The Loss of Pile Axial Capacities due to Scour: 
Vertical Stress Distribution

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ABSTRACT: Pile axial capacities can be decreased as a result of scouring around the pile foundations. This phenomenon is particularly evident for friction piles subjected to large scour depths. As part of study of the loss of pile axial capacities due to scour, this study investigates vertical soil stress at the pile under different scour-hole dimension conditions. An analytical solution based on Boussinesq’s theory is developed for the stress distribution. Comparisons are made between the present method and the other existing methods such as US FHWA manuals for driven piles and drill shafts. The effects of scour-hole dimensions including scour depth, width, and slope angles on the vertical soil stress distribution are discussed. As the scour depth or width increases, the vertical soil stress decreases and the stress distribution curves extend to a greater depth before converging at the constant line. The effect of scour-hole slope angle on vertical stress distribution depends on both scour depth and width. There exists a minimum scour width and a corresponding minimum scour depth at which the effect of scour-hole slope angle can be ignored.

INTRODUCTION

Bridge scour results in the loss of soils around the bridge foundations. The direct consequence of this process is the reduced foundation capacities including both lateral capacities and axial capacities. If the foundation capacity loss is substantial, scour damage will eventually extend to the superstructure, which may even cause the failure of an entire bridge. A handful of studies have been focused on the scour effects on lateral responses of bridge pile foundations (Lin et al., 2010, Lin et al., 2014, Lin et al., 2016, Zhang et al., 2017). However, scour effects on pile axial capacities have not been well studied. In practice, geotechnical engineers are often required to answer the loss of pile axial capacities under scour conditions when designing bridge pile foundations. Therefore, there are both research and practical significances in investigating this problem.

The current versions of US Federal Highway Agency (FHWA) manuals for drilled shafts and driven piles (Brown and Castelli, 2010, Hannigan et al. 2006) state the importance of scour effects in evaluation of pile axial capacities. However, both manuals outline the different approaches for estimating the pile axial capacities under scour conditions, which are briefly summarized below.

- FHWA driven piles (Hannigan et al. 2006): the pile axial capacity is computed from the post-scour ground level (i.e., Point C in Fig. 1). The influence of reduced overburden pressure due to only general and contraction scours is accounted for in estimating pile axial capacity while that due to local scour is ignored. This means even at Point C the vertical stress is not zero but calculated based on the ground level Point B.
FHWA drilled shafts (Brown and Castelli 2010): the pile axial capacity is computed from the post-scour ground level (i.e., Point C in Fig. 1). The influence of reduced overburden pressure due to all types of scour including local scour is accounted for in estimating pile axial capacity. The vertical stress of soils in the immediate vicinity of the pile is assumed to distribute linearly from ground level Point C to a depth of $1.5S_{d2}$ ($S_{d2}$ is scour depth due to local scour) as indicated in Fig. 1. Below this depth, the vertical stress is computed based on ground level Point B.

The procedure recommended by FHWA driven piles is oversimplified compared with that by FHWA drilled shafts. The former simply ignores the overburden pressure loss due to local scour while the latter considers this effect by assuming the linear distribution of vertical stress to a depth of $1.5S_{d2}$. Moreover, the former does not detail how to consider the overburden pressure loss in estimation of pile axial capacity. By contrast, the latter recommends the detailed procedures that employ the relationship between the stress history changes in the remaining (unscoured) soils and soil strength to compute pile axial capacity. Unfortunately, this recommendation only applies to sands but not to clays. The undrained strength of clays is considered to be irrelevant to the stress changes.

![Figure 1. Scour hole definition.](image)

The above methods for pile axial capacity under scour conditions can be interpreted simply as a loss of pile axial capacity in Table 1. In this table, the pile toe capacity is assumed to be independent of scour considering that pile embedment is often much deeper than the scour depth. From this table, the major difference of the two FHWA recommendations is the estimation of the unit side resistance loss due to the influence of reduced overburden pressure by scour. Since the unit side resistance is typically estimated by vertical stress of soils adjacent to the piles, it is important to determine the vertical stress changes before and after scour. Both methods have limitations in terms of vertical stress...
estimation. For FHWA driven piles, the ignorance of the overburden pressure loss due to local scour results in no change of soil vertical stress, which can be unconservative when local scour becomes remarkable. For FHWA drilled shafts, the suggested linear distribution of vertical stress to a depth of \( 1.5 S_{d2} \) is not based on a theoretical or empirical evidence. Moreover, such a linear distribution only applies to one scour-hole condition in which the top width of scour hole is limited to \( 2.0S_{d2} \) as suggested by FHWA HEC 18 (Arnesoz et al., 2012).

