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1. WHAT IS CPT?

A CPT is carried out by pushing a calibrated cone vertically into the ground and measuring the forces applied on its conical tip, the friction on the sides of the cone and, if using a piezocone, the penetration pore water pressure.

2. HISTORY

Probing with a cone attached to rods for the evaluation of the stratum and strength of the ground has been practised since about 1917. In 1932 the CPT as recognised today was developed in the Netherlands with an outer casing through which an inner rod could freely move. At the base of the rod a 10 cm^2 cone with a 60^o apex angle was attached and the outer pipe and inner rod pushed down.

3. EVOLUTION

In 1948 the basic mechanical cone was developed (Figure 1) and this cone is still in use today as the

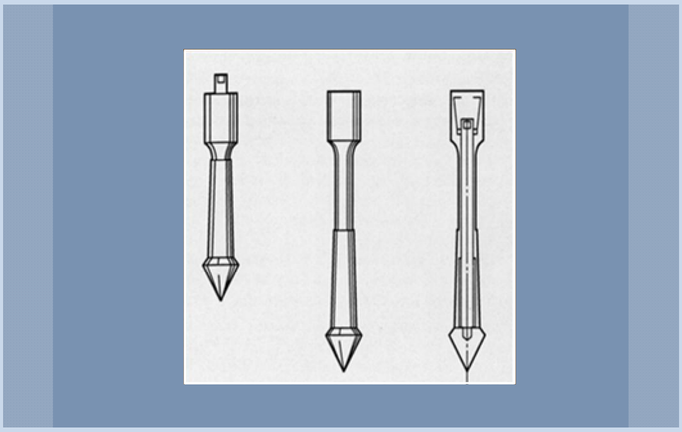

Figure 1 - End Cone Resistance. (Vermeiden, 1948)

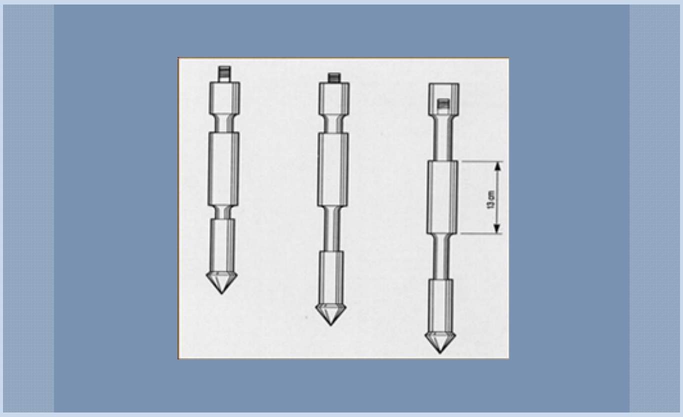

Figure 2 - Cone and Friction Sleeve. (Begemann, 1953)

The test still required an inner rod and outer casing with the outer casing attached to the cone and the inner rod used to push the cone ahead of the casing to measure the soil resistance.

In 1953 Begemann patented the first cone to measure the local skin friction (Figure 2). Begemann (1965) also proposed that the friction ratio could be used to classify soil layers in terms of soil type.

In 1965, Fugro in conjunction with the Dutch State Research Institute developed the electric cone with the shape and dimensions of the cone forming the basis for the international reference test procedures that are still valid today. In 1974 an additional development provided the measurement of pore water pressure (Figure 3).

