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A Review of Light Weight Cone Dynamic Testing and Interpretation for Geotechnical Ground Characterization

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Abstract

Geotechnical investigation is a crucial exercise in availing ground characteristics for safer and economical design and construction of infrastructures. In-situ testing for geotechnical investigation: such as Cone Penetration Test, when adopted to supplement field sampling and Laboratory tests offers economic benefit in terms of time saving and reduced cost for investigation. It is proven that dynamic cone testing offers additional benefits over static cone testing. Intensive research conducted for static cone testing has enhanced its accuracy for ground characterization. There are observed potential benefits of Light cone dynamic testing for shallow depth investigations (to 10 m depth). This review paper is aimed at exploring the information available on equipment specifications, standardization, application and interpretation models/monographs. The review has presented the gaps available in order to enhance predictability power of dynamic light cone penetration test. Furthermore, the review directs the focus on research in advancing the predictability power of the test.

Keywords: Dynamic Light Cone Testing; Dynamic Cone Tests; Static cone Testing; Standard Cone Penetration Test; Correlation

Introduction

The dynamic cone probe sounding test has remarkable potential over conventional probing tests. The use of Dynamic Cone Test through coarse soils (sandy gravels, gravels) or composite soils with coarse fractions is found to be possible unlike the use of Static Cone Test (CPT) where the damage of cone and refusal to penetration is eminent (Czado and Pietras 2012). Additional advantages of dynamic cone testing is its freedom from operability condition, which cannot be assured throughout the ground penetration; maintaining constant penetration velocity (Herrick and Jones 2002). Other advantages observed on the Light Weight(s) dynamic cone tests include; speed of operation, its simplicity in challenging topography with poor access, low costs, detecting soft thin layers, differentiating between cohesive and non-cohesive soils and reducing the need for extensive boring (Hamid 2015, Khodaparast et al. 2015). Notwithstanding remarkable advantages of the test, up to now there is neither test configuration/procedure nor data analytical technique that give direct ground parametric design values such as shear parameters, density and stiffness have been established from this test.

Types of dynamic cone test equipment (categorization)

There are two categories of Dynamic Cone Tests based on the application. Dynamic Cone test equipment for road pavement, (AS1289.6.3.2-1997 2003, D6951/D6951M−18: 2018) referred to as DCP and the Dynamic Cone Tests based on other applications such as buildings. The DCP for road pavement is referred to as shallow depth as the depth of penetration is limited to 3 m while other types of dynamic cone have the limit of depth of penetration depends on the adopted equipment and ground condition (DIN 4094-2: 2003).

Standardization of dynamic cone tests

Since its invention in 1699 as reported by Ghorashi et al. (2020), the standardization of the test was observed to begin in early 1960's as recorded by Massarsch (2014) in German followed by other countries. American standards institute (ASTM International) and Australian Bureau of Standards have standardize one dynamic cone penetration test (DCP) under ASTM D6951/D6951M−18: (2018) and AS1289.6.3.2-1997 (2003) respectively. DIN 4094-2: (2003) of German Standards, BS-EN-ISO-22476-2: (2005) of British Standards and ISO22476-2 (2005) of the International Organization for Standardization (ISO) have standardized many dynamic cone tests and categorized them based of the drop hammer weight. It is noted that most of the standards are adopted or adapted from the German standard. Table 1 below shows formalized specifications of the main parts of the Tests. The standards have formalized two cone diameters for light cone penetrometer, 24.5 mm and 37.4 mm, marinating other specification provisions.

Table 1: Main Specs for Standard Cone Dynamic Tests

			Australian	**American**	**Germany**	**British**	**European**
Type	**Major Specs**	**Unit**	**AS 1289.6.3.2 (1997)**	**ASTM D6951 (2003)**	**DIN 4094-3:2002-01**	**BS EN ISO 22476-2.2005**	**ISO 22476-2 (2005)**
DCP	Drop Weight	Kg	9	8			
	Drop Height	m	0.51	0.575			
	Cone Diameter	mm	20				
	Cone Angle	Degree	30/60*	60			
DPL	Drop Weight	Kg			10	10	10
	Drop Height	m			0.5	0.5	0.5
	Cone Diameter	mm			35.7	35.7	35.7
	Cone Angle	Degree			90	90	90
DPM	Drop Weight	Kg			30	30	30
	Drop Height	m			0.5	0.5	0.5
	Cone Diameter	mm			*35.7/43.7*	43.7	43.7
	Cone Angle	Degree			90	90	90
DPH	Drop Weight	Kg			50	50	50
	Drop Height	m			0.5	0.5	0.5
	Cone Diameter	mm			43.7	43.7	43.7
	Cone Angle	Degree			90	90	90
DPSH	Drop Weight	Kg			63.5	63.5	63.5
	Drop Height	m			*0.75*	*0.5/0.75*	*0.5/0.75*
	Cone Diameter	mm			*50.5*	*0.45/50.5*	*0.45/50.5*
	Cone Angle	Degree			90	90	90