### Table 1. Comparison of methods for calculation of pile axial capacity loss.

<table>
<thead>
<tr>
<th>Scour types</th>
<th>Scour depth, ( S_d ) (( S_d=S_{d1}+S_{d2} ))</th>
<th>The loss of pile axial capacity, ( LQ ) (( LQ=LQ_1+LQ_2 ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>General and contraction scours</td>
<td>( S_{d1} )</td>
<td>( LQ_1 = f_{sd1}C(S_{d1}) ) + ( \Delta f_{s1}C(L_{em}) )</td>
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<td></td>
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<td>( LQ_1 = f_{sd1}C(S_{d1}) ) + ( \Delta f_{s1}C(L_{em}) )</td>
</tr>
<tr>
<td>Local scour</td>
<td>( S_{d2} )</td>
<td>( LQ_2 = f_{sd2}C(S_{d2}) ) + ( \Delta f_{s2}C(L_{em}) )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( LQ_2 = f_{sd2}C(S_{d2}) )</td>
</tr>
</tbody>
</table>

Note: \( LQ_1 \) is the loss of pile axial capacity due to general and contraction scours; \( LQ_2 \) is the loss of pile axial capacity due to local scour; \( C \) is circumference of the pile; \( f_{sd1} \) is the unit side resistance from soils within the depth of \( S_{d1} \); \( f_{sd2} \) is the unit side resistance from soils within the depth of \( S_{d2} \); \( \Delta f_{s1} \) is the reduction of unit side resistance due to the reduction of overburden pressure as a result of the removal of soils due to general and contraction scour; \( \Delta f_{s2} \) is the reduction of unit side resistance due to the reduction of overburden pressure as a result of the removal of soils due to local scour. This table assumes the pile toe capacity will not change as a result of scour.

The objective of this study was to investigate the vertical stress changes due to overburden pressure loss by local scour considering different scour-hole dimensions. The vertical stress ratio (post-scour to pre-scour) distribution of soils adjacent to the pile is obtained based on a theoretical derivation. The equation is derived by integrating the Boussinesq’s point load solution, which is then used to determine the vertical stress ratio distribution along the pile for various scour-hole dimensions as defined in Fig. 1. The outcome of this study will provide the basis for the overall goal of our study: estimation of the loss of pile axial capacity under scour conditions.

### SCOUR-HOLE MODEL AND STRESS DISTRIBUTION DERIVATION

In order to derive the vertical stress for estimating pile axial capacity, the model for scour hole and pile is shown in Fig. 2. The local scour hole is modeled as an inversed truncated circular cone characterized with a bottom width (\( S_{wb} \)), a scour depth (\( S_d \)), and a slope angle (\( \beta \)). In this way, an axisymmetric model is established. The pile is simplified as one dimensional with the pile diameter being neglected. This treatment although is simplified helps utilize the axisymmetric model to facilitate the derivation.
Based on the model in Fig. 2, the vertical stress induced by soils above Plane o-r can be computed by integrating the Boussinesq’s point load solution. The induced vertical stress due to the point load $dP$ is

$$d\sigma_z = \frac{3z^3dP}{2\pi(r^2+z^2)^{3/2}} \quad (1)$$

where $z$ is depth below the post-scour ground level; $r$ is the radial distance between applied point load and pile.

The vertical stress induced by soils above Plane o-r is called additional vertical stress ($\Delta\sigma_z$) herein. By integrating Eq. (1), the total additional vertical stress at the pile at a depth of $z$ is given by Eqs. (2) to (4)

$$\Delta\sigma_z = \int d\sigma_z = \int_0^\infty \int_0^{2\pi} \frac{p(r)z^3r}{2\pi(r^2+z^2)^{3/2}} d\theta dr + \int_0^\infty \int_0^{2\pi} \frac{p(r)z^3r}{2\pi(r^2+z^2)^{3/2}} d\theta dr \quad (2)$$

$$\Delta\sigma_z = 3z^3 \left( \int_{S_{wb}} \frac{\gamma'(r-S_{wb})(\tan\beta)r}{(r^2+z^2)^{3/2}} dr + \int_{S_{wt}} \frac{\gamma'(r-S_{wb})(\tan\beta)r}{(r^2+z^2)^{3/2}} dr \right) \quad (3)$$

$$\Delta\sigma_z = \gamma'z(\tan\beta) \left( \frac{S_{wt}}{S_{wt}^2+z^2} - \frac{S_{wb}}{S_{wb}^2+z^2} \right) \quad (4)$$

where $\gamma'$ is effective unit weight.

