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Soil type identification and fines content estimation using the Screw Driving Sounding (SDS) data

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ABSTRACT

Identification of ground conditions is a very important step before starting to build any geotechnical structure. Geotechnical investigations are performed to determine the soils conditions and to evaluate the cost-effectiveness and design of a proposed engineering construction. Fines contents (*FC*) in sandy soils also play an important role in the engineering design of geotechnical structures, particularly in areas prone to earthquakes. The Screw Driving Sounding (SDS) is a new in-situ test in which a machine drills a screw point into the ground in several loading steps while the attached rod is continuously rotated. At the same time, a number of parameters, such as torque, load and speed of penetration are logged at every rotation of the rod. Because this machine can continuously measure these parameters, an interpreted overview of the soil profile throughout the depth of penetration can be obtained. In this study, a large number of tests were conducted adjacent to boreholes in New Zealand. An attempt was made to correlate the SDS parameters to the soil type as described in the boring logs. In addition, samples from several SDS sites were obtained and sieve analyses were performed in order to formulate a relationship between the fines content and the SDS parameters. From the results, charts were developed to show how soil can be classified and fines content can be estimated using the SDS data. As a simple, fast and economical test, the SDS method can be a reliable alternative in-situ test for soil characterisation.

1 INTRODUCTION

Adequate information about ground conditions is very important for analyses, design and construction of geotechnical systems. Recently, the use of in-situ soil testing has increased in geotechnical engineering practice mainly due to the development of field testing procedures, better understanding of soil behaviour, and identification of the drawbacks and limitations of some laboratory testing (Eslami & Gholami 2006). Standard penetration test (SPT) and cone penetration test (CPT) are the most common in-situ tests around the world due to their capability in accurately characterising soils. Other field tests which are being used in geotechnical practice, such as dynamic cone penetration test (DCP), Swedish weight sounding (SWS), flat dilatometer (DMT), pressure meter test (PMT), vane shear test (VST) and Piezo-cone (CPTu), are less popular than SPT and CPT. Each of these tests applies specific loading pattern to identify the corresponding soil properties, such as strength and/or stiffness (Mayne, 1988). In order to perform some in-situ tests, such as the SPT, PMT and VST, boreholes are required; however, to conduct CPT, CPTu, SWS and DMT, no boreholes are needed. The SDS machine has been recently designed and developed in Japan to reduce the drawbacks of SWS, as well as to include a method of measuring the friction on the rod. The machine previously used for the SWS test has been modified and improved so that it is suitable for the SDS test. In this method, a rod is drilled into the ground in several loading steps at the same time that the rod is continuously turned. An empirical relationship has been developed between the soil parameters and the SDS data (e.g. Tanaka et al., 2012; Maeda et al., 2015); In this study, based on the results of the SDS tests which were conducted adjacent to boreholes in different soil types around New Zealand, a soil classification graph is presented and it is shown that how the soil type can be identified using the SDS data. Furthermore by performing sieve analysis on the samples obtained from the boreholes, a correlation is developed for obtaining fines content directly from the SDS parameter. The SDS test is fast, small in size and relatively cheap compared to other in-situ testing methods and these advantages make it a good alternative for soil characterisation.