Light Dynamic Cone Research Efforts

There are observed diversification of efforts rendered to dynamic tests studies, whereby equipment of varying specifications has been under examination. This diminishes the focus of research on improvement of the already standardized ones. Table 2 presents statistical data based on 88 searched articles for the last thirty years. The Core Geotechnical parameters include unit weight, shear parameters, stiffness, however, less effort has been observed towards establishing these parameters from solely DPL test. Even the available standards for dynamic tests (with the exclusion of DCP) do not show intensive research conducted prior to standardization as observed on the list of references in BS-EN-ISO-22476-2: (2005).

Table 2: Demographic presentation of research of DPL (10kg) vs other Dynamic Probes

Research	DCP			DPL		DPM	DPH	DPSH	
	<8Kg	8Kg	8<Kg<10	10Kg	10<Kg<30	30Kg	50Kg	63.5Kg	>63.5kg
Equipment	12	3	3	5	1	1	1	1	1
Application &Interpretation		28		11	1	4	6	10	
Total					88				

Dynamic Cone Testing and Dynamic Cone Penetrability factors

The dynamic cone testing measures the impedance of the ground against cone penetrability. The factors that govern penetrability are of two categories; penetrating equipment (Dynamic Test equipment) and Ground Characteristic factors. The equipment factors such as cone angle, cone diameter, applied energy (hammer weight, height fall) contribute to the penetrability, (Salgado et al. 1997, Herrick and Jones 2002, Rahim et al. 2004, BS-EN-ISO-22476-2: 2005). There are number of on-going research that examine the equipment for different control applications in Laboratory or field, for pavement or other infrastructure uses like fill (Fakher et al. 2006, Nguyen and Mohajerani 2012, Prasanth et al. 2016, Srivastava 2018). It was further noted that Cone diameter is inversely to penetrability at given uniform applied energy and cone angle. That is the bigger the cone diameter the bigger the impedance to penetrability (Rahim et al. 2004, BS-EN-ISO-22476-2: 2005). It is also noted that some researchers adopted a mult-weights dynamic probing machine so that when the lighter weight fails to penetrate the ground (refusal state) the bigger weight is invoked for deeper cone penetration (Webster et al. 1992).

Ground Properties such as hydrophysical and soil-mechanical properties including Soil type (Sandy soil, clayey Soils), ground densification, penetration depth (in-directly implies ground densification) and Moisture content have been observed to impact on cone penetrability, (BS-EN-ISO-22476-2: 2005, Rejšek et al. 2011). Establishing these grounds in situ properties directly from DPL results is the emphasis of this review. Fixing the type of equipment and method of application is important step so as to focus on the analysis and interpretation of the results subjected to ground properties variability during cone penetration.

Skin friction is another factor that attributes to the cone penetration impendence. Different methods have been devised to overcome or minimize the effect of skin friction. The first method is by increasing the cone diameter where Wzachkowski (1982) overcame the skin friction in cohesion less soil by using test equipment with a cone/rod diameter ratio exceeding 1.3. The same idea was confirmed in the study by Stefanoff et al. (1988), which indicated that the dynamic skin friction is negligible in sandy soils. It was further noted that the cone to rod ration could work with Clay soils, which are free form squeezing in or collapsing along the penetration hole (Abuel-Naga et al. 2011). The second method proposed and adopted by BS-EN-ISO-22476-2 (2005) is by using lubricants where by the distance between the rod and ground is filled with lubricant such as bentonite as the cone penetrate the ground. However, this method needs special care on the equipment as the rods need to be hollow to allow injection (including injection mechanism). Moreover, alteration of ground properties along the test profile is unavoidable and the extent of influence to un-tested area not established, therefore research is needed to fill this gap. BS-EN-ISO-22476-2: (2005), recommends torque measurement after every meter of penetration (during rod extension) as the measure to control the effect of skin friction. The measured torque is then inferred to skin friction. However, the skin friction experienced during penetration is vertical while the measured through torque is horizontal, that does not mimic the actual testing situation. Sawada (2015) proposed 'quasi-static pull–out resistance method for managing the influence of skin friction. The method makes use of disposable cone whereby after every one meter of penetration the rod is pulled out for one meter and the skin friction is measured. Despite its advantage in mimicking the actual testing condition, the re-penetration does not ensure accuracy in the subsequence penetration stage and therefore, there is a need to have many cones as there is no cone recovery at each test point. The simple and sensitive means of measuring skin friction is such that pull out pressure test during rods extraction from test hole still needed. It is also noted that, these Geotechnical or equipment related factors not only influencing dynamic cone penetrability but also the selection, operation of the equipment and the results of the tests (BS-EN-ISO-22476-2: 2005).

