Study of Dynamic Response of the Sandy Soil by Cone Penetration Testing

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Abstract

The surface pressure distribution of the probe is introduced and analyzed during Cone Penetration Testing. It seems that the effect of the probe moving through the soil does not cause large pressures that could create a great deal of disturbance to the soil adjacent to the probe. The location and magnitude of the volume strain in soil during disturbance are also mentioned. By analysis, we get the conclusion that strains are localized at the tip of the probe and do not extend very far past the surface of the probe. We also investigate the velocity of the probe, soil density and viscosity which influence the velocity soil grain and volume strain of the soil greatly. All the parameters studied above are important factors to the generation of soil liquefaction. The results are helpful for soil bearing capacity assessment and the effectiveness evaluation for foundation reinforcement.

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1. Introduction

Soil liquefaction is the term used to describe the transformation of granular soils in a solid state to a liquefied state due to the effect of increased pore-water pressure and it often happens in sandy soil. Sandy soil is a kind of non-cohesive soil and when a reduction in the soils effective stress which caused by large amplitude vibrations happens, there will be an increase in pore pressure. Since water is incompressible, the pressure of the water trapped in the pore spaces of the soil skeleton increases. This increase in pore pressure causes the soil particles to “float” rather than remain rigidly fixed in the skeleton. It is at this
point that liquefaction occurs and the bearing strength of the soil is greatly reduced. It is this presence of
low permeability materials in the soil matrix that reduces the rate of pore-pressure dissipation to a point
where pore-pressures are able to build-up in magnitude and potentially cause liquefaction[3]. Dynamic
penetration and static cone penetration testing methods are often used in situ detection for soil physical
and mechanical properties. The dynamic penetration is a way by detecting probe penetration of a
certain quality of mandrel hammer which falls free from a certain height, then the depths of
penetration should be recorded many times and thus to determine the soil nature. In process of roadbed,
the dynamic compaction is used to exam the subgrade bearing capacity and gets good results[4]. It
is suitable for soft soil, clay, silt and sandy soil, the basic principle is to probe into the soil by
uniform pressure, and through the force sensor to measure the penetration resistance which reflects the
physical and mechanical properties of the soil and other data for the evaluation of foundation
soil properties and design purposes[5]. At the tip of the CPT cone, researchers are able to monitor and
record the build-up and subsequent dissipation rates of the in-situ pore-pressures created during the
advance of the CPT cone in the subsurface[6]. The generation of the pore-pressure is a function of the
stresses and thus strains applied to the soil; and the rate of pore-pressure dissipation is directly
proportional to the permeability of the soil[7-12].

2. Experimental apparatus

The Geotechnical CPT probes are equipped with individual sensors for point resistance, sleeve friction,
pore pressure and a tilt sensor. The data measured by the sensors is digitised, multiplexed and encrypted
with an error detecting code in the probe before it is forwarded to the transmitter or cable adapter for
transmission to the surface. To back-up the data transmission, the cones can also be delivered with a back-
up memory of 8 hours capacity, with 18 bits resolution on all channels. The readings from the three
channels are corrected for temperature drift by a temperature sensor and a processor in the electronic part
of the probe.

Fig.1  CPT Geo-Tech Classic cable system(left) and CPT probe used in this classic systems(right)

The potential for liquefaction to occur is a function of a couple of variables all of which can be related
to the permeability of the soil. The relationship between excess pore-pressure and strain has been
developed by Seed and Booker[7] and can be expressed as follows

\[ \frac{k_n u}{x} \left( \frac{k_n u}{y} \right) + t = 0 \]  \hspace{1cm} (1)

where, \( k_n \) is permeability(m²), \( w \) is pore water density(kg/m³), \( u \) is strain, \( u \) is excess pore water
pressure(Pa), \( t \) is time. The Navier-Stokes equation for incompressible flow was used and is as follows

\[ \frac{u}{t} + \left( u + (u)^T \right) + (u - u) + P = F \]  \hspace{1cm} (2)
with continuity satisfied for,
\[ \nabla \cdot \mathbf{u} = 0 \] (3)
where \( \mathbf{u} \) is the velocity field \((\text{m/s})\), \( \eta \) is viscosity \((\text{kN/m}^2)\), \( \rho \) is fluid density \((\text{kN/m}^3)\), \( p \) is pressure (MPa), and \( \mathbf{F} \) is the body force \((\text{kN})\).

