Kalman Filtering Technique to Remove "Spurious" Cone Bearing Measurements

Introduction

In Cone penetration testing (CPT) the cone bearing measurements q_m are highly susceptible to anomalous peaks and troughs due to the relatively small diameter cone tip penetrating sandy, silty and gravelly soils. The high peaks are due to interbedded gravels and stones and low peaks are due to softer materials or local pore pressure build-up. Lunne, Robertson and Powell (1997) give a detailed outline of these undesired peaks and troughs and refer to them as anomalous and spurious q_m data. Figure 1 is a schematic of the spurious cone bearing data. Figure 2 illustrates an example of a cone bearing profile which contains significant anomalous\spurious q_m data. To date there has been minimal progress in removing the anomalous q_m data aside from *ad hoc* techniques which include discarding q_m measurements and smoothing/averaging q_m measurements over a specific depth interval.

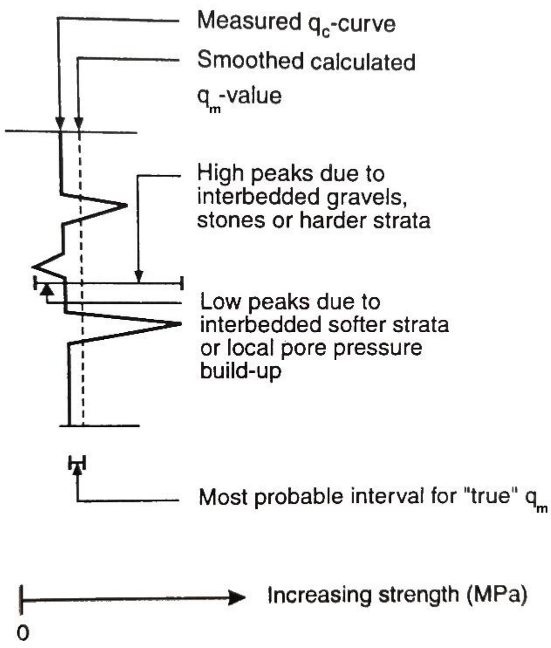


Figure 1. Schematic of anomalous\spurious cone bearing data (after Mortensen and Sorensen, 1991).

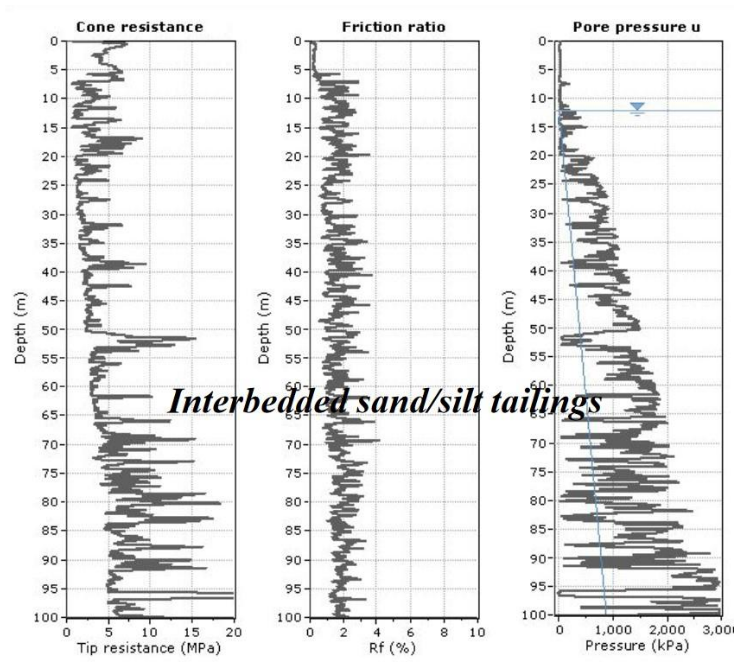


Figure 2. Example of anomalous\spurious cone bearing data (after Robertson, 2015).