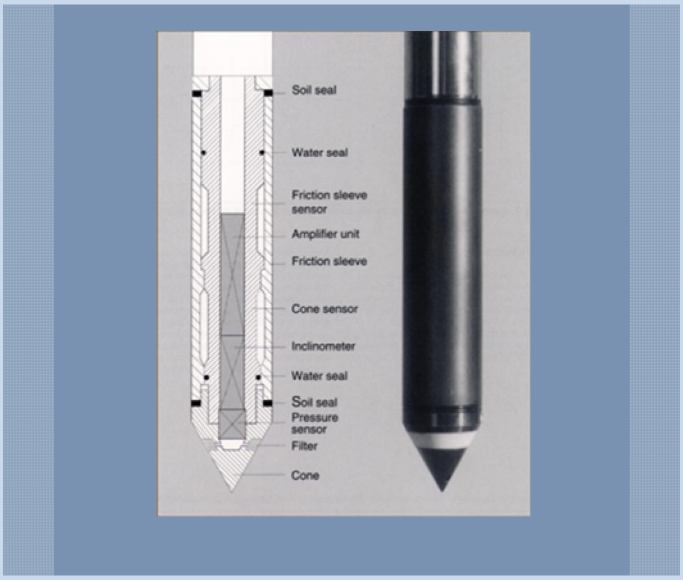

Figure 3 - Electrical Piezocone

The location of the pore pressure filter has been tried in several positions but in practice the filter position is normally in the cone face (U_1) for marine projects and close behind the cone (U_2) for land projects. Triple element piezocones, with a third pore pressure filter above the friction sleeve have been developed; however these cones are normally used for research purposes.

It is important that the verticality of the cone is known whilst the test is being carried out so that the true vertical depth can be calculated and the data corrected.

The basic cone measures tip resistance and sleeve friction with the addition of a pore pressure sensor if detailed parameter calculations are required.

Data is recorded as cone end resistance (q_c), sleeve friction (f_s) and pore pressure. Friction ratio is calculated as [$R_f = (f_s / q_{c})$. 100%]

Special Cones

In addition to the basic cone measurements many additional parameters are now routinely measured with specialist cones, including:

- Seismic Cone - Dynamic Properties by measurement of P and S wave velocities to obtain low strain shear modulus.
- Pressuremeter Cone – Stiffness measurement by measurement of probe expansion versus pressure to obtain shear strength and modulus.
- Electrical Conductivity - Electrical conductivity of the ground for pipeline corrosion assessment and detection of saline ground water.
- Magnetometer Cone – Measurement in changes of the ground magnetic field for detection of UXO or base of sheet pile walls.
- T Bar and Ball Cones – Mainly used offshore for profiling strength of very soft clays and silts for pipeline design.
- Temperature Cone - Measurement of Insitu ground temperature often used for measurement of landfill temperatures.
- Thermal Conductivity Cone - Insitu measurement of the grounds temperature conductivity for design of buried power cables.
- Vibration Cone – Measurement of vibration from piling activities to monitor sensitive underground structures.
- Natural Gamma Cone - Measurement of Natural Radiation within the ground, especially useful for detecting Chalk interface.
- Laser Induced Fluorescence Cone - Use of optical laser light for screening of hydrocarbon derived contamination of soil and water.
- Membrane Interface Cone - Uses a range of sensors to detect contamination by organic compounds within the ground.
- XRF Cone - Use of X – Ray fluorescence to detect metal contaminates within the ground.
- HPT Cone - Hydraulic profiling tool for the continuous logging of relative hydraulic conductivity.

4. CPT EQUIPMENT

In order to carry out a CPT you need equipment that can provide the force and reaction required to push the cone into the ground at the constant rate of 2 cm per second. In the 1940's this required hand installed ground anchors and manual cranking to wind the cone into the ground with the readings taken manually from dial gauges (Figure 4). Today the tests are carried from a wide variety of equipment ranging from 6 wheel drive trucks to crawlers between 1 tonne and 20 tonne for land use using hydraulic rams with data captured on computers Figure 5 to 7).

In the Nearshore environment 20 tonne hydraulic rams are used on Jackup platforms or the seabed units, Roson, from floating vessels (Figure 8 to 11).

With land units every effort is made to ensure that each test is carried out vertically, with the majority of units fitted with hydraulic levelling jacks. On marine units, while a jackup will level the unit legs, the Roson, or similar units, sits on the seabed and has no self-levelling capability. It is therefore very important that a continuous measurement of cone verticality is recorded during a test.

Figure 4 - A CPT Test Carried Out in 1940's

Figure 5 - A Modern 20 Tonne 6x6 Drive CPT Truck

Figure 6 - Offloading a 20 Tonne Crawler from Carrier

Figure 7 - A 1 Tonne CPT Crawler using its own ground anchors for reaction

Figure 8 - Seabed Roson Unit Being Deployed from a Barge

Figure 9 - CPT Ram Set Working on a Jackup Barge

Figure 10 - CPT Units Coming in a Variety of Sizes

Figure 11 - Typical Vessel Used for CPT

5. TESTING PROCEDURES

The cone end resistance and local sleeve friction are registered by calibrated load cells in the cone. The pore water pressure is recorded by means of a calibrated pressure transducer located in the piezocone tip. In order to ensure pore water measurements are not affected by the presence of air in the measuring transducer, a de-airing procedure is carried out prior to each test. This comprises injecting silicon oil (or a suitable miscible and viscous fluid) into the measuring parts of the cone and using a pore pressure filter which has been saturated in silicon oil under vacuum. As a final precaution, a rubber sheath is placed over the filter to prevent the risk of de-saturation before the cone enters the soil.

