# Primary Consolidation Settlement of South Louisiana Clay Deposits in Marsh Environment


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Difficulty estimating primary consolidation settlement due to soft, settlement-prone, variable alluvial material

Magnitude and rate of settlement often critical to construction projects

Lab testing and in-situ testing often limited due to budget and schedule

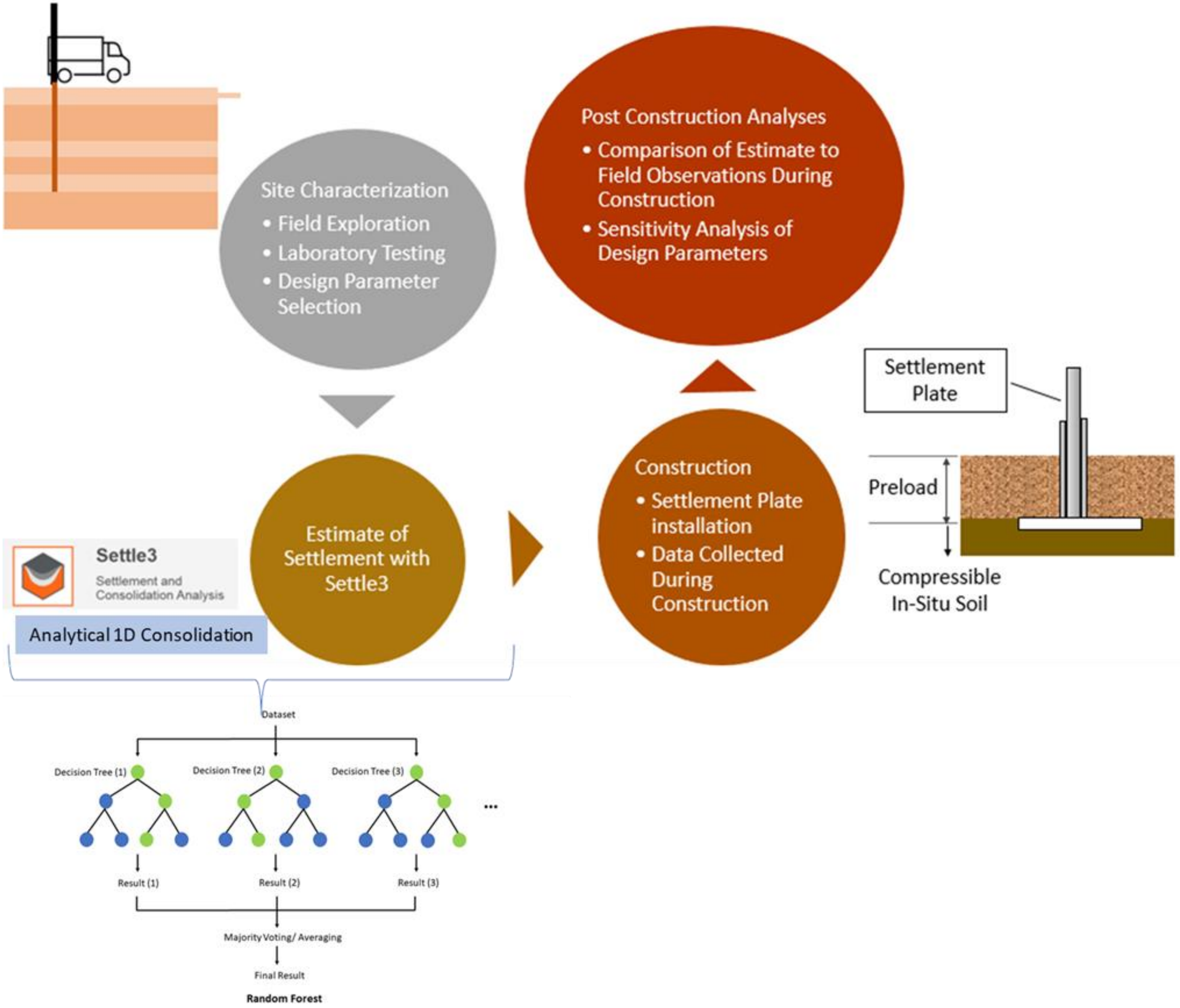
Correlations of less expensive tests-typically lower accuracy

# Research Objective

- Use existing instrumentation equipment to monitor settlement during construction
- Create numerical model to assess reliability and sensitivity of model-based estimate

# Research Method

- Settle 3
- Simplified 1D model for consolidation settlement
- Observation-based model
  - Asaoka method
  - Korhonen method
- Random tree regressor



# Settle3 Reference Simulation

Full flexibility to model embankments adding cross sections, multiple layers and user-defined staging sequences. Define the shape freely in 2D and extruded in 3D with user-defined end angles. (Source: [https://www.rocscience.com/software/settle3](https://www.rocscience.com/software/settle3))

Components

- Input
- Specification of model parameters
- Model sensitivity analysis
- Model simulation and validation

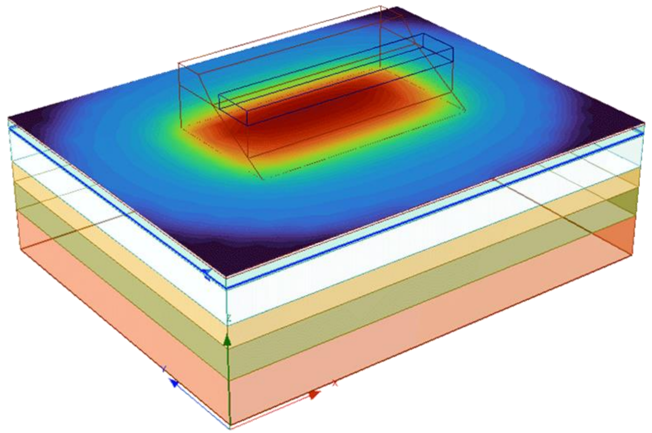
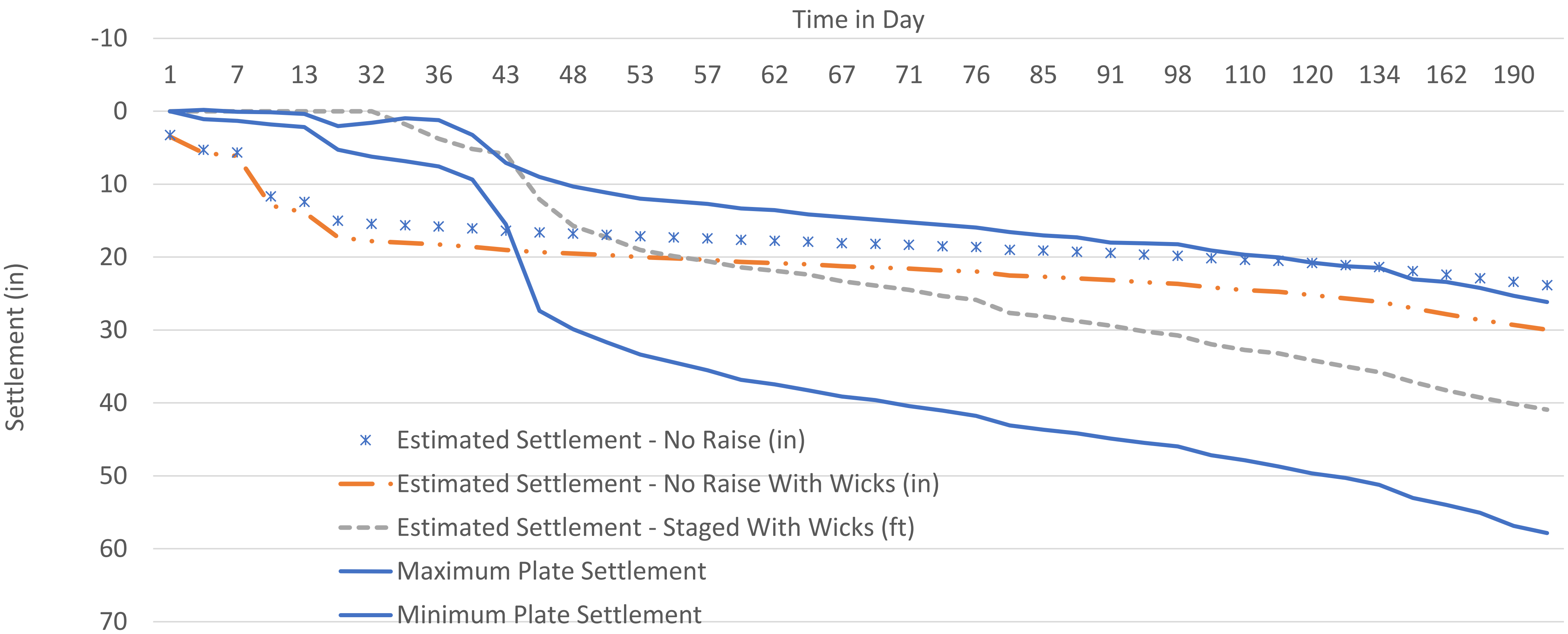


