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A Case Study on Decreasing Vibration of Machine Foundations and Structures

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SYNOPSIS
Foundations under 3 compressors rested on a clay base. With the secondary exciting frequency falling into resonance region, the vibration velocity of foundations reached 8.96 mm/s, exceeding the permissible limit. It was reduced to 4.0 mm/s through the use of combined foundation, thus ensuring normal production.

INTRODUCTION
It is customary to use combined foundation for decreasing vibration of foundations, but so far little research has been done on vibration characteristics of combined foundation and its computing method. While in some countries the provisions are available on vibration computation of combined foundation, certain blindness and incorrectness are involved therein. To eliminate these drawbacks we made special study on combined foundation. The results show that by employing combined foundation the vibration of foundation was decreased only under certain but not all conditions, and that vibration-decreasing effects may vary under different conditions. Consequently, in treating foundations under 3 horizontal compressors we first grasped from forced vibration test the resonance frequencies of foundations and other dynamic characteristics of base. The test results indicate that resonance frequencies of foundations are slightly greater than the secondary exciting frequency of compressors, which provides a sound basis for employing combined foundation. Meanwhile we also made a dynamic model test of combined foundation. Space limitations of this paper permit only presentation of details and practical effect of treating foundations under 3 compressors as well as relevant results of dynamic model test with theoretical background omitted.

Origin of the Problem
The operational speed of 3 large compressors of 3 M-16 type in a chemical plant is 375 rpm. From computation the first and secondary simple harmonic exciting forces in the direction of piston sliding \( P_x = 0 \) and 4.54 T, the moments about Z axis \( M_z = 13.8 \) and 2.7 T·m respectively. Due to imperfect design the maximum horizontal vibration velocities induced by the first and secondary simple harmonic exciting forces reached 0.95 and 8.0 mm/s respectively. The horizontal vibration velocity of shop roof truss reached 8.5 mm/s. As a result, normal shop production and normal work in neighbouring offices were seriously affected. We were asked to strengthen these foundations without interrupting production.

Test of Dynamic Characteristics of Foundations
For proper selection of treating scheme for decreasing foundation vibration, first of all, two foundations (N-1 and N-2) were tested under horizontal forced vibration. A variable-frequency mechanical vibrator was used, maximum exciting force of which may reach 3.7 tons. The base area of each single foundation is 48.5 m\(^2\), its weight is about 300 T. And the section of the foundations are shown in Fig 1.

Table I. Physical Characteristics of Base Soil

<table>
<thead>
<tr>
<th>Water Degree</th>
<th>Void Ratio</th>
<th>Liquid Limit</th>
<th>Plastic Limit</th>
<th>Plasticity Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>W(%)</td>
<td>S_r(%)</td>
<td>( e )</td>
<td>( W_L )</td>
<td>( W_p )</td>
</tr>
<tr>
<td>22</td>
<td>91</td>
<td>0.66</td>
<td>40</td>
<td>20</td>
</tr>
</tbody>
</table>

Fig 1. Section of foundations of compressor

The permissible bearing capacity of base reached 4.0 kN/cm\(^2\). Other physical characteristics of base soil are given in Table I.
During dynamic test all the compressors should be under normal production conditions, hence the point of application of periodic exciting force had to be taken on base plates of foundations as shown in Fig I.

Test results are shown in Fig II.

![Graph 1](image1)

Fig II. Response of amplitude under horizontal exciting force
1—before foundations combined
2—after foundations combined

As can be seen from the Fig., the resonance frequencies of foundation N-1 and N-2 before treatment are 14.2 and 14.0 Hz respectively, the ratio of exciting of machine to resonance frequencies of foundations is 0.92-0.93. Obviously, the compressors were running under resonant vibration, that is why these foundations underwent such intense vibration.

Selection of Vibration-decreasing Scheme and Its Practical Effects

A variety of schemes have been studied, some of which e.g. strengthening of base soil are not acceptable for their interrupting production. By detailed comparison we finally adopted combined foundation, i.e. base plates of foundations are combined to increase elastic resistance, damping ratio and resonance frequency of base, and for the same purpose a reinforced concrete ground beam was placed perpendicular to the direction of piston sliding, depth of beam 1.0 m, thickness 0.8 m as shown in Fig III.

