Evaluation of measurements for vibratory hammers

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ABSTRACT: The liquefaction process for conventional pile driving is often very time consuming and therefore expensive. Projects should be completed faster if all aspects of construction work are performed in parallel. Impressive strides in productivity are being made for vibratory pile hammers. However, comparison of capacity in terms of energy required to design working piles. Traditionally, either extensive static testing or testing under subcritical conditions has been used to determine capacities and impact hammers have been modified and updated. This paper presents the results of a study to evaluate the performance of vibratory hammers. The study was performed by a vibratory hammer at two sites. Both piles were driven to final elevation by a conventional impact hammer. Measurements were made to assess the performance of the vibratory hammer.}

2 SITE CONDITIONS AND INSTALLATION PROCEDURES

The 60-ft diameter masonry piles were installed at two offshore locations (G & Associates, Inc., 1983) referred to as A and B, respectively. Details of the pile geometries and site conditions at the locations are presented in Tables 1 and 2.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Length (ft)</th>
<th>Penetration (ft)</th>
<th>Pile description</th>
</tr>
</thead>
<tbody>
<tr>
<td>111</td>
<td>145</td>
<td>85</td>
<td>1 inch wall and 40 ft section with 1.5 ft in wall</td>
</tr>
<tr>
<td>114</td>
<td>130</td>
<td>85</td>
<td>1 inch wall with 70 ft section of 1.5 ft</td>
</tr>
</tbody>
</table>

Both piles had internal baffles located at the transition location.

1.5 Pile installation monitoring and analysis

For impact measurements and analysis of liquefaction PDA pile monitoring systems have been used (Hanes, Goble, et al., 1986) with sensors attached approximately 17 ft below the pile tops. Since the PDA system balances the energy flow between relative energy dissipated at high strain rate and a different set of signal conditioning equipment required for the steady state hammer. It is desirable to control the energy being dissipated and used for the hammer. The data was recorded on an FM instrumentation tape recorder and reviewed on an oscilloscope.

For all vibratory hammers, acceleration and strain data were collected from the tape recorder through a 100 Hz Low-pass filter and amplified at 2000 samples per second for each channel. The following conclusions were then performed:

<table>
<thead>
<tr>
<th>Reference</th>
<th>Penetration (ft)</th>
<th>Soil description</th>
</tr>
</thead>
<tbody>
<tr>
<td>111</td>
<td>85</td>
<td>Clayey fine sand</td>
</tr>
<tr>
<td>114</td>
<td>85</td>
<td>Gravel to sandy clay</td>
</tr>
<tr>
<td>14</td>
<td>50</td>
<td>Medium dense fine sand</td>
</tr>
<tr>
<td>15</td>
<td>50</td>
<td>Dense fine sand</td>
</tr>
<tr>
<td>6</td>
<td>50</td>
<td>Fine to very stiff clay</td>
</tr>
<tr>
<td>7</td>
<td>50</td>
<td>Dense fine sand</td>
</tr>
</tbody>
</table>

Table 2: Soil Conditions

<table>
<thead>
<tr>
<th>Reference</th>
<th>Penetration (ft)</th>
<th>Soil description</th>
</tr>
</thead>
<tbody>
<tr>
<td>111</td>
<td>1</td>
<td>Clayey fine sand</td>
</tr>
<tr>
<td>111</td>
<td>2</td>
<td>Gravel to sandy clay</td>
</tr>
<tr>
<td>111</td>
<td>3</td>
<td>Medium dense fine sand</td>
</tr>
<tr>
<td>111</td>
<td>4</td>
<td>Dense fine sand</td>
</tr>
<tr>
<td>111</td>
<td>5</td>
<td>Fine to very stiff clay</td>
</tr>
<tr>
<td>111</td>
<td>6</td>
<td>Dense fine sand</td>
</tr>
</tbody>
</table>

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1. Integration of acceleration to velocity including an inte-
geration constant (the average penetration rate). Integra-
tion of velocity to displacement.
2. Addition of the hammer weight to the measured force.
3. Integration of the product of force and velocity to yield
transformed energy in a time function. Calculate power by
dividing transformed energy by the time period.
4. Calculation of "load resistance" by rigid body assump-
tions.
5. Calculation of the Fourier coefficients of acceleration and
time. Calculation of a dynamic surcharge by dividing
the first coefficient by the corresponding displacement
values.