*Table 1 soil design parameters extracted from the Boring logs (Source: Eustis Engineering, L.L.C, LA)*

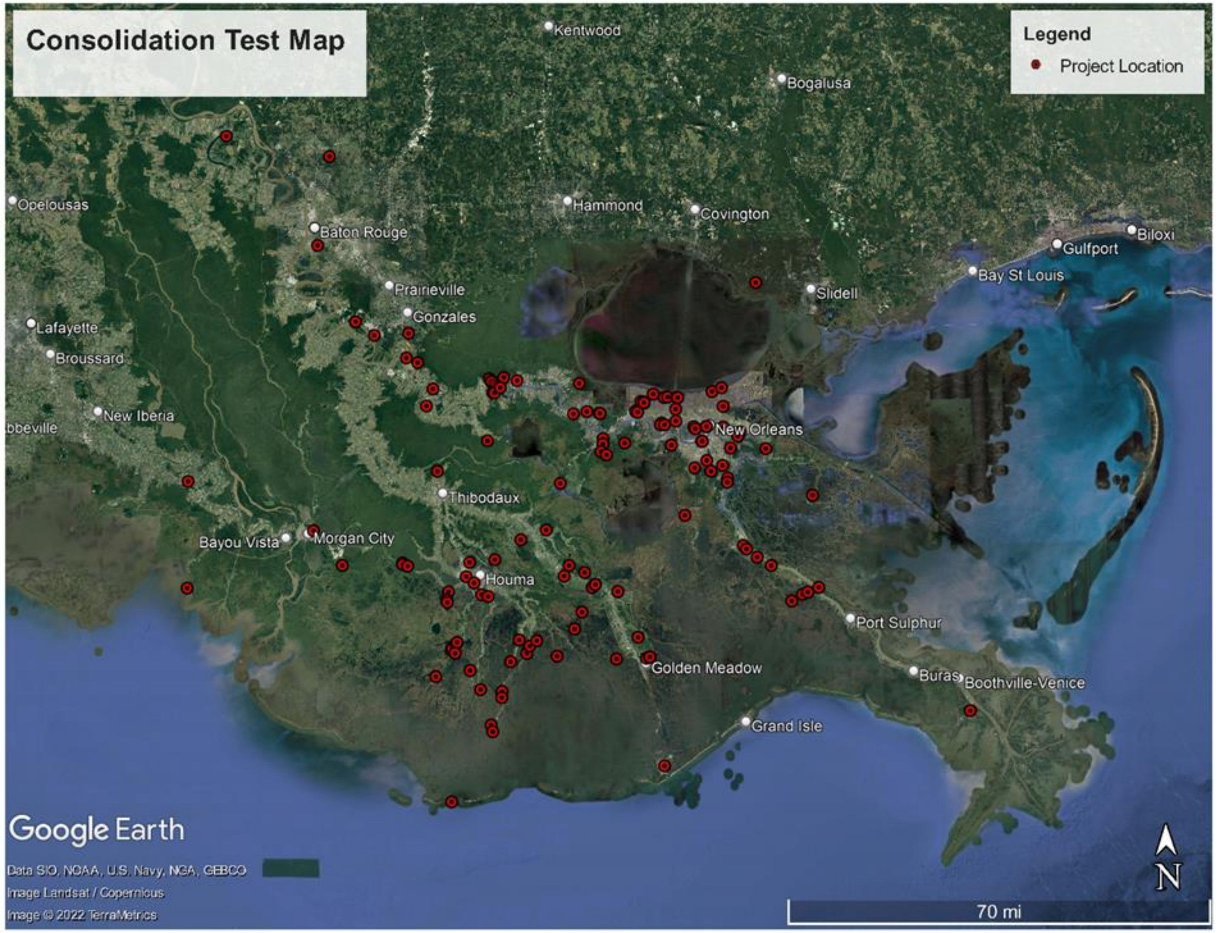
| Sn | USCE soil | Depth (ft) | El (ft) NAVD 88 | Unit wt (pcf) | OCR | Past max (pcf) | Wc % | CR (N/D) | RR | Cv | Total H (ft) | soil drainage condition |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | CH | 2.5 | -2.5 | 81 | 10 | 465 | 150 | 0.358 | 0.54 | 310 | 5 | |
| 2 | CH | 7.5 | -7.5 | 96 | 9.61 | 760.53 | 150 | 0.284 | 0.04 | 7.3 | 5 | |
| 3 | CH | 12.5 | -12.5 | 90 | 4.3 | 817.44 | 100 | 0.305 | 0.05 | 7.3 | 5 | |
| 4 | CH | 17.5 | -17.5 | 90 | 2.48 | 749.07 | 119 | 0.327 | 0.05 | 7.3 | 5 | Yes |
| 5 | CH | 22.5 | -22.5 | 84 | 1.6 | 706.62 | 150 | 0.358 | 0.05 | 7.3 | 5 | |
| 6 | CH | 27.5 | -27.5 | 90 | 1.2 | 965.68 | 150 | 0.354 | 0.05 | 7.3 | 5 | Yes |
| 7 | CH | 32.5 | -32.5 | 102 | 1.35 | 915.99 | 150 | 0.354 | 0.05 | 7.3 | 5 | |
| 8 | CH | 37.5 | -37.5 | 102 | 1.04 | 1080 | 65 | 0.261 | 0.04 | 7.3 | 5 | Yes |
| 9 | CH | 42.5 | -42.5 | 108 | 1 | 1527.31 | 65 | 0.125 | 0.02 | 310 | 5 | |
| 10 | CH | 47.5 | -47.5 | 100 | 1.18 | 1614.22 | 55 | 0.241 | 0.04 | 15 | 5 | Yes |
| 11 | CH | 55 | -55 | 107 | 1.08 | 1818 | 55 | 0.241 | 0.04 | 15 | 5 | |
| 12 | CH | 62.5 | -62.5 | 105 | 1 | 2147.5 | 50 | 0.241 | 0.04 | 15 | 5 | |
| 13 | CH | 67.5 | -67.5 | 105 | 1 | 2360.5 | 50 | 0.241 | 0.04 | 15 | 5 | Yes |
| 14 | CH | 72.5 | -72.5 | 112 | 1.07 | 2762.45 | 63 | 0.26 | 0.04 | 15 | 5 | |
| 15 | CH | 77.5 | -77.5 | 112 | 1.05 | 2894.65 | 63 | 0.26 | 0.04 | 15 | 5 | |
| 16 | CH | 85 | -85 | 104 | 1.09 | 3471.36 | 63 | 0.345 | 0.05 | 9.1 | 5 | Yes |
| 17 | CH | 92.5 | -92.5 | 110 | 1 | 3498 | 63 | 0.345 | 0.03 | 73 | 5 | |

# Settle3 Simulation: With and With Out Raise and Wick Drains



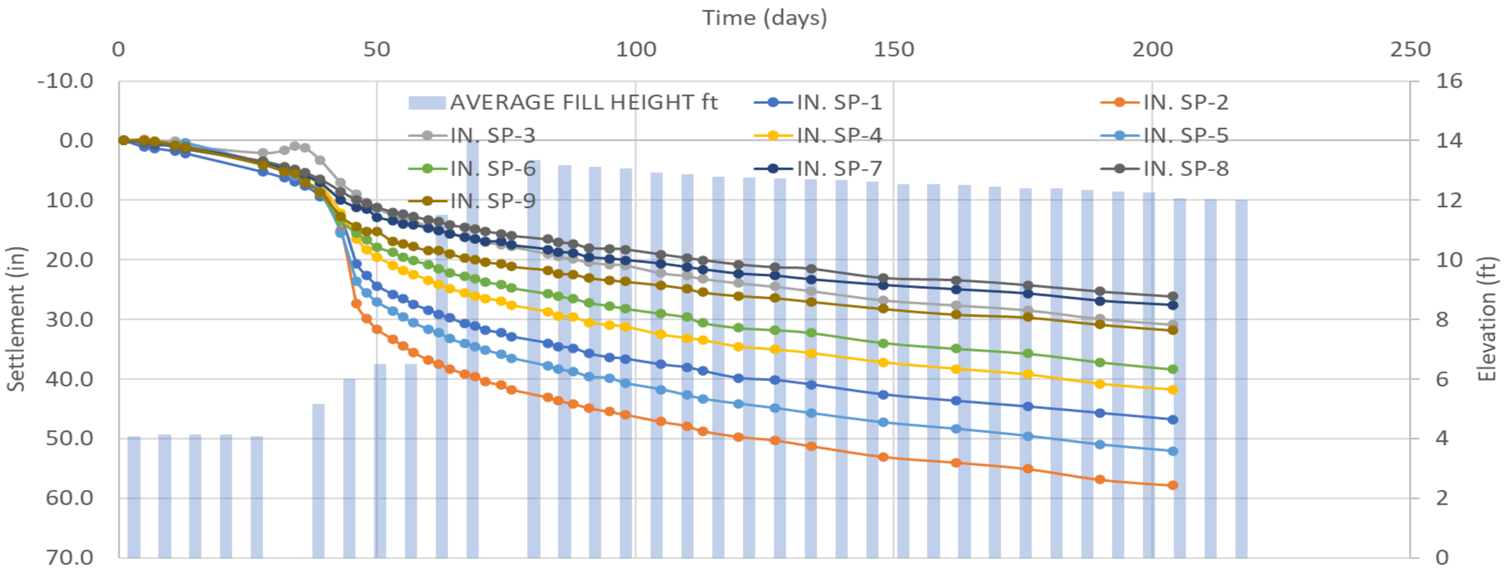
# Correlation Based Approach for Estimation of Soil Compressibility