The spurious q_m data closely resembles additive Gauss-Markov correlated white measurement noise which is extensively present in engineering measurement sensors such as marine navigation dead reckoning devices. The cone bearing measurement is an averaging operation where layers above and below the cone tip affect the measured tip resistance; therefore, sharp peaks and troughs should not be present[1] and are considered as measurement noise. Sophisticated mathematical tools are available which can minimize or remove the anomalous\spurious cone bearing measurements. BCE has designed a Kalman Filter (KF) algorithm (q_mKF) which optimally obtains estimates of q_m with the spurious data removed or minimized. Below are two test bed examples of the q_mKF algorithm.

TEST BED Simulations

TEST BED 1:

Table 1 and Figure 3 outline and illustrate, respectively, the simulated cone bearing profile where the background q_t values linearly increase from 10 MPa to 12 MPa to a depth of 20m.

Table 1. Simulated q_t values

Depth 1	Depth 2	qt [MPa]
1.0	4.0	5
4.2	4.9	18
5.2	6.0	4
6.2	6.9	19
8.0	8.4	9
10.5	10.7	25
12.2	15.5	5

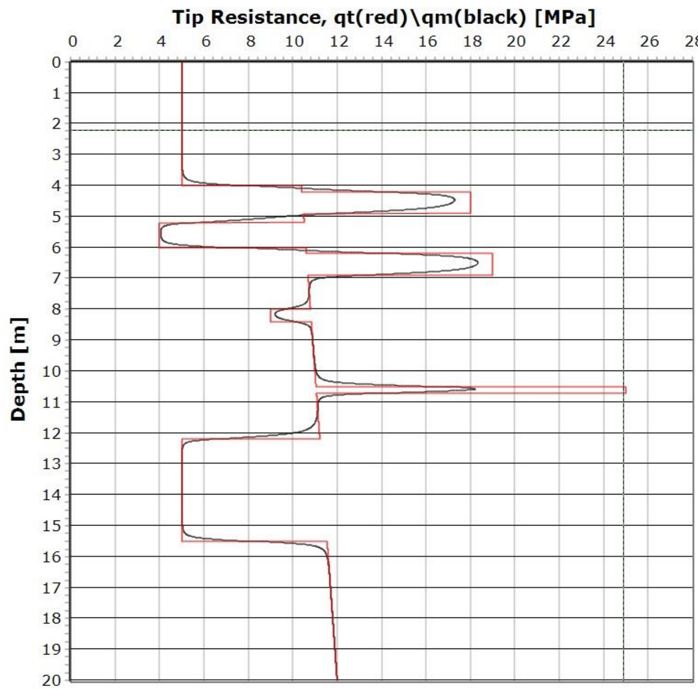


Figure 3. Simulated true cone bearing measurements q_t (red trace) and corresponding averaged/blurred q_m (black trace) measurements.

Figure 4 illustrates the simulated q_m data of Figure 3 (black) with additive noise to represent anomalous\spurious q_m data (orange trace). The light green trace is the q_mKF algorithm estimated q_m profile after processing the spurious q_m data (orange trace). Figure 5 shows the traces illustrated in Fig. 4 but in this case an industry standard four point smoother was applied to the spurious q_m trace (orange trace).