The signals from the measuring devices are transmitted by an umbilical cable through hollow push rods to a laptop computer. During the test, the computer displays instantaneous and continuous graphical records on its screen of cone end resistance, local side friction, and pore water pressure, and these are plotted out after the test. The data are recorded on magnetic media at 2 cm depth intervals and this facility provides for subsequent automatic computer-controlled processing and plotting of cone end resistance, local sleeve friction, friction ratio and pore water pressure. The rate of penetration during all tests is kept constant at approximately 2 cm per second.

6. SPECIFICATIONS AND STANDARDS

An international reference test procedure recommended by the ISSMGE technical committee on ground property characterisation from in-situ testing is available for the cone penetration test (IRTP, 1988), which is generally in agreement with procedures suggested in most of the widely used standards for soil testing such as BSI (2012) and ASTM D 5778 (2012).

In essence, recommendations regarding the geometry of the cone are that a 60^o cone with a face area of 10 cm^2 should be used. Also, enlarged cones with a base area of 15 cm^2 are utilised. The cone is pushed into the ground at a constant rate of penetration of 2 cm/s with an allowable deviation (e.g., ±5 mm/s as suggested by IRTP (1988)).

7. APPLICATIONS OF CPT

The results of a CPT test are used to assess the soil types and their distribution and can provide initial assessments of soil strength and, when combined with additional cone modules, can provide information on dynamic properties, stiffness and detailed stratigraphy.
This information can be used to plan an optimum borehole programme with a selective sampling regime, determining estimated shear strength of clays, estimate settlement and bearing pressures in granular soils, pile capacity and pile tip levels and dynamic compaction control.

8. CPT FOR BASIC SOIL CHARACTERISATION

Static cone penetration test interpretation using cone resistance q_c and sleeve friction f_s

Extensive research has indicated that the ratio of local sleeve friction to cone end resistance (friction ratio - R_f) can provide a guide to the mechanical properties of soils which assists in identifying the soil behaviour type. The results of various research studies collated by Meigh (1987) have been produced in graphical form and a modified version for British soils by Erwig, is presented in Figure 12. This is the basis of the interpretation of estimated soil types from the basic cone and friction cone.

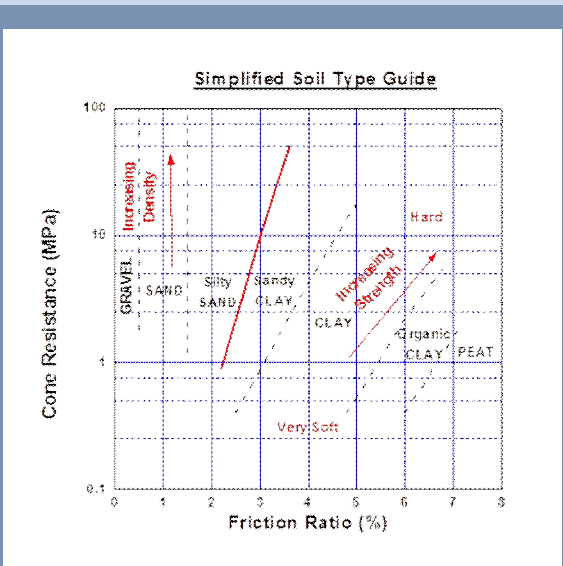

Figure 12 - Estimating Soil Type from Friction Cone

Additional interpretation using pore water pressure (pwp) readings from the piezocone (CPTu)

Robertson (1990) produced a Soil Behaviour Type (SBT) chart using basic CPT parameters of q_c and R_f to make reasonable soil type predictions. However, the estimation of soil properties varies with effective overburden pressure and the measured parameters thus benefit from 'normalisation' which requires knowledge of water depth, pore water pressure (pwp) and soil density. In order to take these effects into account, Robertson proposed an updated (normalised) SBT_N chart using the normalised parameters of Q_n and F_r . The two Robertson charts for SBT (for use with friction cone without pwp) and for SBT_N (for the piezocone with measured pwp) are shown in Figures 13 and 14, and a comparison of Soil Behaviour Type Zones between SBT and SBT_N is shown in Figure 15.

