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Geotechnical considerations in safe operation of crawler cranes

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ABSTRACT

Crawler cranes are commonly used in civil engineering construction. Occasionally, bearing failure or instability of crane supports have been reported across the world. There are a range of risks associated with crane operation and use. In practice, crane pads made of timber or fabricated steel are adopted to distribute the high loading pressure of the crawler crane. The interaction between the crane pad and soil is complicated, and depends on the pad stiffness and the strength and stiffness of the underlying soil. Studies on the bearing capacity and stability of crawler crane working on pads are rarely reported. In this paper, a review of existing design methods for stability of crane pads is provided. The geotechnical bearing capacity of crane pad is governed by both the shear strength of the soil and the allowable settlement criteria of the crane. Case studies are introduced and engineering implications for design are elaborated in the end.

Keywords: crawler crane, bearing capacity, settlement, slope stability, safe operation

1. INTRODUCTION

Crawler cranes are used frequently in civil engineering construction from house building to port and mining handling works. Movement around site of this type of crane is easy because the tracks enable them to travel over uneven ground and manoeuvre into tight working areas. Where soft ground is present, crane pads are typically used to distribute the crane loads. The working surface must be level and capable of supporting the bearing pressure exerted by the tracks. Figure 1 shows a typical crane track with a crane pad, which is most commonly used in practice. Loss of bearing or stability of crane supports have been observed to be the most common failure modes (Raymond, 2001; Zisman, 2012). These failures have caused significant damages to local communities or even loss of life. Crawler cranes are widely used for longer duration operations, and enjoy quick and routine movement over a short distances. There are several national and regional standards and guidance documents addressing the safe use of mobile cranes (AS1993; BS 2000; SS 2008, Workplace Health and Safety - Queensland 2006). These standards and guidance documents offer general insights into practical safe use of cranes in terms of mechanical aspects and OHS. However, geotechnical input in the design of safe operation of cranes is seldom considered or ignored. Liu et al. (2008) proposed a procedure to evaluate foundation support for crawler cranes. The design procedure is clear in concept, however the procedure is tedious and not suitable for top soils of sand or gravel (Stuart, 1962). Ooi et al. (2013) reviewed some working platforms for crawler cranes on soft ground in Malaysia. In the engineering industry, a simple and quick estimation method is required to obtain the allowable bearing pressure for the stability of crawler cranes. In general, the design process of crawler cranes should satisfy the following criteria: allowable soil stress, material allowable stress, and crane stability (Hasan, 2010). The geotechnical consideration in safe use of crawler cranes is elaborated in the paper in terms of bearing capacity and stability.
2. METHOD OF STATEMENT

In order to determine the type of crane pad required, it is necessary first to assess the bearing capacity of the ground. The bearing capacity depends on a number of factors including in-situ geotechnical conditions, sizes of crane tracks, allowable settlements and lifting load conditions et al. The current design methods of crawler cranes are based on the soil bearing capacity and mat strength. Purushothamaraj et al. (1974) proposed a method for bearing capacity of footing on two layered soils with varying cohesion, friction, and unit weight based on the second theorem of Drucker and Prager (kinematical consideration). The failure mechanism considered was fundamentally similar to that of Prandtl–Terzaghi but with different wedge angles. For simple, Terzaghi’s method for predicting ground bearing capacity is adopted in the engineering design.

The formula of ultimate bearing capacity is (Bowles, 1996)

\[
q_{\text{ult}} = cN_c s_c d_c + qN_q s_q d_q + 0.5yBN_y s_y d_y
\]

The allowable bearing capacity is

\[
q_a = \frac{q_{\text{ult}}}{SF}
\]

in which the bearing capacity factors

\[
N_q = e^{\tan \phi \tan^2 (45 + \frac{\phi}{2})}, \quad N_c = (N_q - 1) \cot \phi, \quad N_y = 2(N_q + 1) \tan \phi
\]

The shape factors

\[
s_c = 1.0 + \frac{N_q}{N_c} \cdot \frac{b}{L} \cdot \tan \phi, \quad s_q = 1.0 + \frac{b}{L} \tan \phi, \quad s_y = 1.0 - 0.4 \cdot \frac{b}{L}
\]

Depth factors

\[
d_c = 1, \quad d_q = 1, \quad d_y = 1
\]

In most engineering practice, the safety factor, SF=3 is typically used.

