Chapter 2

Thin Layer Correction

2.1 Abstract

The cone penetration test is a valuable index test for assessing subsurface conditions. When dealing with relatively thin soil strata, bias in tip resistance readings can occur as a function of how thin the layer is and the stiffness ratio between the thin layer and the surrounding soil. Determining an accurate value of tip resistance in a thin layer can be important in an engineering situation such as evaluating a critical layer for liquefaction analysis. Both analytical and empirical results are used to reasonably define a correction factor for the measured tip resistance within thin layers.

2.2 Discussion

One of the strong suits of the cone penetration test (CPT) is that it takes a continuous reading of the soil column. However, it has been noted by previous researchers, in both field and laboratory studies, that the CPT measurements can be adversely affected by thin layers. This study reviews analytical and empirical results to determine the capacity of the CPT in thin layers, and to present improved correction factors for interpreting stiff thin layers.

The CPT measurement at a particular point in a highly stratified soil column represents the resistance at the tip with respect to the layers above and below the tip. This is analogous to the cone tip “sensing” ahead and behind the current location in the soil column. Depending on the thickness of the layer at the cone tip, the measured resistance value can be significantly different from the true resistance value of the strata if it were a continuous thick layer. Vreugdenhil et al. (1994) used a simplified elastic solution to analytically quantify the difference between the measured resistance values in the layered media versus a true resistance value for the layer if it were thick.

The concept of an elastic solution appears contrary to the high strain that occurs when a cone punches through the soil. However, the elastic solution does not need to model the tip resistance *per se*, but the effect of a layer of soil at a distance from the cone tip, and the effect that this layer has on the measured resistance. At a distance, the effect of the cone on the soil can be assumed to be in the elastic range.

Two models were presented in the work by Vreugdenhil et al., 1) where a soft thin layer is embedded within a continuous stiff surrounding material, and 2) where a stiff thin layer is embedded within continuous soft surrounding material. The top and bottom layers were treated as infinite half spaces and the effect of variable stiffness ratios between the soft and stiff materials was explored (see Figure 2.1). Stiffness here is defined as the elastic shear modulus (G).

The elastic solution presented by Vreugdenhil et al. (1994) was verified against chamber tests studies of layered soil profiles (Kurup et al., 1994). In this verification the average relative tip resistance (q_c) values for the soil layers were used as a proxy for the elastic stiffness moduli (G). This is a reasonable assumption if the cone is pushed at a