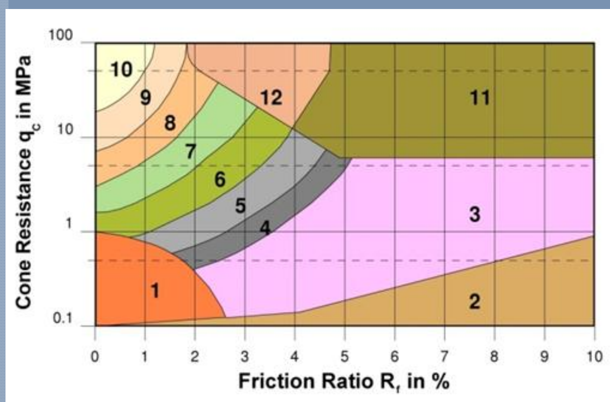

Figure 13 - Robertson (1986) CPT SBT Soil Classification

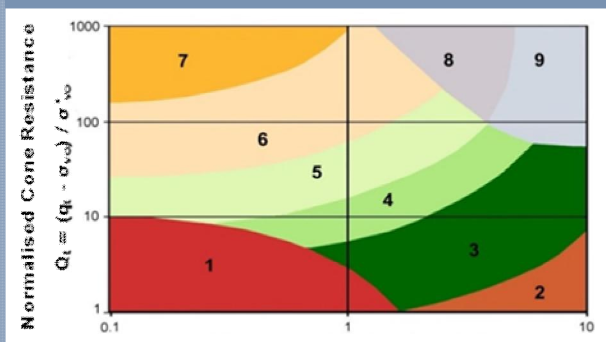

Figure 14 - Robertson (1990) CPT Normalised SBT_N Soil Classification Based on Normalised Cone Resistance and Friction Ratio

1986 Basic		Soil Behaviour Type (SBT)	1990 Normalised	
Legend	Zone		Zone	Legend
	1	Sensitive, fine grained	1	
	2	Organic soils: peat, clay	2	
	3	CLAY	3	
	4	CLAY – Clay to silty clay	4	
	5	SILT mixtures - Clayey silt to silty clay	4	
	6	SILT – Sandy silt to clayey silt	5	
	7	Fine SAND mixtures – Silty sand to sandy silt	5	
	8	SAND – Sand to silty sand	6	
	9	SAND – Coarse to medium sand	7	
	10	Gravel mixtures – Gravel to gravelly sand	7	
	12	Very compact sand to clayey sand	8	
	11	Very stiff fine grained/Hard clay silt weak rock	9	

Figure 15 - Comparison between SBT and SBT_N

Interpreted Plots of CPT data

As discussed above, one of the major applications of the CPT is for soil characterisation and profiling. Figures 16 and 17 illustrate typical plots for the test results from a friction cone and piezocone for inferring soil profiling and identification.