[1] This is true even for the case of extensive thin bed layering

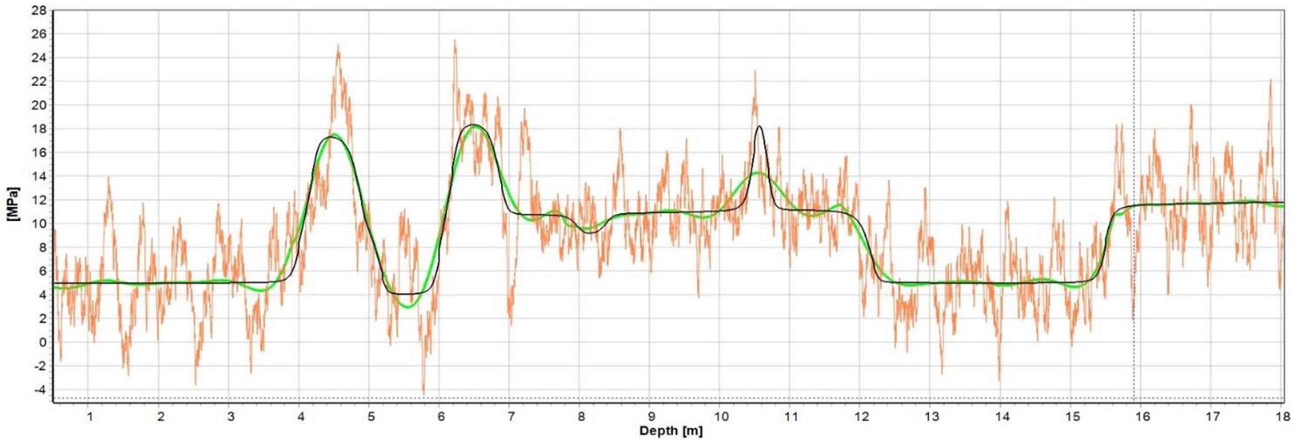


Figure 4. Simulated cone bearing averaged/blurred qm (black trace) of Fig. 3, spurious q_m trace (orange trace) feed into the q_mKF algorithm, and the q_mKF algorithm output (light green trace).

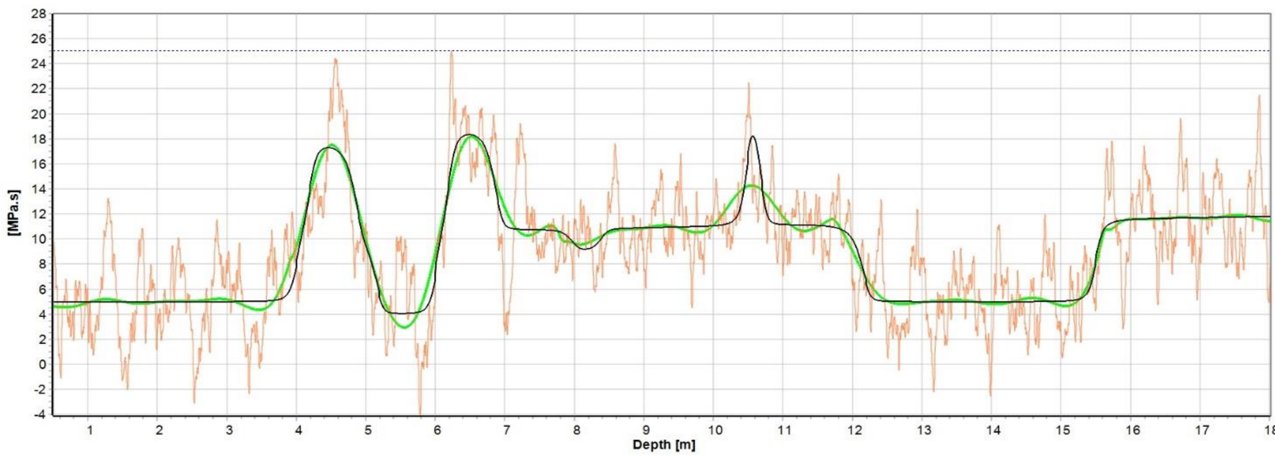


Figure 5. The traces illustrated in Fig. 4 but in this case industry standard four point smoothing\averaging was applied to the spurious q_m trace (orange trace).

TEST BED 2

Figure 6 illustrates a simulation of thin bed layering (0.3m) where there is alternating true q_t values of 45MPa and 75MPa (red trace). As is shown in Fig. 6 there is a resulting oscillation averaged\smooth q_m trace (black trace) with no sharp peaks or troughs. Figure 7 illustrates the simulated q_m data of Fig. 6 (black) with additive noise to represent anomalous\spurious q_m data (orange trace). The light green trace is the q_mKF algorithm estimated q_m profile after processing the spurious q_m data (orange trace). Figure 8 shows the traces illustrated in Fig. 7 but in this case an industry standard four point smoother was applied to the spurious q_m trace (orange trace).