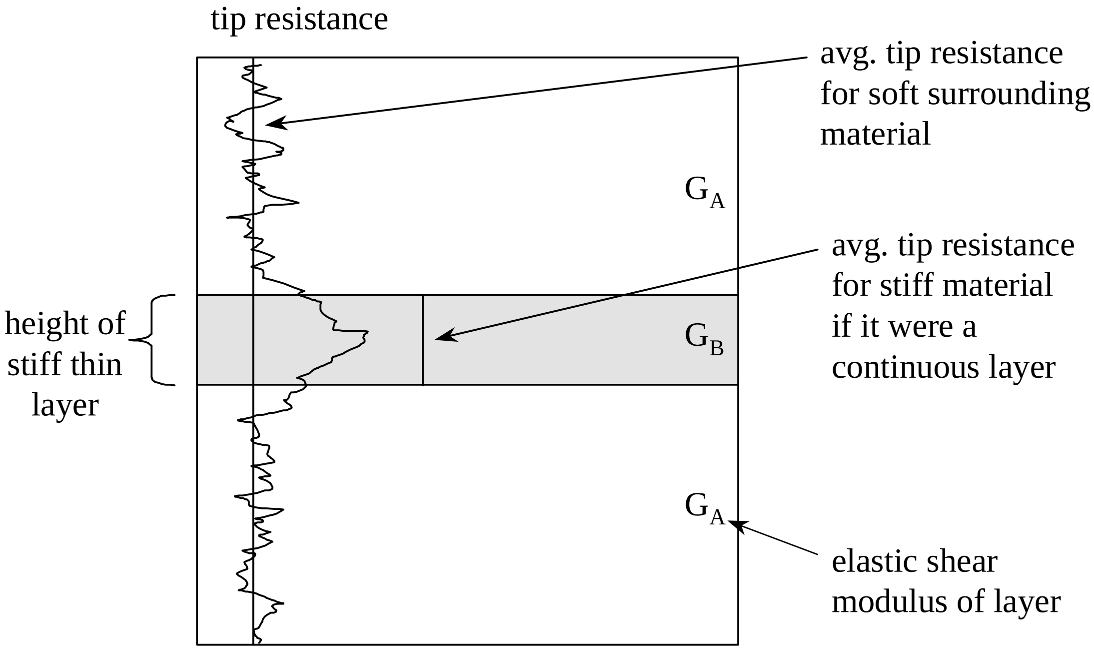


Figure 2.1 Conceptual model of stratigraphic sequence with a stiff thin layer.

continuous rate through the different types of soil (constant strain rate), and the stiffness ratio (G_B/G_A) between two different soil types is not wildly disparate (i.e. the relative response to strain is similar in the two soils).

Analytical results from the first model (embedded soft thin layer) showed that there was little alteration of the measured tip resistance. The soft thin layer appears to isolate the cone from the surrounding stiffer material. The entry and exit zones of altered resistance were on the order of 3 to 5 cone diameters for a 20% change in resistance, where the stiffness ratio between the thin layer and the surrounding material is high.

The results from the second model (embedded stiff thin layer) indicated that the alteration of measured resistance can be high, on the order of 100 to 200 cone diameters for a 20% change in resistance, with a high stiffness ratio. In this instance the stiffness ratio can have a large affect on the measured resistance at a great distance from the cone tip. This can lead to difficulties in determining the true resistance of the thin stiff layer, and in interpreting the depth at which the strata originates and terminates.

Some researchers carried the thin layer analysis further. Robertson & Fear (1995) recommended corrections for a stiff thin layer based on the results from Vruegdunhil et al. (1994). They modified the Vruegdenhil et al. results and suggested a correction curve for a tip resistance ratio of two ($q_{cB}/q_{cA}=2$). NCEER (Youd et al., 1997) suggested a correction range for a tip resistance ratio of two ($q_{cB}/q_{cA}=2$) based on field data from Gonzalo Castro and Peter Robertson.

In this current work the authors returned to the original research by Vrugdenhil et al. was used to generate correction curves for to tip resistance ratios of two, five, and ten (q_{cB}/q_{cA}=2, 5, and 10). Field data was then used to modify the location and range of the tip resistance ratios of concern. The data were from sites with two relatively uniform layers in sequence where the mean tip resistances could be clearly defined at a certain distance away from the layer interface. The resistance ratio between the two layers gives rise to an altered measured tip resistance; it appears as a warping of the tip resistance over a finite distance. This distance corresponds to a thin layer correction of 1.0, in other words no correction is necessary in a thin layer scenario at this resistance ratio with a layer thickness of this value. The correction factors were then determined by decreasing the layer thickness to achieve factors greater than 1.0. The empirical results agreed favorably with the theoretical results with regard to general trends, but the correction factors were found to be smaller at high stiffness ratios. There is high confidence in the resistance ratios of two and five. The data for the resistance ratio of ten is slightly suspect because of the difficulty of interpreting field data with this resistance ratio; it is difficult to discern when the cone is reading an altered resistance due to layer interference and when the cone is the reading an artifact of the geologic depositional environment.

An example of how field data were used for validation follows. Figure 2.2 shows a CPT trace from the Miller Farm Site (Bennett and Tinsley, 1995). The trace records the tip resistance through a transition from sandy silt to medium dense sand over the depth range of 4.0 to 7.5 m. The tip resistance over this transition is affected by the stiffness ratio between the two layers, as seen by a slight warping of the tip reading. The average tip

