Review of Correlations between Unconfined Compressive Strength (UCS) Values and Dynamic Cone Penetrometer (DCP–DN) Values of Stabilized Soils

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ABSTRACT

This paper discussed test methods, test and sample types, types of stabilisers and soils, applications, and limitations of various developed relationships between UCS and DCP DN values. The review of correlations between unconfined Compression Strength (UCS) values and Dynamic Cone Penetration (DCP-DN) values of stabilised soils will provide guidance on the selection of suitable regression models from what is available in the literature to enable the estimation of UCS from DCP values. The DCP test was found to be economical, rapid, portable, easy to operate and understand, and the most versatile test that provides comprehensive results. Many studies and various nations have adopted the ASTM D6951 DCP equipment for use. Previous studies show that DCP DN values are affected by the soil type, stabiliser and curing period, particle size, plasticity, moisture contents, liquid limit, dry density, UCS, confinement in mould, and investigation depth. The various existing regression models are useful for quick estimation of in-situ UCS of stabilised layers since the termination of in-situ UCS is expensive, tedious, difficult, and time-consuming. However, these regression models must be used with caution as they are dependent on material properties and other factors that influence the DCP DN values. Furthermore, the available correlations cannot be treated as an absolute substitute for laboratory values, and their application requires experience and engineering judgment. This allows further research to develop multiple regression models to correlate UCS and DCP with the same compactive effort and mould size, which will consider material properties and the effect of confinement on the laboratory DCP DN test in the standard mould.

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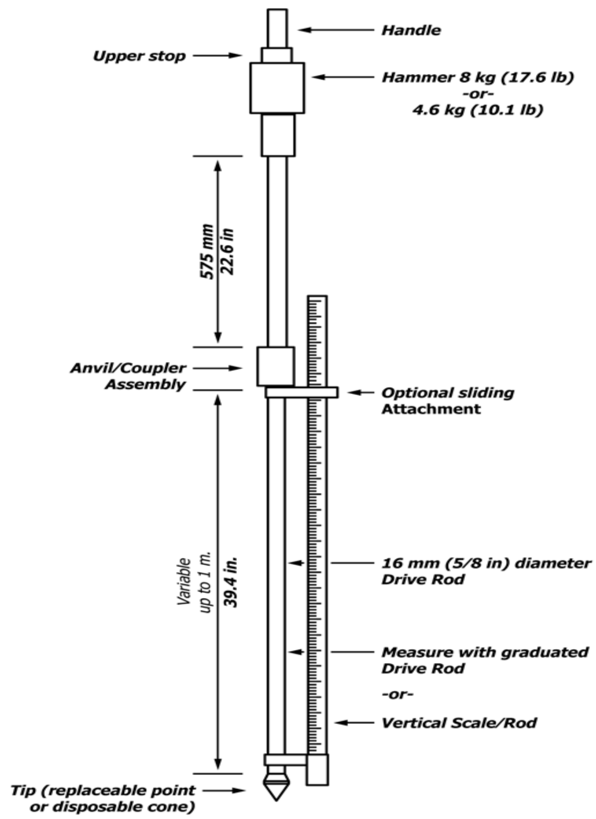
1.0 Introduction

The strength of stabilised soils may be determined in terms of the Unconfined Compressive Strength (UCS) test (ASTM: D2166 – 06, 2007; MoW, 2000; MoW, 1999; TMH1, 1986). The test can be done for specimens prepared in the laboratory or cored from the field (Uchaipichat, 2019; McLaughlin, 2017; Griffin & Tingle, 2009). It is expensive, tedious, difficult, and time-consuming to determine the in-situ compressive strength of pavement layers (Vakili et al., 2021; Patel et al., 2013; Patel & Patel, 2013; Patel & Patel, 2012), especially for low-strength stabilised soil due to excessive breakage and damage to the samples (ASTM: D6236-11, 2011).

On the other hand, the Dynamic Cone Penetration (DCP) test is economical, rapid, portable, easy to operate and understand with minimal disturbance to the pavement layer when used for evaluation of in-service conditions (Rolt & Michael, 2016; Patel & Patel, 2012; Paige-Green & Van Zyl, 2019; Samuel , Done, & TRL, 2005 ; Abdulrahman, 2015). Therefore, alternative methods had been developed to facilitate estimation of UCS using the DCP (Vakili et. al, 2021; Alshkane et. al, 2020; Uchaipichat, 2019; Sisodia & Amin, 2017; Patel et. al, 2013; Patel & Patel, 2013; Patel & Patel, 2012; Chukka & Chakravarthi, 2012; Patel & Patel, 2011; Holderby & Cerato, 2011; Enayatpour et. al, 2006; Mc Elvaney & Bunadidjatnika, 1991).