After hardening of concrete combining slab a horizontal forced vibration test was repeated, test results may be seen from the graph 2 of figure II. As can be seen from the Fig., the resonance frequency of foundation N-1 is increased from 14.2 to 17.0 Hz, while that of N-2 from 14.0 to 16.0 Hz, damping ratio is increased significantly. Fig. II indicates that when exciting frequency w=13 Hz the horizontal amplitudes of foundations N-1 and N-2 are decreased 54% and 67% respectively, when w=20 Hz the vibration response of combined foundation is about the same as each single foundation. It should be noted that the aforementioned test results were obtained when exciting force acts parallel to x axis, i.e. along the short side of combining slab. If exciting force acts along its long side, the dynamic response of foundations will be different from the above-mentioned results. This conclusion is also confirmed by a dynamic model test of a combined foundation consisting of 3 single foundations with base area 1.44 m² each. Results of the model test show that when exciting force acts along the long side of base plate, resonance frequency and damping ratio are increased more significantly than when it acts along the short side, which is apparent from Fig. IV.

![Graph 2](image2)

Fig IV. Dependence of $\alpha_x$ and $\beta_x$ on coefficient
1—Exciting force acts along the long side
2—Exciting force acts along the short side
In the Fig. $\alpha_{x}$ and $\beta_{x}$ are referred to as coefficients of increase of frequency and damping ratio:

$$\alpha_{x} = \frac{\lambda_{x,0}}{\Delta x}$$  \hspace{1cm} (1)

$$\beta_{x} = \frac{\Delta x_{0}}{\Delta x_{x,0}}$$  \hspace{1cm} (2)

The dimensionless parameter $\frac{1}{\alpha_{x}}$ equals:

$$\frac{1}{\alpha_{x}} = \frac{G_{x}}{\rho_{x} I + C_{x} \rho_{x} h_{x}^2}$$  \hspace{1cm} (3)

Where $G_{x}$ is shear modulus of concrete, $h_{x}$ the thickness of combining slab, $C_{x}$ the coefficient of elastic nonuniform compression of soil, $C_{x}$ the coefficient of elastic uniform shear of soil, $F$ the base area of foundation, $I$ moment of inertia of foundation contact area with respect to the axis passing through the centroid of this area, perpendicular to the plane of vibrations, $h_{x}$ distance from center of gravity of mass of foundation to foundation base, $\lambda_{x}$ the first natural frequency of horizontal-rotational vibration of foundation after combination of base plates, $\lambda_{x,0}$ the first natural frequency before combination of base plates, $\Delta x_{0}$ and $\Delta x$ damping ratio before and after combination of base plates of foundations.

Here it should be pointed out that under vertical vibration the resonance frequency is slightly increased as a result of foundations combined, as shown in Fig V.

By the way, we have to explain some phenomena shown in Fig V. If using the Mass-Damping-Spring vibration model without the mass of base soil considered, the test results shown in Fig V could not be explained. This figure points out as a result of foundations combined the resonance amplitude is decreased markedly, while the resonance frequency is increased slightly. When using the above vibration model, it may only be illustrated as follows: the vertical damping ratio is increased, while the vertical stiffness of base changes little. However, the Fig V also shows that following combination of foundations the dynamic response in non-resonance region decreases apparently. Based on this phenomenon it may be considered that the vertical stiffness of base has been improved. This conclusion is contrary to the previous one. It follows that the computing results of the vibration model without considering mass of base soil disagree with the test results. In fact, the base has both elasticity and inertia under vertical vibration. Concerning the inertia action of base, author has made a number of field tests and detailed analysis, which may be referred to author's papers concerned.

To reduce the space of the paper only the relevant computing formulas are herein presented considering the mass of base.

For the harmonic force with constant amplitude

$$D_{x} = 0.707 \sqrt{1 - \sqrt{1 - d}}$$  \hspace{1cm} (4)

$$M = \frac{P_{x}(1-2D_{x})}{2A_{z}(\text{max}) \lambda_{x} \Delta z D_{x}} \sqrt{1 - \frac{1}{D_{x}^2}}$$  \hspace{1cm} (5)

$$K_{x} = \frac{1}{1-2D_{x}}$$  \hspace{1cm} (6)

for the harmonic force with varying amplitude, i.e. $P_{x} = m \omega^{2} w \sin \omega t$

$$D_{x} = 0.707 \sqrt{1 - \sqrt{1 - d}}$$  \hspace{1cm} (7)

$$M = \frac{m \omega^{2} w}{2A_{z}(\text{max}) \lambda_{x} \Delta z D_{x}} \sqrt{1 - \frac{1}{D_{x}^2}}$$  \hspace{1cm} (8)