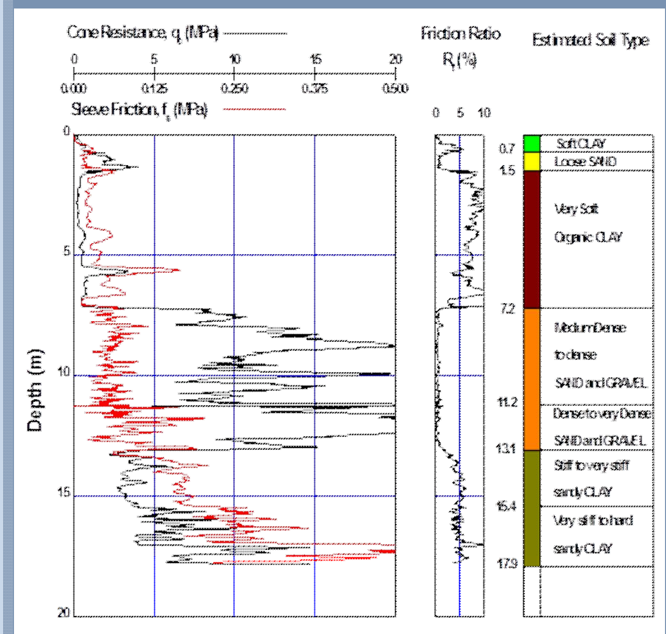

Figure 16 - Report Plot with Soil Type from a Friction Cone

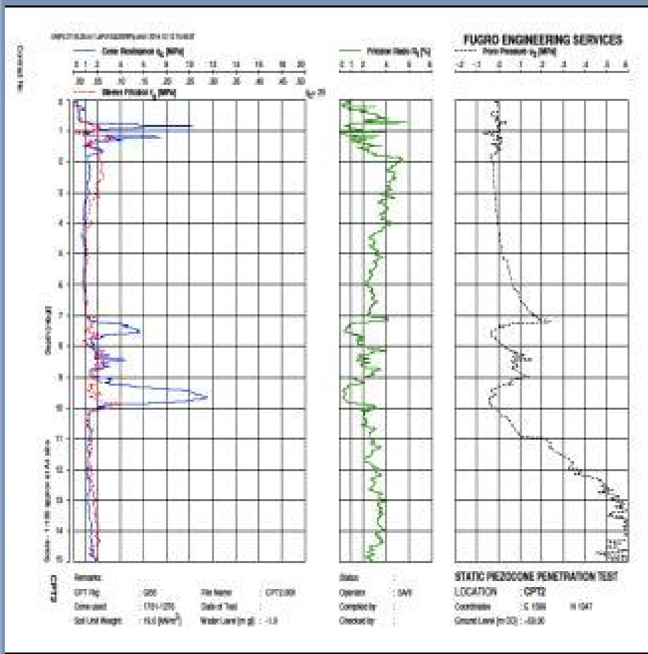

Figure 17 - Report Plot with Pore Pressure Measurement from a Piezocone

9. CPT AS METHOD OF ACCEPTANCE TESTING FOR RECLAMATION FILL

There are currently three popular deep compaction techniques to densify granular soil, namely, dynamic compaction, resonance compaction and vibroflotation (or vibrocompaction). Vibroflotation is the most widely used deep compaction technique in Hong Kong attributed to fact that there have been several successful cases in recent years. Vibroflotation, as its name suggests, is a process to float the soils by vibration to enable them to become arranged in a denser state.

Quality control for the deep compaction is usually based on results of continuous Piezocone tests and surface settlement. CPTs overcome the fact that it is difficult to obtain undisturbed samples of sand for testing and it is also very difficult to measure in situ density directly.

10. CORRELATION OF UNDRAINED SHEAR STRENGTH

Correlations of the undrained shear strength c_u with the cone resistance q_c have been made for many years. The undrained shear strength c_u of a fine-grained cohesive soil (clay) depends on a number of factors related to material composition, anisotropy, strain rates and directions and stress history amongst others.

In general terms, bearing capacity theory for $\varnothing = 0^o$ conditions, can be used to show that the cone resistance q_c is related to overburden pressure (σ_{vo}) for estimation of an average undrained shear strength c_u.

For friction cone - $c_u = (1000q_c - \sigma_{vo}) / N_c$

For piezocone with pore water pressure measurement - $c_u = (1000q_n) / N_k$

where

- c_u is the inferred undrained shear strength (kPa)
- q_c is the measured cone resistance (MPa)
- N_c is an empirical bearing capacity or “cone" factor relating q_c to strength
- σ_{vo} is the total overburden pressure (kPa)
- q_n is net cone resistance (MPa) that is corrected cone resistance minus vertical stress
- N_k is an empirical bearing capacity or “cone" factor relating q_n to strength

The cone factor must be determined empirically, from correlations based on previous investigations in the same material or correlated with Insitu vane tests. Experience has shown that an $N_{c/k}$ factor in the range 15 to 20 may normally be used to give an initial estimate of shear strength (Lunne et al. (1997)). Studies show that the value of the cone factor varies from 4 to greater than 30 due to a number of factors, including sensitivity, plasticity, fissuring and possibly consolidation.