Assessment of Penetrability Behavior

It has been established that the dynamic cone test is repeatable under the same cone angle and diameter in fine soils and coarser soils. Butcher et al. (1965), Wadi et al. (2022), undertook repeatability test on clay and silty clay whereby the analysis was done using Coefficient of variation (Cv) as suggested by Herrick and Jones (2002). The value between 0 to 12.4% with an average of 5.1% was obtained, which is within the allowable value of 30% as recommended by Fakher et al. (2006). While Khodaparast et al. (2015) assessed repeatability using the same cone geometry (specifically reported DPM), Gholami et al. (2019) assessed repeatability by using different cone geometry (cone length) while maintaining the hammer weight, cone angle and diameter. Using the Coefficient of variation, the value between 10.0 and 13.6% with an average of 11.5% was established with Silt and Silty Sand Materials. The same conclusion was also deduced by Huntley (1990). This makes the test reliable, yet the cause of variation observed that is not stated by any of the researchers it might be caused by ground heterogeneity property or operation deficiencies. Nevertheless, un-repeatability of the test when cone diameter and cone angle are varied provide avenue for the possibility of ground characterization.

Test Result Presentation

Generally, there are three commonly adopted presentations of DPL test results. The first mode of presentation is the Plot of Penetration Blows versus Depth (N10 – Depth (m)) whereby the blows required to penetrate 10 cm is plotted against corresponding depth (Khodaparast et al. 2015, Patrick et al. 2019, MacRobert et al. 2019). The second presentation is Plot of Penetration Index versus Depth (PI-Depth (m)) whereby the average penetration per blow is plotted against depth (Alam et al. 2013, Lin et al. 2019, MacRobert et al. 2019). The last commonly adopted presentation is the Plot of Tip Resistance versus depth, (qc-Depth (m)), whereby the penetration blows are converted to tip resistance by a formula relationship (either standards or researcher derived) then plotted at each corresponding depth (Goncharov and Mukhametzyanov 2005, BS-EN-ISO-22476-2: 2005, Lingwanda et al. 2015, Ghorashi et al. 2020). The advantage of the above presentations is the ability to exemplify the penetration impedance at a micro stage of 10 cm where the smaller the recording interval the sensitive the test results to ground variability to enable accurate characterization. However, other types of data presentation can also be used to enable assessment of general ground properties. Such presentation may include Total energy/blows at each recording interval/depth, maneuvering with scales on the plots (may also be used to deduce information) or the combination of different presentations within the plot.

Interpretation of Dynamic Light Cone (DPL) Tests Results

Under this review, the gathered and recorded discussion involves a 10 kg hammer dropping weight as categorized in most of standards.

Qualitative Data Interpretation of DPL Results

One of the utmost advantages of DPL is the sensitivity of the test against ground variability along the penetrated profile. The results presentation by BS-EN-ISO-22476-2: (2005), Khodaparast et al. (2015), Lingwanda et al. (2015) and Patrick et al. (2019) have shown the sensitivity of the DPL to the impedance against ground penetrability. There are presentations of some results that merged the penetration blows/index/tip resistance with the observed ground profile layers (DIN 4094-2: 2003, BS-EN-ISO-22476-2: 2005, Goncharov and Mukhametzyanov 2005, Brzeziński et al. 2017). However, there is no qualitative interpretation of the observed variation (increasing/decreasing) of penetration blows/index/tip resistance within the layer.