Many researchers have adopted the DCP tools created by the American Society for Testing Materials (ASTM) for the development of the relationship between UCS and DCP. This machine has a weight of 8 kg, a dropping mass of 575 mm, a steel drive rod with a diameter of 16 mm, and a 60° cone with a diameter of 20 mm (ASTM: D6951, 2015). Continuous measurements can be made down to a depth of approximately 850 mm or, when extension shafts are used, to a recommended maximum depth of 2 m (Samuel et al., 2005; Jones, 2004). The previously developed regression analysis models between DCP and UCS values have a reasonable to very strong coefficient of determination (R^2) as indicated in Table 1. Vakili et al (2021) Alshkane et al. (2020), Uchaipichat (2019), Sisodia and Amin (2017), Chukka and Chakravarthi (2012), Patel and Patel (2011), and McElvaney and Bunadidjatnika (1991) developed simple regression models, whereas Patel et al. (2013), Patel and Patel (2013), Patel and Patel (2012), Holderby and Cerato (2011), and Enayatpour et al. (2006) developed multiple regression models.

Fig 1
Schematic of DCP Device (ASTM: D6951, 2015)



The summary of correlation equations developed, their respective R^2 values, and descriptions of their applications are tabulated in Table 1 and discussed in the following section.

1.1 Available Correlations between DCP and UCS Values

Vakili et al. (2021) developed relationships between different soil parameters by conducting Dynamic Cone Penetrometer (DCP) test with Unconfined Compressive Strength (UCS) on marl soil. The physical and chemical weathering of parent rocks containing 35–65% carbonates, including limestone, dolomite, and carbonate sandstones (Al-Amoudiet et al., 2010; Yong & Ouhadi, 2006; Vakilie et al., 2019), forms Marl soil. The main objective of the Vakili et al. (2021) study was to evaluate the feasibility of the DCP test to predict the physical properties of lime-stabilised marl soils at different curing times.

In 2020, Alshkane et al. did a study to find a link between the DCP DN value (average penetration rate in mm/blow) and the shear strength of cohesive soils. The DCP was used to figure out the UCS and compressibility indices for light structures built on clay soils (Alshkane et al., 2020). Uchaipichat (2019) developed a relationship between the DCP and UCS of cemented lateritic soils for quality control in road construction.

Sisodia and Amin (2017) established a relationship between DCP and UCS for clayey soils to assess the subgrade of various low-volume roads (LVRs). Patel and Patel (2011) described the outcome of an experimental investigation of the effect of Fly-Ash and cement stabilised with non-cohesive soils. The effects of stabilising agents on soils were measured using sieve analysis, Liquid Limit, Plastic Limit, Compaction, DCP, and UCS tests. Chukka and Chakravarthi (2012) established a relationship between DCP DN value and the physical properties of subgrades with clayey sand soils.

McElvaney and Bundadidjatnika (1991) developed a correlation between DCP and the strength properties of lime-stabilised materials used in highway construction. The aim of the study was to predict UCS from DCP for cohesive soils added with lime for the evaluation of pavement foundations.

The regression line is a 50% probability line with R^2 of 0.68, which means there is a 50% probability that the value of UCS determined from the measured DCP test value (DN) using the corresponding regression equation will underestimate or overestimate the actual value (McElvaney & Bunadidjatnika, 1991). It was decided to develop equations with different degrees of confidence of 95% and 99%. That way, the probability of underestimation was reduced to 15% (McElvaney & Bunadidjatnika, 1991).

Patel and Patel (2013) developed empirical correlations from multiple variable regression analysis to predict UCS, DCP from Maximum Dry Density (MDD), and Optimum Moisture Content (OMC) of subgrades from experimental investigations of soils in soaked conditions. Patel and Patel (2012) developed a multiple regression model between DCP and other soil properties such as UCS, Modified Liquid Limit (W_{LM}) and MDD in a soaked condition for direct estimation of DCP DN values. The empirical correlation developed by Patel and Patel (2013) and Patel and Patel (2012) is suitable for rapid prediction of the UCS and DCP DN values of subgrades based on their physical properties.

