.406	0.1069	undefined
15	254521	602563	10.00	10.40	8.57	-1.43	-1.83	0.40	34.81	46.15	11.34	24.57	2.420	0.2511	Naaldwijk_Walcheren
16	254788	602141	7.30	7.63	8.03	0.73	0.40	0.33	3.20	5.05	1.85	36.63	1.710	0.4093	undefined
17	254611	601712	6.30	6.65	7.97	1.67	1.32	0.35	2.14	3.14	1.00	31.85	1.510	0.3619	undefined
19	254938	601464	5.00	5.37	8.12	3.12	2.75	0.37	4.76	9.19	4.43	48.20	1.760	0.6535	undefined
20	254938	601464	8.20	8.54	8.12	-0.08	-0.42	0.34	4.62	8.74	4.12	47.16	1.925	0.6535	Naaldwijk_Walcheren
21	254913	600981	5.00	5.40	8.10	3.10	2.70	0.40	4.19	6.71	2.52	37.56	1.920	0.4046	undefined
22	254913	600981	8.60	8.83	8.10	-0.50	-0.73	0.23	1.79	3.05	1.26	41.33	1.725	0.4046	Naaldwijk_Walcheren
23	254913	600981	9.00	9.22	8.10	-0.90	-1.12	0.22	2.52	4.56	2.03	44.62	1.987	0.4046	Naaldwijk_Walcheren
24	254913	600981	9.80	10.00	8.10	-1.70	-1.90	0.20	2.12	4.37	2.25	51.44	2.688	0.4046	Naaldwijk_Walcheren
25	254891	600485	3.40	3.80	7.98	4.58	4.18	0.40	14.88	18.44	3.56	19.31	1.960	0.5170	undefined
26	254891	600485	7.40	7.63	7.98	0.58	0.35	0.23	1.72	3.39	1.67	49.14	1.535	0.5170	undefined
27	255142	599530	4.00	4.40	8.15	4.15	3.75	0.40	4.09	5.48	1.39	25.36	1.900	0.4720	undefined
28	255142	599530	9.20	9.60	8.15	-1.05	-1.45	0.40	5.80	10.26	4.46	43.47	2.072	0.4720	Naaldwijk_Walcheren
29	255348	599101	8.40	8.80	8.22	-0.18	-0.58	0.40	2.48	4.12	1.64	39.81	1.860	0.4749	Naaldwijk_Walcheren
30	255835	596727	8.40	8.80	8.04	-0.36	-0.76	0.40	3.59	7.33	3.74	51.02	1.770	0.3985	undefined
31	256686	596338	9.80	9.91	8.14	-1.66	-1.77	0.11	7.34	14.51	7.17	49.41	1.690	0.3444	undefined

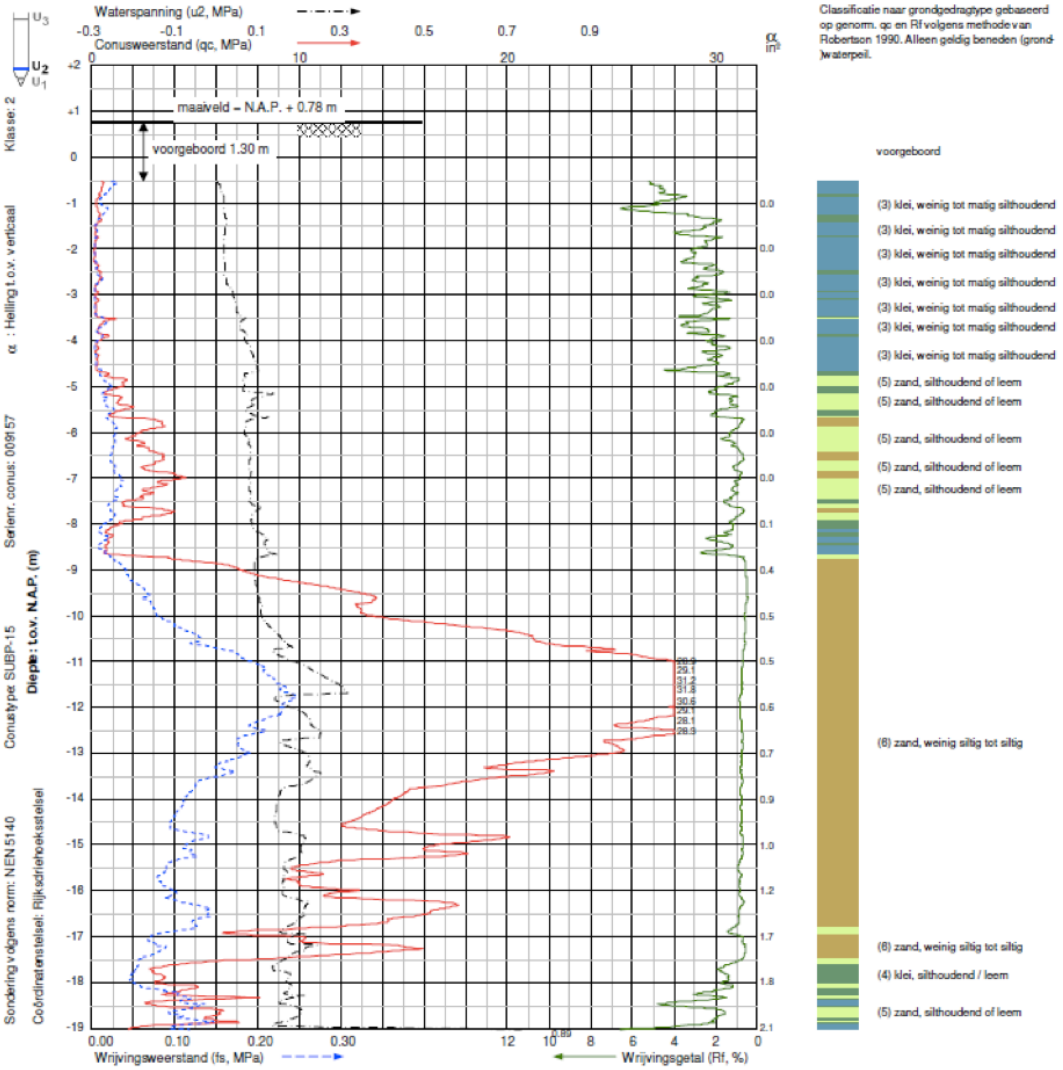
Sample of Excel sheet for the Depth Criteria