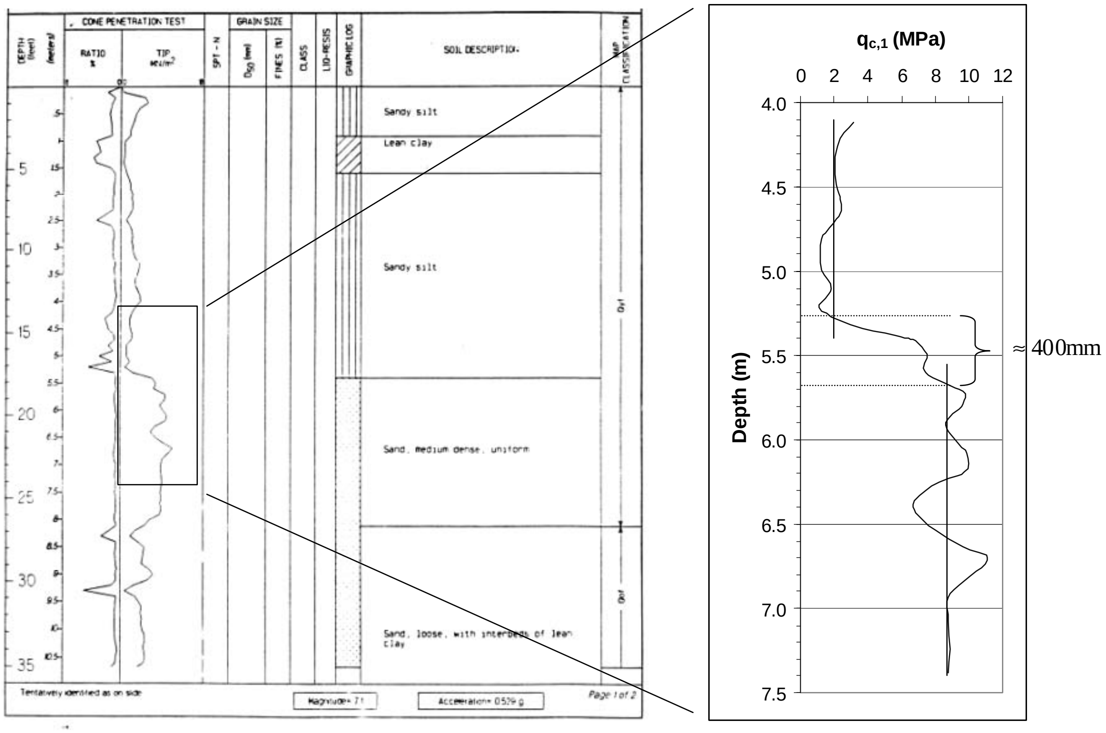


Figure 2.2 Example of the process used to derive thin layer correction factors from empirical data; subsurface log of Miller Farm #49 (Bennett and Tinsley, 1995).

resistance for the two layers is taken over a depth range near the layer transition. These average values are used as reference points for defining the range of the affected zone. Using the average tip resistance as a proxy for material stiffness, the tip resistance ratio between the two layers is determined to be approximately four ($q_{cB}/q_{cA} \approx 4$). The distance over which the transition from average tip resistance in the sandy silt layer to average tip resistance in the medium dense sand layer is approximately 400 mm. This distance represents the linear extent the CPT, at the given tip resistance ratio, requires to achieve full tip resistance. Reducing the total distance by some factor thereby gives a field measurement of the thin layer correction factor. A thin layer, at this tip resistance ratio, measuring 276 mm, would require a correction factor of 1.45. Data from 23 different cases were used to determine the case specific correction factors. These were then collected into "bins" for layer stiffness ratios of q_{cB}/q_{cA}=1.0 to 3.5, 3.6 to 7.5, and 7.6 to 15.0, and these were compared against correction factors corresponding to the theoretical curves backed out of the elastic solution (Figure 2.3).