In the field, the load-settlement relationship established from a plate load test is expressed by a shape of Weibul distribution curve and it will be shown that the relationship can be estimated to some extent by the initial response of loading by numerical iteration (Fukagawa and Muro, 1994).

2.1. Effective pad width

In practice, an economic pad width will help distribute the load to the soil effectively. It is generally considered that the effective pad width depends on the type of soil the pad is resting on. Firm to hard soil strata cause limited soil contact, i.e., no settlement. When the pad stiffness is greater than the soil, there is a uniform soil pressure distribution is below the crane pad, provided that the bearing pressure is less than allowable soil stress. The full pad width is in contact with soil, and the settlement controls the design of crane pads. If the soil stiffness is greater than the crane pad, the soil underneath the crane pad experiences an uneven soil pressure distribution. In some extreme cases, weak timber crane pads will bend due to the soil pressure concentration. Crane pad may fail by bearing (crushing at the surface), bending or horizontal shear (splitting longitudinally). Figure 2 shows the crawler track load distribution on the crane pad. The angle of the load spread for the top soil is taken to be 1 vertical to 1 horizontal (i.e., 1V: 1H).
2.2. Pad width based on soil bearing capacity

In practice, it is important to carry out the ground classification based on the site investigation results. We have to determine the crane pad materials, i.e., timber or prefabricated steel.

![Figure 2. Model of theoretical effective pad width](image)

The design method is straightforward. The required crane pad area can be determined by dividing the crane loading over the allowable ground bearing pressure. Divide this area by the length of the track and we can get the required effective pad width. This pad width is adopted to calculate the bending and shear stresses in the pad based on the assumption of uniform soil pressure distribution. If the actual stresses are less than the allowable stresses, the pad design is acceptable.

2.3. Pad width based on pad strength

This method is the reverse of the method for pad width based on soil bearing capacity. The effective bearing length of the pad is assumed initially and is then adjusted until the resulting bending or shear stress reaches the corresponding allowable stress. The ground bearing pressure is then calculated assuming the effective bearing length. If the actual pressure is equal to or less than the allowable ground bearing pressure, the design of the pad is acceptable. The design method described herein is iterative. There are available commercial programs for crane designers to check the soil pressure or pad strength to determine the pad width. Geotechnical engineers normally provide the soil bearing pressure before the design of crane pad.

![Figure 3. Soil pressure distribution underneath crane pad for firm to hard soil](image)

![Figure 4. Soil pressure distribution underneath crane pad for soft ground soil](image)
2.4. Deformation and stability

Typically, some settlement and differential settlements are allowable depending on crane types, ground conditions and local standards. Settlement of the crane pad can be estimated using Schmertmann method and in situ soil moduli. Sometimes the crane may work on sloping ground and the global and local stability should be checked. An offset distance of the crane from the slope edge can be determined by the slope stability analysis. In practice, 2-D finite element software packages Plaxis and Geo-Studio are adopted to analysis crane loading stability problems. The loading of the crane is usually assumed as a plane strain problem.

3. DESIGN PRACTICE STUDIES

3.1. Bearing capacities of crawler cranes

An assessment of ground bearing capacity was undertaken for crane operation on a filled bund at a construction stockyard site. The following inputs were used for the design of the crawler crane pad:

a) The compacted gravel layer on top of the stockyard bund is 1.2 m, which overlies on a 2.7 m thick MA4-1 rockfill.

b) Assumed maximum allowable settlement of the crawler crane is 25mm which is equivalent to a tilt of 1/333 for the track spacing of 8.4 m (Note: this allowable settlement needs to be confirmed by the crane operator prior to a lifting operation, it may vary for different cranes).

