Electric friction cone penetrometer testing

The **cone penetration** or **cone penetrometer test** (**CPT**) is a method used to determine the geotechnical engineering properties of soils and delineating soil stratigraphy. It was initially developed in the 1950s at the Dutch Laboratory for Soil Mechanics in Delft to investigate soft soils. Based on this history it has also been called the "Dutch cone test". Today, the CPT is one of the most used and accepted soil methods for soil investigation worldwide.

The early applications of CPT mainly determined the logistics of soil geotechnical property of bearing capacity. The original cone penetrometers involved simple mechanical measurements of the total penetration resistance to pushing a tool with a conical tip into the soil. Different methods were employed to separate the total measured resistance into components generated by the conical tip (the "tip friction") and friction generated by the rod string. A friction sleeve was added to quantify this component of the friction and aid in determining soil cohesive strength in the 1960s.[1] Electronic measurements began in 1948 and improved further in the early 1970s.[2] Most modern electronic CPT cones now also employ a pressure transducer with a filter to gather pore water pressure data. The filter is usually located either on the cone tip (the so-called U1 position), immediately behind the cone tip (the most common U2 position) or behind the friction sleeve (U3 position). Pore water pressure data aids determining stratigraphy and is primarily used to correct tip friction values for those effects. CPT testing which also gathers this piezometer data is called CPTU testing. CPT and CPTU testing equipment generally advances the cone using hydraulic rams mounted on either a heavily ballasted vehicle or using screwed-in anchors as a counter-force. One advantage of CPT over the Standard Penetration Test (SPT) is a more continuous profile of soil parameters, with data recorded at intervals typically of 20 cm but as small as 1 cm.

Additional in situ testing parameters

In addition to the mechanical and electronic cones, a variety of other CPT-deployed tools have been developed over the years to provide additional subsurface information. One common tool advanced during CPT testing is a geophone set to gather seismic shear waveand compression wave velocities. This data helps determine the shear modulus and Poisson's ratio at intervals through the soil column for soil liquefaction analysis and low-strain soil strength analysis.

Soil liquefaction

Soil liquefaction occurs when a cohesionless saturated or partially saturated soil substantially loses strength and stiffness in response to an applied stress such as shaking during an earthquake or other sudden change in stress condition, in which material that is ordinarily a solid behaves like a liquid. In soil mechanics, the term "liquefied" was first used by Allen Hazen[1] in reference to the 1918 failure of the Calaveras Dam in California. He described the mechanism of flow liquefaction of the embankment dam as:

If the pressure of the water in the pores is great enough to carry all the load, it will have the effect of holding the particles apart and of producing a condition that is practically equivalent to that of quicksand... the initial movement of some part of the material might result in accumulating pressure, first on one point, and then on another, successively, as the early points of concentration were liquefied.

The phenomenon is most often observed in saturated, loose (low density or uncompacted), sandy soils. This is because a loose sand has a tendency to compress when a load is applied. Dense sands, by contrast, tend to expand in volume or 'dilate'. If the soil is saturated by water, a condition that often exists when the soil is below the water table or sea level, then water fills the gaps between soil grains ('pore spaces'). In response to soil compressing, the pore water pressure increases and the water attempts to flow out from the soil to zones of low pressure (usually upward towards the ground surface). However, if the loading is rapidly applied and large enough, or is repeated many times (e.g., earthquake shaking, storm wave loading) such that the water does not flow out before the next cycle of load is applied, the water pressures may build to the extent that it exceeds the force (contact stresses) between the grains of soil that keep them in contact. These contacts between grains are the means by which the weight from buildings and overlying soil layers is transferred from the ground surface to layers of soil or rock at greater depths. This loss of soil structure causes it to lose its strength (the ability to transfer shear stress), and it may be observed to flow like a liquid (hence 'liquefaction').