CID (Chai ID)	75.000	63.000	45.000	31.500	22.400	20.000	16.000	11.200	8.000	4.000	2.000	1.400	1.000	0.710	0.500	0.355	0.250	0.180	0.125	0.090	0.075	0.063	0.045	0.038	0.020	0.016	0.002	0.001	Area under the curve	Total area of the graph	Igs= Area under curve / Total area of the graph	D10	D30	D60	Coefficient of Uniformity=D60/D10	Coefficient of Curvature=D30*D30/D60*D10
1.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.66	99.54	99.45	99.33	99.26	99.11	98.63	88.40	40.96	26.14	16.26	13.31	12.49	10.69	10.50	7.40		702.472	1053.200	0.667	0.014	0.079	0.104	7.57	4.35
5.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.94	99.87	99.78	99.11	96.17	59.14	24.55	17.88	13.43	11.10	10.29	8.39	8.00	4.20		677.256	1053.200	0.643	0.035	0.096	0.126	3.59	2.05
7.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.85	99.41	85.20	36.06	21.11	11.14	7.99	7.10	5.70	5.50	3.21		683.590	1053.200	0.649	0.056	0.084	0.107	1.90	1.16
9.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.85	99.69	99.15	78.49	25.57	14.33	6.84	5.20	4.70	3.90	3.80	2.50		670.932	1053.200	0.637	0.068	0.093	0.113	1.66	1.13
15.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.81	99.69	99.49	99.22	97.84	92.43	63.16	46.15	34.81	28.19	25.00	19.20	18.30	12.70		745.225	1053.200	0.708	0.002	0.050	0.087	43.61	14.28
22.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.96	99.87	99.34	97.60	89.10	63.22	26.52	4.93	3.05	1.79	1.58	1.32	1.06	0.61	0.28		617.737	1053.200	0.587	0.098	0.130	0.175	1.78	0.99
23.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.40	95.68	83.00	41.23	7.61	4.56	2.52	2.30	2.20	2.00	1.90	1.40		637.567	1053.200	0.605	0.092	0.113	0.150	1.62	0.93
24.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.95	99.93	99.88	99.68	99.12	95.99	85.05	43.77	7.75	4.37	2.12	2.01	1.90	1.31	1.02	0.59		636.525	1053.200	0.604	0.092	0.112	0.147	1.59	0.92
28.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.95	99.78	99.61	99.32	98.79	95.25	83.35	44.33	16.95	10.26	5.80	4.70	4.40	3.80	3.60	2.50		647.565	1053.200	0.615	0.074	0.107	0.147	1.98	1.04
29.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.89	99.87	99.84	99.72	98.48	89.31	65.30	22.12	6.57	4.12	2.48	2.30	2.20	1.85	1.70	0.81		620.824	1053.200	0.589	0.098	0.135	0.173	1.77	1.08
33.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.94	99.89	99.81	99.48	57.57	17.56	11.08	6.76	5.60	5.00	4.00	3.70	3.10		661.944	1053.200	0.629	0.072	0.101	0.128	1.78	1.10
49.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.90	99.82	99.69	99.55	99.25	96.48	56.25	28.55	10.08	8.20	7.59	6.60	6.49	5.19		697.192	1053.200	0.662	0.062	0.076	0.093	1.50	0.99
50.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.94	99.89	99.88	99.80	99.58	96.55	51.20	31.93	19.09	12.30	10.19	7.69	7.30	5.80		703.260	1053.200	0.668	0.037	0.073	0.097	2.64	1.51
51.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.85	98.59	85.21	50.31	14.69	3.07	2.10	1.46	1.30	1.21	1.10	0.80	0.19		607.718	1053.200	0.577	0.111	0.149	0.199	1.80	1.00
52.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.87	99.76	99.60	99.38	98.98	98.52	97.65	94.93	87.98	83.34	77.41	72.99	55.69	52.10	35.69		885.521	1053.200	0.841	0.002	0.002	0.024	12.24	0.08