Holderby and Cerato (2011) carried out a study for in-situ confirmation of the quality of stabilised soils by conducting field DCP and UCS in the laboratory. A multiple linear regression analysis was used for predictions of UCS values from the in-situ DCP DN value and laboratory-measured parameters. We were able to get good estimates of UCS values from the lab and field tests by creating correlations with the total Specific Surface Area (SSA) parameter (Holderby & Cerato, 2011). The developed correlation shows that the A-4 soils are more accurate than the A-6 soils using the field DCP DN value, Total Specific Surface Area (SSA) g/m^2, curing time (t) in days, and Chemical Stabiliser Content (S.C.) in percentage (Holderby & Cerato, 2011). The study shows that the DCP can be used to check the quality of stabilised layers in the field or to make sure that the layers meet the requirements for UCS for stabilisation design (Holderby & Cerato, 2011).

The study by Enayatapour et al. (2006) was used to correlate DCP DN values to the strength properties of stabilised soil at different curing times after stabilization. An attempt was made to evaluate correlations for providing reliable predictions by back calculating the predicted UCS using the measurement variables and comparing them with the measured UCS values. The correlations provided a very good coefficient of determination (R^2) for the percentage of cement (CC) and lime (LC) since the original correlations were derived from the same group of measured soil properties.

Tab 1

Summary of Correlation Equations and their Application

S/No.	Author	Year	Equation	R^2	Application
1.	Vakili et al.	2021	$UCS=433.31^{(-0.066DCP)}$	0.7567	Predicting the engineering properties of lime-stabilised marl soils at different curing periods.
2.	Alshkane and Rashed	2020	$\mathrm{UCS} = 1033.6(\mathrm{DCP})^{-0.968}$	0.91	Prediction of the undrained shear strength parameters, bearing capacity and settlement of cohesive soils.
3.	Uchaipichat	2019	$UCS = 437.4(DCP)^{-0.59}$	0.817	Quality control for the lateritic soil stabilised with cement in road constructions.
4.	Sisodia and Amin	2017	UCS=- 0.087DCP+2.459 , Soil type CI UCS=- 0.070 DCP+1.990 Soil type CL UCS= 0.014DCP+0.776 Soil type CH	0.681 0.943 0.789	Prediction of UCS values based on the average penetration rates of DCP DN value performed for field density of various low volume roads.
5.	Patel et al.	2013	$UCS\left(^{kg}/_{cm^2}\right) = 0.08DCP-0.06W_{LM}-0.07MC+3.223$	0.8	Determination of shear strength parameters of subgrade
6.	Patel and Patel	2013	$UCS=3.367 \times 10^{(-1)}MDD-2.524 \times 10^{(-2)}OMC-5.060$ $DCP=-1.683MDD-4.280 \times 10^{(-2)}MDD+36.704$	Unknown	Quick estimation of strength parameters of subgrade from physical properties of soil.
7.	Patel and Patel	2012	$UCS\left(^{kg}/_{cm^2}\right)=6.905 \times 10^{(-1)}MDD-1.147 \times 10^{(-2)}OMC-1.705 \times 10^{(-2)}W_{LM}+0.23DCP-12.617$	Unknown	Prediction of strength parameters and physical properties of soils.
8.	Patel and Patel	2011	$UCS=2.300 \times (0.2218)^{DCP}$, soil cement only $UCS=0.9912 \times (0.4757)^{DCP}$, soil FA only $UCS=1.7905 \times (0.2805)^{DCP}$, soil 10% FA ,cement $UCS=1.8091 \times (0.2887)^{DCP}$, soil 20% FA ,cement	0.9671 0.9434 0.9894 0.9752	Estimation of strength parameters of non-cohesive soils stabilized by Fly-Ash (FA) and cement.

S/No.	Author	Year	Equation	R^2	Application
			$UCS=2.0173 \times (0.2464)^{DCP}$, soil 30% FA ,cement	0.9777	
			$UCS=1.8483 \times (0.2791)^{DCP}$, soil 40% FA ,cement	0.9813	
			$UCS=1.2525 \times (0.4060)^{DCP}$, soil 50% FA ,cement	0.9249	
9.	Chukka and Chakravarthi	2012	Log (UCS)=18.51-13.66Log (DCP)	Unknown	Evaluation of the field strength properties of subgrade soils with low plasticity characteristics.
10.	Holderby and Cerato	2011	UCS=7.184xDCP + 10.324xt – 13.544xS.C + 7.047xSSA+413.356	0.94	Estimation of in-situ testing methods of the stabilized subgrades to the laboratory determined strengths.
11.	Enayatapour et al.	2006	UCS(kPa)=470.0+104.3 x CC+201.0xt-4052.7 x DCP	0.97	Estimation of strength properties of lime and cement stabilized subgrades of highway infrastructure.
			UCS(kPa)=341.2-26.2 x LC+21.6 x t-335.7 x DCP	0.91	
12.	McElvaney and Bundadidjatnika	1991	50% probability of underestimation: log (UCS) =3.56-0.807 log (DCP)	0.68	Prediction of UCS from DCP for cohesive soils added with lime for evaluation of pavement foundation
			95% confident that probability of underestimation will not exceed 15 percent: log UCS =3.29-0.809 log (DCP)		
			99% confident that probability of underestimation will not exceed 15 percent; log UCS =3.21-0.809 log (DCP)		