In order to evaluate the top soil properties, plate load tests were carried out within crane’s working area. Figure 5 shows plate load test carried out at the top soil layer. The summary of the plate load test results are shown in Table 1.

![Figure 5. Plate load test in progress](image)

<table>
<thead>
<tr>
<th>Location</th>
<th>Test No.</th>
<th>Modulus of subgrade reaction ks (MPa/m)</th>
<th>Young’s Modulus E (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outbound Track</td>
<td>PLT1</td>
<td>572</td>
<td>102</td>
</tr>
<tr>
<td></td>
<td>PLT2</td>
<td>717</td>
<td>128</td>
</tr>
<tr>
<td>Inbound Track</td>
<td>PLT1</td>
<td>526</td>
<td>94</td>
</tr>
<tr>
<td></td>
<td>PLT2</td>
<td>431</td>
<td>77</td>
</tr>
</tbody>
</table>

The permissible bearing pressure for a crawler crane with 2 m wide tracks is 400kPa based on the shear failure bearing capacity theory. The maximum bearing pressure recommendation is based on a factor of safety of 3 against bearing capacity failure, and a typical settlement
tolerance of 25mm. This permissible pressure is also applicable for a crane with 1.5 m to 3.5 m wide tracks and/or load spread pads. Indicative maximum bearing pressures for the range of footing widths considered is presented in Figure 6. It should be noted that the recommended maximum bearing pressures presented make no allowance for any simultaneous horizontal load or vertical load eccentricity, as the presence of either may have a reducing effect on the maximum bearing pressure recommendations.

**Figure 6. Bearing capacity of shallow foundations**

### 3.2. Deformation and stability analysis of crane foundation

A stability and settlement assessment was undertaken for crane pad foundations at a stockyard site. The cross sections of the trial embankment modelled is shown in Figure 7.

**Figure 7. Numerical model of crane working platform**

The numerical modelling was carried out based on the following conditions:

- The internal berm slope is 1 (vertical) to 1.7 (horizontal).
- The upper course of the embankment comprises a one metre thick layer of select fill compacted to 98% MMDD.
- The embankment is to be constructed using gravel or rock fill compacted to 98% MMDD, to achieve a minimum friction angle of 38 degrees.
- The subgrade below the track is to be improved with concrete.

The input geotechnical parameters of the model are summarized in Table 2. The crane pads were modelled as linear elastic model with $k=24kN/m^3$, $E=25Gpa$, and $\mu=0.2$.

**Table 2: Summary of input parameters**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Ferricrete</th>
<th>Colluvium</th>
<th>Backfill</th>
<th>Embankment Gravel</th>
<th>Compact Fill</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil Model</td>
<td></td>
<td>MC</td>
<td>MC</td>
<td>MC</td>
<td>MC</td>
<td>MC</td>
</tr>
<tr>
<td>Unit Weight ($kN/m^3$)</td>
<td>$\gamma$</td>
<td>23</td>
<td>20</td>
<td>20</td>
<td>21</td>
<td>20</td>
</tr>
<tr>
<td>Elastic Modulus</td>
<td>$E$</td>
<td>150</td>
<td>60</td>
<td>40</td>
<td>60</td>
<td>60</td>
</tr>
</tbody>
</table>
The stability of the cranes working on the berm was assessed using limit equilibrium methods for both static and seismic loading conditions. Three loading cases were considered for the analysis as summarized in Table 3.