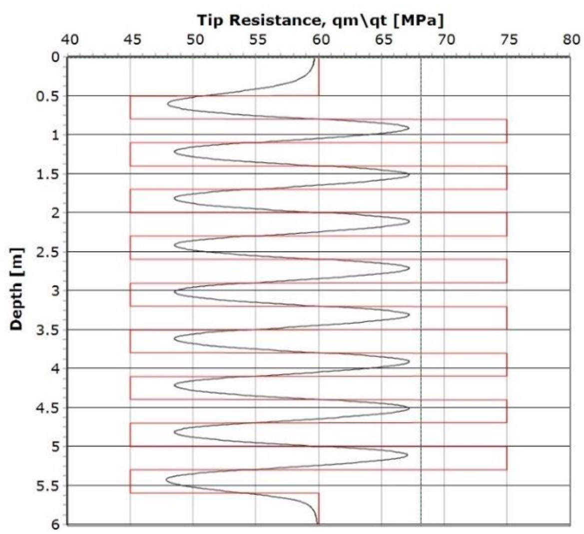


Figure 6. Simulated highly variable and thin bed layering true cone bearing measurements qt (red trace) and corresponding averaged/blurred q_m (black trace) measurements.

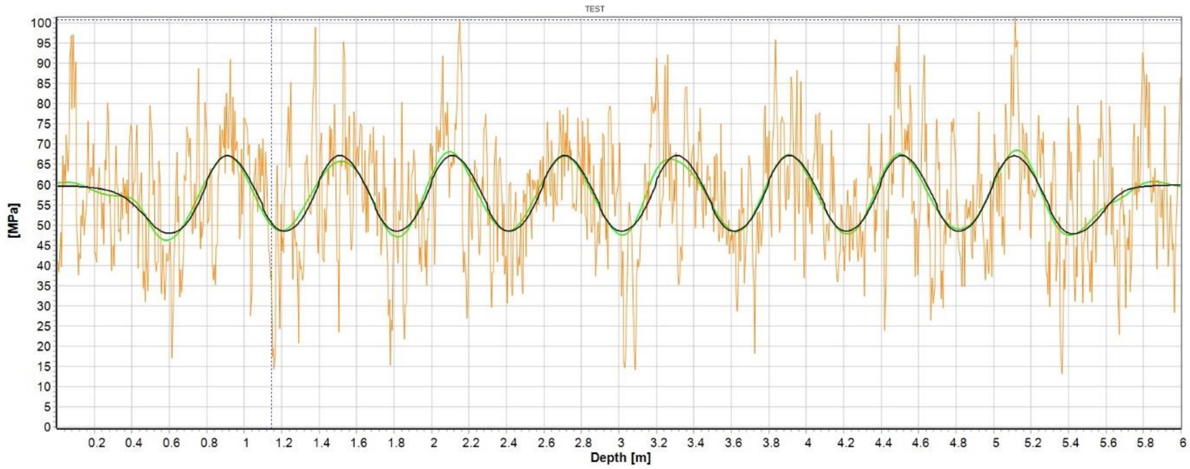


Figure 7. Simulated cone bearing averaged/blurred q_m (black trace) of Fig. 6, spurious q_m trace (orange trace) feed into the q_mKF algorithm, and the q_mKF algorithm output (light green trace).