2 SCREW DRIVING SOUNDING TEST

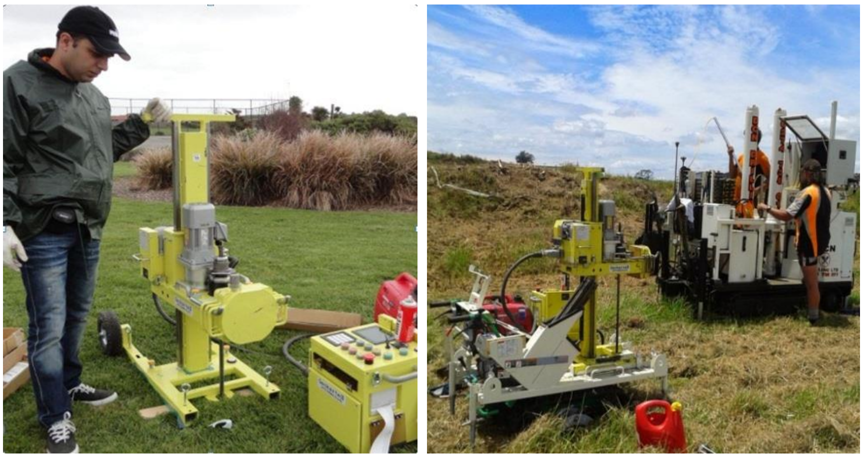
2.1 SDS test procedure

A monotonic loading system is used in the SDS test and the number of load steps is set to 7. The rod is continuously turned at a constant rate of 25 rpm while the test is going on. The load steps are 0.25, 0.38, 0.50, 0.63, 0.75, 0.88, 1.0 kN in this order, and the load is increased at every rotation of the rod. The parameters measured in the test are: maximum torque (T_{max}), average torque (T_{avg}), minimum torque on the rod (T_{min}), penetration length (L), penetration velocity (V) and number of rotations of rod (N). These data are measured on the completion of each revolution of the rod. In SDS, the rod is automatically moved up by one centimetre after each 25cm penetration and then rotated to measure the rod friction. Due to the effects of rod friction on the measured torque and load during penetration, the amount of measured load and torque required for penetration is greater than that required at the screw point. The rod friction can be divided into a vertical component (W_f) and a horizontal component (T_f) as the rod rotates and penetrates into the ground. The corrected torque (T) and corrected load (W) are defined as follows:

$$T = T_a - T_f \tag{1}$$

$$W = W_a - W_f \tag{2}$$

Where W_a and T_a are the total applied load and applied torque by the SDS machine, respectively. The procedure of calculating W_f and T_f is explained by Tanaka et al. (2012).



(a) (b)

Figure 1 Screw driving sounding (SDS) equipment: (a) SDS machine during operation; (b) SDS machine mounted on a crawler side-by-side with a CPT rig.

Figure 1(a) illustrates the small-scale SDS machine during operation while Figure 1(b) shows the machine on top of a crawler (which was designed to ease the transportation of the machine) and CPT rig side by side. As shown in the figure, SDS does not need large space for operation (especially without crawler) and is much smaller in scale than the smallest CPT rig. The SDS machine can be disassembled for ease in transport and the whole SDS machine on top of the crawler can be placed inside a van. Except gravelly soils, the SDS test can be performed in most of the soil types and the maximum depth of penetration depends on the type of the soil which cause the rod friction and difficulty of penetration.

2.2 Definition of SDS parameters

Figure 2 shows typical SDS results. The test was conducted along Avonside Drive in Christchurch, New Zealand. The SDS results illustrate the corrected load, corrected torque and the speed of penetration at every 25 cm. Data points are connected to each other by lines.

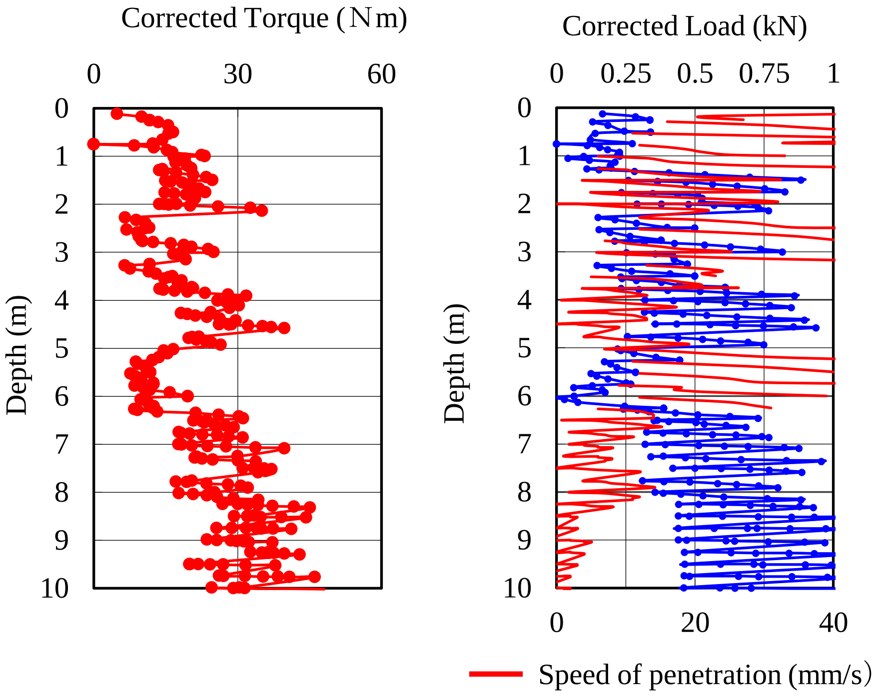


Figure 2 SDS results (torque, load and velocity).

