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Analysis and Measurement of Foundation Vibrations at Two Compressor Stations in Yugoslavia

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SYNOPSIS: The design procedure and the measurements of foundation vibrations at two compressor stations are presented. Simple methods and models were used to predict machine foundation behavior and it is shown that they were effective in estimating the expected range of amplitudes through simple parameter variation.

In attempt to lower vibrations amplitudes, spreading of gravel layer under machine foundation was suggested, the effect of which is discussed in the paper.

INTRODUCTION

The basic goal in the machine foundation design is to keep its motion in the limits which will enable the satisfactory operation of the machine without disturbing the people in the immediate vicinity. Thus, to achieve this goal, it is expected from the designer to correctly predict the machine foundation motion. As shown in figure 1, the prediction of machine foundation vibrations is a system which involves (1) the determination of machine loads and selection or first guess of the shape and mass of foundation (if it is not predefined due to other reasons), (2) the evaluation of soil profile and soil properties, (3) the selection and application of adequate method of analysis. The design procedure requires additional step: establishment of acceptance criteria. If the predicted motion does not meet these criteria (and all other steps are properly done), it would usually require the change in geometry and mass of the proposed foundation, or, in some cases, improving the soil properties.

According to Gazetas (1983), the post construction observation of foundation performance is also "an additional and often overlooked step in machine foundation design". The measured response foundation on dynamic machine loads serves as a reliable source of information for verification of the whole design procedure:

a) comparison of real performance with established criteria

b) data for numerical comparison of measured and predicted vibrations.

Since it is not easy to separate the influences of all relevant factors needed for prediction of motion, the measured vibrations could be for instance used in (keeping other factors unchanged):

- verification of assumptions and models on which the method of analysis is based
- correlating the soil properties estimated from ground investigations with those obtained from back analysis with particular method
- verification of proposed design measures for reducing amplitudes of vibrations.

The experience gained from such analyses improves...
ves the design procedure and understanding of the nature of the problem.

In this paper the design procedure and post-construction observation of the compressor foundation in two compressor stations is presented.

The geometry and mass of compressor foundation in both cases came out satisfying other design requirements. Since the mass of the foundations was more than five times the weight of the supported machines, according to some "rules of thumb" no analysis of vibration would be necessary. The ground investigations on both sites showed that surface layers were of poor characteristics and it was decided to substitute them with densified gravel. Relatively simply-to-use analysis according to Richart, Hall and Woods (1970) and Gazetas (1983), using only dominant loads, were performed "just to verify" additional costs.

Finally, post-construction measurements were undertaken to "everybody make sure".

COMPRESSOR STATION LEGRAD

Compressor station Legrad (c.s.Legrad) was settled in 1985. It consists of eleven compressors, eight compressors, type C-200, and three, type C-100.

Soil characteristics were determined by geotechnical investigations and geophysical measurements (Fig.2).

Upper two meters of poor characteristics were substituted with gravel layer. Shear wave velocity (Vs) of sand was measured by surface refracti-voni method; range of Vs was from 220 to 250 m/s, what correspond to values of shear modulus of 700 MN/m2.

The shear modulus of gravel was estimated as 100 MN/m2.

Dominant unbalanced inertia forces act in longitudinal direction (Fig.2). According to the manufacturer of compressors the foundations must be designed to resist the following forces (dynamic loads):

<table>
<thead>
<tr>
<th>Type</th>
<th>Maximum longitudinal primary force</th>
<th>Maximum longitudinal secondary force</th>
<th>Operating frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-200</td>
<td>11.8 kN</td>
<td>3.40 kN</td>
<td>294 c/min</td>
</tr>
<tr>
<td>C-100</td>
<td>20.1 kN</td>
<td>5.67 kN</td>
<td>353 c/min</td>
</tr>
</tbody>
</table>

Compressor foundations were designed as massive concrete blocks (Fig.2) separated 1,0 m from each other. Mass of one compressor and foundation was 46.3 t. Schematic presentation of foundation layout is in the Fig.3.