53.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.91	99.85	99.76	99.58	99.31	97.87	70.06	42.29	23.78	15.60	12.10	6.70	6.20	4.00		709.387	1053.200	0.674	0.031	0.067	0.085	2.73	1.71
1160.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.98	99.91	99.87	99.69	99.46	98.93	96.79	67.95	47.20	33.36	26.30	22.70	15.60	14.70	8.10		736.497	1053.200	0.699	0.006	0.054	0.084	13.98	5.83
1161.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.98	99.96	99.89	99.79	99.61	99.25	97.19	66.92	50.35	39.30	34.50	31.30	22.90	21.50	11.71		758.961	1053.200	0.721	0.002	0.035	0.084	41.87	7.40
1162.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.96	99.94	99.92	99.86	99.84	99.70	99.46	98.27	71.35	47.07	30.89	21.80	18.10	12.90	12.20	7.70		730.051	1053.200	0.693	0.009	0.061	0.083	9.07	4.94
1163.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.95	99.93	99.87	99.71	99.26	90.99	50.70	23.84	14.90	11.59	7.80	7.41	4.60		719.195	1053.200	0.683	0.030	0.066	0.078	2.58	1.81
1164.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.91	99.88	99.87	99.85	99.82	99.78	99.71	99.46	95.86	43.84	26.20	14.44	10.41	8.80	6.71	6.50	3.99		694.368	1053.200	0.659	0.043	0.078	0.101	2.33	1.40
1165.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.96	99.95	99.94	99.92	99.73	96.32	54.48	28.71	11.53	8.00	6.90	5.20	5.00	3.00		692.596	1053.200	0.658	0.055	0.076	0.095	1.71	1.10
1166.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	98.97	96.90	95.79	95.31	95.07	94.93	94.76	94.49	93.64	91.70	83.41	30.31	18.81	11.14	9.10	8.30	7.10	6.90	4.10		666.544	1053.200	0.633	0.053	0.090	0.110	2.07	1.38
1169.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.93	99.86	99.80	99.75	99.73	99.66	99.59	99.10	96.16	59.66	37.79	23.21	18.90	17.29	14.50	13.90	9.31		725.527	1053.200	0.689	0.004	0.069	0.090	21.96	12.66
1170.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.93	99.91	99.86	99.79	99.68	99.50	99.12	98.40	96.23	71.97	49.14	33.91	26.19	22.91	17.40	16.60	9.50		741.720	1053.200	0.704	0.003	0.054	0.082	27.59	11.87
1171.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.94	99.92	99.83	99.75	99.56	98.48	88.21	66.77	52.48	45.39	42.21	34.01	32.19	19.21		803.419	1053.200	0.763	0.002	0.014	0.069	34.66	1.34
1172.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	97.68	97.39	96.82	96.22	95.39	94.27	91.45	87.31	80.69	75.75	61.56	41.65	29.51	21.41	17.59	15.91	11.69	11.09	6.90		668.201	1053.200	0.634	0.012	0.076	0.122	9.89	3.78
1173.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.92	99.86	99.85	99.75	99.59	99.46	99.05	98.44	96.87	77.87	56.95	43.01	36.81	33.70	25.99	24.39	13.50		770.975	1053.200	0.732	0.002	0.029	0.077	38.59	5.58
1174.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.90	99.84	99.74	99.70	99.58	99.43	99.22	98.87	98.08	91.78	75.11	64.01	55.70	50.80	37.80	35.10	21.00		820.609	1053.200	0.779	0.002	0.011	0.054	27.16	1.10
1175.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.93	99.91	99.82	99.67	99.48	99.13	97.99	88.43	71.43	60.09	50.50	45.41	34.59	32.20	18.80		808.134	1053.200	0.767	0.002	0.014	0.063	31.41	1.49
1191.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	98.97	98.06	97.11	93.70	84.83	70.42	52.39	36.12	25.68	16.36	11.44	10.18	9.34	8.10	7.71	6.71	6.50	4.30		569.946	1053.200	0.541	0.072	0.209	0.416	5.75	1.45