The review of correlations between UCS values and DCP-DN values of stabilised soils will provide a guide on the appropriate selection of alternative methods to facilitate estimation of UCS using DCP in regards to the application and limitations of the existing relationship. The review discussed test methods and types of regression models developed the type of DCP device, the type of soil and stabiliser, the effect of curing period and strength gain of stabilised soil, and the application and limitations of results from previous studies.

2. Material and Methods

2.1 Material

Vakili et al. (2021) and McElvaney & Bundadidjatnika (1991) stabilised soils with lime; the amount of lime varies from 0% to 8%. The soils used in the studies of McElvaney & Bundadidjatnika (1991) and Vakili et al. (2021) are Silty-Clay, clay, Sandy-Clay and marl soils of low Plasticity respectively. Uchaipichat (2019) used cement to stabilise lateritic soils with a cement content between 1% and 3%.

Holderby & Cerato (2011) conducted stabilisation of Silty and Clayey soils (A-4 and A-6) using stabilising agents of Class C Fly Ash (CFA) and quick lime, whereas Enayatapour et al. (2006) stabilised Clay soils with cement ranging from 5% to 10% and lime from 4% to 8%. Patel and Patel (2011) performed tests on stabilised soil by adding 53-grade OPC cement varying from 1% to 6% and fly ash from 10% to 50%.

The soils used for the studies of Patel & Patel (2013), Patel et al. (2013), and Patel & Patel (2012) were unstabilized Sandy, Sand-Clay and Clayey soils. However, DCP and UCS tests for both studies were done in the laboratory. Alshkane et al. (2020), Chukka & Chakravarthi (2012), and Sisodia & Amin (2017) developed a relationship between DCP DN value in the field and UCS in the laboratory. Alshkane et al. (2020) and Chukka & Chakravarthi (2012) performed studies on Brown Clay with carbonates and Clayey sand soils (SC), respectively, while Sisodia & Amin (2017) conducted studies on Cohesive soils of Low to High Plasticity (CI, CL, and CH). A summary of test methods, test and sample types, and material of the various developed relationships between UCS and DCP are shown in Table 2.

2.2 Methods

Vakili et al. (2021), Uchaipichat (2019), Enayatpour et al. (2006), McElvaney & Bundadidjatnika (1991), Patel & Patel (2013), Patel & Patel (2011), and Patel et al. (2013) all used DCP tests at different curing times after stabilisation to figure out how to predict UCS and engineering properties of soil. They performed DCP on cylindrical moulds and UCS on moulded cylindrical specimens of soil in the laboratory.

Alshkane et al. (2020), Sisodia and Amin (2017), Chukka and Chakravarthi (2012), and Holderby and Cerato (2011) established relationships between DCP and UCS to assess the shear strength of cohesive soils in the field. Their studies involve the determination of in-situ DN values and other soil properties in the laboratory.

Vakili et al. (2021), Alshkane et al. (2020), Uchaipichat (2019), Chukka and Chakravarthi (2012), and Holderby and Cerato (2011) performed UCS and DCP in accordance with ASTM standards.

McElvaney & Bundadidjatnika (1991) performed a laboratory DCP test in a compaction mould as per ASTM standards and UCS in accordance with BS 1924.

Patel &Patel (2013), Patel et al. (2013), Patel & Patel (2012), Patel & Patel (2011), and Sisodia &Amin (2017) conducted field DCP tests in accordance with ASTM standards and UCS tests in the laboratory as per IS 2720.

2.2.1 Dynamic Cone Penetration (DCP)

The DCP test was originally designed to be performed in situ. However, when necessary, researchers find a way of conducting the test in the laboratory using moulds of different sizes. In their study, Vakili et al. (2021) conducted a laboratory Dynamic Cone Penetration (DCP) test on a vertical cylinder composed of a rigid metal material. The cylinder had a diameter of 750 mm and a height of 700 mm. It was affixed to a rigid base plate that was 5 mm thick. In contrast, Uchaipichat (2019) obtained laboratory DCP DN values by compacting specimens in a mould with a diameter of 15.24 cm. Similarly, McElvaney and Bundadidjatnika (1991) conducted their experiments using moulds with a diameter of 152 mm and a height of 116 mm.