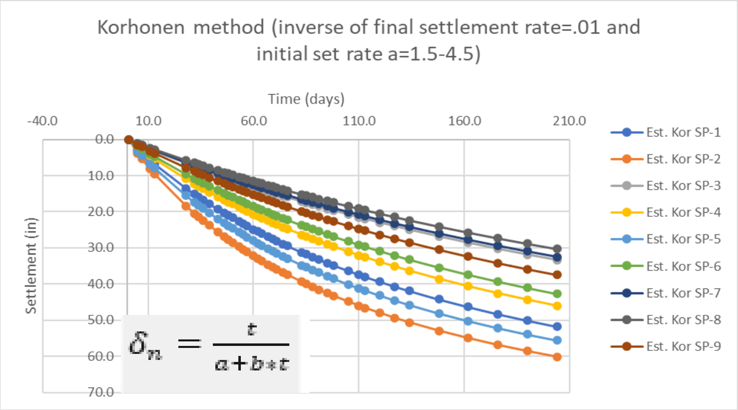
| Equation # | Equation | Notes | Reference |
|---|---|---|---|
| 1 | $0.017w_n - 0.299$ | CH/CL | Brandon, et al (2011) |
| 2 | $0.012w_n - 0.163$ | CH/CL | Harris and Jafari (2018) |
| 3 | $0.014w_n - 0.12$ | CH/CL | Deubert (1982) |
| 4 | $0.012w_n - 0.06$ | CH Only | Deubert (1982) |
| 5 | $0.016w_n - 0.29$ | CL only | Deubert (1982) |
| 6 | $0.012w_n + 0.137$ | OH/PT | Brandon, et al (2011) |
| 7 | $0.008w_n + 0.375$ | OH/PT | Harris and Jafari (2018) |
| 8 | $0.673e_0 - 0.377$ | CH/CL | Brandon, et al (2011) |
| 9 | $0.611e_0 - 0.28$ | OH/PT | Brandon, et al (2011) |
| 10 | $8e^{-0.038\gamma_d}$ | CH/CL | Brandon, et al (2011) |
| 11 | $7.82e^{-0.043\gamma_d}$ | OH/PT | Brandon, et al (2011) |
| 12 | $0.009LL - 0.1$ | CH/CL | Deubert (1982) |
| 13 | $0.0085(LL+9.5)$ | CH only | Brandon, et al (2011) |
| 14 | $0.018(LL-19.6)$ | CL only | Brandon, et al (2011) |
| 15 | $0.0067(LL+95)$ | OH/PT | Brandon, et al (2011) |
| 16 | $0.0067(LL+95)$ | $0.01PI + 0.06$ | Deubert (1982) |
| 17 | $0.54*(2.6w_n - 0.35)$ | CH/CL (moisture content as decimal) | Nishida (1956) |
| 18 | $0.01w_n$ | CH/CL | Azzouz (1976) |
| 18 | $0.0115w_n$ | OH/PT | Azzouz (1976) |
| 20 | $0.208e_0 + 0.0083$ | CH/CL | Azzouz (1976) |
| 21 | $1.15*(e_0 - 0.35)$ | CH/CL | Nishida (1956) |
| 22 | $0.29*(e_0 - 0.27)$ | CH/CL | Hough (1957) |
| 23 | $0.35*(e_0 - 0.50)$ | OH/PT | Hough (1957) |
| 24 | $0.0046(LL - 9)$ | CH/CL | Azzouz (1976) |
| 25 | $0.002 + 0.014PI$ | CH/CL | Nacci (1975) |

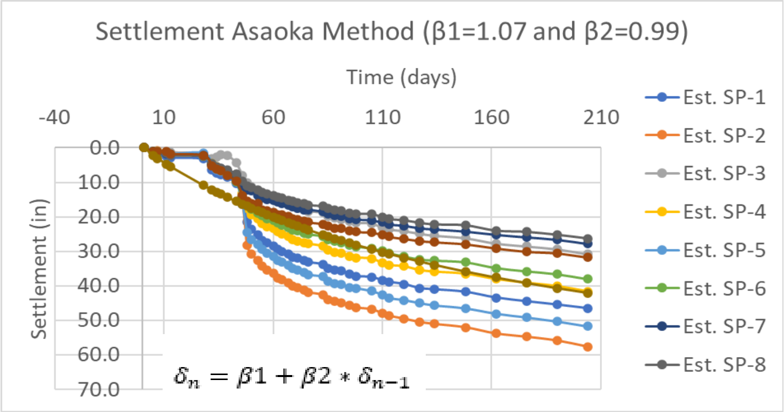



Compression Coefficient Correlations from Southeast Louisiana (source Clay Worley, 2022 personal communication)

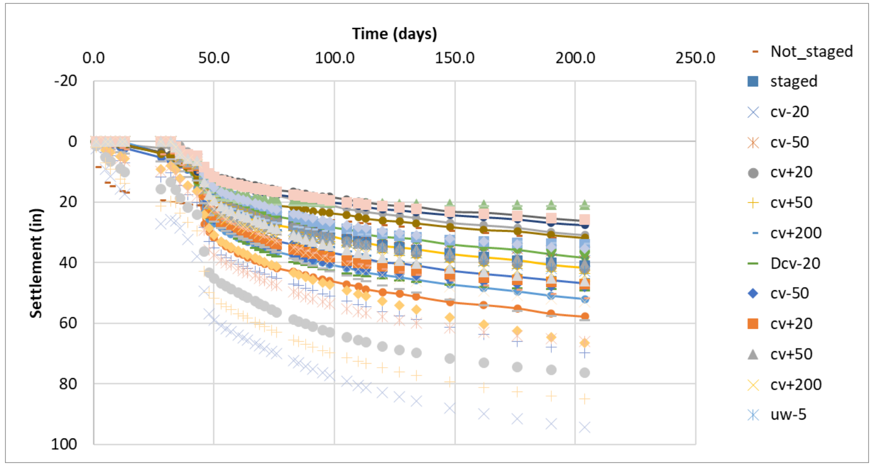
# Methods – Observed Settlement Data



# Methods – Simulated Settlement Data




Sensitivity Analyses

Create Database

Korhonen Method:

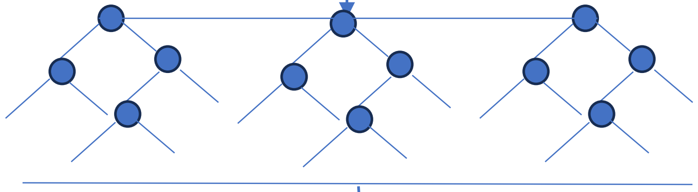
$$Settlement(t) = f(\emptyset, Filling, drainage)$$

$$\delta(\emptyset, Filling, drainage, t) = \frac{t}{a(\emptyset, Filling, drainage) + b(\emptyset, Filling, drainage)}$$

$$Settlement(t)$$

Machine Learning Algorithm:

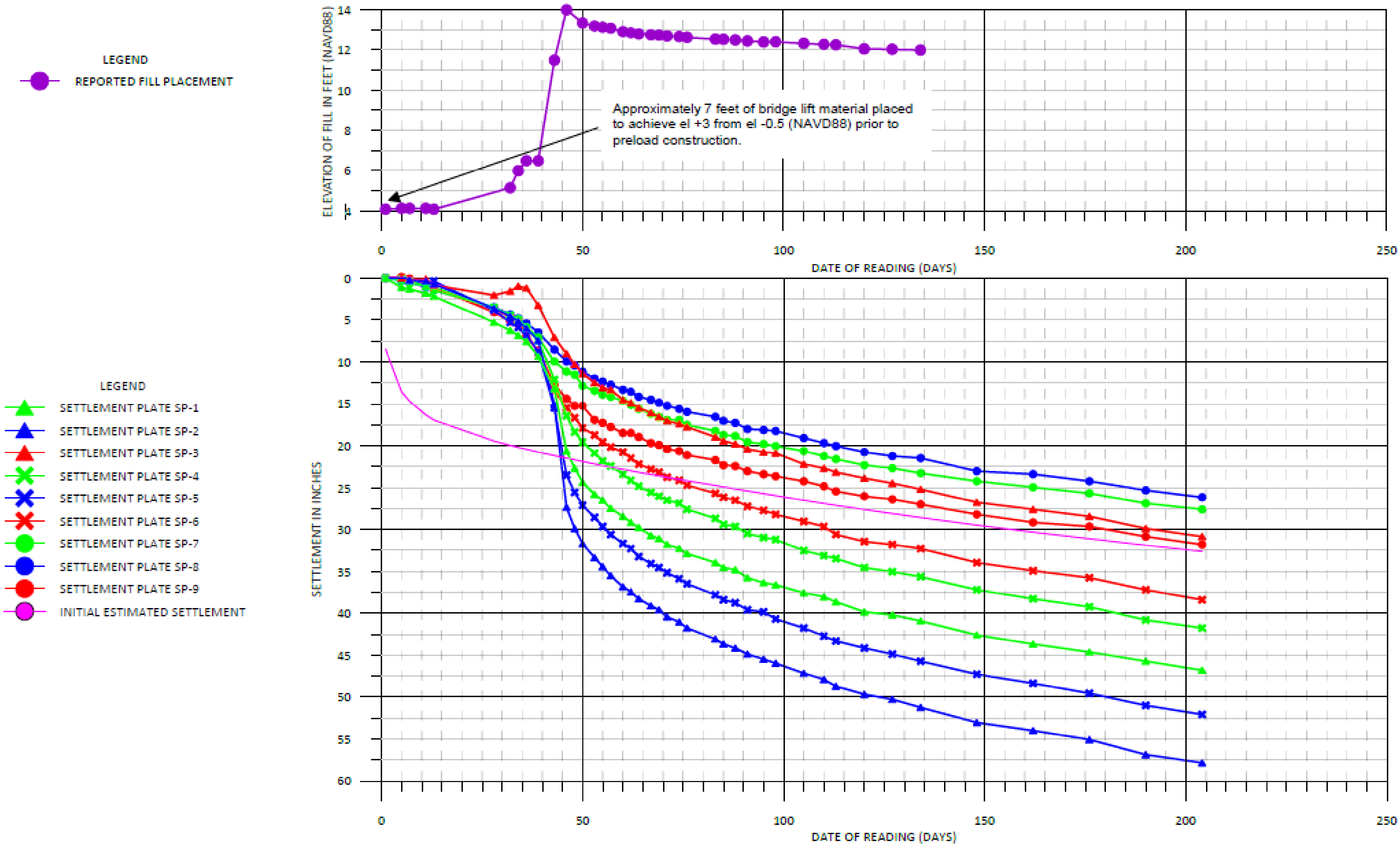
$$Settlement(t, \emptyset, Filling, drainage)$$



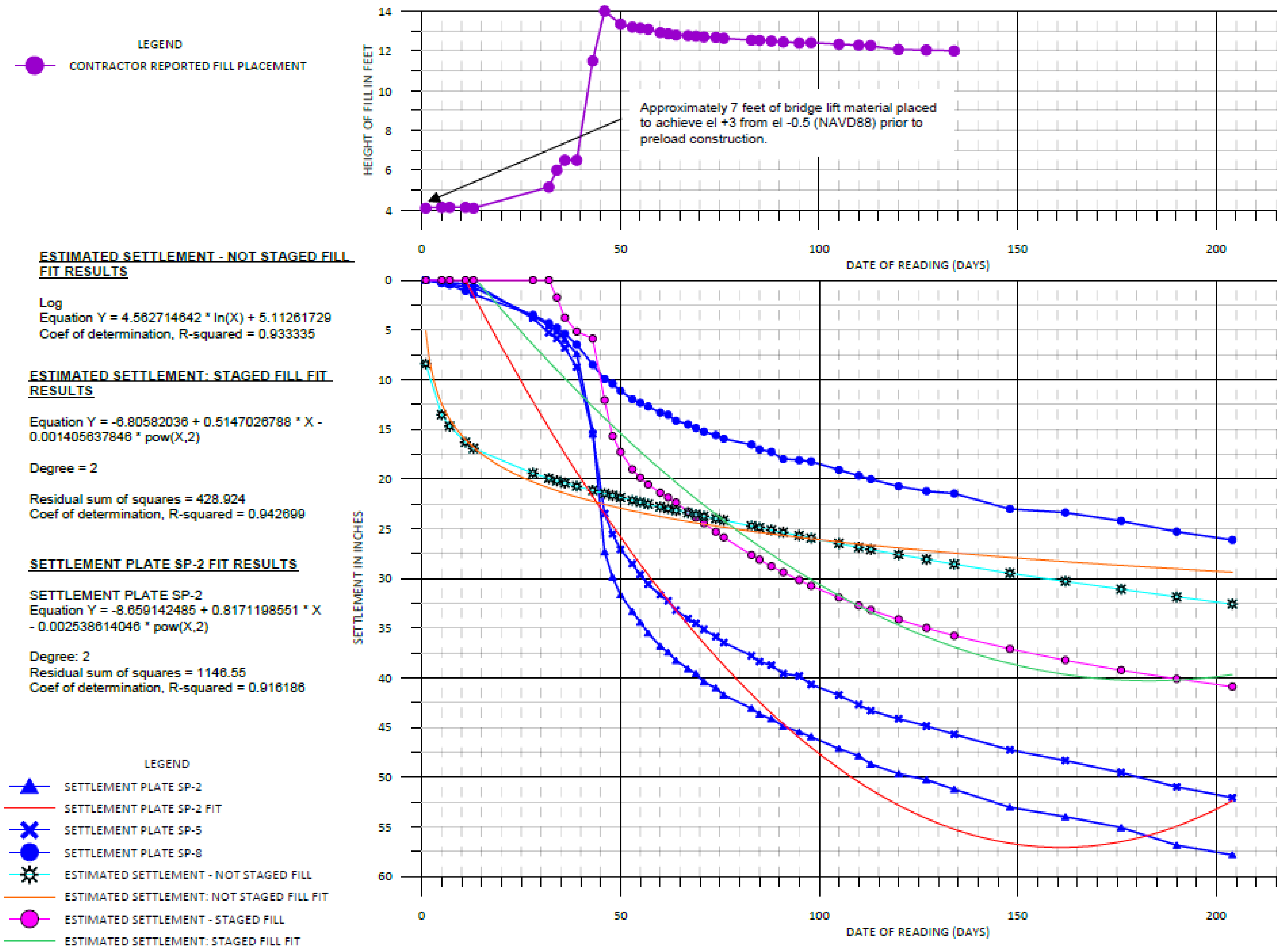
$$Settlement(t)$$

Regional relationship/classifier for the estimation of settlement

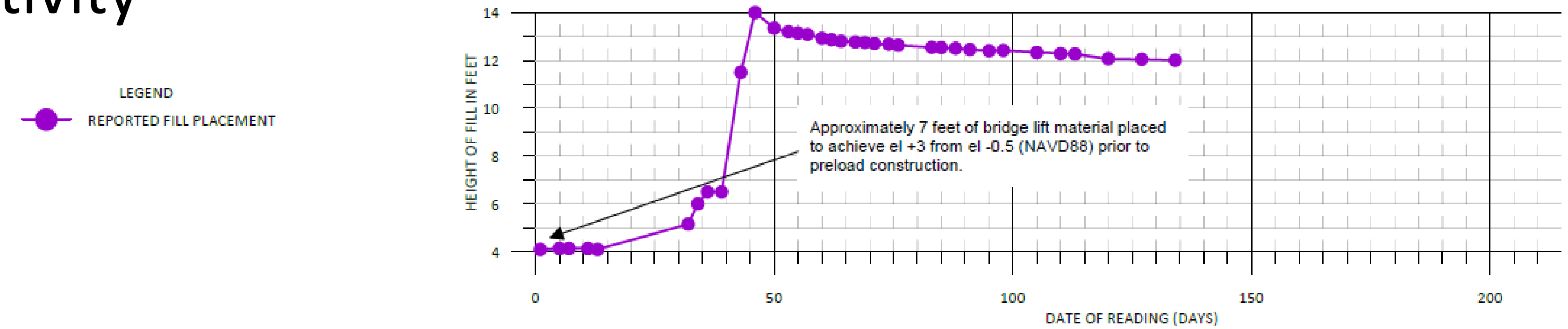
# Settlement Plates and Initial Settlement Estimate