**Table 3: Summary of loads for cranes**

<table>
<thead>
<tr>
<th>Location</th>
<th>Distance* (m)</th>
<th>Load Case I (LCI)</th>
<th>Load Case II (LCII)</th>
<th>Load Case III (LCIII)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Total load (kN/m)</td>
<td>Total load (kN/m)</td>
<td>Total load (kN/m)</td>
</tr>
<tr>
<td>A</td>
<td>16.38</td>
<td>193</td>
<td>13</td>
<td>186</td>
</tr>
<tr>
<td>B</td>
<td>16.38</td>
<td>199</td>
<td>13</td>
<td>189</td>
</tr>
<tr>
<td>C1</td>
<td>5.46</td>
<td>426</td>
<td>30</td>
<td>448</td>
</tr>
<tr>
<td>C2</td>
<td>5.46</td>
<td>426</td>
<td>30</td>
<td>448</td>
</tr>
</tbody>
</table>

Note: Loading Case I (LCI) - normal operation  
Loading Case II (LCII) - normal op. w/ wind + skew loads  
Loading Case III (LCIII) - abnormal operation  
Distance is the centre of the crane to the slope crest.

The stability of the berm under the three loading conditions was calculated by using limit-equilibrium methods. For seismic loading conditions, an acceleration coefficient of $a = 0.09g$ was adopted. Under normal operation loading case (static), the safety factor of crane foundation berm is about 1.43, higher than 1.3 for the abnormal loading case. However, it is just slightly less than 1.5. The safety factors of crane working under different loading combination cases are summary in Table 4. All safety factors under seismic loading conditions are higher than 1.1, which are deemed acceptable.

**Table 4: Safety factors of cranes under different loading cases**

<table>
<thead>
<tr>
<th>Location</th>
<th>Safety Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Loading Case I (LCI)</td>
</tr>
<tr>
<td></td>
<td>Static</td>
</tr>
<tr>
<td>A &amp; B</td>
<td>1.81</td>
</tr>
<tr>
<td>C1 &amp; C2</td>
<td>1.43</td>
</tr>
</tbody>
</table>

The summary of numerical modelling for crane pad foundation is listed in Table 5. It can be found that for loading combination at B & C, the settlement is more critical. However, for the vertical stress beneath the crane pad foundation does not change too much. The numerical results for the crane foundation are presented from Figure 8 to Figure 10. The maximum settlement of crane foundation is approximately 30 mm based on the available information and worst loading conditions, which is considered acceptable. The maximum stress under the crane foundation is 550 kPa based on our numerical modelling results, which is lower than the designed unconfined compression strength of 1 MPa.
Table 5: Summary of Settlements and Vertical Stresses of crane foundation

<table>
<thead>
<tr>
<th>Case</th>
<th>Location</th>
<th>Max Settlement (mm)</th>
<th>Max Vertical Stress under Concrete footing (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCI</td>
<td>A &amp; B</td>
<td>18</td>
<td>174</td>
</tr>
<tr>
<td></td>
<td>C1 &amp; C2</td>
<td>29</td>
<td>373</td>
</tr>
<tr>
<td>LCII</td>
<td>A &amp; B</td>
<td>7</td>
<td>188</td>
</tr>
<tr>
<td></td>
<td>C1 &amp; C2</td>
<td>22</td>
<td>453</td>
</tr>
<tr>
<td>LCIII</td>
<td>A &amp; B</td>
<td>6</td>
<td>170</td>
</tr>
<tr>
<td></td>
<td>C1 &amp; C2</td>
<td>30</td>
<td>532</td>
</tr>
</tbody>
</table>

Figure 8. Vertical displacement of crane foundation for LC III (C1 and C2)

Figure 9. Settlement at the base of crane foundation for LC III (C1 and C2)
4. CONCLUSIONS

The geotechnical issues in safe operation of crawler cranes have been reviewed and outlined in this paper. Bearing capacity calculation of crane pad is outlined in terms of design based on soil bearing capacity and pad strength. Two design practice studies are elaborated to address the design concerns encountered in daily geotechnical professional work, namely bearing capacity and deformation. The paper offers a general insight of geotechnical considerations of crawler cranes working on different ground profiles and loading conditions.

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