$$K_{x} = M \lambda_{x} \Delta z (1 - 2D_{x})$$  \hspace{1cm} (9)

in which:

$$d = \frac{(1-\alpha)^2}{\alpha^2 + \beta^2 - 2\alpha}$$  \hspace{1cm} (10)

$$D = \frac{(1-\alpha)^2}{\alpha^2 + \beta^2 - 2\alpha + 1}$$  \hspace{1cm} (11)

$$\alpha = \frac{\omega^2}{\lambda_{x} \lambda_{z}}$$  \hspace{1cm} (12)

$$\beta = \frac{A_{z}(\text{max})}{A_{z}}$$  \hspace{1cm} (13)

$$M = m + m_{b}$$  \hspace{1cm} (14)

Where $\lambda_{x}$ is the vertical resonance frequency of foundation, $A_{z}(\text{max})$ the vertical resonance amplitude, $A_{z}$ the amplitude value under certain exciting frequency, $M$ the total mass participating in vibration, $m_{b}$ the mass of foundation.
'm' the mass of base soil participating in vibration, 'Dz' the vertical damping ratio, 'Kz' the vertical stiffness of base, 'm0' the eccentric mass of vibrator, and 'r0' the eccentricity of mass of vibrator.

When using the computing formulas to analyse the test results shown in Fig. V, we obtain the mass participating in vibration before combination of foundations \(M = 1.47\) tons \(\text{sec}^2/\text{m}\) and after that \(M_1 = 1.77\) and \(M_2 = 3.10\) tons \(\text{sec}^2/\text{m}\) with respect to parameter \(f = 0.11\) and 0.77. Needless to say, the stiffness of base has increased with an increase in mass participating in vibration. Thus these phenomena shown in Fig. V could be easily explained. Meanwhile when using these dynamic parameters to compute amplitude, the theoretical results shown by solid line well agree with test values, as shown in Fig. V.

Now let us return to study the practical effects of decreasing compressor-induced vibration. Following treatment by employing combined foundation, a detailed vibration measurement of foundation of compressors was made under normal production conditions. Table II gives only partial list of results along X direction and Table III gives results along Z direction under secondary exciting force: \(A_0\) and \(A_1\) — vibration amplitude before and after treatment respectively.

### Table II. Variation in Horizontal Vibration Amplitude before and after Treatment (in micron)

<table>
<thead>
<tr>
<th>No. of working foundation</th>
<th>foundation</th>
<th>roof</th>
<th>compressor A0</th>
<th>A1</th>
<th>A0</th>
<th>A1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>63.5</td>
<td>44.1</td>
<td>103.5</td>
<td>45.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>79.0</td>
<td>35.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 and 2</td>
<td>65.6</td>
<td>46.2</td>
<td>77.0</td>
<td>34.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1,2 and 3</td>
<td>65.6</td>
<td>36.9</td>
<td>89.1</td>
<td>34.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

It should be pointed out that small amplitude variation results induced by first simple harmonic exciting force. It is easily understood from the fact that the first simple harmonic frequencies of compressors have been far apart from resonance frequencies of each single foundation before treatment, and that the ratio of first simple harmonic frequency to resonance frequency of foundations varies insignificantly after combination of base plates.

As a result of decrease in vibration induced by the secondary harmonic exciting force the workers feel much better than before treatment and the persons who worked in the neighbouring of

### Table III. Variation in Vertical Vibration Amplitude before and after Treatment (in micron)

<table>
<thead>
<tr>
<th>No. of foundation</th>
<th>foundation</th>
<th>foundation</th>
<th>foundation</th>
</tr>
</thead>
<tbody>
<tr>
<td>working N-1</td>
<td>N-2</td>
<td>N-3</td>
<td></td>
</tr>
<tr>
<td>compressor A0</td>
<td>A1</td>
<td>A0</td>
<td>A1</td>
</tr>
<tr>
<td>1</td>
<td>31.8</td>
<td>19.7</td>
<td>36.8</td>
</tr>
<tr>
<td>2</td>
<td>34.3</td>
<td>19.2</td>
<td>39.5</td>
</tr>
<tr>
<td>3</td>
<td>32.7</td>
<td>16.4</td>
<td>39.9</td>
</tr>
</tbody>
</table>

The foundation under 3 compressors has been so far working under normal condition since treatment accomplished in 1974.

### REFERENCES

