

**GEOTECHNICAL SOLUTIONS NOTEBOOK**ISSUE F-1 (2013) (rev. 0)

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**More Accurate Estimation of Driven Pile Length During Design****1. Problem**

Differences between the contract pile length estimated in the design and pile length finalized in the field during construction are reported by Highway Agencies.

Assuming no downdrag effect, the governing equation for the geotechnical strength limit state for the axial compression resistance of a single pile is:

$$Q_f \leq \phi R_n \quad (1)$$

Where  $Q_f$  is the largest factored axial compression load applied to the top of a single pile in a pile group,  $R_n$  is the nominal bearing resistance of a single pile, and  $\phi$  is the geotechnical resistance factor of the method employed to determine  $R_n$ , either a static analysis method (e.g.,  $\alpha$ - and  $\beta$ - methods) where  $R_n=R_{nstat}$  and  $\phi=\phi_{sta}$ , or a field analysis method (e.g., dynamic load test or formulas, or wave equation or static load test) where  $R_n=R_{nfield}$ ,  $\phi=\phi_{dyn}$ .

The pile length is often determined by meeting the geotechnical strength limit state (Eq. 1). Pile lengths are typically finalized during construction using  $R_{nfield}$  measured from a field analysis method. In the design phase, pile resistances from field analysis methods,  $R_{nfield}$ , are not available. Therefore, static analysis resistances are used in the design to estimate pile lengths by assuming  $R_{nfield}=R_{nstat}$ . These pile lengths are used for cost estimating, bidding, contracting, and/or procurement. Assuming  $R_{nfield}=R_{nstat}$  for estimation of contract pile length may lead to differences between the contract pile length and pile lengths finalized in the field, which may then cause construction problems and delays. To minimize this difference, improved accuracy of the estimated  $R_{nfield}$  resistances is desired in the design phase.

**2.0 Givens and Assumptions**

1. Geotechnical strength limit state for the axial compression resistance of a single pile controls the pile length (e.g., not lateral loading).

2. Downdrag effect is zero.
3. Future geotechnical resistance losses (GL) for the pile, for example due to scour, liquefaction, are zero
4. Static analysis method(s) will be used in the design phase to estimate pile length. With  $GL=0$ ,  $R_{nstat}$  is estimated as the sum of the side and base resistances of all the soil layers around the pile.
5. Field analysis method(s) will be used to finalize pile length during construction. There are two options to obtain pile bearing resistances and finalize pile lengths:
  - **End of driving (EOD) conditions.** Resistances are measured during driving and at EOD ( $R_{ndr}$ ). With  $GL=0$ ,  $R_{nfield} = R_{ndr}$ .
  - **Beginning of redrive (BOR) conditions.** Resistances are measured at EOD conditions ( $R_{ndr}$ ) and at BOR ( $R_{nre}$ ) from restrikes or load tests. Change in the pile bearing resistances after EOD (e.g., due to setup and relaxation) is needed in the design and will be verified in the field. With  $GL=0$ ,  $R_{nfield} = R_{nre}$ .

### 3.0 Solution

To improve the accuracy of the estimated  $R_{nfield}$  resistances in the design phase using the  $R_{nstat}$  resistances, it is suggested to correct for the bias between the resistances computed with static analysis methods and with field analysis methods. Develop a resistance median bias factor,  $\alpha$ , between the static and field analysis methods that generate  $R_{nstat}$  and  $R_{nfield}$  resistances as:

$$\alpha = R_{nfield}/R_{nstat} \quad (2)$$

Parameter  $\alpha$  can be expanded to  $\alpha_{BOR}$  at BOR conditions, when  $R_{nfield}$  resistances at BOR conditions are used to develop  $\alpha$ , and  $\alpha_{EOD}$  at EOD conditions. Then, use the following relationship to predict the resistances for a field analysis method,  $R_{nfield}$ , in the design phase from the resistances calculated with a static analysis method,  $R_{nstat}$ :

$$R_{nfield} = \alpha R_{nstat} \quad (3)$$

Use the estimated  $R_{nfield}$  from Eq. 3 to address Eq. 1 and estimate the pile length during design.

**Determination of local  $\alpha_{BOR}$ ,  $\alpha_{EOD}$  and setup factors.** These factors can be obtained as illustrated in Table 1 by compiling the predicted  $R_{nre}$  resistances from the calibrated static analysis method and measured  $R_{nre}$  and  $R_{ndr}$  resistances from the calibrated field analysis

method at EOD and BOR conditions. Analyze these data to obtain the resistance bias between the static analysis method and field analysis method at BOR conditions and at EOD conditions. Then, obtain the resistance median bias factors at BOR conditions,  $\alpha_{BOR}$ , and at EOD conditions,  $\alpha_{EOD}$ . A similar procedure (also shown in Table 1) can be used to obtain the median setup factor. Develop  $\alpha_{BOR}$ ,  $\alpha_{EOD}$ , and the setup factor for different combinations of typical conditions encountered in the design and construction of production piles in actual projects. For example, develop these factors for an H-pile driven into sand, using  $\beta$ -method as the static analysis method and wave equation analysis as the field analysis.

There are uncertainties in the procedure suggested above for estimating pile length in the design phase. Consequences of underestimating pile length are typically greater than overestimating pile length. Based on these consequences and the confidence in the developed  $\alpha_{BOR}$ ,  $\alpha_{EOD}$  factors, it is recommended to apply an appropriate safety factor to the estimated pile length.