1192.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.87	99.62	99.26	98.75	98.21	97.57	96.10	84.67	67.82	56.58	50.10	46.10	33.90	31.41	16.90		800.367	1053.200	0.760	0.002	0.015	0.067	33.33	1.61
1193.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.93	99.85	99.65	99.32	98.97	98.44	97.96	97.20	94.48	88.26	84.12	77.30	72.61	55.50	51.30	30.49		878.229	1053.200	0.834	0.002	0.002	0.025	12.37	0.08
1199.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.92	99.87	99.79	99.64	99.39	98.66	97.24	92.99	70.61	53.56	42.20	33.19	29.40	21.40	20.00	12.90		756.161	1053.200	0.718	0.002	0.039	0.081	40.33	9.48
1200.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.94	99.84	99.80	99.59	98.69	96.61	91.64	72.08	56.06	45.38	37.39	33.69	25.20	23.59	13.51		766.531	1053.200	0.728	0.002	0.030	0.079	39.34	5.79
1206.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.93	99.89	99.85	99.81	99.78	99.74	99.46	99.17	97.01	77.53	54.62	39.35	32.21	28.70	22.10	20.91	12.00		759.735	1053.200	0.721	0.002	0.041	0.079	39.26	10.49
1207.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.94	99.89	99.81	99.57	99.23	98.77	94.94	84.24	77.11	69.41	63.70	46.10	42.10	24.19		851.049	1053.200	0.808	0.002	0.007	0.034	17.11	0.63
1213.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.94	99.92	99.84	99.61	99.14	97.41	72.75	52.69	39.31	30.49	26.80	20.10	18.90	12.10		754.312	1053.200	0.716	0.002	0.044	0.080	40.23	12.07
1219.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.90	99.85	99.74	99.58	99.16	98.52	96.99	95.62	93.06	53.45	36.54	25.27	20.40	18.30	14.20	13.40	8.60		719.738	1053.200	0.683	0.006	0.068	0.096	15.74	7.94
1228.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.88	99.66	99.48	99.32	99.07	98.86	98.52	97.47	90.52	78.30	70.15	61.20	56.60	43.49	41.20	29.29		843.569	1053.200	0.801	0.002	0.003	0.043	21.58	0.09
1229.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.75	99.45	98.87	98.25	97.28	96.33	94.72	83.52	63.42	50.03	42.80	39.01	29.40	27.61	14.60		782.552	1053.200	0.743	0.002	0.021	0.072	35.97	3.10
1230.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.92	99.85	99.70	99.53	99.38	99.12	98.86	98.45	97.62	94.17	87.91	83.73	76.60	72.00	57.50	54.50	31.90		883.949	1053.200	0.839	0.002	0.002	0.023	11.55	0.09
1354.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.93	99.92	99.89	99.88	99.87	99.80	99.70	99.38	95.65	35.40	21.89	12.88	9.30	8.10	6.10	5.90	3.70		689.187	1053.200	0.654	0.049	0.084	0.104	2.15	1.40
1355.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.98	99.97	99.96	99.96	99.95	99.87	99.45	96.77	53.93	28.82	12.07	7.60	6.10	4.20	4.00	2.50		690.120	1053.200	0.655	0.055	0.076	0.095	1.74	1.10
1357.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.92	99.84	99.54	99.30	98.92	98.65	98.19	97.67	96.21	95.24	92.39	90.11	75.59	71.29	38.90		935.712	1053.200	0.888	0.002	0.002	0.011	5.56	0.18
1358.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.97	99.94	99.92	99.89	99.86	99.81	99.65	99.32	98.27	93.62	71.56	56.85	44.69	37.50	23.50	22.10	13.19		781.974	1053.200	0.742	0.002	0.028	0.066	32.79	6.13