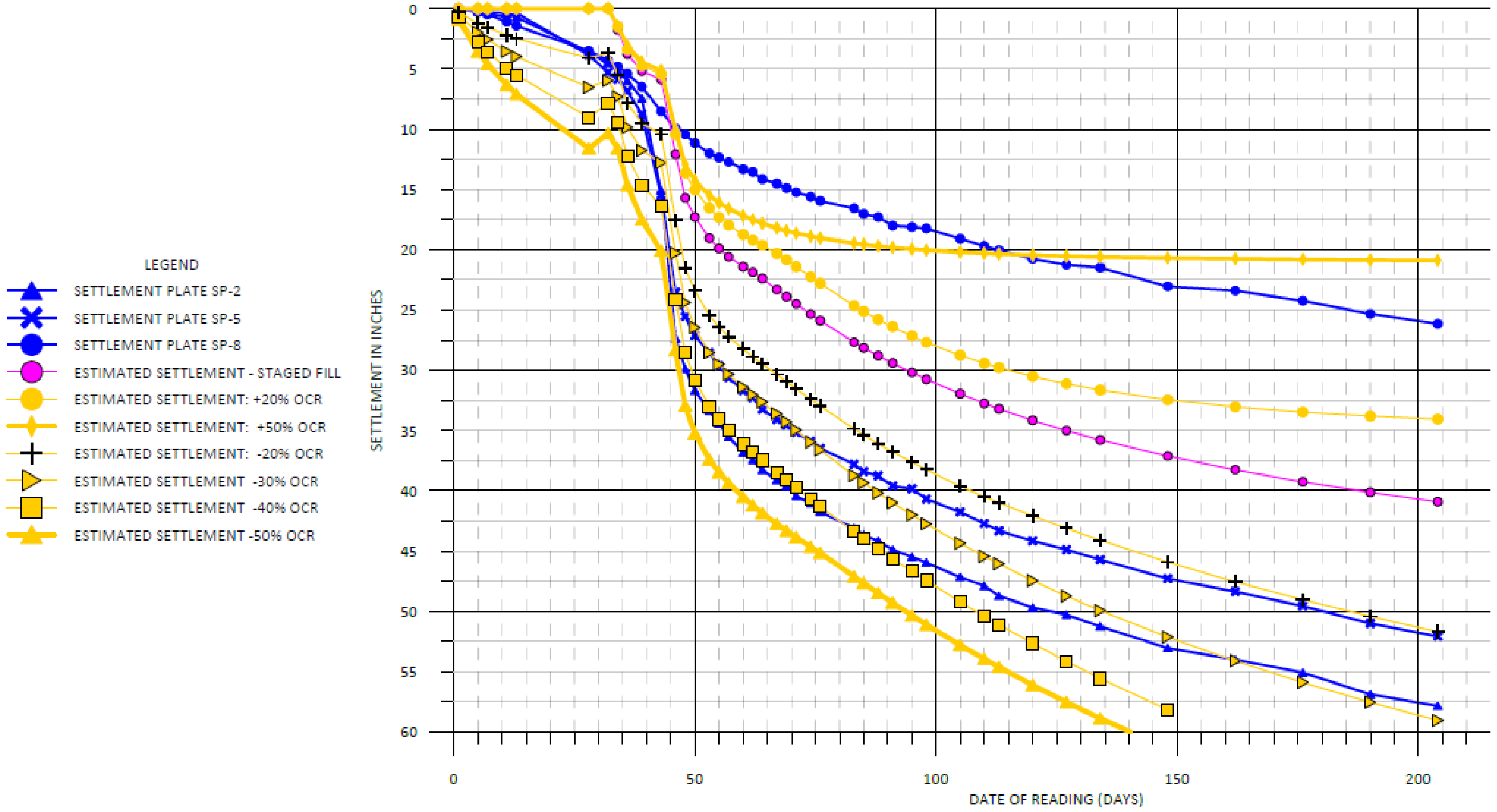


# Staged vs. Un-Staged Fill Placement

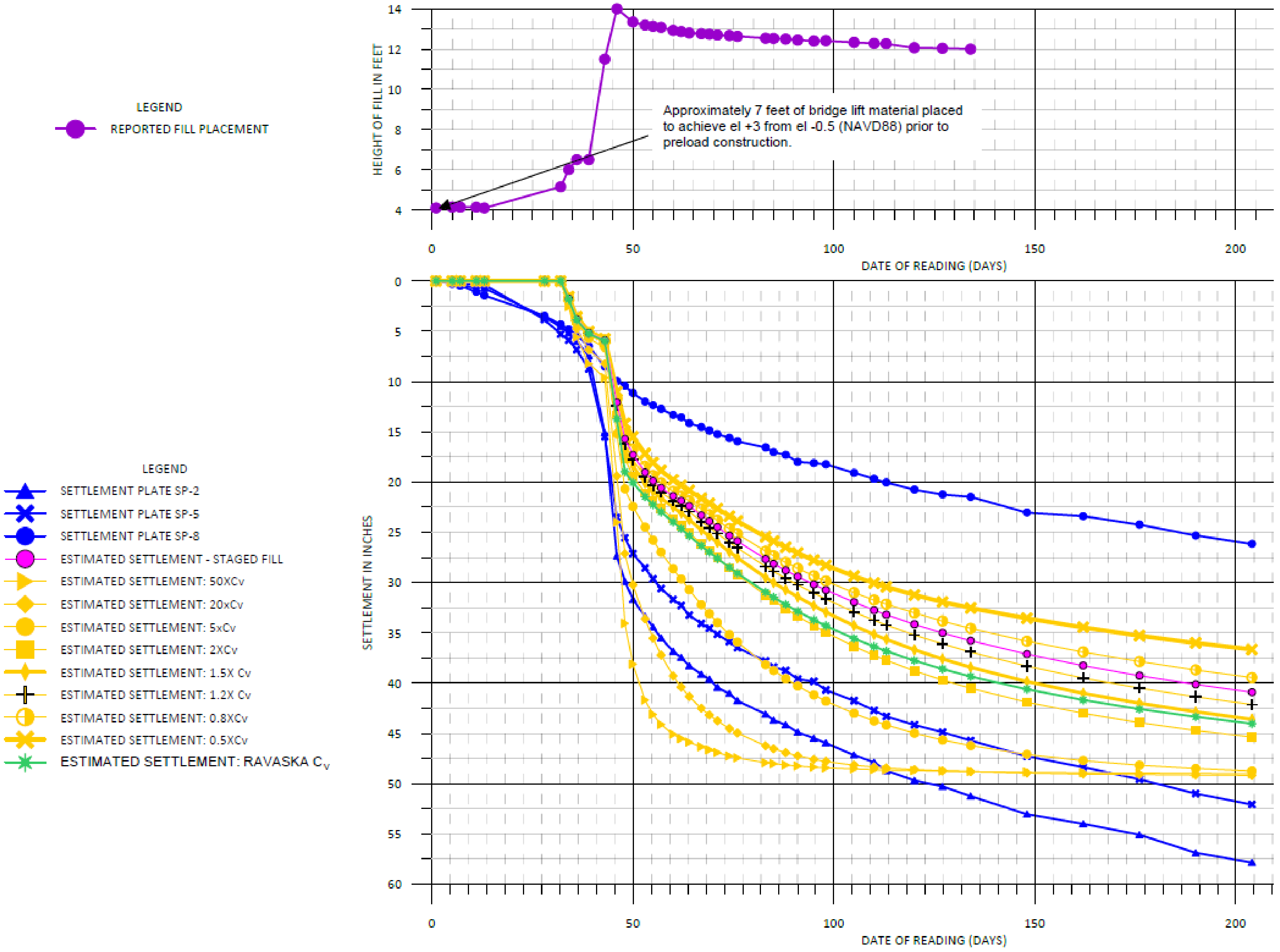


# OCR Sensitivity



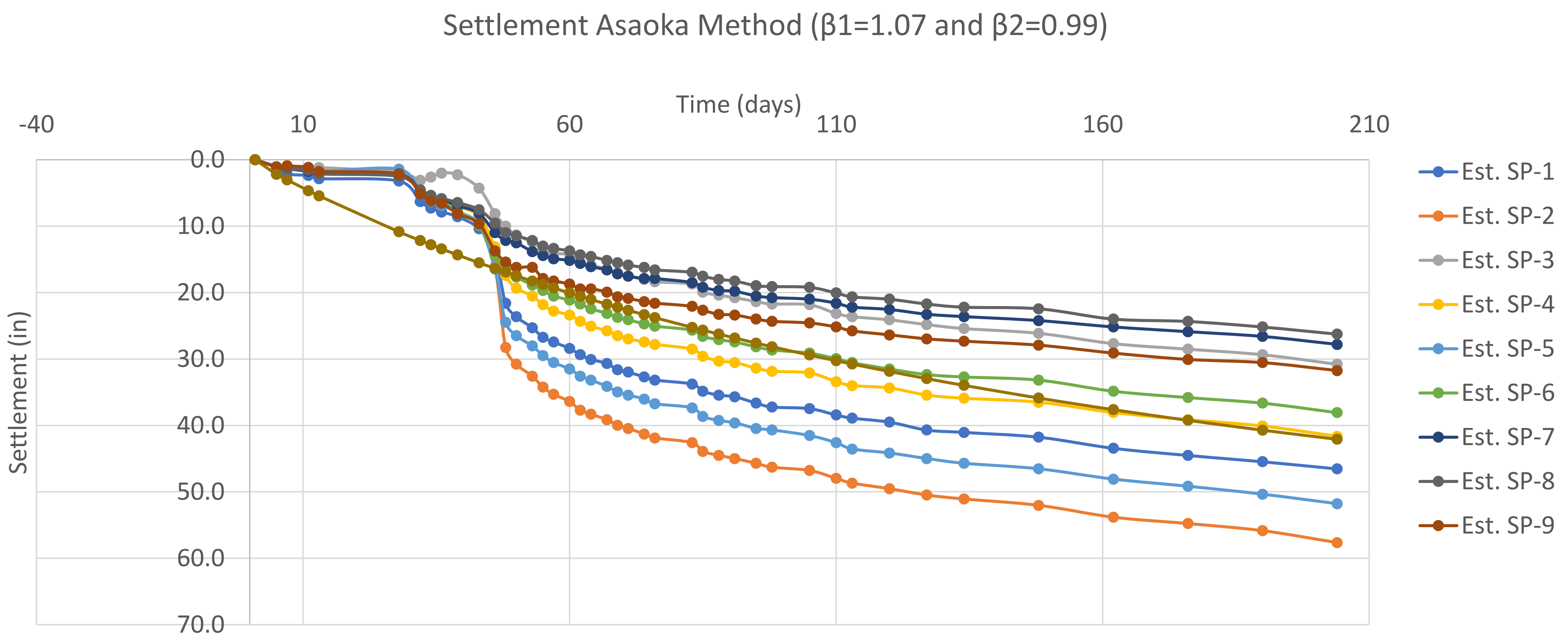
# Coefficient of Consolidation Sensitivity



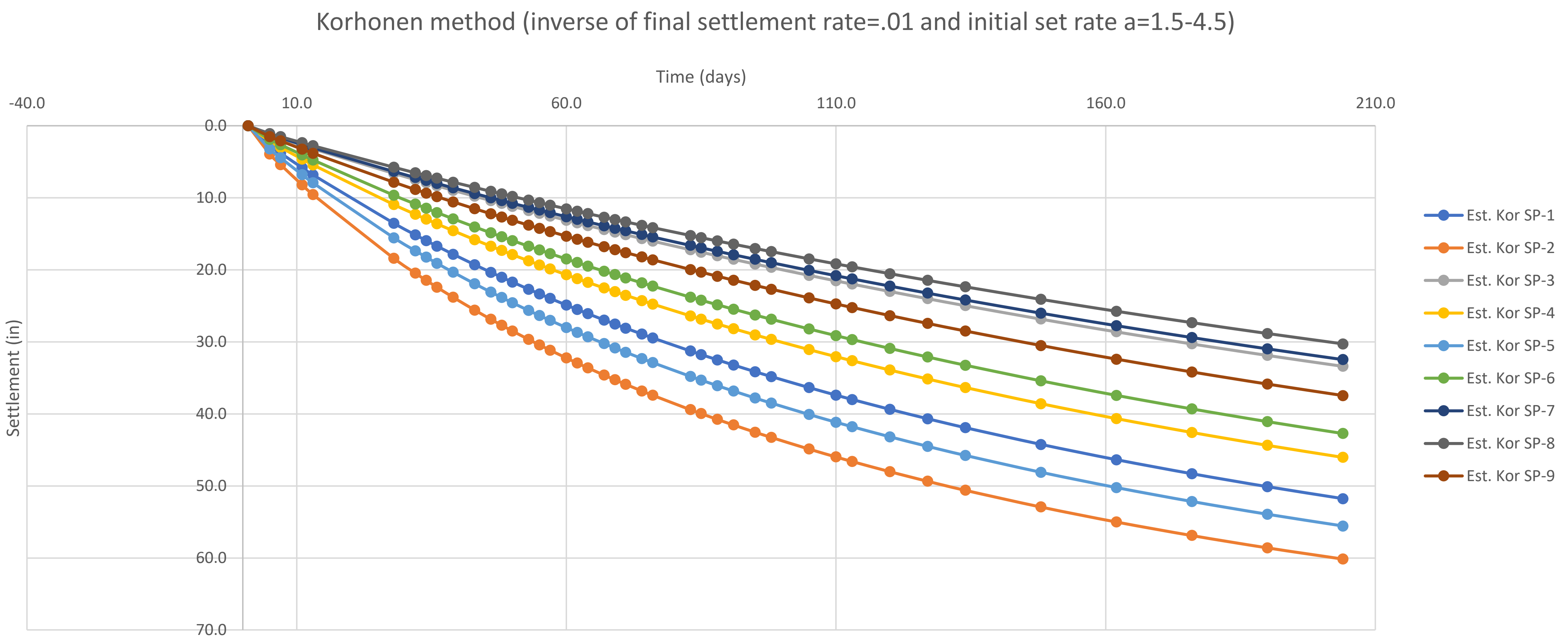
# Summary of Sensitivity Experiment by Percentage Change in Settlement

| Parameter | Change with respect to baseline parameter (One parameter at a time method) (% Change in Settlement at Day 204) | | | | | | |
|---|---|---|---|---|---|---|---|
| OCR | +20% ( -17%) | +50% (-49%) | -20% (+26%) | -30% (+44%) | -40% (+62%) | -50% (+71%) | |
| Unit weight | +5% (-11%) | -5% (+5%) | | | | | |
| Wick Area (Width of Wick Area) | +10ft (0%) | +50ft (0%) | +100ft (0%) | +200ft (0%) | | | |
| Smear Zone Ratio | 2/2 (-1%) | | | | | | |
| Wick Horizontal Flow (Ratio of Ch/Cv) | 4 (+7%) | 3 (+4%) | 2 (+2%) | 0.5 (-5%) | | | |
| Drained Interfaces | Drained Interface (+12%) | | | | | | |
| Coefficient of Consolidation | 50 (+20%) | 20 (+20%) | 5 (+19%) | 2 (+11%) | 1.5 (+7%) | 1.2.. 0.8, 0.5 (-10% to +3%) | X (+8%) |
| Coefficient of Compression | +20% (+13%) | +50% (+30%) | -20% (-13%) | -50% (-37%) | | | |