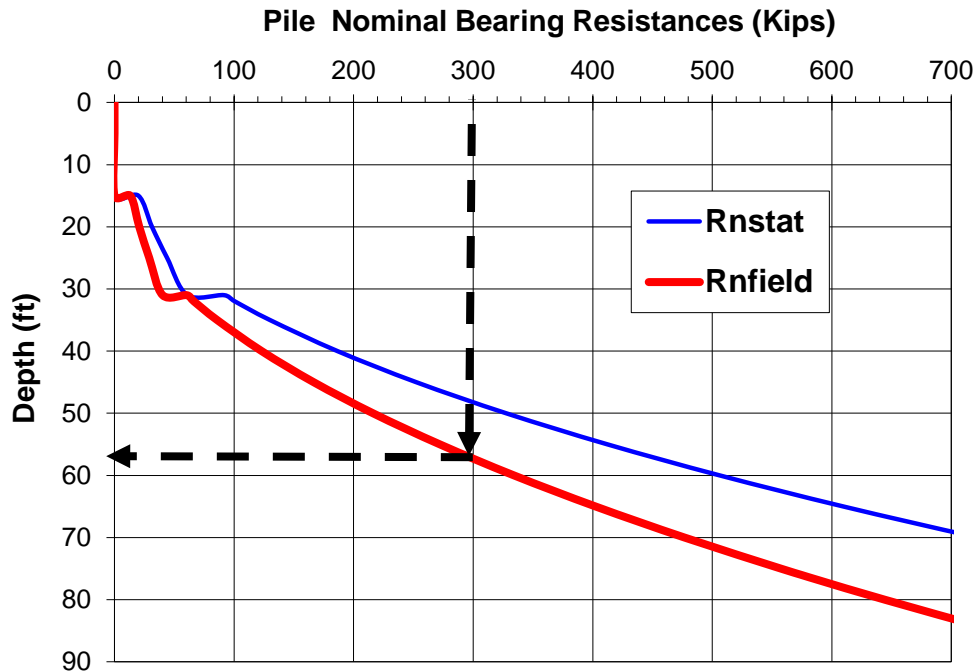
**Table 1. Developing the Resistance Median Bias Factors between a Field Method and a Static Analysis Method and Setup Factor (Assuming GL=0)**

<b>R<sub>nstat</sub> from a Static Analysis Method (Kips)</b>	<b>R<sub>nfield</sub> Resistances from a Field Analysis Method (Kips)</b>				<b>Setup (%) = (R<sub>nre</sub>-R<sub>ndr</sub>)/R<sub>ndr</sub></b>
	<b>EOD Conditions</b>		<b>BOR Conditions</b>		
	<b>R<sub>ndr</sub>, R<sub>nfield</sub></b>	<b><math>\alpha_{EOD} = R_{ndr} / R_{nsta}</math></b>	<b>R<sub>nre</sub>, R<sub>nfield</sub></b>	<b><math>\alpha_{BOR} = R_{nre} / R_{nsta}</math></b>	
625	410	0.66	512	0.82	25
633	504	0.80	610	0.96	21
571	308	0.54	381	0.67	24
489	409	0.84	470	0.96	15
853	475	0.56	590	0.69	24
550	426	0.78	533	0.97	25
817	412	0.50	515	0.63	25
<b>Median</b>		<b>0.66</b>		<b>0.82</b>	<b>23</b>

#### 4.0 Example Problem

**Problem.** A field analysis method at EOD conditions with a resistance factor ( $\phi_{dyn}$ ) of 0.5 is selected to finalize the pile length during construction in the field. In the design, it is required to estimate that pile length using  $R_{nstat}$  from a selected static analysis method and  $\alpha_{EOD} = 0.67$  as the resistance median bias factor between the selected field and static analysis methods. Estimate the design pile length needed to support  $Q_f = 150$  kips?

**Solution.** Estimates of  $R_{nstat}$  resistances at various depths from the static analysis method (Figure 1) are obtained and used to estimate estimates of  $R_{nfield}$  ( $= 0.67 R_{nstat}$ ) resistances at various depths from the field analysis methods at EOD conditions (Figure 1). Required  $R_{nfield}$  resistance is  $150/0.5= 300$  kips. Pile length is estimated as 57.5 ft from Figure 1 at the depth where  $R_{nfield}$  is equal to 300 kips. For the contract documents, include an estimated pile length of 60 ft and required  $R_{ndr}$  of 300 kips to finalize this length during construction in the field.



**Figure 1. Estimated Pile Bearing Resistances from Static and Field Analysis Methods**

## 5.0 Conclusion

This FHWA Geotechnical Solutions Notebook Issue describes with solved example a procedure to improve the agreement between the pile length estimated during design and the pile length finalized in the field. This procedure generates improved accuracy of the estimated pile field resistances,  $R_{nfield}$  resistances, through use of Eq. 3. To use this procedure, highway agencies should develop their local resistance median bias factors,  $\alpha$ , by compiling and analyzing predicted resistances from the static analysis methods and measured resistances from the field analysis methods as illustrated in Table 1. The conditions considered to develop the local resistance median bias should be similar to those used in the design and construction of driven piles.