3. CPT probe dynamic response in sandy soil

To define the system, the soil was chosen to be the fluid object and the probe was held in place. This is an effective way to represent the soil moving past the probe without the need to make the probe move in the model. Fig. 1 shows an illustration of how the model was defined. Choose 31m×25m sandy soil as the object in our study and according to symmetry, part of system is chosen (Fig. 1). The data that we get from the experiment is as follows.

| Parameters     | Value |
|----------------|-------|
| Probe Velocity | 0.02  |
| Soil density   | 20    |
| Soil viscosity | 282   |
| Pore pressure  | 88.3  |
| Inflow pressure| 17,768.3 |
| Horizontal depth| 6    |
| Probe depth    | 15.01 |

From the data, we design a numerical model to validate our hypothesis. The values were chosen to represent a depth of 15.01 meters below ground-surface. The matrix of the soil at this depth is mostly sandy soil and the water-table is at approximately 6 meters. The density and viscosity are 20 kN/m³ and 282 kN/m², with the viscosity values assumed as the total stress present at the given depth prior to advancing the probe. They are based on the assumption that the force required to push the probe through the soil is equivalent to the total stress at the given depth. Fig.2 shows the initial conditions that were applied to the model. Mei-Feng Cai et al. studied the problem and combined the slope displacement trends with destruction fields to determine the slope stability, the method improved reliability of the numerical analysis. CPT tests can also be used for the study of soil particle velocity and soil bearing capacity. During the probe moving through the soil, the soil particles nearby may transport in different directions and rates.

![Fig.2 Parameter values used in boundary and sub-domain settings](image)

The inflow pressure (17,680 kPa) listed at the bottom of the model represents the end bearing force (\( q_t \)) that was recorded by the CPT load cell while advancing the probe at the given depth at 2 cm/s. The actual end bearing force recorded was 17,768.3 kPa, but for simplicity the static pore-pressure (88.3 kPa) was
subtracted. This eliminated the need to define the effect of the pore-pressure at the top of the system, which would have a downward vector and negate the presence of 88.3 kPa of the end bearing force. An initial velocity condition of 0.02 m/s was applied to the soil, to represent the 2 cm/s advancement of the probe, and was maintained by prescribing an inflow/outflow velocity of 0.02 m/s at the top and bottom boundaries.

![Fig.3 Pressure and velocity profile of the CPT probe during steady-state advancement.](image)

Analysis of the pressure field distribution shows the expected result of having excess pressure generated at the tip of the CPT probe. The excess pressure is then quickly reduced as distance from the probe is increased. This illustrates favorable results in two ways: one is that we see the pressure generated at the probe tip can be defined as being caused by the probe moving through the soil. And the other is that the effect of the probe moving through the soil does not cause large pressures that could create a great deal of disturbance to the soil adjacent to the probe. This supports the assumption that data collected by monitoring instruments in the CPT probe can be considered uncorrupted and trustable. The results are presented as a pressure field in Fig.3a. Assuming the soil particles are incompressible, and the conservation equations meet the Navier-Stokes type, we got the soil particles state at 10 seconds near CPT probe as shown in Fig.3b. The results of Fig.3c and Fig.3d show that the effect of increasing the density and viscosity of the soil greatly increases the disturbance of the soil as it passes by the probe. This is justified in that fluids with a higher viscosity will have more resistance to movement.

4. Conclusion

From the data we get from the experiment, we design a numerical model to validate our hypothesis. The emphases are pressure and velocity which influence vibration and stability of the foundation. So, the pressure and velocity profile of the CPT probe during steady-state advancement are studied. The results and conclusion are as follows.

1) Excess pressure generates at the tip of the CPT probe during it moving through the soil and it does not cause large pressure which creates a great deal of disturbance to the soil adjacent to the probe.
2) Strain localized at the tip of the probe is obvious but it does not extend very far past the surface of the probe. This result is meaningful for the study of ground or soil seam deformation and foundation reinforcement, even for the explanation of soil vibration and liquefaction.

3) Increasing the density and viscosity of the soil will greatly increase the disturbance of the soil as it passes by the probe and when probe’s velocity increase, the observed response was pressure increase at the tip of the probe, but the two may not be exactly proportional.

4) For the limitation of the governing equation, the model and simulation are not perfect. Future analysis will likely include the coupling of this model to that of a one which is able to define the characteristics of the soil including compressibility and permeability.

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