Quantitative Data Interpretation of DPL Results

Correlation with other tests such as CPT and SPT tests

Correlation is the measure of relationship between variables, for this section CPT and SPT was assumed to avail the baseline information for establishment of the relationship as realized from reviewed articles. DPL and SPT provide similar mode of output of the test that includes penetration blows/ index in a specified interval. The CPT has different types of output depending on the type of CPT (Pore pressure, sleeve friction, Seismic and Tip resistance) and mode (Tip resistance "in force" instead of penetration Blows). Tip resistance commonly presented in Stress Units while DPL is presented in Blows analogous to energy, therefore unit conversion is essential. Despite the limited research on DPL for geotechnical insitu ground characterization, it is found that DPL correlates well with CPT (Lingwanda et al. 2015, dos Santos and Bicalho 2017). The correlation of DPL with other in-situ tests such as CPT, SPT aim at exploring the possibility of adopting the already established relationships of soil parameters to the tests results of CPT and STP.

Some researchers have provided the conversion formula of Blows (energy) to analogous penetration resistance stress/force prior to establishing correlation. The Dutch conversion formula is widely adopted (Card et al. 1990, DIN 4094-2: 2003, BS-EN-ISO-22476-2: 2005, dos Santos and Bicalho 2017, Opuni et al. 2017) etc. Wiesner (1982) proposed formula when studying/predicting the behavior of the pile driving. Since then, the adoption of the formula by researchers and standards was recorded. It was later established that as far as dynamic cone testing is concerned the cone geometry influences the penetrability and therefore tip resistance (Herrick and Jones 2002, Rahim et al. 2004, BS-EN-ISO-22476-2: 2005). With these findings the Wiesner (1982) formula needs to be improved suitably in dynamic cone testing. It is further noted that the Dynamic–Static cone tip resistance is much affected by many factors such as fines content, cone geometry as presented in Table 3.

Correlation of DPL with Densities and Relative Density

There are a number of research that has tried to establish the relationship between relative density and penetration index from dynamic light cone penetration test. unfortunately, most of research focused on compaction controls for fill or pavement quality control (Alam et al. 2013, Brzeziński et al. 2017 and Lin et al. 2019) where fill material properties are known. Models established based on compaction control are bound to the materials properties mostly grading (fines content, D_{50}, etc) as shown in Table 4 below. The relative density is the state of looseness to the densest state of the materials.

Table 3: Other correlation developed for Dynamic Light Cone Testing

S/N	Correlation Method	Correlated Test	Soil Type (D_{50}, Fines,W_L,etc)	Country	Remark(s)	Reference
1	$q_c/q_d = 2.25$, $R^2=0.92$, RMSE=0.12, $K'_e=N_{DPL}/q_c=0.23$, $R^2=0.92$, RMSE=0.12	CPT	Sand; $0.27<D_{50}<0.7$mm,	Brazil	***DPL Specifications:*** Hammer of 10 kg mass, fall height of 230 mm, tip of 28.6mm in diameter. ***Cone angle NOT stated.***	dos Santos and Bicalho (2017)
2	$(q_c+f_s)=0.4N_{10}+1.66$ $(q_c+f_s)/N_{10}=0.46$	CPT	Sand; $0.16<D_{50}<0.60$mm Mean D_{50} = 0.38mm (SD 0.22mm)	Tanzania	The DPL Equipment consisted of a 10 kg hammer with a falling height of 500 mm and rods of 22 mm diameter fitted to a 25.2 mm diameter cone of 90_ apex angle.	Lingwanda et al. (2015)
	$N_{60}=1.01N_{10}+0.44$ $N_{60}/N_{10}=1.03$	SPT				
3	DCPT-N_{10} < 40, $N_{70} = 0.6243N_{10} + 1.9644$	SPT	Sand; $0.5<D_{50}<0.8$mm,	Ghana	The DPL Equipment consisted of a 10 kg hammer with a falling height of 500 mm and rods of 22 mm diameter fitted to a 25.2 mm diameter cone of 90_ apex angle.	Opuni et al. (2017)

Table 4: Relative Density and Compaction Percentage Correlations

S/N	Correlation Method	Correlation Parameter (s)	Soil Type (D_{50}, Fines,W_L,etc)	Country	Remark(s)	Reference
1	$D_r(\%) = 69.43-14.37(P_{index}sqrt(D_{50}C_u)^{0.27}$	Relative Density	Sand (Carbonate) and Quatz;	Ghana	-Laboratory experiment with 0.6m depth, the influence of depth cannot be realized	Lin et al. (2019)