Sample of Excel sheet with Unique ID (Chai ID) corresponding to the Grain size analysis lab results

A sample of CPT reading and soil profiling is presented here.



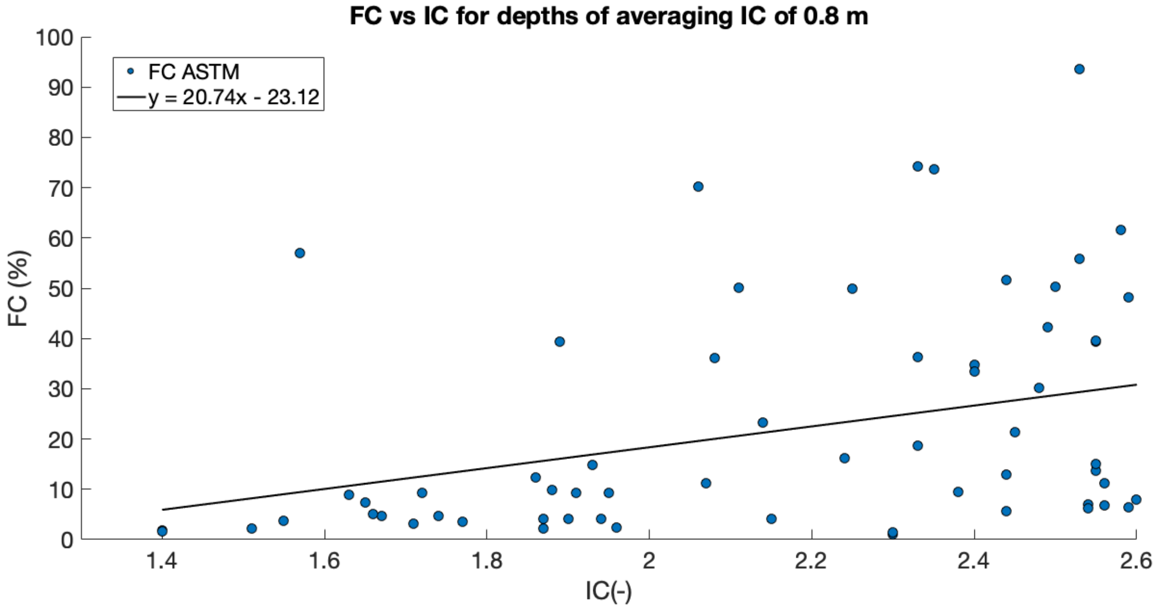
Sample of a CPT result

Appendix B

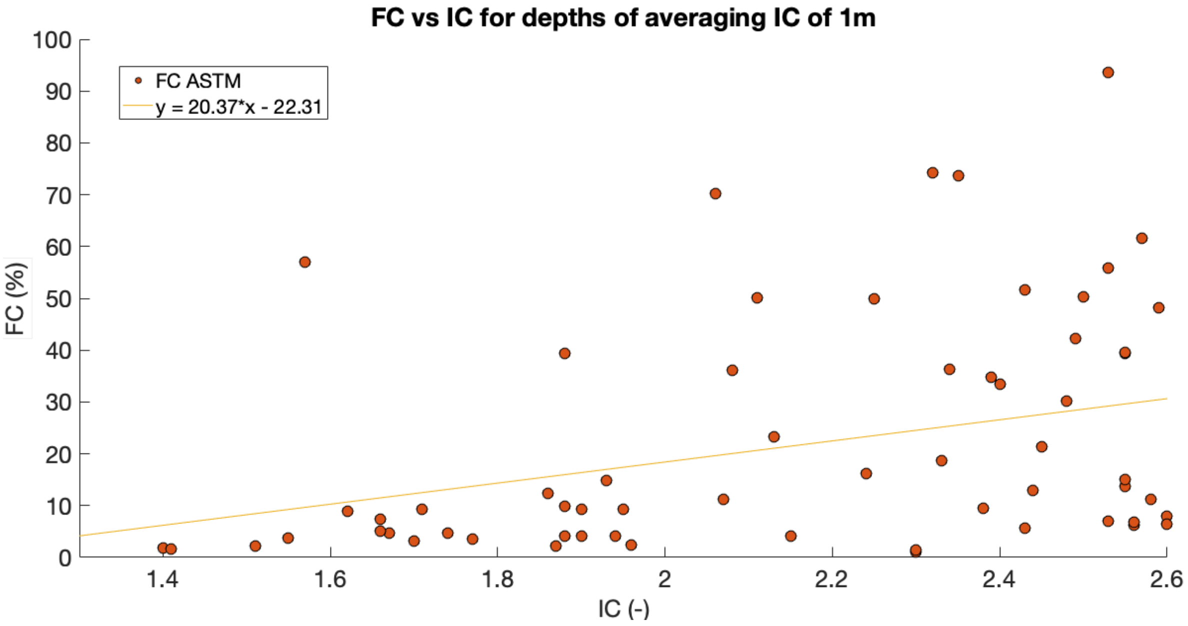
This section shows the additional graphs that were plotted during the analysis

