Screw driving sounding method: field testing & numerical simulation

Méthode de sondage du tournevis: Essai sur site et simulation numérique

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ABSTRACT: The Screw driving sounding (SDS) method, which has been recently developed in Japan, is a new field testing technique for site characterisation. It measures the required torque, load, speed of penetration and rod friction using a machine-driven and portable device and therefore provides more robust way of characterising soil stratigraphy especially in small-scale and confined areas. In this paper, the results of SDS testing performed at a variety of sites in New Zealand are presented, with emphasis on the method's ability to classify soils based on measured data. The SDS tests are conducted at sites where borehole logs and CPT data are available. Moreover, the mechanism of SDS penetrating sandy ground is simulated using the 3D finite element program ABAQUS. Here, the coupled Eulerian/Lagrangian method is utilized to simulate the penetrating screw point and the very large distortion of the surrounding soil. The FEM model, which provides very good validation of the field results, is then used to develop a design chart to correlate soil shear strength parameters with the measured SDS parameters. The results indicate that the SDS method has great potential as an in-situ testing method for geotechnical site characterisation, especially for residential house construction.

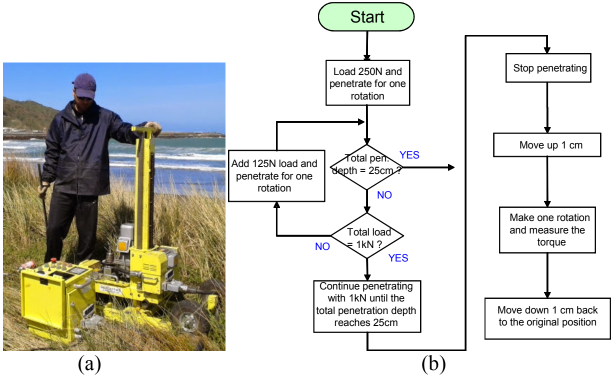
RÉSUMÉ : La méthode de sondage du tournevis (*screw driving sounding*, SDS) est une nouvelle technique de mesure des propriétés des sols directement sur site récemment développée au Japon. Le couple, la charge, la vitesse de pénétration et le frottement de tige requis sont mesurés à l'aide d'un dispositif portable mécanisé permettant une caractérisation plus robuste de la stratigraphie des sols, particulièrement dans le cas de zones confinées de petites échelles. Dans ce document, les résultats des tests SDS pour différents sites néo-zélandais sont présentés en attachant une attention particulière à la classification des sols à partir des données mesurées par cette méthode. Les tests SDS sont menés sur des lieux disposants au préalable d'historiques d'activité de forage et de données d'essai CPT. Par ailleurs le comportement du module SDS au cours de la pénétration dans un terrain sableux est simulé à l'aide du code de calcul aux éléments finis (FEM) 3D ABAQUS. Pour cette étude, l'approche couplée Eulerienne-Lagrangienne est appliquée de manière à simuler le point de perçage et les très grandes déformations du terrain alentour. Le modèle FEM aboutit à une très bonne validation des mesures et est ensuite utilisé afin de définir une table de corrélation des paramètres de contraintes des sols avec les paramètres mesurés par la méthode SDS. Les résultats indiquent que la méthode SDS a un grand potentiel en tant que solution de caractérisation geotechnique in-situ, spécialement dans le cas de construction de maisons résidentielles.

KEYWORDS: site characterization, field testing, screw driving, FEM, Eulerian/Lagrangian method.

1 INTRODUCTION

A number of field testing techniques, such as standard penetration test (SPT), cone penetration test (CPT), and Swedish weight sounding (SWS), are popularly used as economical alternatives over the conventional methods of sampling and laboratory testing for in-situ site characterisation.

The screw driving sounding (SDS) method, which has been recently developed in Japan, is an improved version of the SWS and can be used to characterise soft shallow sites. It consists of a machine drilling a rod into the ground in 7 steps of monotonic loading, and the load increases at every complete rotation of the rod (load step: 0.25, 0.38, 0.50, 0.63, 0.75, 0.88, and 1kN). The speed of rotation is set constant at 25 rpm and the test measures the following parameters at every complete rotation of the rod: applied torque (*T*); amount of penetration (*L*); penetration velocity (*V*); and number of rotations (*N)* of the rod. The set of loading is applied at every 25cm of penetration after which the rod is lifted by 1cm and then rotated to measure the rod friction.