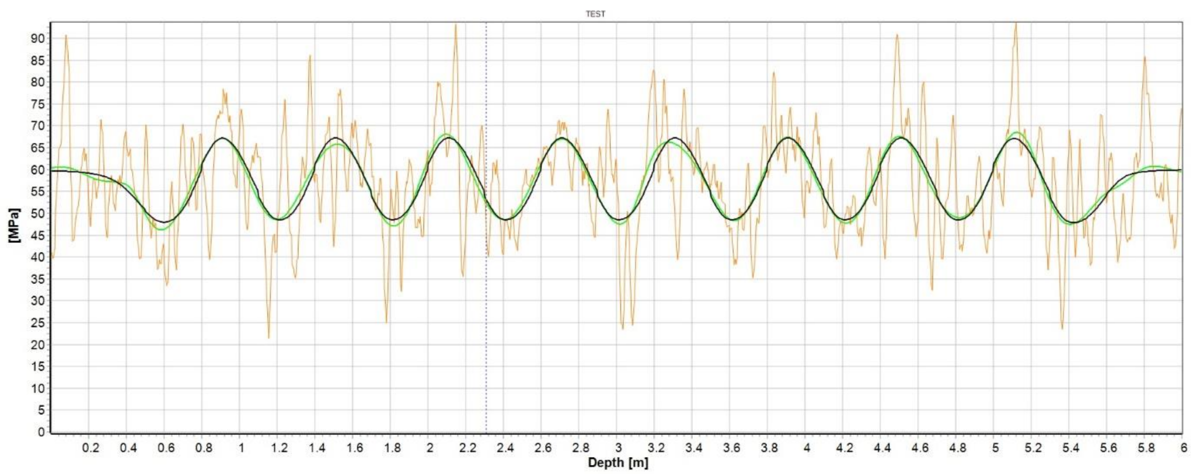


Figure 8. The traces illustrated in Fig. 7 but in this case industry standard four point smoothing\averaging was applied to the spurious q_m trace (orange trace).

Figure 9 (A) illustrates the smoothed q_m (orange) trace of Fig. 8 superimposed upon true q_t (red) trace of Fig. 6. Figure 9(B) illustrates the estimated q_t (orange) trace from the *qtHMM-IFM* algorithm[2] (after processing the light green trace of Figs. 7 and 8) superimposed upon true q_t (red) trace of Fig. 6. As is evident from Fig. 9(B), the combination of the *qmKF* and *qtHMM-IFM* algorithms results in obtaining impressive estimates of true q_t values from challenging q_m data sets.