Based on the elastic solution of Vrugdenhil et al. (1994), the NCEER (1997) recommendations, and field data, new thin layer correction curves are recommended as shown in Figure 2.4. Curves are suggested for tip resistance ratios of two and five, with the recommendations for a ratio of ten as the upper bound. The curves encompass correction factors up to a recommended limit of 1.8. These results are based on a standard cone of diameter 35.7 mm (cone tip area 10 cm^2). These recommendations are for stiff thin layers embedded in softer surrounding material as shown conceptually in

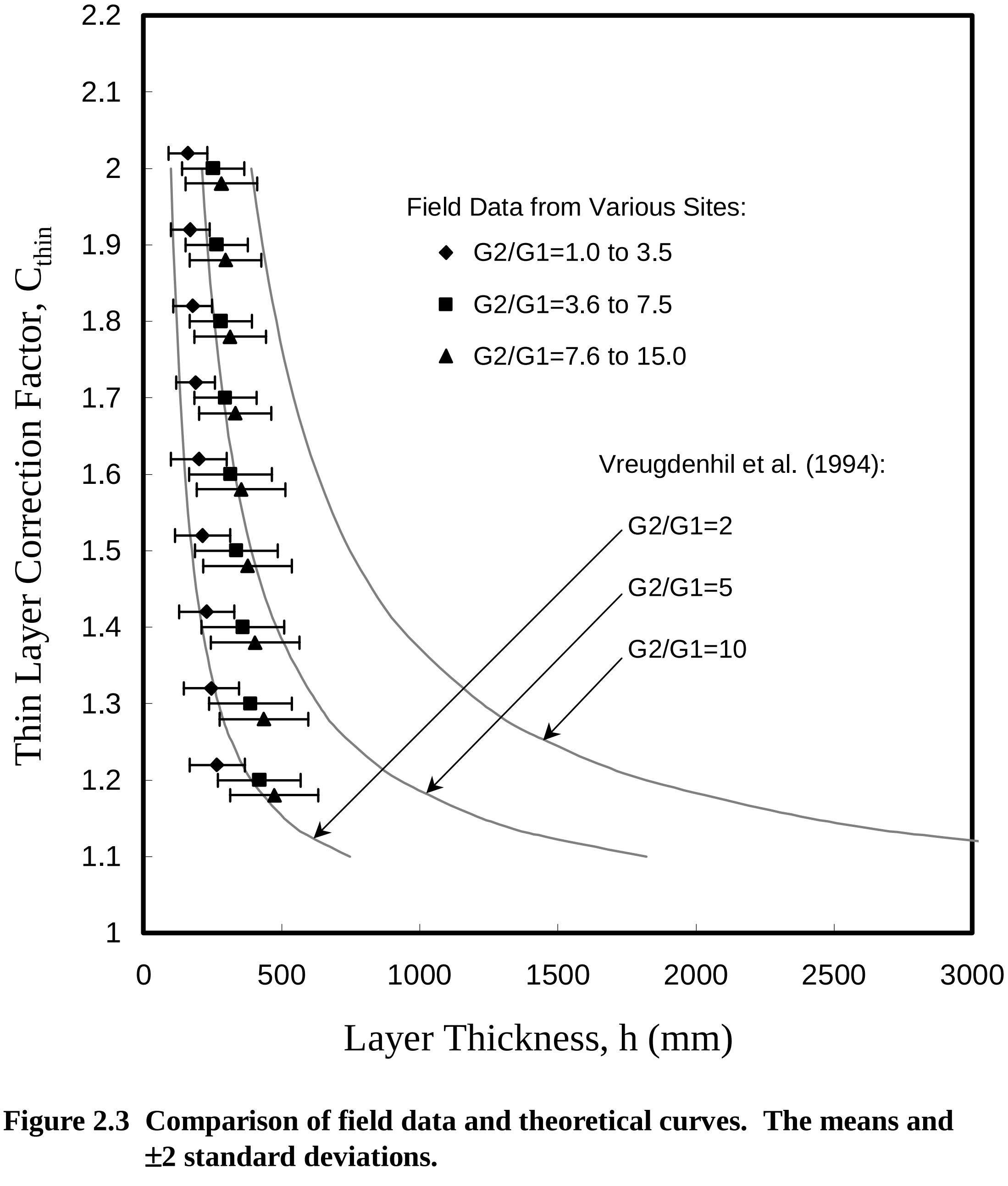


Figure 2.3 Comparison of field data and theoretical curves. The means and ±2 standard deviations.