(a) (b)

Figure 1. (a) SDS equipment; and (b) SDS test procedure

Figure 1(a) illustrates the SDS test machine during operation while Figure 1(b) summarises the test procedure adopted. Further details of the SDS method are reported by Tanaka et al. (2012; 2014) and Maeda et al. (2015).

2 APPLICATION OF SDS TESTS IN NEW ZEALAND

The SDS method was introduced in New Zealand in 2013 and to date, a total of 198 SDS tests have been conducted at various sites to evaluate the geotechnical properties of NZ soils and to compare the results with typical field investigation techniques used. Figure 2 shows a typical SDS test result which was was conducted within 2m of a CPT site and borehole. It can be inferred from the profile that the site consists of loose deposits up to a depth of 4m overlying a relatively harder layer. Comparison of the CPT tip resistance and measured torque indicates a good correlation between the two, i.e. the torque required to penetrate the screw point increases with increase in cone resistance. Within a given 25 cm interval, the change in torque with the applied load appears to increase when the penetration resistance is high; on the other hand, the change in torque in softer layer is small. Moreover, the penetration velocity significantly decreased when a hard layer is encountered. Preliminary SDS results of application in NZ have been reported by Mirjafari et al. (2013; 2015a; 2015b) and Orense et al. (2013). A soil classification chart based on SDS parameters have been reported by Mirjafari et al. (2016).

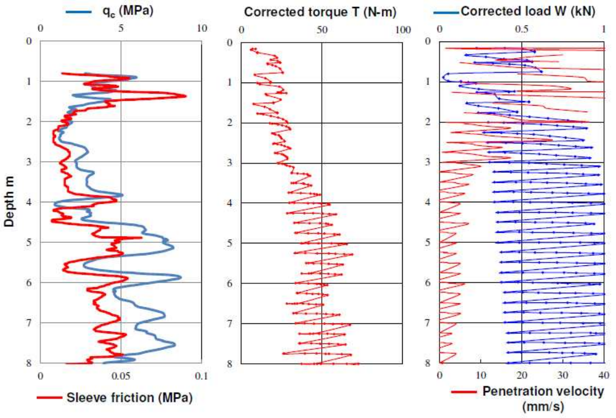


Figure 2. CPT profile and SDS results (torque, load and velocity) at a site in Christchurch.

For design purposes, it is necessary to estimate the soil properties from measured in-situ data. Generally, empirical relationships between field parameter(s) and soil properties are developed based on correlations and regression analysis. Some of the previous research mentioned above attempted to correlate SDS parameters with SPT *N* data, CPT q_c value and cyclic resistance (*CRR*) of soils. In the following section, attempts to numerically simulate the SDS screw point penetration into a sandy ground layer is presented from which correlation between SDS data and friction angle of soil is derived.

3 NUMERICAL SIMULATION

To simulate the penetration of the screw point during the SDS test, Abaqus software was used to deal with the large soil deformation. In the analyses, coupled Eulerian-Lagrangian (CEL) approach was adopted in order to avoid mesh problems when performing simulations that involve high/extreme deformations. The method enables the user to selectively mesh the analysis components accordingly, i.e. the components/ bodies undergoing large deformations can be meshed using Eulerian technique with the remainder using the conventional Lagrangian technique. The interaction behaviour between the two is defined using a general contact where the constraints are enforced using the penalty method. Further details of the CEL method are discussed elsewhere (Abaqus 2013) while discussions of the modeling are presented by Mirjafari (2016).

3.1 *Modeling*

3.1.1 *Geometry*

Due to the asymmetric shape of screw point and the applied CEL Method, a three dimensional model has to be used. The drilling tool is modelled as a rigid body, with the screw point having a diameter of 33.5mm and the drill rod about 20mm. The screw point was drawn using AutoCAD software and then imported to Abaqus. Figure 3 depicts the screw point modeled using AutoCAD and exported to Abaqus.