By processing the raw data obtained from the SDS tests more, helpful information for soil characterisation can be obtained. Based on the plasticity theory, Suemesa et al. (2005) defined the coefficient of plastic potential, c_p is as follows:

$$c_p = \frac{N_{SD}D}{\pi T/WD} \tag{3}$$

Where $N_{SD}D$ is the normalized half-turns and is obtained by multiplying the number of half-turns for every 25 cm of penetration (N_{SD}) by the outer diameter of the screw point (D)., T and W are, corrected torque and corrected load, respectively. c_p is a parameter that indicates the difficulty of penetration. Based on the large set of data base in Japan, c_p is highly dependent on the types of soils (Tanaka et al. 2012). Figure 3 shows the changes of $N_{sd}D$, $\pi T/WD$ and c_p along a soil profile.

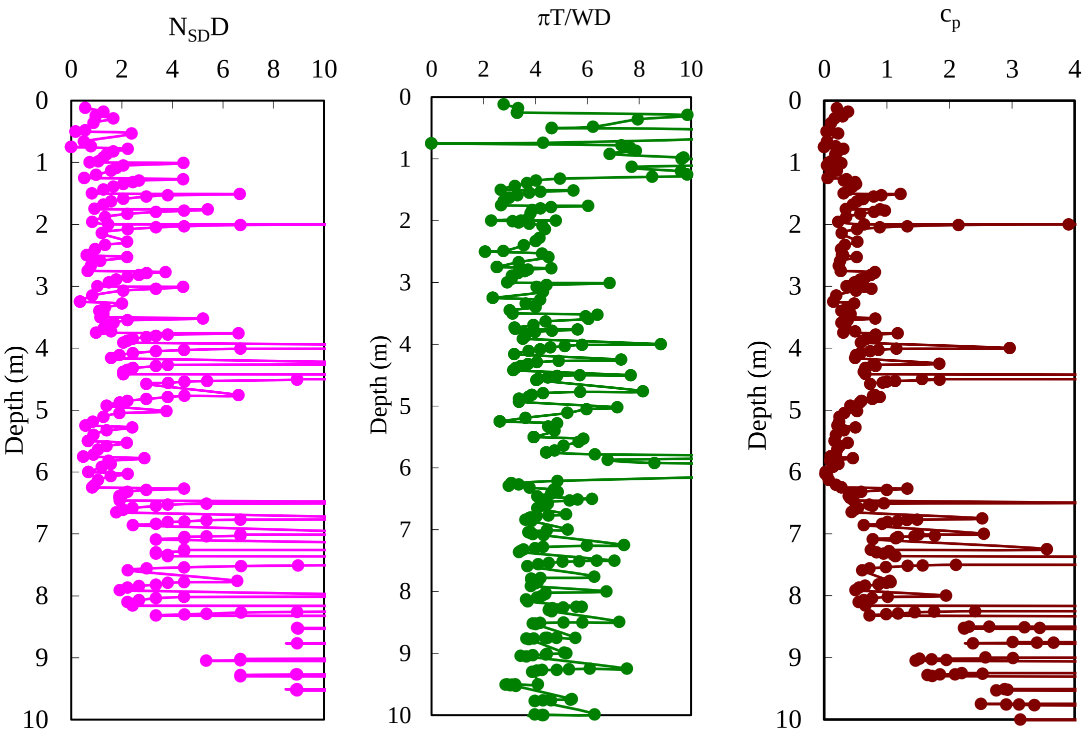


Figure 2 Additional information from test

3 SOIL CLASSIFICATION CHART

Overall, SDS tests were performed at 164 sites in New Zealand (74 in Christchurch, 56 in Auckland and 34 in Wellington). These tests were conducted adjacent to boreholes and therefore the soil types within a given layer are known. Boreholes were done after 2011 Christchurch earthquake and prior to the SDS tests and the data were obtained from New Zealand geotechnical data base (NZGD, 2016). Various SDS parameters (expressed in terms of measured torque, load, energy, etc.) were investigated to examine which of these best correlate with the appropriate soil types. The following parameters were considered:

$$\text{Ave}\delta\text{T}=\frac{1}{n}\sum\nolimits_{n=1}^{6}\text{T}_{n+1}\text{-T}_{n} \tag{4}$$

$$c_p''=\frac{1}{n}\sum_{i=1}^{n}\left(\frac{N_{SD}D}{\pi T/WD}\right)_i \tag{5}$$

where δT is the change in torque, T, at each step of loading, i; n is the number of load step; c_p" is the modified coefficient of plastic potential; N_{SD} is the number of normalised half-turns; W is the applied load; and D is the cross-sectional diameter of the screw point. The soil classification chart obtained based on the NZ soil database is shown in Figure 4. The horizontal axis is $Ave\ \delta T$ which related to the grain size of soil is high in frictional soils due to their drained behaviour and low in cohesive soils due to the undrained behaviour (Mirjafari, 2016). The vertical axis is c_p" which represents the difficulty of penetration.

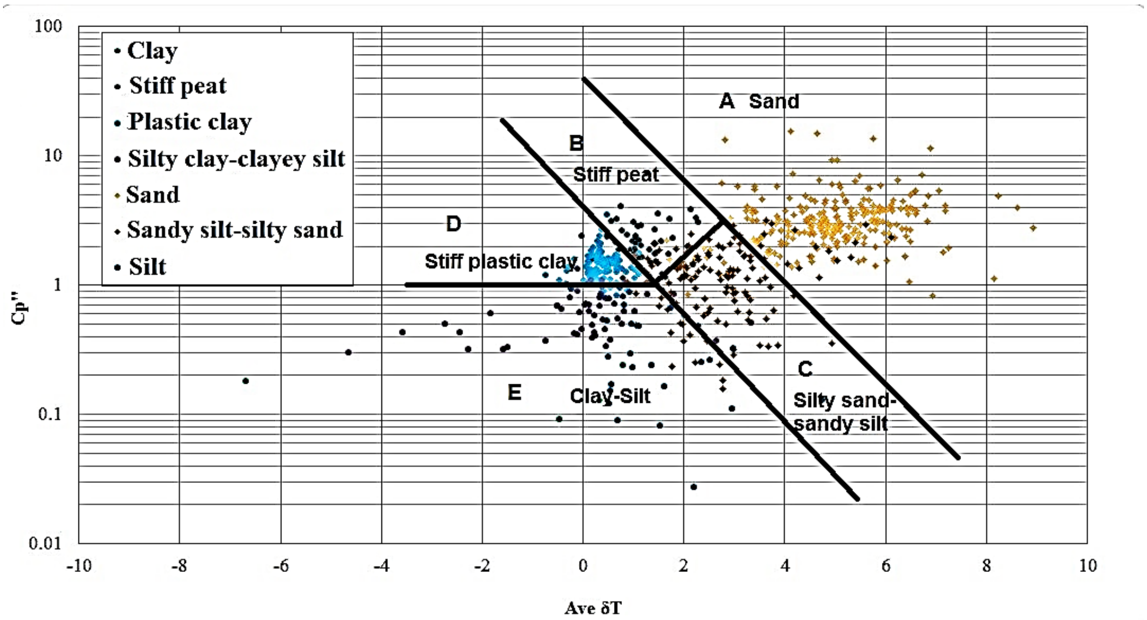


Figure 4 SDS-based soil classification chart for New Zealand soil

Note that the boundary lines were drawn visually to separate data such that points representing similar soil types are grouped together. Data points in region A are sandy soils which, because of their frictional nature, are expected to have higher $Ave(\delta T)$ and c_p” values compared to the other soil types. Based on borehole data analysis, sands on the left part of the region are finer than those on the right part. In addition, as c_p'' is an indication of the difficulty in penetration, the upper part of region A would be denser than those on the lower part. Region B is for stiff peat, which can be found in South Auckland; peat is considered as c-ϕ soil and it is reasonable that it is positioned to the right side of Regions D and E, both of which represent cohesive soils. Region C represents sandy silt and silty sands. Soils at the bottom left of region B contain more silt than sand; therefore, this region can be considered as a transition zone from frictional behaviour to frictionless (cohesive) one. Soils in region D are highly-plastic stiff clays which have $Ave\delta T$ values < 1 and $1 < c_p'' < 2$. Finally, region E belongs to clayey silt, silty-clay, silt and clay. Note that the available borehole data for clayey soils were scarce and more analysis are planned to separate clay and silt. However, it is expected that the upper part of this region would represent stiff clay or silt while the lower part would be for soft clay.