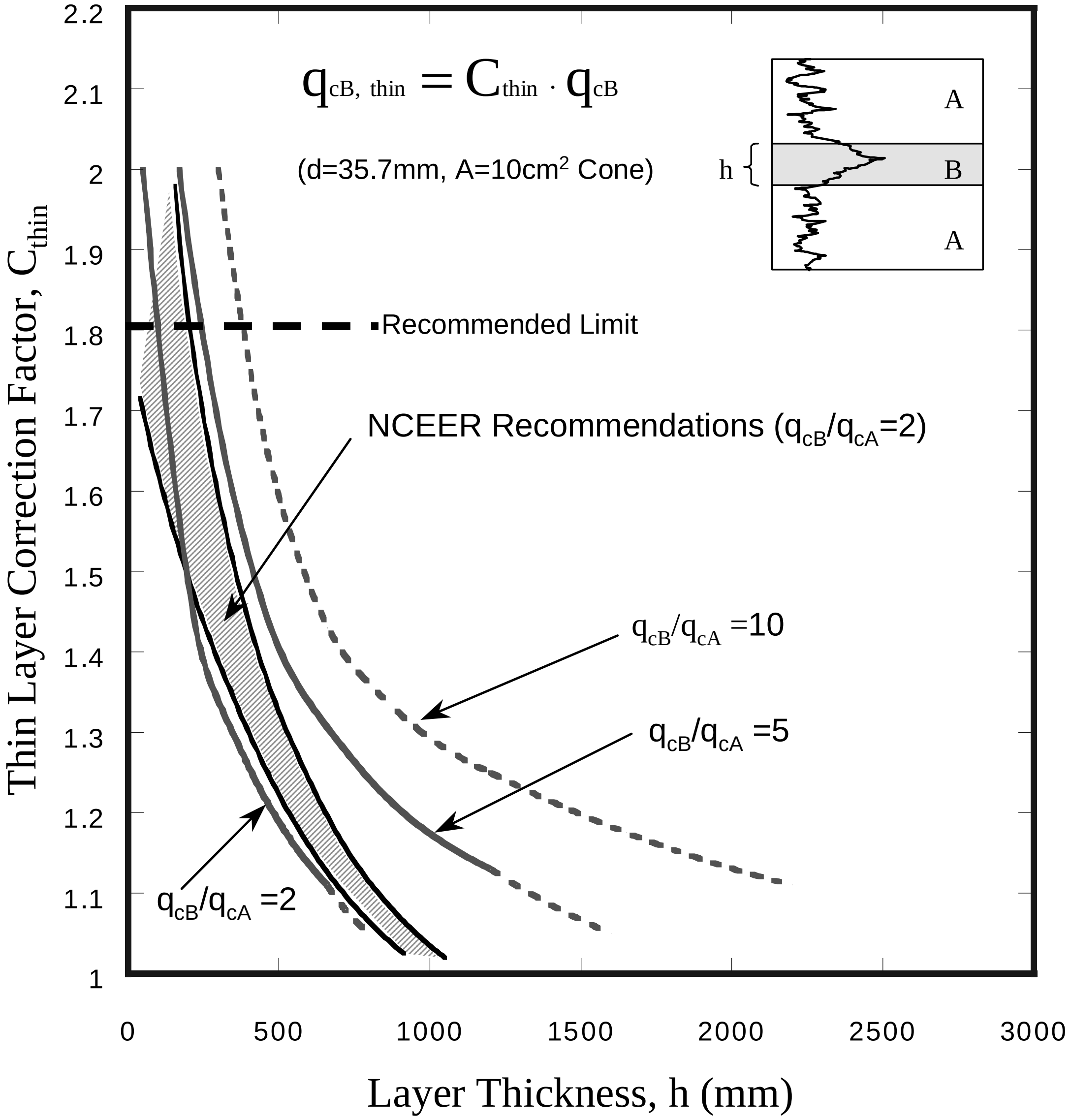


Figure 2.4 Proposed correction curves for a stiff thin layer.

Figure 2.1. The recommendations can also be applied to a stratigraphic sequence where there is a stiff thin layer embedded in softer surrounding material in which the top and bottom soil layers do not necessary have the same stiffness. This situation, as shown conceptually in Figure 2.5, can be spatially averaged or treated as two half-space problems.