Although the effects of soil liquefaction have been long understood, engineers took more notice after the 1964 Alaska earthquake and 1964 Niigata earthquake. It was a major cause of the destruction produced in San Francisco's Marina District during the 1989 Loma Prieta earthquake, and in the Port of Kobe during the 1995 Great Hanshin earthquake. More recently soil liquefaction was largely responsible for extensive damage to residential properties in the eastern suburbs and satellite townships of Christchurch during the 2010 Canterbury earthquake[2] and more extensively again following the Christchurch earthquakes that followed in early and mid-2011.[3] On 28 September 2018, an earthquake of 7.5 magnitude hit the Central Sulawesi province of Indonesia. Resulting soil liquefaction buried the suburb of Balaroa and Petobo village 3 metres (9.8 ft) deep in mud. The government of Indonesia is considering designating the two neighborhoods of Balaroa and Petobo, that have been totally buried under mud, as mass graves.[4][*needs update*]

The building codes in many countries require engineers to consider the effects of soil liquefaction in the design of new buildings and infrastructure such as bridges, embankment dams and retaining structures.[5][6][7]

Liquefaction is more likely to occur in loose to moderately saturated granular soils with poor drainage, such as silty sands or sands and gravels containing impermeable sediments.[9][10] During wave loading, usually cyclic undrained loading, e.g. seismic loading, loose sands tend to decrease in volume, which produces an increase in their pore water pressures and consequently a decrease in shear strength, i.e. reduction in effective stress.

Deposits most susceptible to liquefaction are young (Holocene-age, deposited within the last 10,000 years) sands and silts of similar grain size (well-sorted), in beds at least metres thick, and saturated with water. Such deposits are often found along stream beds, beaches, dunes, and areas where windblown silt (loess) and sand have accumulated. Examples of soil liquefaction include quicksand, quick clay, turbidity currents and earthquake-induced liquefaction.

Depending on the initial void ratio, the soil material can respond to loading either strain-softening or strain-hardening. Strain-softened soils, e.g., loose sands, can be triggered to collapse, either monotonically or cyclically, if the static shear stress is greater than the ultimate or steady-state shear strength of the soil. In this case *flow liquefaction* occurs, where the soil deforms at a low constant residual shear stress. If the soil strain-hardens, e.g., moderately dense to dense sand, flow liquefaction will generally not occur. However, cyclic softening can occur due to cyclic undrained loading, e.g., earthquake loading. Deformation during cyclic loading depends on the density of the soil, the magnitude and duration of the cyclic loading, and amount of shear stress reversal. If stress reversal occurs, the effective shear stress could reach zero, allowing cyclic liquefaction to take place. If stress reversal does not occur, zero effective stress cannot occur, and cyclic mobility takes place.[11]

The resistance of the cohesionless soil to liquefaction will depend on the density of the soil, confining stresses, soil structure (fabric, age and cementation), the magnitude and duration of the cyclic loading, and the extent to which shear stress reversal occurs.[

Effects

The effects of soil liquefaction on the built environment can be extremely damaging. Buildings whose foundations bear directly on sand which liquefies will experience a sudden loss of support, which will result in drastic and irregular settlement of the building causing structural damage, including cracking of foundations and damage to the building structure, or leaving the structure unserviceable, even without structural damage. Where a thin crust of non-liquefied soil exists between building foundation and liquefied soil, a 'punching shear' type foundation failure may occur. Irregular settlement may break underground utility lines. The upward pressure applied by the movement of liquefied soil through the crust layer can crack weak foundation slabs and enter buildings through service ducts and may allow water to damage building contents and electrical services.

Bridges and large buildings constructed on pile foundations may lose support from the adjacent soil and buckle or come to rest at a tilt.

Sloping ground and ground next to rivers and lakes may slide on a liquefied soil layer (termed 'lateral spreading'),[22] opening large ground fissures, and can cause significant damage to buildings, bridges, roads and services such as water, natural gas, sewerage, power and telecommunications installed in the affected ground. Buried tanks and manholes may float in the liquefied soil due to buoyancy.[22] Earth embankments such as flood levees and earth dams may lose stability or collapse if the material comprising the embankment or its foundation liquefies.

Over geological time, liquefaction of soil material due to earthquakes could provide a dense parent material in which the fragipan may develop through pedogenesis.[23]