.1. Analysis based on Averaging of IC

The R^2 values are lower for 80cm and 1m averaging depth of IC, than 40cm which is equal to the height of the sample. The R^2 values are 0.20 and 0.18



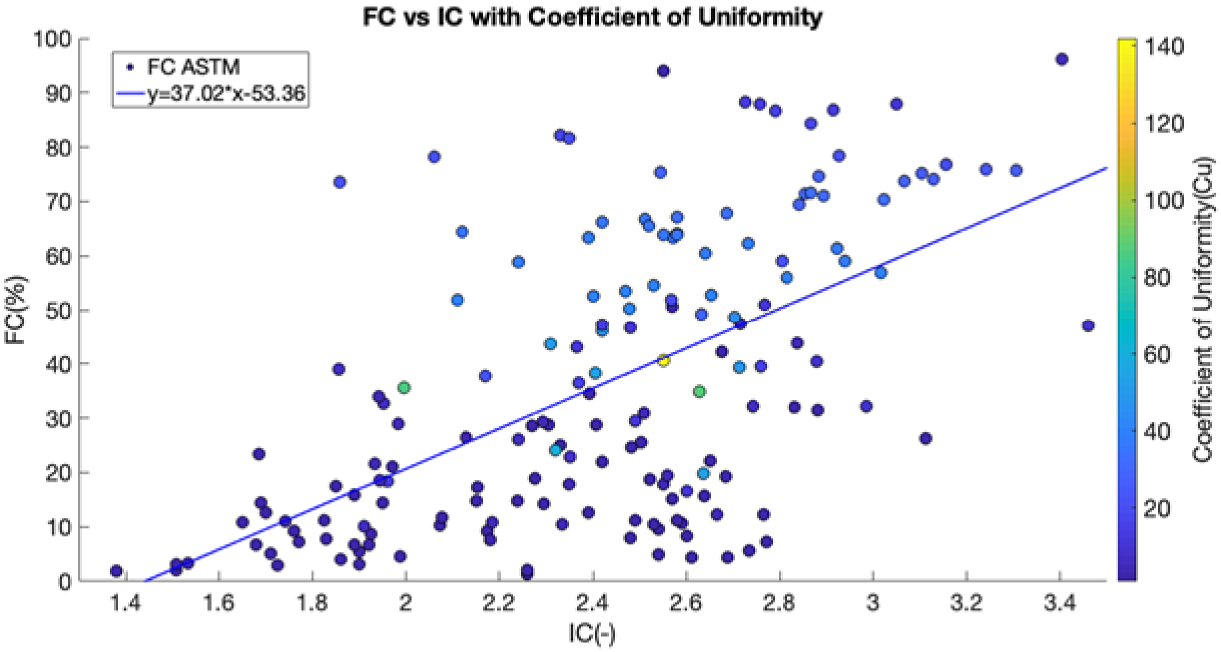
FC vs IC for depths of averaging IC of 0.8m



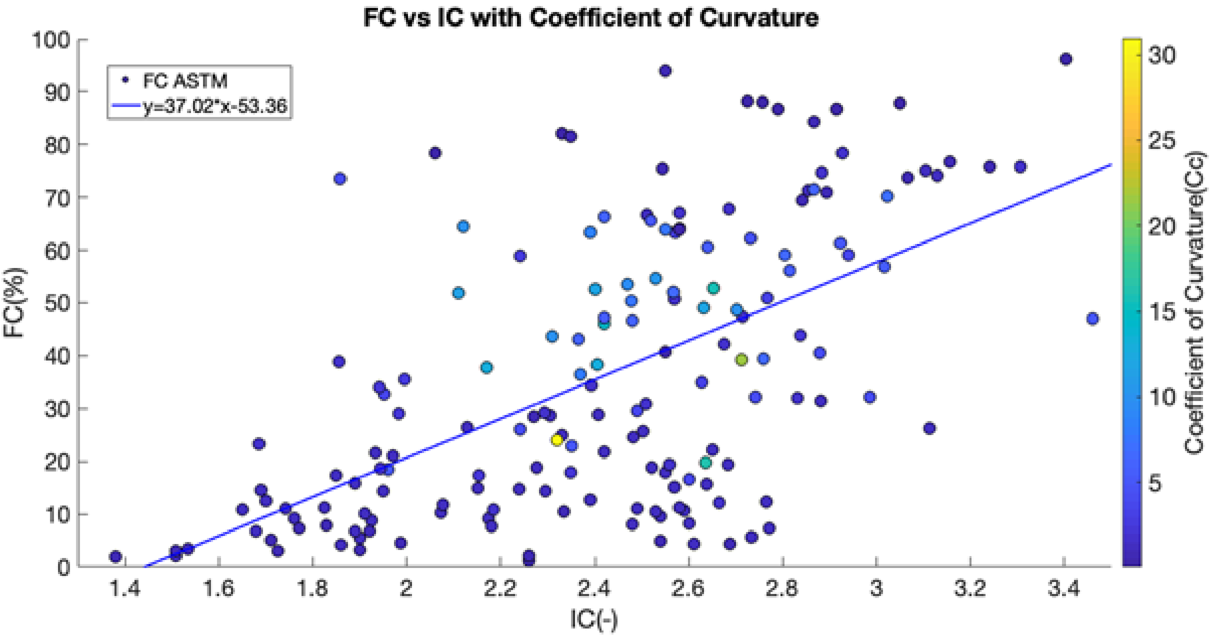
FC vs IC for depths of averaging IC of 1m