Determining the layer thickness of concern can be a difficult step in applying the thin layer correction. The use of sleeve resistance and/or friction ratio is invaluable for interpreting the boundaries between soil layers. Although sleeve measurements tend to be highly variable, a marked change in the trend of the sleeve trace can usually be noted when transitioning between layers of different stiffness and character. The sleeve, in conjunction with the tip resistance, can give a reasonable estimate of a layer boundary. Using SPT bore logs, as well as V_s measurements or other *in situ* tests, is recommended for increasing the accuracy of this layer boundary estimation.

2.3 Example

The use of the thin layer correction curves requires thorough understanding of the problem to which it is being applied and careful exercise of engineering judgment in its application. The thin layer correction is a tool that allows the engineer to roughly quantify the limitations of the CPT when encountering thin stiff strata. An example is provided to demonstrate the use of the thin layer correction.

Example: Shown in Figure 2.6a is a CPT trace from Adapazari (PEER, 2002). Upon inspection of the tip, sleeve, and friction ratio traces, it is apparent that there is a stiff thin layer embedded in softer surrounding material. This example will focus on the stiff thin layer at the depth range of approximately 3.6 to 4.1 meters (see Fig. 6b). Representative average values were calculated for the layers above and below the thin layer. A representative peak value was chosen for the thin layer. The average value for $q_{cA} \approx 1.0$ MPa, the peak for $q_{cB} \approx 3.9$ Mpa, which gives a tip resistance ratio of 3.9 ($q_{cB}/q_{cA}=3.9$). With a layer thickness of 500mm and a resistance ratio of approximately four, a thin layer correction factor of 1.35 is chosen from Figure 2.4. The corrected tip resistance for the thin layer, to a value representative of the tip resistance if it were a continuous thick layer, is then 1.35 (3.9 MPa) =5.3 MPa ($C_{thin} \cdot q_{cB} = q_{cB, thin}$).

2.4 Conclusions

The cone penetration test can give a biased tip resistance reading within a stiff thin layer of soil, where the bias is in relation to the thickness of the stiff thin layer and the stiffness ratio of the thin layer to the surrounding strata. Presented in this study are new thin layer correction curves, based on analytical and empirical results, which aid in the interpretation of the tip resistance in situations where this bias occurs. An example of the application of the thin layer correction has been provided.