4 COMPARISON BETWEEN SDS AND CPT FOR SOIL CLASSIFICATION

The SDS-based soil classification is compared to the CPT-based one; for this purpose, the CPT soil behaviour type classification used in this study is based on the Robertson (2010) soil behaviour type chart. Tables 1 and 2 show a comparison of the results of soil classification using SDS, CPT and boreholes for two randomly selected sites, one located in Avonside Drive (Christchurch) and another in Ihumatao Road (Auckland), respectively. As can be seen in Tables 1 and 2, the results obtained from SDS test are very accurate and almost similar to those shown in the borehole description.

A very good example of the advantage of SDS is the ability to recognise peat behaviour. In Table 2, SDS accurately predicted the peat soil while CPT found it as silty sand. Because of its high compressibility, peat can be a very problematic material for any construction.

Table 1 Soil classification using SDS, CPT and BH data (Avonside Drive, Christchurch).

CPT Soil description	SDS Soil description	Soil description	Depth (cm)
-	-	Fill: Fine sand, dry, poorly graded	0-80
Silty sand- Sandy silt	Sandy Silt Silty Sand	Sandy silt, Moist, low plasticity, sand is fine	80-275
Sand and Silty sand	Sandy Silt Silty Sand	Fine sand with trace silt, wet, poorly graded	275-300
Silty sand-Sandy silt	Sandy Silt Silty Sand	Sandy silt, moist, low plasticity, sand is fine	300-350
Silty sand-Sandy silt	Sandy Silt Silty Sand	Fine sand with trace silt, Wet, poorly graded	350-375
Sand and Silty sand	Sand		375-470
Sand and Silty sand	Sand	Fine to medium sand with trace silt, wet, well graded	470-525
Silty sand	Sand		525-600
Silty sand- Sand	Sand		600-750

Table 2 Soil classification using SDS, CPT and BH data (Ihumatao Road, Auckland).

CPT Soil description	SDS Soil description	Soil description	Depth (cm)
-	-	Fill	0-150
Clayey silt to silty	Stiff plastic clay	Clayey silt-Silty clay	150-300
Clayey silt to silty	Stiff plastic clay	Silty clay-very plastic	300-350
Clayey silt to silty	Sandy Silt Silty Sand	Silty fine sand	350-400
Sandy Silt Silty Sand	Sandy Silt Silty Sand	Clayey silt-Silty clay	400-450
Sand	Sandy Silt Silty Sand	Silty sand	450-600
Sandy Silt Silty Sand	Silty clay-clayey silt	Silty clay	600-650
Sandy Silt Silty Sand	Sandy Silt Silty Sand	Fine sand –some clay	650-700
Sandy Silt Silty Sand	Silty clay-clayey silt	Silt-some clay	700-750
Sandy Silt Silty Sand	Stiff Peat	Peat-very stiff	750-1000

5 ESTIMATION OF FINES CONTENT

Fines content (*FC*) in sandy soils plays an important role in the engineering design of geotechnical structures, particularly when the area is prone to earthquakes. The amount of *FC* significantly influences the liquefaction potential of soil. In engineering practice, it is very common to estimate the *FC* using the CPT data, as this test has become the most common field test for the design of structures. However, recently it was found that the CPT soil behaviour type often appears to overestimate the fines content within a soil (Van T Venn, 2015). In the previous section, it was shown that the SDS machine can identify the soil type with a high degree of accuracy that is even better than with the CPT in some soils. Hence, an attempt was made to formulate a relationship between the fines content and the SDS parameter, as an alternative to CPT. As mentioned earlier, *AveδT* relates to the grain size of soils. Hence a relationship between fines content (*FC*) and *AveδT* parameter was sought.