The laboratory study done by McElvaney & Bundadidjatnika (1991) involves two compactive efforts: standard and modified AASHTO determined for each lime content mixed with soil. Then, samples were kept in the mould and transferred to the oven for curing at 50 oC for one or two days. Both ends of a sample were sealed with wax and aluminium foil (McElvaney & Bunadidjatnika, 1991). The DCP test was carried out in the mould containing the sample, whereby, to avoid any influence of base restraint, penetration was not continued beyond 50 mm. In some cases, when a single hammer blow resulted in penetration greater than 50 mm, the result was not taken for analysis (McElvaney & Bunadidjatnika, 1991).

Patel & Patel (2013), Patel et al. (2013), Patel & Patel (2012), and Patel & Patel (2011) obtained laboratory DCP DN values on a prototype cylindrical mould of 490 mm diameter and 490 mm height made of 10 mm thick steel. The DCP test hammer was 8 kg, 60ocone of 20 mm diameter and a dropping height of 575 mm, made by mechanical pulling with digital facilities for blow count and penetration measurement.

Enayatpour et al. (2006) achieved DCP tests of treated soils in small calibration chambers. The DCP equipment used was a 6.8 kg hammer with a 508 mm dropping height and a tip angle of 45 degrees (Enayatpour et al., 2006). The soil specimen's height for the unconfined compressive strength (UCS) test was measured to be 320 mm in gallons. To mitigate the impact of non-uniform compaction within a few centimetres of the lower portion, a depth of 250 mm was selected. The DCP readings for this depth were treated as if they were obtained from shallow depths with zero confinement conditions during the analysis of the results (Enayatpour et al., 2006).

Studies by Alshkane et al. (2020), Sisodia & Amin (2017), Chukka & Chakravarthi (2012), and Holderby and Cerato (2011) involve the determination of field DCP DN values at different depths ranging from 0.15 m to 0.4 m below the layers. Alshkane et al. (2020) carried out a study on 35 sites. There were about 100 boreholes dug, 150 in-situ DCP tests done between 1 m and 4 m deep, and 150 samples taken from the boreholes using the hand augur method and tested to find out the natural moisture content and dry density (Alshkane et al., 2020). The field DCP test was performed at the position where the undisturbed samples were obtained for UCS tests.

Chukka and Chakravarthi (2012) carried out experiments on five different locations for subgrade testing with varying plasticity characteristics. The DCP tests were performed twice in the field for each position. Undisturbed and disturbed samples were collected for laboratory tests from an average depth ranging from 0.4 m to 0.8 m below ground level, where DCP tests were conducted (Chukka & Chakravarthi, 2012).

The study conducted by Holderby & Cerato (2011) indicated that the average DCP penetration in the stabilised layer of the three test points at each location of each construction site ranges from 152.4 mm to 203.2 mm (Holderby & Cerato, 2011). The compaction method used a repeatable mechanical compaction device that had been calibrated to the standard Proctor compaction and produced similar OMC and MDD (Holderby & Cerato, 2011). The calibrated compaction device needs the sample to be compacted into five equal layers at 10 blows per layer.

2.2.2 Unconfined Compressive Strength (UCS)

Many researchers are using the ASTM D2166 test method in the current relationship between UCS and DCP. In accordance with Indian Standard (IS) 2720 (Part 10): 1991, which some researchers have adopted. The specimen shall have a minimum diameter of 38 mm, and the largest particle in the specimen shall be smaller than one eighth of the specimen diameter, whereas ASTM D2166 requires specimens with a minimum diameter of 30 mm, and the largest particle contained within the test specimen shall be smaller than one tenth of the specimen diameter. Both ASTM D2166 and IS 2720 recommend that the compacted specimen be prepared at any predetermined water content and density.

Vakili et al. (2021) performed UCS on moulded specimens of 38 mm diameter and 76 mm height, while McElvaney and Bundadidjatnika (1991) tested specimens of 50 mm diameter and 100 mm height prepared by the static compaction procedure specified in BS 1924. It was considered preferable to compact the samples using exactly the procedures used in the preparation of samples for DCP testing and to subsequently extract a suitably sized sample by coring (McElvaney & Bunadidjatnika, 1991). However, in view of the possibility of samples being damaged during coring, it was decided instead to prepare samples for UCS in accordance with BS 1924 (McElvaney & Bunadidjatnika, 1991).