.2. Gradation

The FC vs IC is plotted against Cu and Cc, but there is not much significant correlation between these. Thus, they are discarded, only D50 with I_{GS} is used for the gradation analysis.



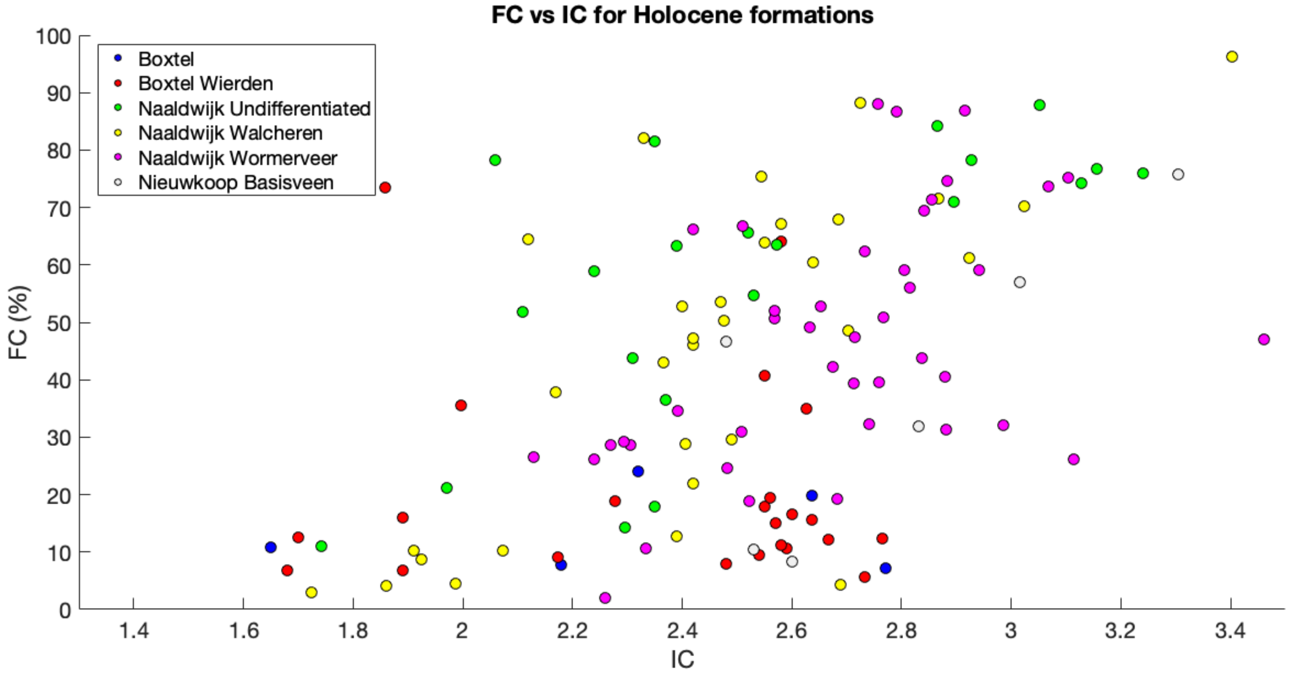
FC vs IC with coefficient of uniformity for all samples