[2] Outlined in Technical Note 30

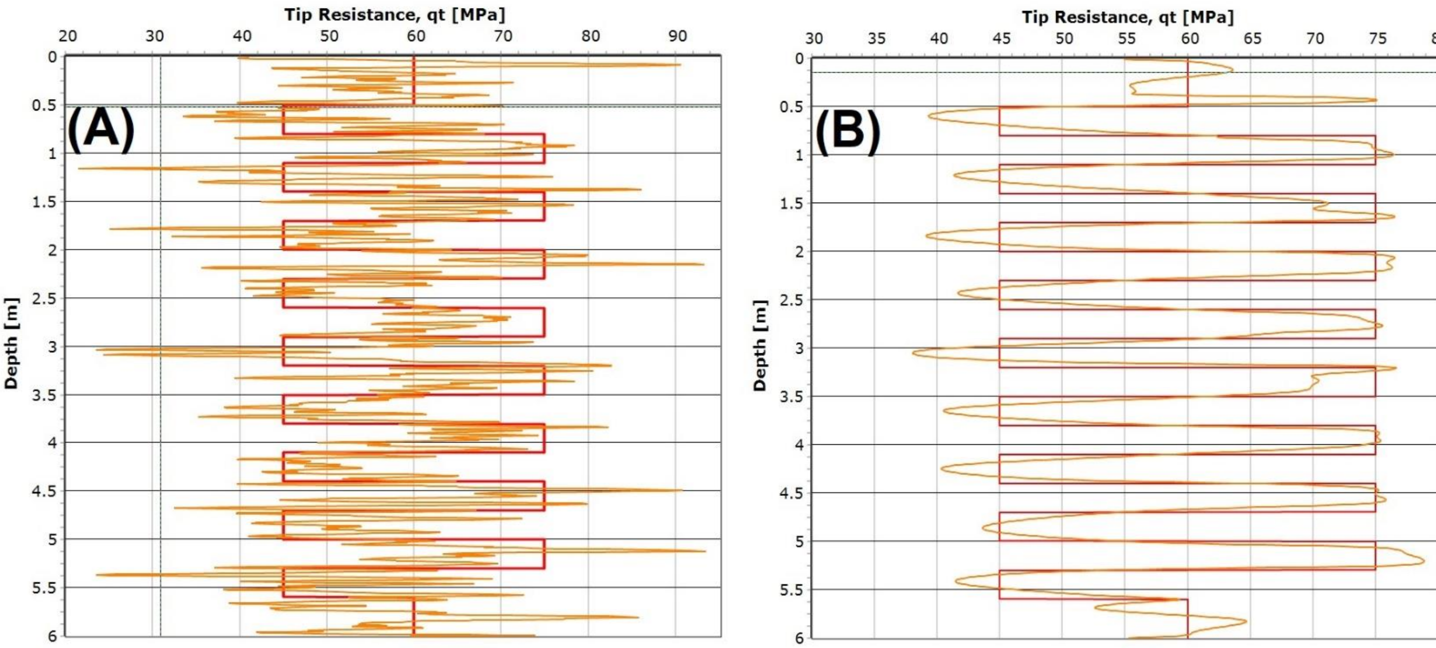
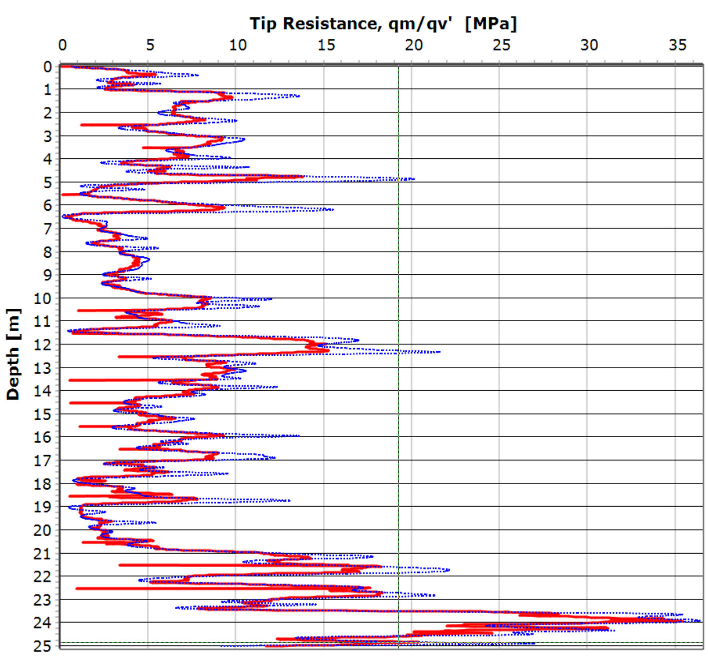
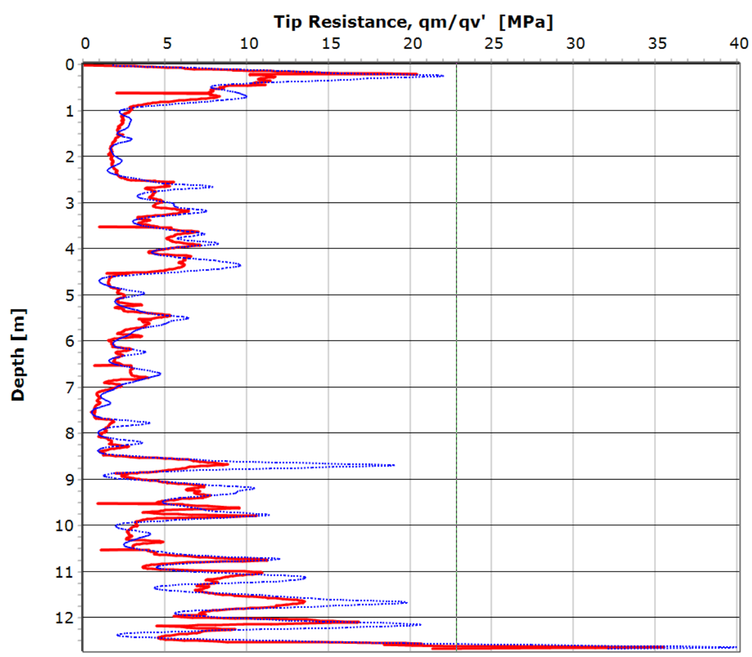