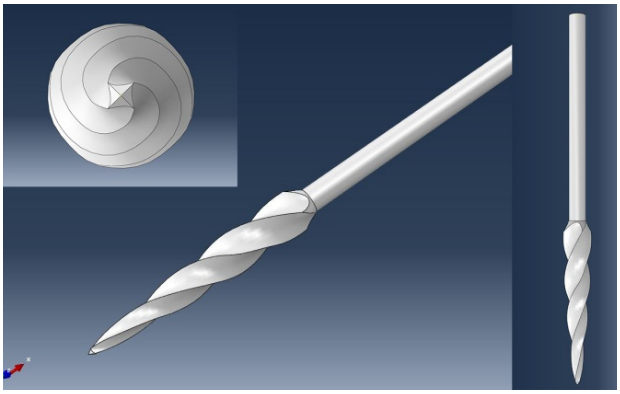


Figure 3. Model of the screw point.

The soil, modelled using Eulerian method, is cylindrical in shape with a diameter of 500mm and a height of 750mm; verification indicates that the boundary is far enough from drilling tool so it does not affect the results. Above the soil model, a 2cm void area is provided, so that the soil can move into this free space during the drilling process. The whole Eulerian zone comprises 98592 eight-noded elements with reduced integration. The discretised model is shown in Figure 4.

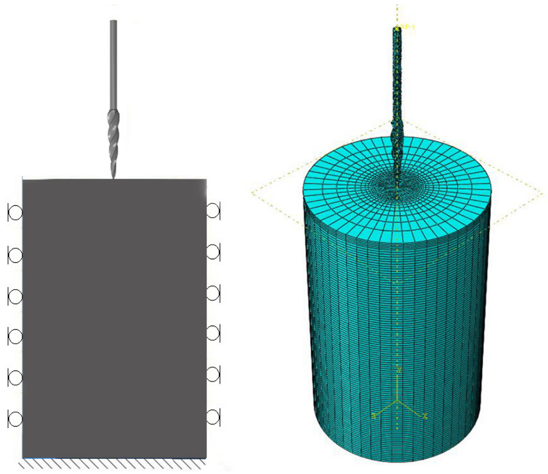


Figure 4. Discretised model used in Abaqus.

The drilling tool penetrates the soil at constant rotational speed of 25 rpm. The reaction forces and torques are recorded during the simulation. The vertical and horizontal displacements of the ground are fixed at the base while horizontal displacements are restrained along the sides.

3.1.2 *Constitutive model*

To describe the behaviour of the sand model, a simple elastic-perfectly plastic constitutive model based on Mohr-Coulomb yield criterion is used. The elastic behaviour is described by the elastic Young's modulus and the plastic deformation is defined by the friction angle and dilation angle. A non-associated flow rule is adopted to describe the dilatancy of the soil.

3.1.3 *Interface modelling*

In the CEL method, the contact between Eulerian zone and Lagrangian region is discretised using the general contact algorithm, which is based on the penalty contact method. Seeds are made on the Lagrangian element edges and faces while anchor points are created on the Eulerian material surface.

Classical isotropic Coulomb friction model is used to relate the maximum allowable frictional stress across an interface to the contact pressure between the contacting parts. In the simulation the normal contact is chosen as hard contact (i.e: no friction, no thermal interaction in normal direction) while for the tangential contact, a value of δ/ϕ =0.5 is adopted, where ϕ is peak angle of internal friction and δ is the angle of interface friction.

3.1.4 *Initial stress and soil properties*

The SDS simulation was performed to a 15m depth at 5 levels of effective vertical stresses while the coefficient of lateral earth pressure is calculated using Jaky's formula. The dilation angle is calculated by adopting the 'saw blade' model of dilatancy:

$$\phi=\phi_{cv}+\psi \tag{1}$$

where ϕ is the peak angle of effective internal friction, ϕ_{cv} the residual angle of internal friction, and ψ the dilation angle. In this study, three samples were obtained at specified depths from SDS test sites. The samples were then reconstituted to their in-situ densities which were estimated based on nearby CPT records. A constant value of ϕ_{cv}=33° was adopted based on the results of drained triaxial tests on samples. The stress-strain relation proposed by Duncan and Chang (1970) was used:

$$E_t=\left[1-\frac{R_f(1-\sin\phi)(\sigma_1-\sigma_3)}{2c\cos\phi+2\sigma_3\sin\phi}\right]^2 K_E P_A\left(\frac{\sigma_3}{P_A}\right)^n \tag{2}$$