# Models Based on Observations: Asaoka Method

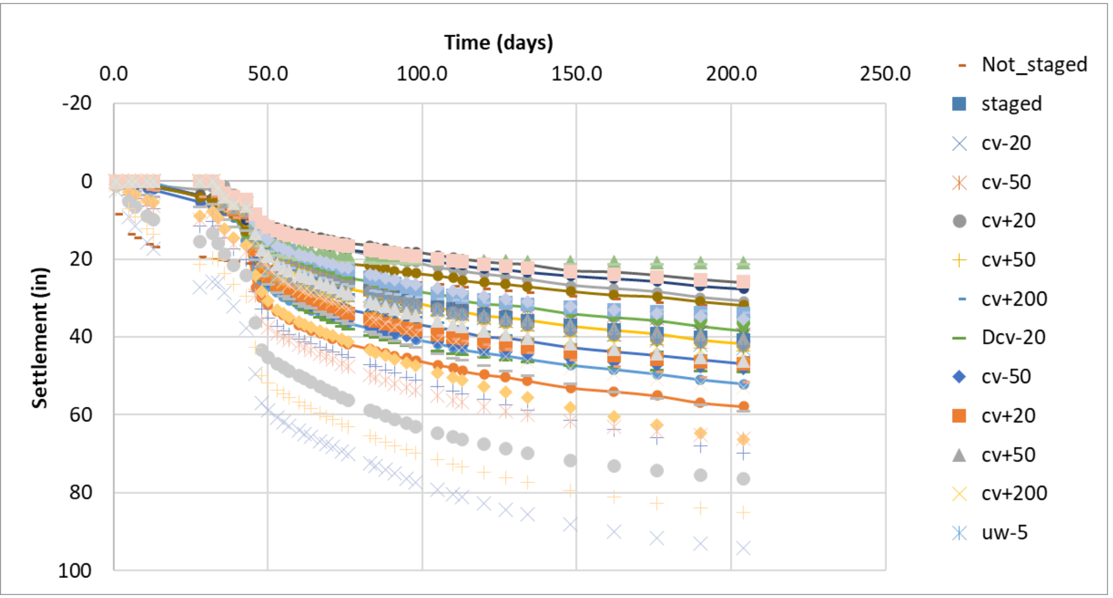


# Models Based on Observations: Koronen method

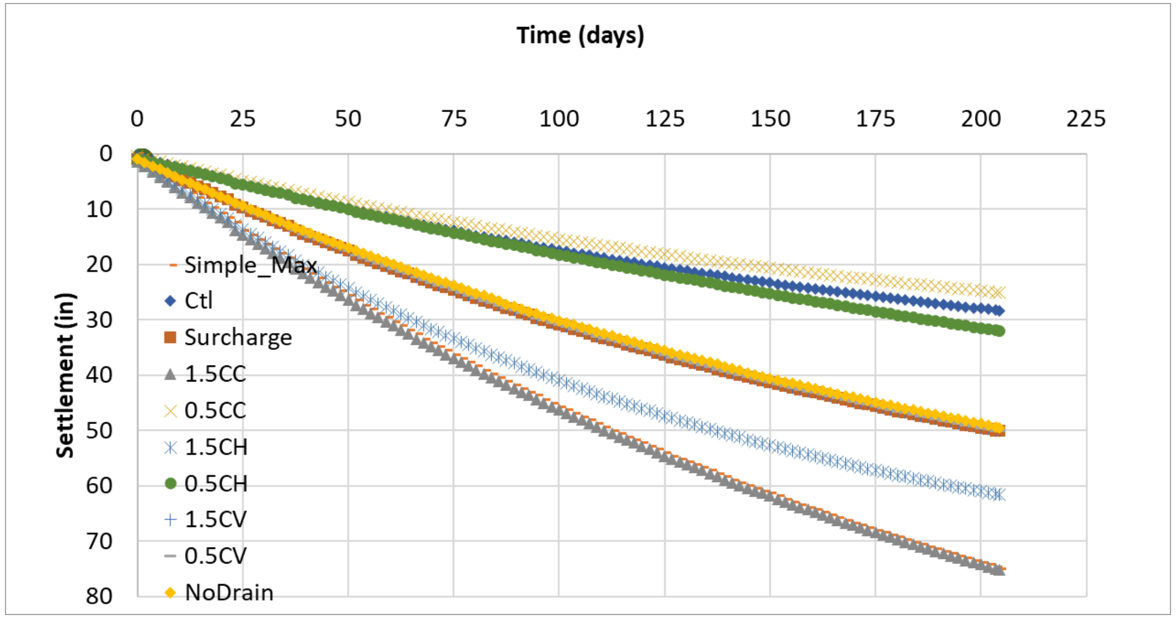


# Settle 3 vs Simple 1D Consolidation

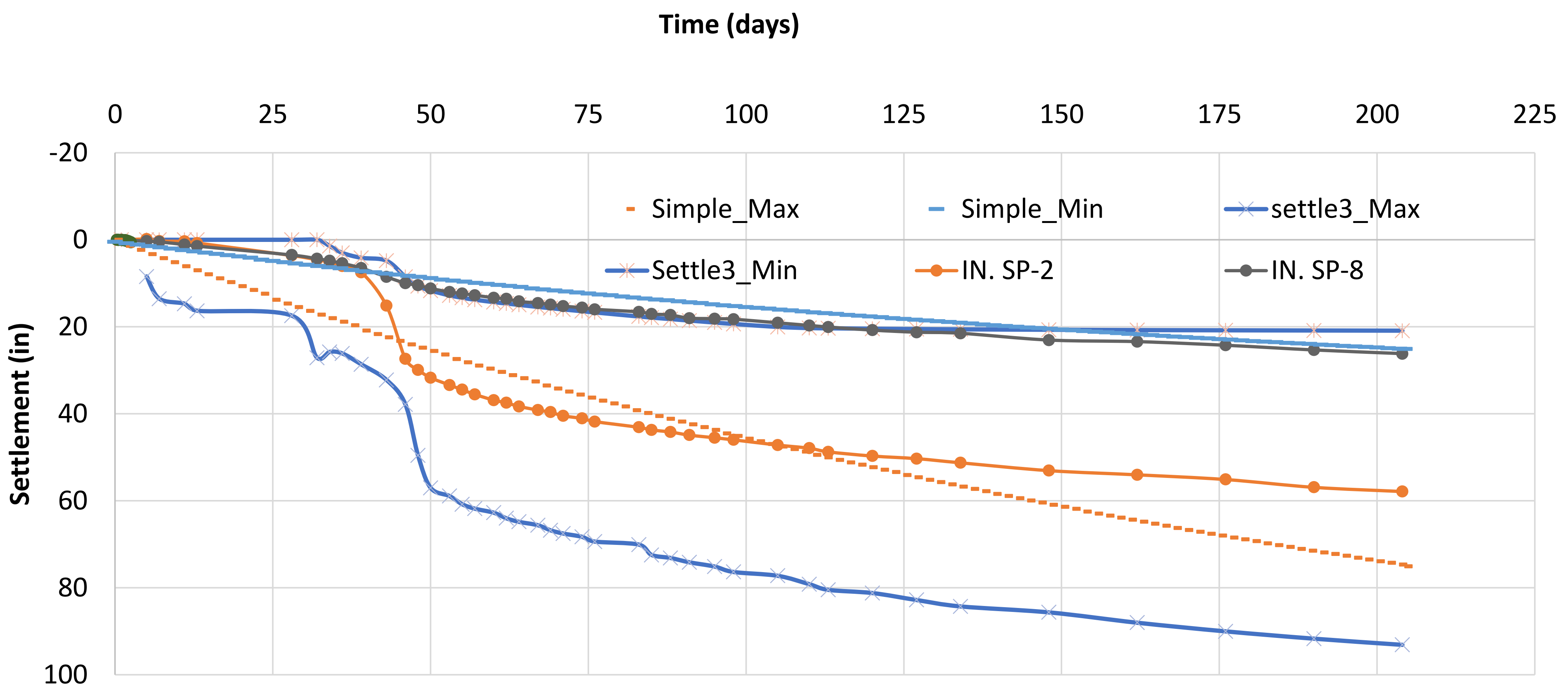
Settle3




Simple approximate method: PVD-improved deposits induced by a time-dependent loading