The top width of the scour hole ($S_{wt}$) can be substituted by scour depth ($S_{d2}$) using

$$S_{wt} = \frac{S_{d2}}{\tan\beta} + S_{wb} \quad (5)$$

Then Eq. (4) becomes
\[ \Delta \sigma_z = \gamma' z (\tan \beta) \left( \frac{S_{d2} + S_{wb}}{(S_{d2} + S_{wb})^2 + z^2} - \frac{S_{wb}}{S_{wb}^2 + z^2} \right) \]  

(6)

Total vertical effective stress at depth \( z \) is

\[ \sigma_z(\text{post-scour}) = \Delta \sigma_z + \gamma' z \]  

(7)

The post-scour to pre-scour vertical stress ratio (or normalized vertical stress) is expressed as

\[ N \sigma_z = \frac{\sigma_z(\text{post-scour})}{\sigma_z(\text{pre-scour})} = \frac{\Delta \sigma_z + \gamma' z}{\gamma'(S_{d2} + z)} \]  

(8)

In Eq. (8), the scour consists of only local scour for simplification as this study focuses on local scour effects on the changes of vertical stress and thus \( S_{d1} = 0 \). The effects of general and contraction scours on vertical stress are uniform, which can be easily accounted for during pile axial capacity calculation. Therefore, the pre-scour ground level refers to the ground elevation at Point B.

**RESULTS AND DISCUSSION**

Using Eq. (8), the normalized vertical stress distribution along the pile is determined. The result for \( S_{wb} = 0 \) and \( \beta = 26.6^\circ \) (equivalent to \( S_{wt} = 2S_{d2} \)) is plotted in Fig. 3 where the stress distributions based on the methods of FHWA driven piles and drilled shafts are also included for comparison. At different scour depths, the present method based on integration of Boussinesq’s solution shows general agreement with FHWA drilled shafts except that smaller vertical stress in the present method extends deeper than that in the FHWA drilled shafts (i.e., \( 1.5S_{d2} \)). In comparison, the FHWA driven piles determine much higher vertical stresses than both the present method and FHWA drilled shafts at shallower depths. Since FHWA driven piles neglect the loss of overburden pressure due to local scour, the vertical stress before scour and after scour remains the same, resulting in the normalized vertical stress equivalent to 1.0.
Fig. 3. Comparisons of vertical stress distribution at different scour depths ($S_{wb}=0, \beta=26.6^\circ$).

**Effects of scour depth on vertical stress distribution**

Fig. 4 shows the vertical stress distribution of soils along the pile at different scour depths. It can be seen from Fig. 4 that with the increase of scour depth, the vertical soil stress decreases at a same shallow depth. In addition, the curve for a higher scour depth extends to a greater depth before reaching 1.0. This result indicates that unless the local scour depth is very small, the ignorance of effect of local scour on the vertical soil stress change is not appropriate, which can lead to overestimation of vertical soil stress and thus pile axial capacity.

![Normalized vertical stress](image)

**Figure 4. Vertical stress distribution at different scour depths ($S_{wb}=0, \beta=26.6^\circ$).**
Effects of scour width on vertical stress distribution

Fig. 5 shows the vertical stress distribution varying with bottom scour width. The bottom scour width is called scour width for short from here on. As the scour width increases, the vertical soil stress decreases at the same depth. Moreover, the stress distribution curve for a higher scour width extends to a greater depth before reaching 1.0. When scour width increases beyond eight times pile diameter, the vertical stress distribution curve seems to approach a constant line. The above results imply that scour width can play an important role in vertical stress distribution, whose effects should not be ignored.

Effects of scour-hole slope angle on vertical stress distribution

Fig. 6 shows the vertical stress distribution varying with scour-hole slope angles. From the figure, the effects of scour-hole slope angles on vertical stress distribution also depend on scour depth and scour width. At a smaller scour width and a higher scour depth, the effect of scour-hole slope angle becomes more evident and vice versa.

Fig. 6 also shows that at certain levels of scour width and scour depth, effects of scour-hole slope angles vanish. When $S_d = 1D$ and $S_{wb} = 3D$, the effects of scour-hole slope angles on the vertical stress distribution almost disappear. In this case, the effect of scour-hole slope angles on vertical soil stress distribution can be ignored. Table 2 summarizes the minimum $S_{d2}$ and $S_{wb}$ at which the effect of scour-hole slope angles can be neglected.
CONCLUSIONS

This paper studies the vertical soil stress distribution considering different scour-hole dimensions using the equation that integrates the Boussinesq’s point load solution. Based on this study, several conclusions are drawn:

- The present method develops generally agreeable vertical stress distribution as FHWA drilled piles but much smaller vertical stress than FHWA driven piles at shallow depths. As such, the procedures recommended by FHWA drilled shafts are preferred than FHWA driven piles for a practical design purpose. However, since FHWA drilled shafts are only applied to one scour-hole dimension condition, its use has significant limitations. The present method offers solutions for various scour-hole dimension conditions and therefore shows advantages over both FHWA drilled shafts and driven piles.

- All scour-hole dimensions including scour depth, width, and slope angle affect the vertical stress distribution. As the scour depth or width increases, the normalized vertical stress decreases and the stress distribution curves extend to a greater depth before reaching a constant
value (i.e., 1.0). The effect of scour-hole slope angle on vertical stress distribution depends on both scour depth and scour width. At a certain level of scour depth and width, the effect of scour-hole slope angle can be ignored.

ACKNOWLEDGMENTS

The author appreciates the support of Canadian National and Science Engineering Research Council (NSERC) Discovery Grant.

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