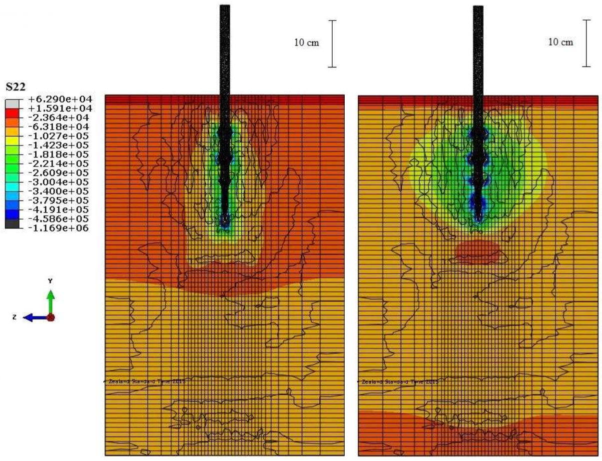
in which E_t: tangent drained Young's modulus; R_f: failure ratio (taken as $0.9(\phi_{cv}/\phi)$); σ_f: stress condition at failure; K_E: modulus number for primary loading; n the modulus exponent; P_A: atmospheric pressure (=100 kPa); σ_1:major principal stress; and σ_3: minor principal stress.

3.2 *Results and discussions*

In this study, one complete rotation of screw point is simulated with 1 kN of applied vertical load on the top of the rod (which is the maximum applied load) at a constant rotational speed of 25rpm. Analyses by Mirjafari (2016) indicate that measurement of torque at the last loading step is sufficient.

3.2.1 *Stress contours*

Figure 5 shows typical contours of stresses within the model ground. The advancement forces of the screw point is produced by its wings (edges) which convert the applied torque to vertical force for penetration by pushing the surrounding materials upward and sideways. This concept can be clearly observed in the figure. The stresses in the area in the periphery of the screw point edges are maximum and these generate the forces for vertical advancement of screw point.



(a) (b)

Figure 5. Contour of stresses (in Pa) within the soil after one complete rotation: (a) vertical; and (b) horizontal stresses (σ_v'=60 kPa, ϕ=34°).

3.2.2 *Reaction moments*

Before applying the rotational speed to place the whole length of screw point into the soil, a predefined vertical penetration speed is defined after which another step is included to rotate the screw point. During the second step, the reaction moment, which is caused by the interaction between Lagrangian and Eulerian parts, is calculated and this is conceptually similar to the measured torque in the SDS test during operation. For different combinations of friction angle and vertical effective stress, the reaction moment is calculated. Figure 6 shows the measured reaction moment for the soil with friction angle of 34° and vertical effective stress of 30kPa.

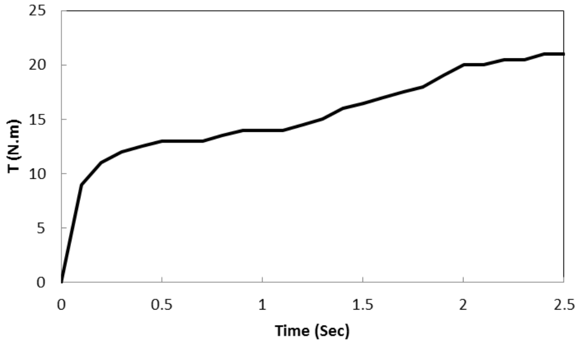


Figure 6. Numerically-derived reaction moment of the soil (σ_v'=30 kPa, ϕ=34°) for one load step at 1 kN.

3.2.3 *Effect of friction angle*

Various friction angles were considered, assuming the soil is cohesionless. Figure 7 shows the effect of increasing friction angle on the reaction moment for the same effective overburden pressure. As expected, increasing the friction angle increases the amount of torque as the screw point requires more torque to penetrate denser sands. It is also found that the changes in torque are more significant as the overburden pressure increases.