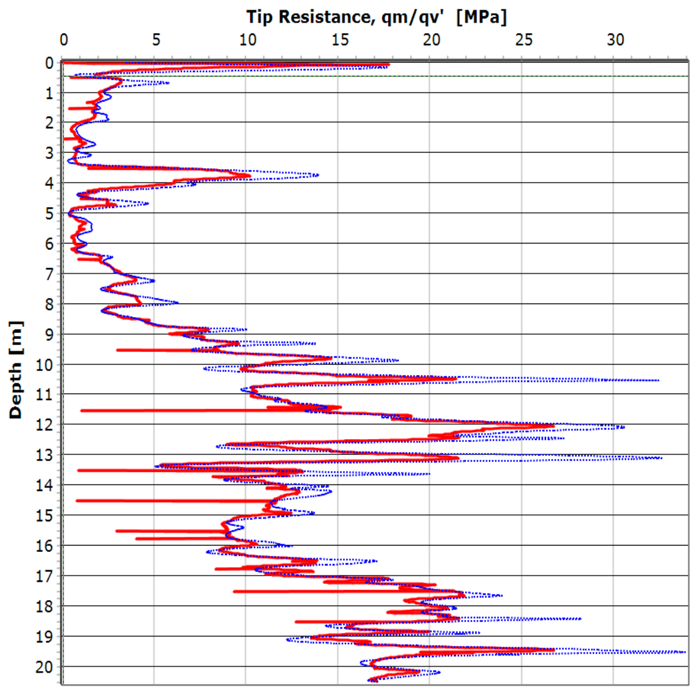
Figure 9. (A) Smoothed q_m (orange) trace of Fig. 8 superimposed upon true q_t (red) trace of Fig. 6. (B) Estimated q_t (orange) trace from the *qtHMM-IFM* algorithm superimposed upon true q_t (red) trace of Fig. 6.

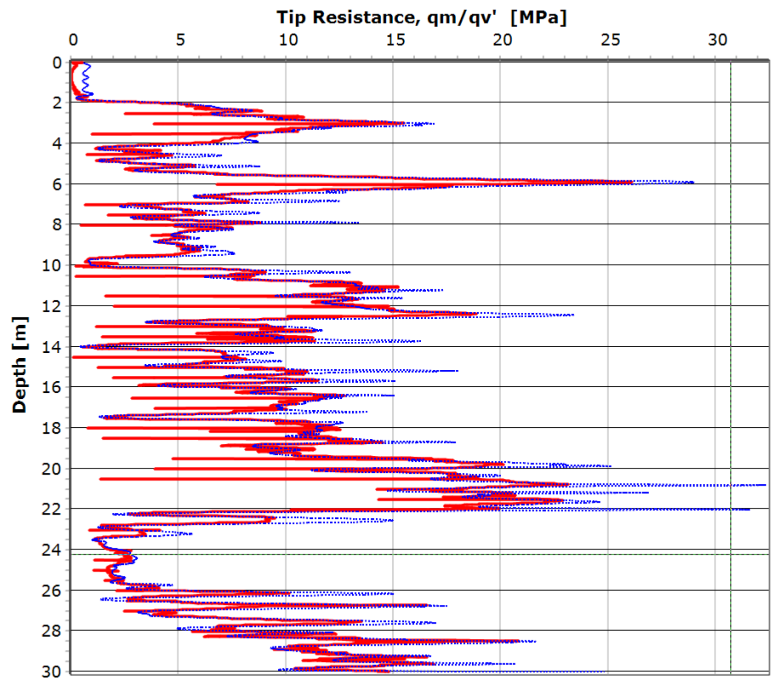
Several real data examples are outlined below which illustrate the significant differences between measured cone bearing data q_m and estimated true values $q_v^{/}$ after implementation of the q_m*KF* and *qtHMM-IFM* algorithms.

Red Trace – Measured Cone Bearing q_m
Blue Trace – Estimated True Cone Bearing $q_v^{/}$









Erick Baziw
Gerald Verbeek

BCE's mission is to provide our clients around the world with state-of-the-art geotechnical signal processing systems, which allow for better and faster diagnostics of the sub-surface. Please visit our website (www.bcengineers.com) or contact our offices for additional information:

e-mail: info@bcengineers.com

phone: Canada: (604) 733 4995 – USA: (903) 216 5372