Analyses were performed by two methods:

- lumped parameter approximation (Richart et al, 1970) and dynamic impedance functions as described in Gazetas (1983). The acceptance criteria were adopted from Richart et al (1970).

![Figure 2. Croosssection of a foundation and soil in C.S.Legrad](http://ICCHGE1984-2013.mst.edu)

![Figure 3. Layout of compressors in C.S.Legrad](http://ICCHGE1984-2013.mst.edu)
Only the compressors of type C-100 using primary forces were analyzed on two models:

I foundation on the surface of elastic half-space
\[ G = 100 \text{ MN/m}^2, \, \nu = 0.33 \]

II as I, but \( G = 50 \text{ MN/m}^2 \)

The first model was assumed to be "the real" one, and second "the worst" one, covering the neglected or unexpected influencing factors with variation of single parameter - \( G \).

The results of the analyses are presented in Table I.

Table I Calculated values of amplitudes of longitudinal vibrations - C.S.Legrad

<table>
<thead>
<tr>
<th>Case</th>
<th>Richart et al (( \mu m ))</th>
<th>Gazetas (( \mu m ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>19.8</td>
<td>19.7</td>
</tr>
<tr>
<td>II</td>
<td>40.8</td>
<td>38.2</td>
</tr>
</tbody>
</table>

For cases analyzed, two methods correspond quite well.

The measurements were taken while nine of eleven compressors were simultaneously in operation (compressors C-103 and C-201 were not prepared). The measured amplitudes of vibrations are presented in Table II.

Table II Measured values of amplitudes of vibrations - C.S.Legrad

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>Vertical</th>
<th>Transv.</th>
<th>Longit.</th>
<th>frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(( \mu m ))</td>
<td>(( \mu m ))</td>
<td>(( \mu m ))</td>
<td>Hz</td>
</tr>
<tr>
<td>C-101</td>
<td>6</td>
<td>2</td>
<td>34</td>
<td>6.2</td>
</tr>
<tr>
<td>C-102</td>
<td>1</td>
<td>2</td>
<td>30</td>
<td>6.2</td>
</tr>
<tr>
<td>C-202</td>
<td>1</td>
<td>2</td>
<td>20</td>
<td>5</td>
</tr>
<tr>
<td>C-203</td>
<td>5</td>
<td>4</td>
<td>18</td>
<td>5</td>
</tr>
<tr>
<td>C-204</td>
<td>2</td>
<td>2</td>
<td>18</td>
<td>5</td>
</tr>
<tr>
<td>C-205</td>
<td>3</td>
<td>1</td>
<td>23</td>
<td>5</td>
</tr>
<tr>
<td>C-206</td>
<td>1</td>
<td>1</td>
<td>28</td>
<td>5</td>
</tr>
<tr>
<td>C-207</td>
<td>1,5</td>
<td>1</td>
<td>21</td>
<td>5</td>
</tr>
<tr>
<td>C-208</td>
<td>1</td>
<td>2</td>
<td>20</td>
<td>5</td>
</tr>
</tbody>
</table>

Typical plot of measured vibrations is shown on Fig.4.

The intensity of amplitudes changed periodically showing low frequency "superior" influence. Anyhow, the average amplitude (cca 20 \( \mu m \) for type C-100) corresponded well to predicted amplitudes using the model with best estimate of soil properties. The rest between 20 and 30 \( \mu m \) is attributed to the influence of neighbouring compressors or unbalanced secondary forces.

Shear wave velocity of clay in upper three meters was between 140 and 160 m/s, so shear modulus of clay was supposed to be 50.0 MN/m2. Shear wave velocity in sand ranged from 225 to 250 m/s and estimated shear modulus was 100 MN/m2.

Dominant unbalanced inertia forces act as horizontal moments (torque). According to the manufacturer of compressors their amplitudes were:
- maximum vertical moment: 4.16 kNm
- maximum horizontal primary moment: 15.2 kNm
- operating frequency: 740 c/min

Compressor foundations were designed as massive concrete blocks (Fig.5.) separated 3.0 m from each other. Mass of one compressor and foundation was 93.5 t.

