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# Evaluation of hydraulic conductivity for both marine and deltaic deposits based on piezocone testing

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ABSTRACT

In order to rapidly determine the hydraulic conductivity for both marine and deltaic deposits in field, an approach is proposed to evaluate the hydraulic conductivity of soil using cone penetration tests with pore water pressure measurement, known as piezocone testing. This approach is based on the test results from a series of laboratory penetration tests investigating the expansion shape of soil using a model cone tip with different tip angles and considering the influence of the soil characteristics. To derive the calculation method, two assumptions are made: *i*) the flow surface of pore water is assumed to be a half ellipsoid shape, covering the whole tip of the cone, and *ii*) the initial state of induced excess pore pressure is assumed to be have a negative exponential distribution and to dissipate from the half ellipsoid surface. The proposed approach is compared with the existing approach based on piezocone data and laboratory testing. All of the three methods were applied to analyze three field cases, in which two cases is marine deposit and one is deltaic deposit. The results show that the proposed approach can predict hydraulic conductivity of both marine and on-land deposit, which extends the range of the application of the existing approaches as proposed by Chai et al.



## 1. Introduction

In foundation design for both land and marine structures, there are two approaches to evaluating the safety of the foundation system. The first is the direct method, in which a correlation between the response of the foundation system and the measured parameters is established, and the second approach is an indirect method in which test results are interpreted to obtain the mechanical properties of the soil (Lunne et al., 2004). The cone penetration test with pore water pressure measurement (the piezocone test) is a useful field investigation method that has been widely employed in both land and marine projects (Lunne et al., 1984). The piezocone test can provide a quantitative measurement of a soil's properties in situ; these include soil stratigraphy, the mechanical properties of the soil, the type of soil, and the distribution of soil saturation. (Douglas and Olsen, 1981; Campanella and Robertson, 1988; Robertson, 1990; Mitchell and Brandon, 1998; Lu et al., 2004; Cetin and Ozan, 2009; Shen et al., 2010; Wang et al., 2013). Thus, engineering judgment combined with the experiences of engineers based on using measured soil parameters is the key to safe and economic design for geotechnical systems (Lunne et al., 2004). In the evaluation of the bearing capacity of piles, the cone penetration resistance index can be directly correlated to the bearing capacity. However, other properties (such as type of soil, shear strength, and hydraulic conductivity) need to be interpreted, and the evaluation method needs to be established based on the test results.

The hydraulic conductivity is one of the important mechanical properties of soil, which influences the long-term consolidation deformation and soil stability (Shen et al., 2003; Zeng et al., 2011; Chai et al., 2014). Many challenges in geotechnical engineering are related to the hydraulic conductivity of soil; these include the design of foundation pit dewatering (Ma et al., 2014), the estimation of foundation settlement, and the analysis of soil consolidation (Shen et al., 2006, 2013; Shen and Xu, 2011; Xu et al., 2008, 2012a, 2012b, 2013a, 2013b; Horpibulsuk., 2011; Huang et al., 2009). The hydraulic conductivity of soil can be indirectly obtained by the dissipation test, which measures the pore pressure dissipation process from which a graph of the pore pressure dissipation with time can be derived, in order to evaluate the coefficient of consolidation of the soil (Gupta and Davidson, 1986; Robertson et al., 1992; Danziger et al., 1997; Burns and Mayne, 1998). The hydraulic conductivity of the soil can then be estimated. However, the dissipation test often takes a long time and needs a pre-determined depth, which can result in discontinuous measurements. Much research has been dedicated to the study of an alternative direct and rapid method to determine the hydraulic conductivity of soil in place of the dissipation test.

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In recent decades, many attempts have been made to directly estimate the hydraulic conductivity of soil using the piezocone test which does not require a pre-determined depth (Randolph and Wroth, 1979; Clarke et al., 1979; Robertson et al., 1992; Lunne et al., 1997; Sully et al., 1999). However, most of the existing approaches are empirical and lack a theoretical basis, which can cause large errors in various areas. Moreover, many approaches have no explicit equations. Because of the deficiencies of the existing approaches, Elsworth and Lee (2005; 2007) proposed a semi-rigorous approach and an explicit equation based on dislocation analysis, Darcy's law and a spherical flow assumption. However, Elsworth and Lee's approach is only applicable to partially drained conditions and is specifically not for undrained clay deposits. Based on Elsworth and Lee's approach, Chai et al. (2011) presented a modified approach to estimate the hydraulic conductivity of soil based on a half spherical flow assumption, which can be used in normally or lightly overconsolidated clayey deposits and loose sandy deposits. Chai's approach extended the application range of Elsworth and Lee's approach for sandy soil to almost all soil types. However, the theoretical assumptions of Chai's approach, like Elsworth and Lee's approach, are proposed for a piezocone with a tip angle of 90. The hydraulic conductivity of soil is greatly affected by pore water pressure. Elsworth (1991; 1998) discussed dissipative pore water pressure around the cone considering sharp and blunt tip angles of penetrometers respectively. The results indicated that the tip angles of the penetrometers influence the pore water pressure. Therefore, the effect of tip angles on the hydraulic conductivity of soil should be considered and it is unreasonable to directly apply the aforementioned two approaches to a piezocone with a standard tip angle of 60 which is specified in the international test procedure (ISSMFE, 1989).