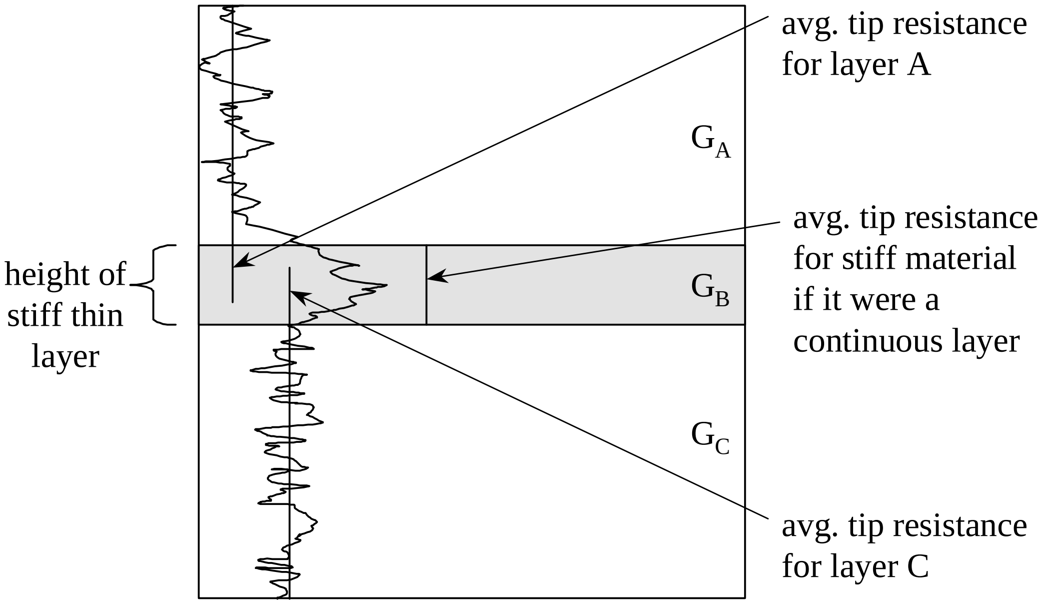
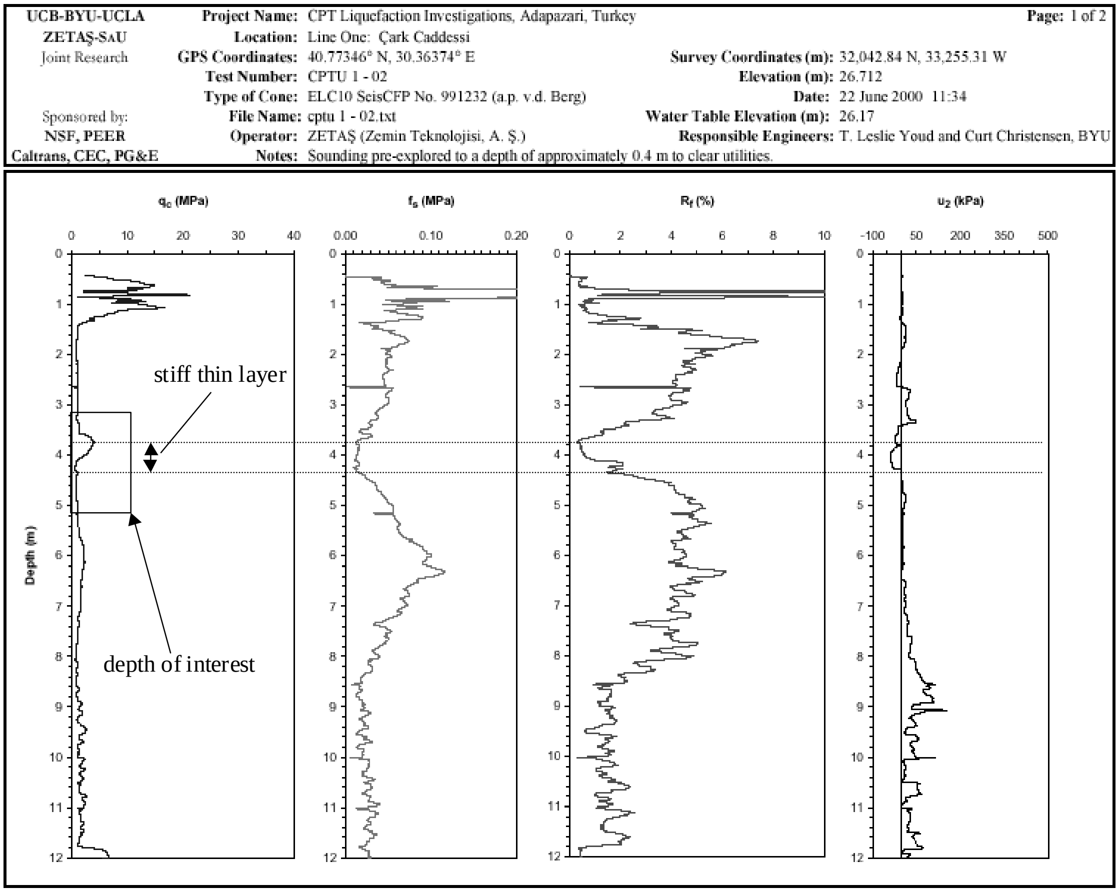


Figure 2.5 Conceptual model where the stiff thin layer is surrounded by softer layers of soil having different stiffnesses.