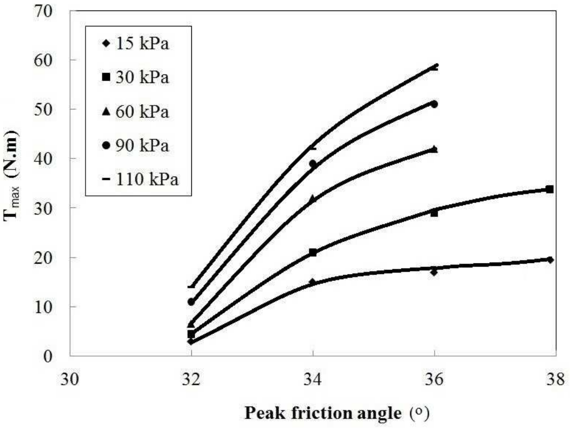


Figure 7. Relationship between peak friction angle and measured torque for different overburden pressure.

3.2.4 *Effect of overburden pressure*

Figure 8 illustrates the relationship between torque, effective overburden pressure and friction angle. It can be seen that for a specified friction angle, the amount of torque increases as overburden pressure increases and this change is more significant for denser sands with higher friction angle.

The proposed graph can be used for predicting the friction angle of soil using the SDS results. The proposed graph is based on the observed trend of increasing torque at the end of one complete rotation with increasing friction angle and effective overburden stress.

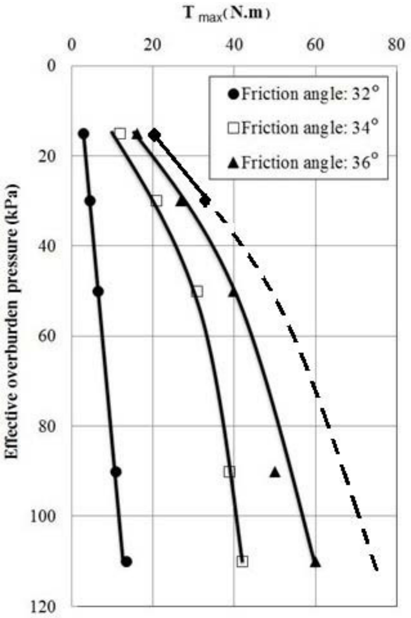


Figure 8. Relationship between torque, effective overburden pressure and friction angle

3.3 *Validation*

To check whether the developed chart (Figure 8) can predict the friction angle with reasonable accuracy, the results of the SDS test conducted at the three different sites mentioned above, supplemented by friction angles obtained from laboratory drained tests, are compared to the results of numerical analysis. Table 1 summarises the comparison between the actual laboratory test results and numerical simulation.

Table 1. Comparison between numerically predicted and laboratory measured friction angles.

Test site	Depth (m)	σ_v' (kPa)	T_{meas} (N-m)	Friction angle (°)	
				Lab	FEM
Avondale Rd	5.0	46	51.7	36	38
Pages Rd	6.2	56	53.0	39	38
Bideford Pl	6.1	58	34.1	33	34

As can be seen from the table, the numerical model could predict the angle of friction with an acceptable degree of accuracy. It should be noted that there were a lot of assumptions and limitations in the input parameters, such as the assumed coefficient of interface friction between the soil and screw point, the Young's modulus adopted based on empirical relationship, the use of simple constitutive model, etc. Furthermore, there were also some uncertainties on the results of laboratory tests on reconstituted samples and the preparation of samples based on estimated relative density from CPT tests. Taking these factors into the account, the FE model works quite well, but there is always room for further improvement.

4 SUMMARY AND CONCLUSIONS

In this paper, the screw driving sounding (SDS) method was introduced. The results of some field investigations conducted in New Zealand were presented. Focus was made on the numerical analysis of screw point penetration process in clean sand layer during the SDS test using the coupled Eulerian-Lagrangian method in Abaqus. It was shown that CEL method can deal with problems involving large deformations and avoided numerical problems associated with high distortion of elements due to large deformation. The soil was modelled using elastic-perfectly plastic constitutive model based on Mohr-Coulomb yield criterion and a non-associated flow rule was used to describe the dilatancy of the soil. In spite of using very simple constitutive model for sand, the finite element model was able to simulate the penetration process during the SDS with acceptable degree of accuracy. Increasing the friction angle resulted in increase in the amount of torque required, which was more significant at higher effective overburden pressure. A chart was proposed for estimating the friction angle of clean sand directly using the SDS data. The chart was used to estimate the friction angles from three SDS sites and the results agreed quite well with laboratory obtained values. Thus, the possibility of estimating the friction angle directly using the SDS machine makes it a powerful tool for soil characterisation.

5 ACKNOWLEDGMENTS

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