The objective of this study is to present a new approach to estimating the hydraulic conductivity of soil from a piezocone test with different cone tip angles. A laboratory tests were performed first to observe soil deformation beneath a cone tip with different angles. To verify the effectiveness of the proposed new approach, three case studies were presented.

## 2. Test for soil deformation around tip during penetration

### 2.1. Equipment and soil materials

Laboratory tests were carried out to simulate the cone penetration test and to investigate soil deformation beneath cone tips with different angles. Fig. 1 shows the device used for the model test. The test box is made of transparent PVC and has internal dimensions of length, 0.4 m, width, 0.4 m and height, 0.51 m. A grid with 5 mm squares is drawn on the surface of the test box. The model cones used in these experiments were 35.7 mm in diameter and made of steel, which were adapted to have four tip angles of 30°, 60°, 90° and 120°. A static penetrometer is fixed on a prefabricated support to simulate the penetration system. The measurement system included a fast shutter camera and an automatic data acquisition instrument.

Two types of air-dried sand are used in the model test: white sand and yellow sand. The physical properties of these two sands are listed in Table 1.

### 2.2. Test method

Prior to these experiments, two types of sand were poured through a 100 mm diameter funnel with a 20 mm diameter nozzle. The nozzle was lifted away from the surface of the sand by an amount sufficient to allow the sand to flow freely, and then was moved along the length. The white and yellow sands were prepared by layering them alternately in the test box. Each layer was 5 mm deep, which is equivalent to the size of one grid square on the surface of the test box, as shown in Fig. 1. When the depth of sand reached 440 mm, the soil sample for the test was complete and the model cone with a tip angle of 30 was placed on the sand surface. The model cone was then pushed into the sand at 2.5 mm/s by the penetration system until the tip of the cone reached a depth of 60 mm. At the same time photographs were taken at intervals of 1 second. Subsequently, the test box was emptied and the soil sample was prepared again. The test was repeated using other model cones with tip angles of 60°, 90° and 120°, respectively.

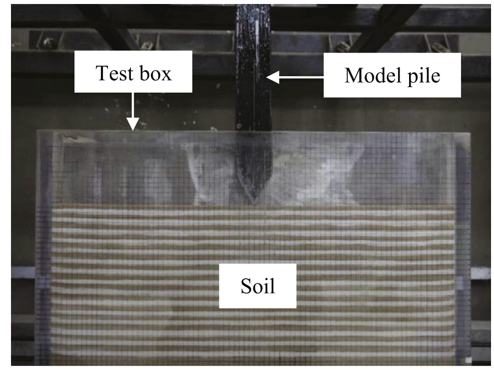


**Fig. 1.** Photo of laboratory model test equipment.

### 2.3. Test results and discussion

Fig. 2 shows expansion deformation of the sand soil below the different tip angles. The deformation of sand around the tips was close to a half ellipsoid rather than sphere. For tip angles of 30°, 60°, and 90°, the phenomenon of half ellipsoid deformation is clearly observed (see Fig. 2). For a tip angle of 120°, the half ellipsoid deformation of sand trends to sphere because its angle is very blunt, which leads to not only shear stress but also compressive stress in the soil. The result is in accordance with tests on pile end-bearing capacity carried out in sand by Yasufuku and Hyde (1995), in which they observed the spherical expansion of sand beneath a flat-ended cone bottom. Based on the theory of soil mechanics, it is obvious that the soil below the cone tip in this test not only suffered compressive stress but also shearing force during the penetration, which causes half ellipsoid deformation of soil.

Some previous studies has reported the excess pore pressure distribution and soil deformation during cone penetration in sand and clayey soil measured in field test (Tang et al., 2004; Cai and Tan, 2014 ). The results indicated that the pore water pressure distribution and soil deformation behaviors in the clay due to cone penetration is similar to that in the sand. Both sand and clayey soil follow the assumption of half ellipsoid.

## 3. Modification approach for calculating *k*

### 3.1. Review of Chai's approach

In order to evaluate the hydraulic conductivity of soil from a piezocone test directly, Chai et al. (2011) presented a half spherical flow approach based on Elsworth and Lee's approach (2005), as shown in Fig. 3. In this approach, the following hypotheses were assumed: *i*) during the piezocone test, a half spherical flow of pore water covers the tip of the cone because pore water cannot flow into the cone; *ii*) Excess pore water pressure in the soil around the cone has a power function distribution for radial distance, and there is no excess pore water pressure at an infinite distance from the cone; *iii*) The rate of half spherical flow of pore water through the periphery of the cavity is linearly proportional to the rate of volume penetration of the cone.