Uchaipichat (2019) and Enayatpour et al. (2006) conducted UCS tests on specimens of 101.6 mm diameter and 320mm gallon, respectively. Alshkane et al. (2020) conducted UCS tests on undisturbed samples collected by a Shelby tube sampler. Patel &Patel (2013), Patel et al. (2013), Patel & Patel (2012), Patel & Patel (2011), and Sisodia &Amin

(2017) tested UCS in accordance with Indian Standard (IS) 2720 using a length to diameter (L/D) ratio of 2.0.

3.0 Results and Discussion

The DCP equipment used in most of the existing studies is in accordance with ASTM D6951, as shown in Figure 1. The most recent DCP device is ASTM D6951, and countries all over the world have adopted it (Sisodia & Amin, 2017).

The existing studies show that the increase in the percentage of stabiliser agent and the curing period enhanced the UCS value and DCP DN value. The DCP DN values decreased with an increase in the UCS value. The UCS values increase with the increase in stabilising agent content, which is influenced by the initial amount of water and curing period (Vakili et al., 2021; Asgari et al., 2013; Uchaipichat, 2019; Enayatpour et al., 2006; McElvaney & Bunadidjatnika, 1991). Excessive addition of stabilising agents to soils reduces the UCS value and DCP DN value, which may result in excessive crack development in stabilised soils (Vakil et al., 2021; Patel and Patel, 2011; Enayatpour et al., 2006; MoW, 1999). The effects of stabilisers, curing periods, and limitations of the developed relationship between UCS and DCP by various researchers are summarised in Table 2 and discussed in the following sub-sections:

3.1 Effect of Stabilizer and Curing Period

The DCP DN values for cement-stabilised soils are lower than the DCP DN values for lime-stabilised soils of the same content. This is because cement-treatment soils produce significantly higher compressive strengths than lime-treatment soils. MDD and OMC decreased with the increase in cement content; MDD decreased with the increase in lime content, while OMC increased from unstabilized soil and decreased with the increase in lime content (Enayatpour et al., 2006; Uchaipichat, 2019; Patel & Patel, 2011).

Vakil et al. (2021) developed a relationship between UCS and DCP of lime-stabilised marl soils at different curing periods, stabilised with 2%, 5%, and 8% of pure hydrated lime and curing for 1 day, 7 days, and 15 days. The addition of 2% lime for 1 and 7 days of curing did not have a noticeable effect on the strength; however, the increase of the curing time to 15 days increased the UCS by about 100% (Vakil et al., 2021). The tests showed that samples with 5% lime had the highest UCS and DCP DN values, which were about 2.5 and 0.36 times higher after 15 days of curing, compared to marl soil that hadn't been stabilised. Additional lime of more than 5% had a negative effect on the UCS value and DCP value (Vakil et al., 2021).

The goal of the McElvaney and Bundadidjatnika (1991) study was to find the UCS from DCP for clay soils that had 0%, 3%, 5%, and 8% lime added to them in order to test the foundation of a pavement. Adding data from soils that aren't stable doesn't have much of an effect on the models. This suggests that the relationship that was found is mostly based on strength and not on how strength was achieved (McElvaney & Bundadidjatnika, 1991).

Uchaipichat (2019) stabilised lateritic soils with cement contents of 1%, 2%, and 3% for a curing time ranging from 1 day to 28 days. The tested soil samples were prepared by removing soil particles larger than 4.75mm to avoid damaging DCP equipment. The DCP DN values decrease with an increase in the amount of cement and curing time; the decrease rate was dramatic for the curing time, ranging from 1 to 7 days.

Holderby and Cerato (2011) conducted a study on five stabilised construction roads using the stabilising agents of Class C Fly Ash (CFA) and quick lime. The five selected roads include three sites stabilised with CFA, one site stabilised with quick lime, and one road modified with quick lime and then stabilised with CFA. In their study, quick lime was used to increase workability and reduce the plasticity index, and the soils used in the study were classified as A-4 and A-6.

Enayatpour et al.'s (2006) study included three different soils: one control (unstabilised) and two stabilised soils. The soils were stabilised with 5% and 10% cement and 4% and 8% lime at 0 days, 3 days, 7 days, and 14 days of curing periods. The samples stabilised with cement provide more resistance to the penetration of the DCP than lime; therefore, the test was stopped for 10% cement-treated soil for 14 days of curing when the rate of penetration was less than 3 mm per 10 blows (Enayatpour et al., 2006). This is because DCP cannot penetrate highly stabilised soils (ASTM: D6951/D6951M, 2015; Rolt & Michael, 2016). The soil stabilised with 5% cement at 14 days of curing yielded a UCS value that was 18 times higher than that of unstabilised soil and three times higher at 3 days of curing (Enayatpour et al., 2006).