Analysis was performed according to Gazetas (1983) and soil profile was modelled as (clay) stratum-over-(sand) half-space. It was difficult to estimate the positive influence of embedment with much confidence and it was conservatively neglected. The results are presented in Table III (case I).

Since the radial amplitudes were considered to be high and since there was not confidence in clay as direct foundation supporting soil, it was decided to substitute the clay above ground water level with one meter thick densified gravel layer. The gravel and the rest of the clay layer were separated with dense geotextile. The shear modulus of gravel was assumed as \( G = 100 \text{ MN/m}^2 \).

The analyses were performed in the same way as before using two models:

a) foundation on half-space with \( G = 100 \text{ MN/m}^2 \) (thus, neglecting the clay sublayer). case II in Table III.

b) foundation stratum-over-halfspace with stratum having the "average" modulus \( G = 80 \text{ MN/m}^2 \), thickness \( h = 2 \text{ m} \) and half-space with sand properties (\( G = 100 \text{ MN/m}^2 \)) - case III in Table III. The embedment effects were again neglected in analysis.
LONGITUDINAL DIRECTION

Figure 5. Crosssection of soil and foundation in C.S. Bokšić

Table III Calculated amplitudes of vibrations at corners of foundations - C.S. Bokšić

<table>
<thead>
<tr>
<th>case</th>
<th>longitudinal (μm)</th>
<th>vertical (μm)</th>
<th>radial (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1,1</td>
<td>4,2</td>
<td>23,2</td>
</tr>
<tr>
<td>II</td>
<td>0,6</td>
<td>2,3</td>
<td>5,9</td>
</tr>
<tr>
<td>III</td>
<td>0,8</td>
<td>2,7</td>
<td>11,3</td>
</tr>
</tbody>
</table>

The measurements were taken in the middle (M) and at the corners (C) of the foundation edge for three foundations C1, C2 and C3 (table IV).

Table IV Measured values of amplitudes

<table>
<thead>
<tr>
<th></th>
<th>longitudinal (μm)</th>
<th>vertical (μm)</th>
<th>radial (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1 (M)</td>
<td>0,4</td>
<td>0,8</td>
<td>1,08</td>
</tr>
<tr>
<td>(C)</td>
<td>0,4</td>
<td>1,25</td>
<td>1,33</td>
</tr>
<tr>
<td>C2 (M)</td>
<td>0,9</td>
<td>1,2</td>
<td>2,19</td>
</tr>
<tr>
<td>(C)</td>
<td>0,9</td>
<td>1,2</td>
<td>2,5</td>
</tr>
<tr>
<td>C3 (M)</td>
<td>1,2</td>
<td>1,7</td>
<td>2,5</td>
</tr>
</tbody>
</table>

Comparing the results of estimated and observed vibrations it may be concluded that amplitudes were considerably lowered by putting the gravel layer under foundation.

The order of magnitude of vibrations is 1 mikron and it could not be felt (by humans) when the hand was put on the foundation.

Figure 6. Layout of compressors in C.S. Bokšić

CONCLUSIONS

The design procedure and the results of measurements of foundation vibrations at two compressor stations are presented. The design procedure attempts to cover unfavourable conditions selected by engineering judgement and includes the best estimate of soil properties and relatively simple models and methods of analysis. During design, it was decided to improve the soil conditions by replacing the natural soil in shallow depths by densified gravel.

The observed performance supports the actions undertaken, showing that the measured amplitudes are in the range of predicted values.

It may be concluded that simple methods and models are effective in design practice allowing estimate of the expected range of amplitudes through simple parameter variations. Also spreading a relatively thick gravel layer under machine foundation is considered to be an effective low cost measure towards the lowering of the amplitudes of vibrations. This effect is primarily attributed to the increased stiffness of soil which directly supports the foundation.

ACKNOWLEDGMENTS

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REFERENCES