For this purpose, samples from 6 different sites in Christchurch were provided by the Earthquake Commission (EQC) and sieve analysis was performed on 115 samples. The particle size distribution for the samples was obtained by the method of wet sieving described by NZS 4402.2.8 (1986). Soil characterisation using sieve analysis yielded fines content (*FC*), defined as the percentage by weight passing through a 63μm sieve. All the data were compiled and Figure 5 shows how *AveδT* changes as *FC* increases. It can be seen that there is a good correlation between *FC* and *AveδT* where the coefficient of correlation is 0.792.

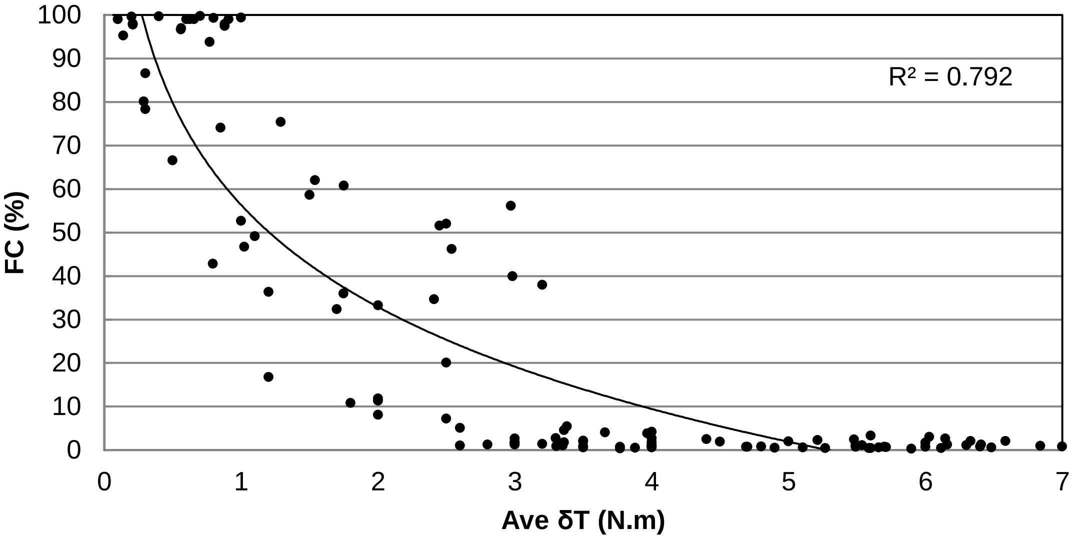


Figure 5 Estimation of fines content using SDS parameter.

The equation for the line is:

$$FC = -33.81 \ln(\text{Ave } \delta T) + 56.32 \qquad (6)$$

As can be seen from the figure, a high value of *AveδT* parameter (i.e *AveδT*>3 Nm) represents clean sand and, for the *AveδT* values less than 3 Nm, soil would contain fines. Although the graph shows a good correlation between *FC* and *AveδT*, more tests need to be performed, especially for soils with *AveδT* values of less than 3 Nm (including silty sand, sandy silt, clayey sand and sandy clay). It should be noted that the plasticity of fines was not taken into consideration in the plot. Further investigation needs to be done to evaluate the applicability of the proposed method if it is being used for soils in areas different from Christchurch. Currently more tests are being conducted to improve the developed plot.

6 CONCLUSIONS

A total of 164 tests in the three cities of Christchurch, Wellington and Auckland were conducted adjacent to available CPT/SPT locations. A new soil classification chart was generated based on New Zealand soil. A variety of soil types was included in the graph such as sand and silty sand available in Christchurch and Wellington, and peat or clayey soil existing in Auckland. The soil classification graph was validated by evaluating its accuracy in classifying the soil at two sites in Auckland and Christchurch. It was shown that SDS can predict the soil type with a high degree of accuracy. To find a relationship between *FC* and SDS parameters, 115 sieve analyses were performed on samples taken from 6 sites in Christchurch. A correlation between $Ave\delta T$ and *FC* was formulated that can estimate *FC* directly using SDS parameter ($Ave\delta T$). In comparison with other methods, SDS is simpler and it does not need a large space to conduct the test, and by measuring a variety of parameters continuously including torque, load, and speed of penetration it can give a clear image of the soil profile.

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