Patel and Patel (2011) conducted UCS and DCP tests on unstabilised and stabilised soil by adding 53-grade OPC cement of 1% to 6% in increments of 1% and Fly ash of 10% to 50% in increments of 10%. The tests were performed for (i) only soil and (ii) soil and cement (1, 2, 3, 4, 5, and 6%). (iii) soil and Fly ash (10, 20, 30, 40, and 50%); (iv) soil, cement (1, 2, 3, 4, 5, and 6%); and Fly ash (10, 20, 30, 40, and 50%). Patel and Patel (2011) observed that with the addition of cement and fly ash, the MDD decreased with an increase in cement and fly ash content, whereas moisture content increased with an increase in cement and fly ash content. The value of UCS increased with an increase in fly ash content, up to 30% in the soil, and thereafter decreased with the addition of fly ash (Patel & Patel, 2011).

3.2 Limitation of Existing Relationships between DCP and UCS

The previously developed relationship between UCS and DCP has a reasonable to very strong coefficient of determination (R2), However, there are some limitations in using these relationships due to variations in soil properties, the type of stabiliser used, the number of samples, and the type of regression model developed. The limitations of various developed correlations between UCS and DCP are summarised in Table 2 and discussed below.

The developed single regression models by Vakili et. al (2021), Alshkane et. al (2020), Uchaipichat (2019), Sisodia and Amin (2017), Chukka & Chakravarthi (2012), Patel & Patel (2011), and Mc Elvaney & Bunadidjatnika (1991) were not reliable for estimation of UCS from DCP because UCS and DCP depends on other soil parameters such as soil type, particle size of soil, plasticity, moisture contents, modified liquid limit, dry density, confining pressures and investigation depth (Amena, et al., 2021; Alshkane et al., 2020; MacRobert, et al., 2019; Amadi, et al., 2018; Dirriba & Teferra, 2017; MoWTC, 2016; ASTM: D6951/D6951M, 2015; Chukka & Chakravarthi, 2012; Siekmeier, et al., 2009; Amini, 2003; Azmi, 1996). The multiple regression analysis was recommended to get a strong relationship (Alshkane et al., 2020).

The study by Uchaipichat (2019) tried to find a link between DCP and UCS for cemented lateritic soils. To keep the DCP equipment from getting damaged, the particles in the soil sample that was tested could not be bigger than 4.75 mm. The study may not represent the field condition because particle size affects the DCP DN values as described above.

According to studies by Patel & Patel (2013), Patel et al. (2013), Patel & Patel (2011), Enayatpour et al. (2006), and McElvaney and Bundadidjatnika (1991), the correlations they came up with overestimate the UCS value for DCP DN values below 20 mm/blow. More independent field studies are needed to get a better idea of how these relationships work in real-world conditions so that they can be used to interpret strength accurately (Alshkane et al., 2020; Enayatpour et al.

The samples were limited to about 32 tests for the studies of Patel et al. (2013), Patel & Patel (2013), and Patel & Patel (2012), which were small and statistically unsound (Alshkane et al., 2020).

Holderby and Cerato's (2011) study showed an anomaly in the results, which may be due to saturation of the stabilised layer caused by rainfall. Different studies (Vakili et al., 2021; Asgari et al., 2020; Uchaipichat, 2019; Enayatpour et al., 2006) have found that this saturation leads to inconsistent test results and a drop in the UCS value as the curing time goes up. The study may not reflect the real site conditions and may overestimate the DCP DN value because of the effects of the moisture content.

Tab 2

Summary of Test Method, Test and Sample Type, Material and Limitation of Various Developed Relationships between UCS and DCP