11. DISSIPATION TEST

During tests being carried out with piezocones the test can be stopped and the dissipation of any excess pore pressure recorded against time as presented in Figure 18. The rate of dissipation depends upon the coefficient of consolidation, which in turn, depends on the

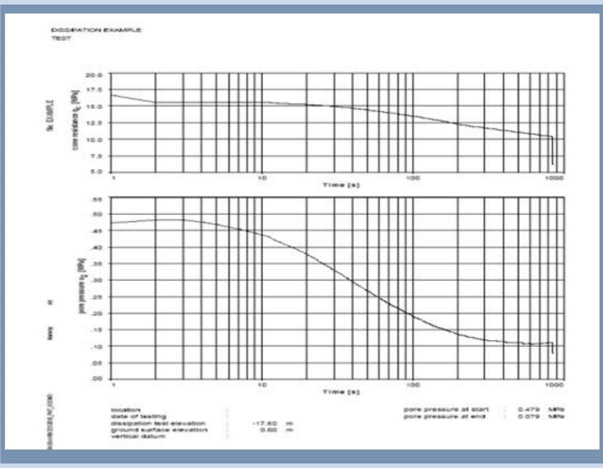

Figure 18 - Report Plot for Dissipation Test

A dissipation test is often continued until a pre-determined degree of dissipation (U), recommended to at least U = 50%.

$$U = \frac{u_t - u_o}{u_i - u_o} \cdot 100\%$$

where

- u_t = pore pressure at time t
- u_o = equilibrium pore pressure *in situ*
- u_i = pore pressure at start of dissipation test

The Teh and Houlsby theoretical curve for dissipation is superimposing on the actual curve, T* (modified time factor) is estimated and from that the value of t. An example of this is given in Figure 19.

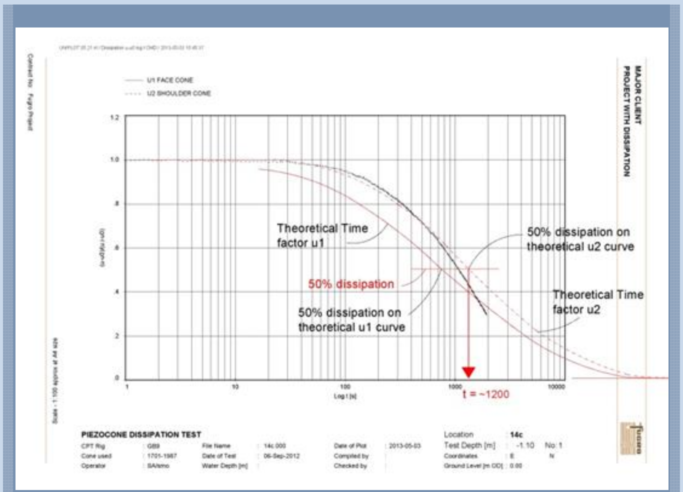

Figure 19 - Dissipation Test for Determining t_{50}

From the value of the modified time factor T* it is possible to determine c_h from the following formula.

$$T^* = c_h \cdot t / r^2 \cdot I_r^{0.5}$$

Where

- T^* = modified time factor
- t = actual time
- r = radius of probe
- I_r = rigidity index = G / c_u. (Assumed to be 100)
- c_h = coefficient of consolidation in horizontal direction

ABBREVIATION AND SYMBOLS

Standard Cone Measurements and Factors

pwp Pore water pressure

q_c Measured cone end resistance (MPa)

q_t Total cone end resistance corrected for pwp effect where qt = (1-α) . (U_0 + β (U_2-U_0))

q_n Net cone end resistance (MPa) where $q_n = q_t - \sigma_{vo}$

f_s Sleeve friction

α Cone shaft face to face ratio

β value of excessive pwp cone ratio- 0.8 for the face (U_1) and 1.0 on the shoulder (U_2)

R_f Friction ratio of sleeve friction (f_s) to measured cone end resistance (q_c)

SBT Soil Bar Type

U_o Theoretical hydrostatic pwp relative to ground level acting on cone.

U_1 Measured pwp at cone face elevation

U_2 Measured pwp at cone shoulder

Normalised Parameters for overburden Pressures

F_r Friction Ratio= $f_s / (q_t - \sigma_{vo})$

SBTN Soil Bar Type

Pressures

σ_{vo} Total overburden pressure relative to ground (kPa)

13. REFERENCES

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