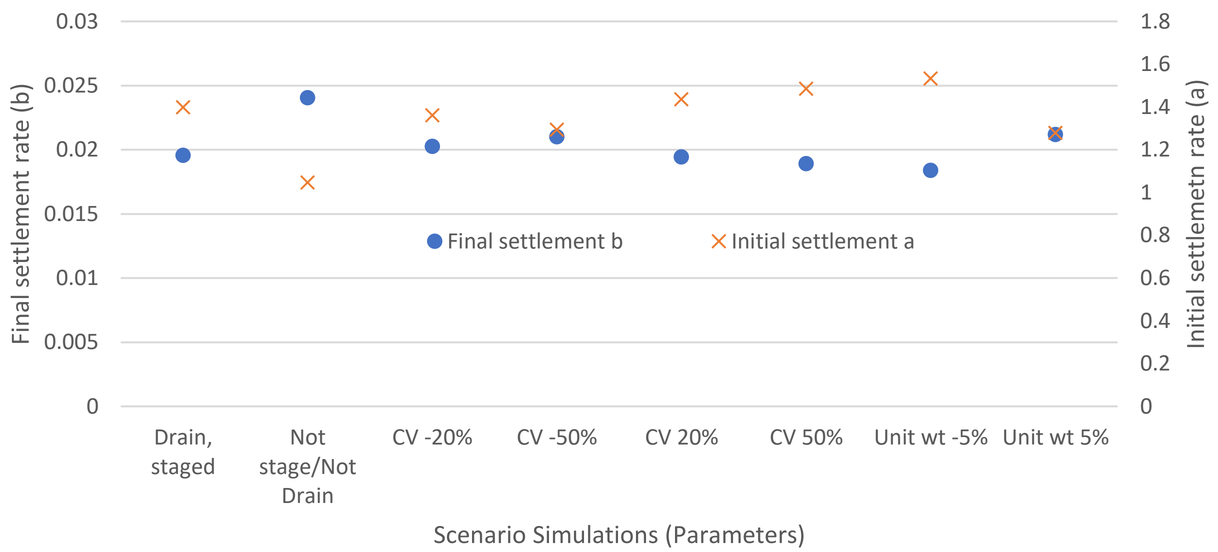
# Settle 3 vs Simple 1D Consolidation



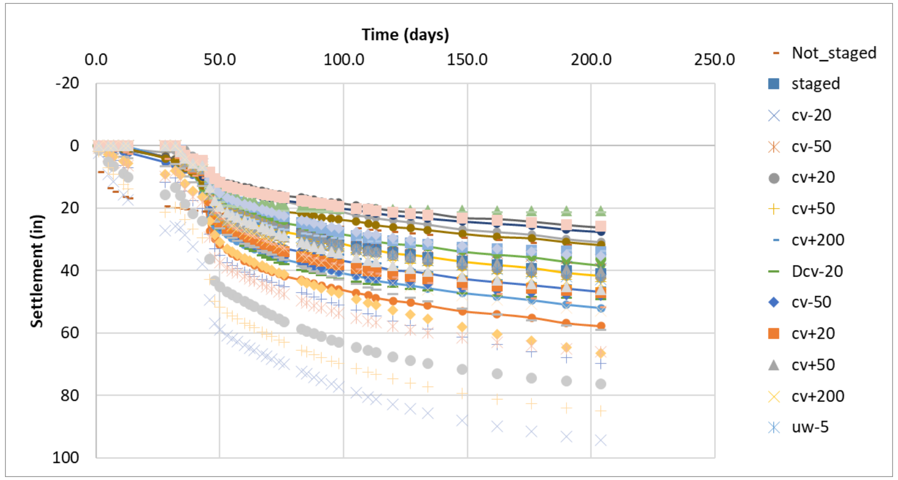
# Regionalization of Parameters of the Korhonen Method

$$Settlemetn(t) = f(\emptyset, Filling, drainage)$$

$$\delta(\emptyset, Filling, drainage, t) = \frac{t}{a(\emptyset, Filling, drainage) + b(\emptyset, Filling, drainage)}$$



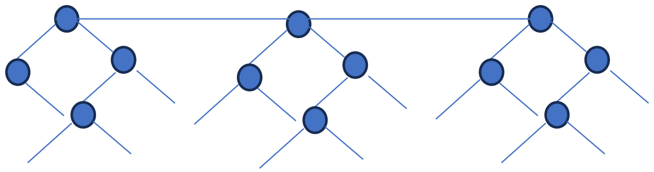
# Random Forest Regression Classifier




Sensitivity Analyses

Create Database

$Settlement(t, \emptyset, Fill\ Height, Drainage$ Interface)



$Settlement(t)$

*Figure Calibration and testing of Random Forest regressor (RMSE for calibration and validation are 0.99, and testing is 0.95), CV (CVd) is the coefficient of compressibility (with PVC drain), Stage (option=1) the option for embankment fill to accelerate the consolidation settlement, and un-staged (stage =0); ocr (ocrd) over consolidation ratio with (without) PVC drain, cc coefficient of compression, uw unit weight of soil*

# Random Forest Regression Classifier

## Features

| Time | Stage | CV | CVd | uw | ocr | ocrd | cc | Settlement_Settle3 |
|---|---|---|---|---|---|---|---|---|
| Calibration | | | | | | | | |
| 1 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 8.4 |
| 5 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 13.5 |
| 7 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 14.7 |
| 11 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 16.3 |
| 13 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 16.9 |
| … | … | … | … | … | … | … | … | … |
| Valiation | | | | | | | | |
| 1 | 1 | 1 | 0 | 1 | 1 | 0 | 1.5 | 48.0 |
| 5 | 1 | 1 | 0 | 1 | 1 | 0 | 1.5 | 49.5 |
| 7 | 1 | 1 | 0 | 1 | 1 | 0 | 1.5 | 50.8 |
| 11 | 1 | 1 | 0 | 1 | 1 | 0 | 1.5 | 52.0 |
| 13 | 1 | 1 | 0 | 1 | 1 | 0 | 1.5 | 53.0 |

## Features

| Model testing | | | | | | | |
|---|---|---|---|---|---|---|---|
| Time | Stage | CV | CVd | uw | ocr | ocrd | cc |
| 1 | 1 | 0.8 | 0 | 1 | 1 | 0 | 1 |
| 5 | 1 | 0.8 | 0 | 1 | 1 | 0 | 1 |
| 7 | 1 | 0.8 | 0 | 1 | 1 | 0 | 1 |
| …. | …. | …. | …. | …. | …. | …. | …. |
| 204 | 1 | 0.8 | 0 | 1 | 1 | 0 | 1 |

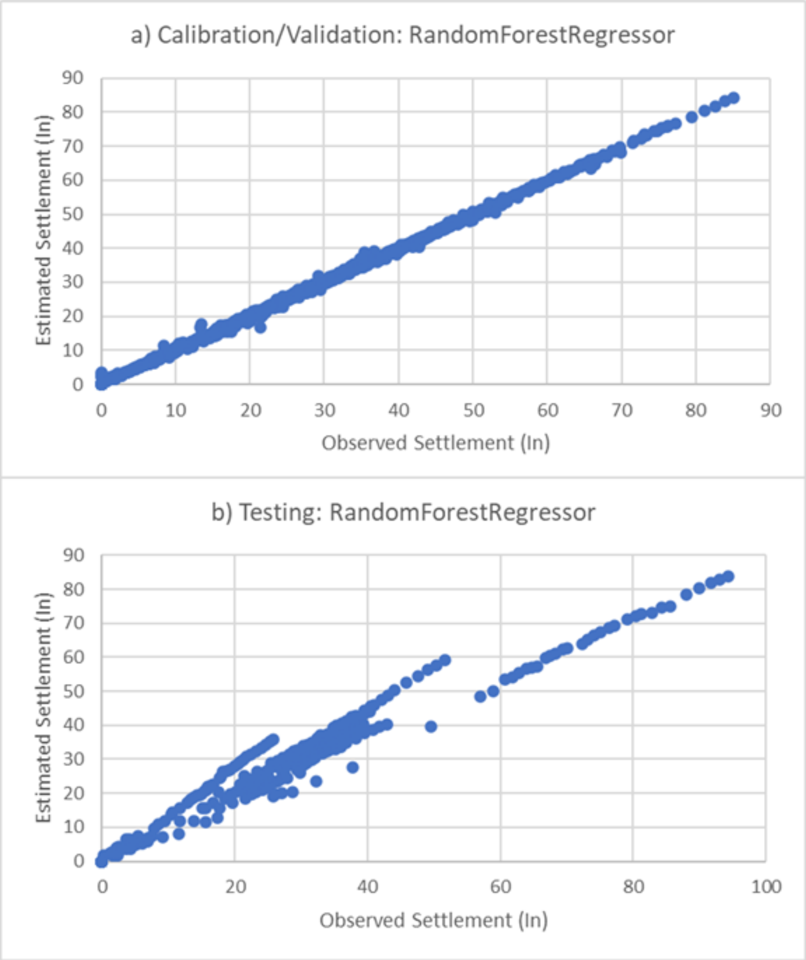



*Figure Calibration and testing of Random Forest regressor (RMSE for calibration and validation are 0.99, and testing is 0.95), CV (CVd) is the coefficient of compressibility (with PVC drain), Stage (option=1) the option for embankment fill to accelerate the consolidation settlement, and un-staged (stage =0); ocr (ocrd) over consolidation ratio with (without) PVC drain, cc coefficient of compression, uw unit weight of soil*

# Conclusions

- Overall, typical Terzaghi 1-D model analyzed through Settle3 acceptable for construction estimates with less time sensitivity
- Likely that multiple parameter inaccuracies contribute to accuracy of settlement estimate
- Possible inaccuracies in field data collected (reliance on contractors, disturbance of equipment)

# Recommendations for Future Research

- Additional research of local construction sites: site/regional specific settlement prediction models
- Explore other instrumentation at the subject site (settlement gauges, magnet extensometers, piezometers, Shape Array Accelerometers (SSAs)
- Advanced capabilities of LiDAR have potential for near surface monitoring at extremely low cost (Anderson, 2023)

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# Thank You!

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