UCB-BYU-UCLA **Project Name:** CPT Liquefaction Investigations, Adapazari, Turkey **Page:** 1 of 2
ZETAŞ-SAU **Location:** Line One: Çark Caddessi
Joint Research **GPS Coordinates:** 40.77346° N, 30.36374° E **Survey Coordinates (m):** 32,042.84 N, 33,255.31 W
Test Number: CPTU 1 - 02 **Elevation (m):** 26.712
Type of Cone: ELC10 SeisCFP No. 991232 (a.p. v.d. Berg) **Date:** 22 June 2000 11:34
Sponsored by: **File Name:** cptu 1 - 02.txt **Water Table Elevation (m):** 26.17
NSF, PEER **Operator:** ZETAŞ (Zemin Teknolojisi, A. Ş.) **Responsible Engineers:** T. Leslie Youd and Curt Christensen, BYU
Caltrans, CEC, PG&E **Notes:** Sounding pre-explored to a depth of approximately 0.4 m to clear utilities.

Figure 2.6a Example demonstrating the use of the thin layer correction, subsurface log from Adapazari CPTU#1-02 (PEER, 2001).

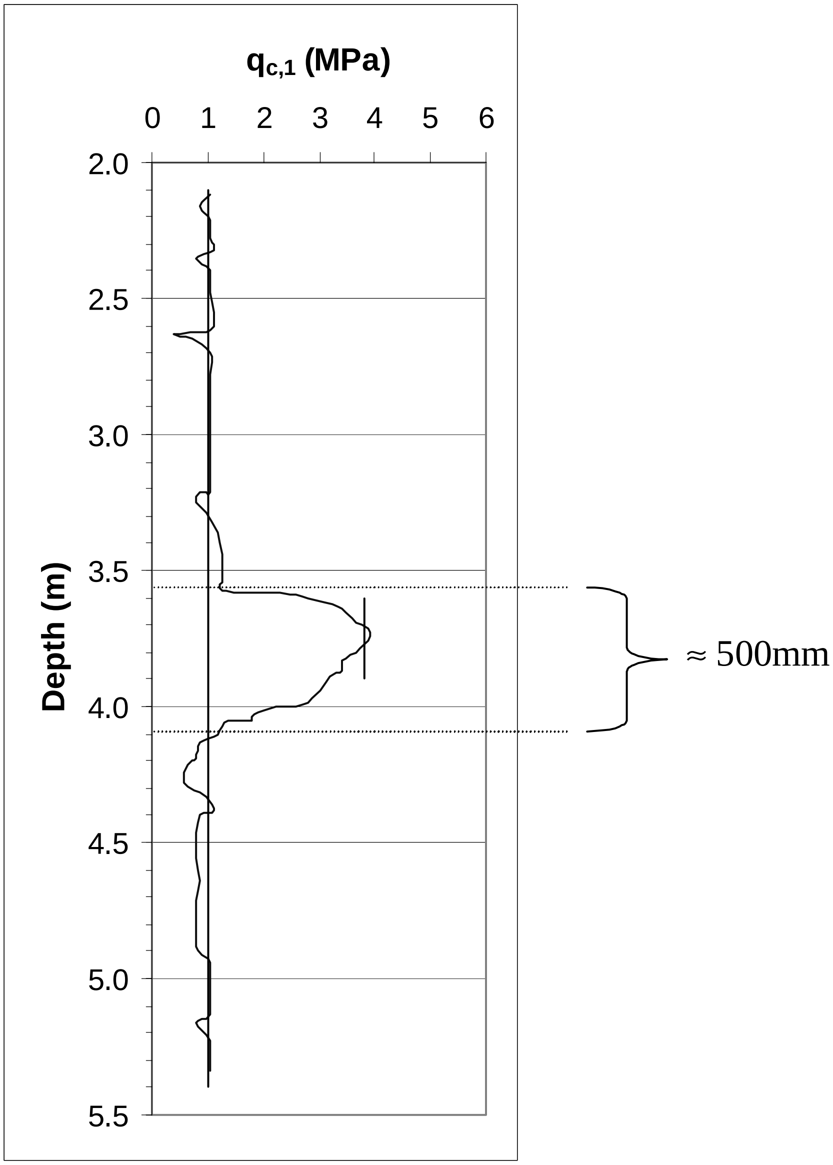


Figure 2.6b Example demonstrating the use of the thin layer correction, subsurface log from Adapazari CPTU#1-02 (PEER, 2001).