All resulting time and frequency curves were plotted and
measured, and amplitudes and spans were determined
and are summarized in Tables 3a and 3b. A sample plot
result is included in Figure 9.

FIDA results were obtained under the impact hammer
from the beginning to the end of impact pile driving. In
the present case, the primary interest was the correlation
between bearing capacity predictions from the end of
voluntary driving records and the beginning of impact
testing. Therefore, a very early record of the impact driv-
ing of each pile was analyzed by CAPWAP.

### Table 3a. Summary of volatility results, Pile 111

<table>
<thead>
<tr>
<th>Post.</th>
<th>Rate</th>
<th>Freq.</th>
<th>First</th>
<th>Span</th>
<th>Accl.</th>
<th>Power</th>
<th>Resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>ft</td>
<td>ft/s</td>
<td>Hz</td>
<td>kips</td>
<td>g/s</td>
<td>kips</td>
<td>HP</td>
<td>Max. kips</td>
</tr>
<tr>
<td>30</td>
<td>.167</td>
<td>17.6</td>
<td>423</td>
<td>3.9</td>
<td>66.6</td>
<td>-178</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>.256</td>
<td>17.6</td>
<td>458</td>
<td>3.4</td>
<td>79.0</td>
<td>364</td>
<td>-260</td>
</tr>
<tr>
<td>41</td>
<td>.123</td>
<td>16.6</td>
<td>499</td>
<td>4.0</td>
<td>184</td>
<td>426</td>
<td>-473</td>
</tr>
<tr>
<td>43</td>
<td>.009</td>
<td>16.6</td>
<td>610</td>
<td>5.8</td>
<td>173</td>
<td>421</td>
<td>-479</td>
</tr>
</tbody>
</table>

### Table 3b. Summary of volatility results, Pile 114

<table>
<thead>
<tr>
<th>Post.</th>
<th>Rate</th>
<th>Freq.</th>
<th>First</th>
<th>Span</th>
<th>Accl.</th>
<th>Power</th>
<th>Resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>ft</td>
<td>ft/s</td>
<td>Hz</td>
<td>kips</td>
<td>g/s</td>
<td>kips</td>
<td>HP</td>
<td>Max. kips</td>
</tr>
<tr>
<td>15</td>
<td>.167</td>
<td>16.6</td>
<td>411</td>
<td>8.4</td>
<td>145</td>
<td>430</td>
<td>-435</td>
</tr>
<tr>
<td>35</td>
<td>.208</td>
<td>16.6</td>
<td>423</td>
<td>7.8</td>
<td>138</td>
<td>404</td>
<td>-311</td>
</tr>
<tr>
<td>45</td>
<td>.075</td>
<td>15.6</td>
<td>451</td>
<td>10.8</td>
<td>187</td>
<td>390</td>
<td>-473</td>
</tr>
<tr>
<td>46</td>
<td>.017</td>
<td>15.6</td>
<td>520</td>
<td>6.5</td>
<td>107</td>
<td>613</td>
<td>-670</td>
</tr>
</tbody>
</table>

### 2 Discussion of Results

2.1 Results from Fourier Analysis

The Fourier coefficients of both acceleration and force
outlined the very dominant peak of the hammer-based
transient at 17 Hz (Fig. 9). The 17 Hz excitation was identi-
cally indicated in the acceleration records of Pile 111.
For Pile 114, the 17 Hz transient (60 to 80 Hz) of the hammer frequency is
very near the pile's base frequency and the pile frequency
was seen apparent in the record.