					-the inclusion of D_{50} and C_u make the formula and test slave of other variables/test	
2	$D_r(\%) = (104.3312e^{\frac{-p_{index}\sqrt{D_{50}}}{18.1307}} - 1.4769)R_dR_{FC}$ $R_d = \left(\frac{0.8}{d}\right)^{0.03}$ $R_{FC} = 1 + 0.003F_C$	Relative Density	Sand	Bangladesh	-Laboratory experiment with 1.0 m depth, the influence of depth cannot be realized.	Alam et al. (2013)
3		Density Index (DI)	Cohesionless soils	Poland	-Field tests were made to analyse differences in the DI results obtained by various dynamic probing (DPL, DPM and DPH). DPM and DPH gave similar results to each other, but slightly overestimate the degree of compaction relative to that of DPL.	Brzeziński et al. (2017)
3	$CP = 16.654q_d^{0.193}$	Compaction percentage (CP)	Soft to Stiff Clays	Iran	-The establishment of the adopted base compacted density not stated as the object was to control fill compaction.	Khodaparast et al. (2015)

There is a challenge in establishing the relative density of unknown subsurface materials being penetrated during the test. Moreover, the influence of the underneath layer properties on the density, stiffness and cone penetrability has not well been studied. That is the behavior of cone penetrability through the soil layer that overlays a weaker layer (i.e. less dense) and vice versa.

Interpretation for Bearing Capacity of the Soil

Effort to use the light dynamic cone test for establishing the resistance of the soil against shear failure has been done for Sandy Soils (Goncharov and Mukhametzyanov 2005, Opuni et al. 2017) and for Clayey Soils (Khodaparast et al. 2015). It is evident that there exists a close relationship between allowable bearing capacities to penetration blows from the light dynamic cone test despite different methods of establishment. For instance Opuni et al. (2017) used bearing capacity derived from SPT correlations and obtained $q_a = 15.75N_{10} + 54.19$ while Ampadu and Dzitse-Awuku (2009) used soil parameters and model footing and obtained $q=14.2N_{all10} +22.6$, the discrepancy between the two are assumed to emanate from the difference on the source of bearing capacity adopted as base value for correlation. It was noted that the penetration blows greater than 40 scatter away and weaken the correlation and therefore were excluded in the analysis (Khodaparast et al. 2015, Opuni et al. 2017). Blows greater than 40 reported by researchers were excluded from model data analysis without detailed information on the cause and management of such cases. There is no quantification of the effect of equipment variability on the evaluation of bearing capacity despite being reported to affect the correlation similarity. The additional discrepancies noted are presented in Table 5.

Table 5: DPL-Bearing Capacity Correlations

S/N	Correlation Method	Correlation Parameter(s)	Soil Type	Country	Remark(s)	Reference
1	$q_a = 15.75N_{10} + 54.19$	Bearing Capacity	Sand;	Ghana	-Bearing Capacity derived from SPT results with some empirical equation	Opuni et al. (2017)
2	$\log q_d = 0.637\log C_u + 2.243$ $C_u = q_d^{1.57}/3320$	Undrained Shear Strength	Soft to Stiff Clays	Iran	Bearing Capacity derived from soil test results from Laboratory used to derive the (Mechanistic Principle)	Khodaparast et al. (2015)
3	$q_s = 0.27N + 0.28$ $E = 7q_s$	CPT Tip resistance		Ufa	Bearing Capacity derived from CPT Test undertaken in sideway with the DPL	Goncharov and Mukhametzyanov (2005)

Conclusion

Despite notable benefits of Light Cone dynamic test over other cone tests, there are observed diversification of research efforts in advancing predictability of the test results. The gaps observed in this review include;

The effect of equipment variability, specifically cone geometry (cone angle and diameter) has not been well established for enhancing data base that will enable evaluation of the penetration behavior in view of in-situ ground characterization.

Despite the observed remarkable research with promising results for use of equipment on quality control activities such as compaction of fill or pavement layers, there is still limited research and without promising results on the use of equipment for in-situ ground characterization.

There are limited research efforts rendering in data presentation and analysis in ascertaining penetration pattern/ behavior in focus to in-situ ground characterization.

Current researches on DPL focus on establishment of correlation model equations to the standard tests such as CPT and SPT, whereby, adopting the already established 'soil parameters constitutive models' of such standard tests as baseline and thus enhances aggregation of errors. In order to minimize these errors, intensive research is needed to establish direct correlation between dynamic light cone test results and in-situ soil parameters from laboratory soil test results.

There is a need of a large database of in-situ soil parameters and corresponding dynamic cone penetration behavior to enable evaluation of dynamic light cone behavior in stratified/ layered ground.

Addressing these observed gaps, will enhance predictability power of the dynamic light cone test for ground characterization and maximizing its envisaged benefits.

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Conflict of Interest

Authors declare that there is no conflict of interest.

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