S/No.	Author	Year	Test Method	Test and Sample Type	Material	Limitation
1.	Vakili et al.	2021	ASTM	Both DCP and UCS on moulded Disturbed Sample in Laboratory	Marl soil of Low Plasticity (CL)and Hydrated Lime	Single regression models not reliable since UCS and DCP depends on other soil parameters.
2.	Alshkane and Rashed	2020	ASTM	DCP in field and UCS on Undisturbed field core Sample	Brown Clay with carbonates	Single regression models not reliable since UCS and DCP depends on other soil parameters.
3.	Uchaipichat	2019	ASTM	Both DCP and UCS on moulded Disturbed Sample in Laboratory	Lateritic Soil with particle size less than 4.75 mm and Portland Cement type I	Single regression model not reliable and soil particle size was limited to maximum 4.75 mm to avoid DCP equipment since UCS and DCP depends on other soil parameters.
4.	Sisodia and Amin	2017	ASTM and IS 2720.	DCP in field and UCS on moulded Disturbed Sample in Laboratory	Cohesive soils of Low to High Plasticity (CI, CL and CH)	Single regression models not reliable since UCS and DCP depends on other soil parameters
5.	Patel et al.	2013	ASTM and IS 2720.	Both DCP and UCS performed on Disturbed sample in Laboratory	Sandy soils (SM, SM-SC), Sand-Clay soils (CL, CL-ML, SC) and Clayey soils (CH, CI)	The samples were small and statistically unsound. The model overestimates the UCS value for the DCP DN values below 20 mm/blow.
6.	Patel and Patel	2013	ASTM and IS 2720.	Both DCP and UCS performed on Disturbed Sample in Laboratory	Sandy, Sand-Clay and Clayey soils	The samples were small and statistically unsound and the model overestimate the UCS value for the DCP DN values below 20 mm/blow.
7.	Patel and Patel	2012	ASTM and IS 2720.	Both DCP and UCS performed on Disturbed Sample in Laboratory	Sandy, Sand-Clay and Clayey soils	The samples were small and statistically unsound and the model overestimate the UCS value for the DCP DN values below 20 mm/blow.
8.	Patel and Patel	2011	ASTM and IS 2720.	Both DCP and UCS performed on Disturbed Sample in Laboratory	Sandy soils, Fly Ash and 53grade OPC	Single regression model not reliable since UCS and DCP depends on other soil parameters. The samples were small and statistically unsound and the model overestimate the UCS value for the DCP DN values below 20 mm/blow.
9.	Chukka and Chakravarthi	2012	ASTM	DCP in field and UCS on moulded Disturbed Sample in Laboratory	Clayey sand soils (SC)	Single regression models not reliable since UCS and DCP depends on other soil parameters

S/No.	Author	Year	Test Method	Test and Sample Type	Material	Limitation
10.	Holderby and Cerato	2011	ASTM	DCP in field and UCS on moulded Disturbed Sample in Laboratory	Class C Fly Ash, Quicklime and fair to poor Silty and Clayey soils (A-4 and A-6)	The study may overestimate the DCP DN value and not reflect the real site conditions because DCP DN value affected by other soil properties.
11.	Enayatapour et al.	2006	Unknown	Both DCP and UCS on moulded Disturbed Sample in Laboratory	Clay soils, Cement and Lime	The developed relationships overestimate the UCS value for the DCP DN values below 20 mm/blow
12.	McElvaney and Bundadidjatnika	1991	ASTM and BS 1924	Both DCP and UCS on moulded Disturbed Sample in Laboratory	Silty-Clay, Clay, Sandy-Clay and Lime	Single regression model not reliable since UCS and DCP depends on other soil parameters. The developed relationships overestimate the UCS value for the DCP DN values below 20 mm/blow

4.0 Conclusion and Recommendation

This paper discussed the method, application, and limitations of various developed relationships between UCS and DCP DN values. The available regression models have an acceptable coefficient of determination (R2) with a reasonable to very strong prediction of UCS values from DCP DN values. Several studies show that the soil type, gradation, plasticity, moisture contents, liquid limit, dry density, UCS, confining pressures, and investigation depth influence the DCP DN value.

The results from the studies indicated that UCS increases with a decrease in DCP DN values; the DCP DN value decreases as the modified liquid limit and Dry Density increase. The increase in percentage of stabiliser agent and curing period enhanced UCS, whereas MDD and OMC decreased with the increase in stabiliser content. Previous studies demonstrate that many studies and nations have adopted the ASTM D6951 DCP equipment. It is suitable to develop a correlation between UCS and DCP that provides comprehensive results for in-situ evaluation of subgrade layers.

However, a good correlation between Dynamic Cone Penetration (DCP) and Unconfined Compression Strength (UCS) has been developed, and since these are dependent on material properties, they should be used with caution. Additionally, these developed relationships cannot be expressed as a perfect substitute for laboratory values, and their application requires experience and engineering judgments. In this regard, the following topics would permit further research work:

i. The development of multiple regression models to correlate UCS and DCP with the same compactive effort and mould size, which consider soil basic index properties,
ii. The effect of confinement on the laboratory DCP DN test in the standard mould

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7.0 Conflicts of Interest

The authors declare no any conflict of interest.

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