An attempt was made to use the Fourier analysis for a
measurement of soil response. Probably, the low frequency
solutions can be related to the soil response. How-
ever, at this time no experience exists and further study
is needed.

2.2 Hammer Performance

For the vibratory hammer, no readily available mean-
performance data exists in terms of power, maximum force,
which with which to compare the current results.
However, these quantities may be compared with manufacturer's
specifications. For example, the read 10 kip-inarcy
moment produces centrifugal forces of 250 kips at a fre-
frequency of 17 Hz (the most common observed hammer
speed). The force amplitude (peak-to-peak) would then be
590 kips. The observed force span amplitudes ranged from
200 and 520 kips. The higher stresses are due to extreme
stress concentrations under the clamp, and the low average
value pile stresses are therefore commercial as far as the
potential of pile damage is concerned.

The maximum power transmitted to the piles was 187 HP.
Thus, of, average, appreciable energy (power) remaining
in the hammer itself (rotating weights, etc.) and it is not
known how much power was actually transmitted.
Furthermore, the power output depends on the hammer's operat-
ing frequency which was always less than the read 20 Hz.
All of these reasons help explain why, at most, only 36% of
the read power (350 HP) was transferred to the pile.

### Soil Resistance and Bearing Capacity

The soil resistance was calculated under the vibratory
hammer based on a rigid body pile model. It is justified
since the driving frequency (17 Hz) is much less than
the pile's natural frequency (about 60 Hz). The results,
however, are only intended as a general idea since the
analysis (Avery-West) is therefore a measure of the resistance
of the hammer at the time of driving.
The following values are presented under the
hammer and the negative under upward pile motions
and are made for any dynamic soil resistance effects.
Since vibratory methods are less than 50% effective,
vertical forces were probably also small. It is
believed that the resistances encountered are about certain
damped motions however, the static resistance is
not degraded (degradation, no set-up considered). Reducing
Fig. 1. Data for Pile 114 at a) 15 ft above final elevation and b) final elevation.

The total resistance encountered by the dynamic component (maybe as much as 20% in the sand) would therefore not improve the accuracy of this prediction as perhaps the two effects cancel.

The positive resistance values encountered at the end of vibratory driving were 823 kips for Pile 111 and 633 kips for Pile 114, respectively. The corresponding CAPWAP (Rausch, Moses, Getle 1972) results from the early driving were 474 and 605 kips. The good correlation between the soil resistance results from vibratory and impact data is rather encouraging. Actually, this good correlation may be a coincidence because (a) no dynamic (damping) influence was deducted from the total vibratory resistance. (The vibration occurred after the time of the
(right) positive pie velocity but below the velocity zero) and (b) the static resistance occurring during vibratory driving is usually thought to be the same as the static resistance occurring during impact driving (pulverization).

It should be noted that a trial run in CAPWAP significant importance in which were required in the pile model. For both piles the resistance was increased in the buff area. The performance of the heavy wall section was increased for both piles (but particularly high variance were made for Pile 114). These could be most effects of the set or perhaps more than local stress concentrations due to se buff piles near the monopole jacketing.

A static analysis for Pile 114 using APA ZP 5A (1980) spreadsheet gave 477 kips ultimate shaft resistance (reduced to actual 40-inch pile from calculating 38-inch pile-resist) which is in good agreement with both dynamic measurement results. For Pile 111, the similarly predicted shaft resistance was 377 kips, also in good agreement; however, the end bearing was over predicted in the static analysis.

3 CONCLUSION

A method of measurement and analysis of dynamic data acquired during vibratory driving is presented. Capacity calculated from the Vibratory driving torque frequently with both static analysis prediction and dynamic impact test analysis using CAPWAP. Comparisons of forces and power were lower than the manufacturer's rated values.

REFERENCES