FC vs IC with coefficient of curvature for all samples

.3. Geology

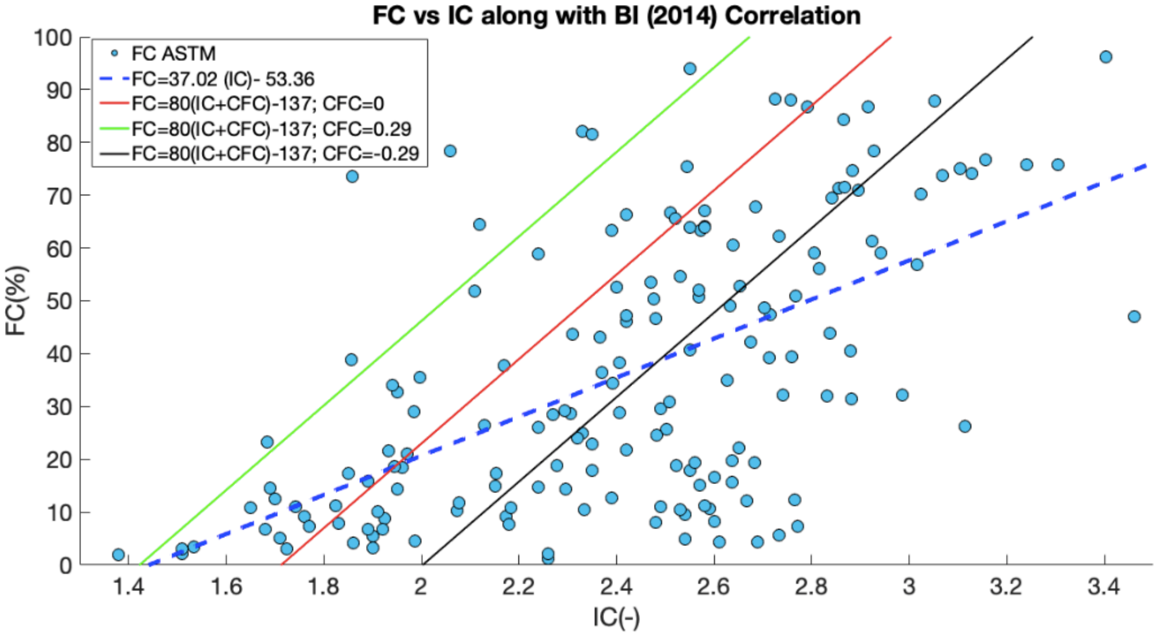
Initially Boxtel was considered alone with Holocene formations, yielding a lower R^2 value of 0.27.



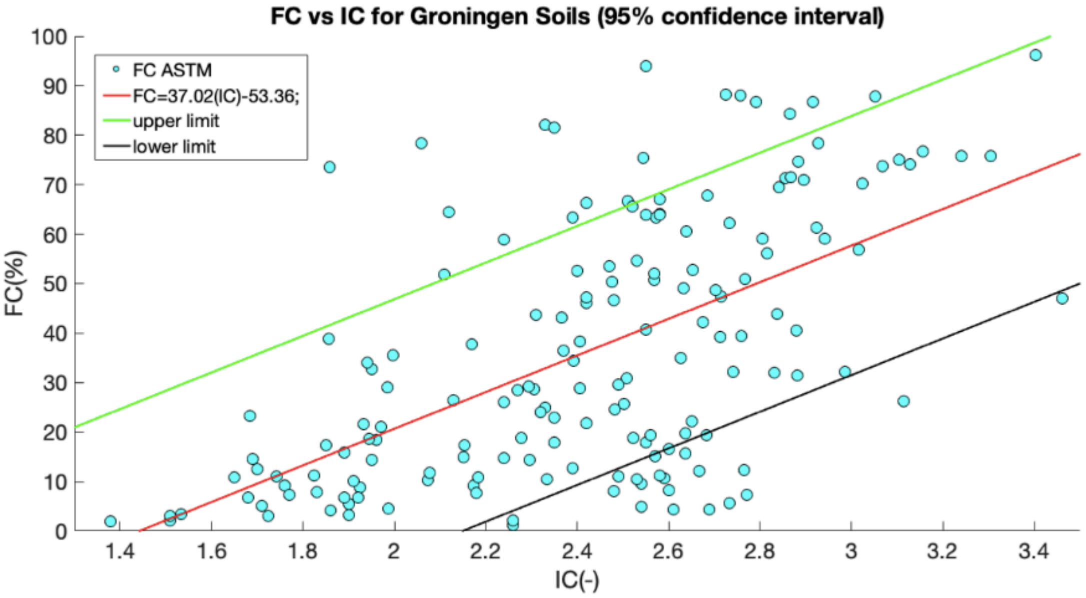
FC vs IC for all Holocene (including Boxtel)samples

.4. Boulanger and Idriss(2014) Correlation

The difference in the trend-line for Groningen soils and between Boulanger and Idriss (2014) can be seen in this graph shown below.



FC vs IC comparing Boulanger and Idriss correlation



FC vs IC with newly proposed correlation for Groningen soils with upper and lower limits (CFC=+/-0.27)