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Analysis and Design of Elevated Foundations for Reciprocating Machines

By Suresh C. Arya and George Pincus

Synopsis: Most reciprocating machines are critical to the operation of the plant and, therefore, the supporting structure must be carefully designed to avoid potential undesirable behavior such as attainment of a resonance condition. The designer is then confronted with selecting the best possible techniques in order to accomplish a trouble- free condition. Available engineering analysis tools include theory of vibrations, half-space theory, soil-structural analysis computer programs and rational modeling techniques. This paper summarizes and reviews the steps that must be considered during design of the supporting structure for an elevated reciprocating machine and provides practical guidelines which serve to obtain a realistic and useful design. Four different models are presented and discussed and an example problem is used to illustrate the main features and results of each model. It is concluded that the combination of the best modern scientific tools and modeling technique coupled with practical guidelines yields a reliable structural configuration.

Keywords: foundation; machine bases; structural design; vibration.

Suresh C. Arya is a Principal Engineering Specialist, Civil - Structural Group, with the C-E Lummus Company. He is responsible for all vibration and dynamics analysis of structures and foundations made in Lummus' Houston office. He has a Ph.D. from the University of Texas with 16 years of experience in structural and dynamics analysis for the petrochemical industry, nuclear power plants, and marine terminals. He is a registered professional engineer in Ohio, Texas, and California.

George Pincus is Chairman and Professor of Civil Engineering, University of Houston. He teaches structural engineering and directs graduate student research in structural mechanics, structural analysis and design, and he supervises full-scale laboratory testing. He has a Ph.D. from Cornell University. Dr. Pincus is a registered professional engineer in Texas, Kentucky, Florida, and California.

INTRODUCTION

Reciprocating machines are relatively heavy machines that generate vibrating forces of substantial magnitude at low operating frequencies. Reciprocating machines are being manufactured in increasingly larger sizes and oftentimes, require that they be placed at higher than grade elevations to accommodate exhaust piping connections below their bases. Therefore, even though the preferred supporting foundation for reciprocal-type machines has been a flat, relatively thick slab or block at grade, it is now common to design elevated foundations to support reciprocating compressors. Relatively wide and thick blocks bearing directly on the soil or supported by piles and having piers rising from the slab to support the various machine components are often used for elevated reciprocating compressors. This type of structural arrangement is common in larger sized reciprocating machines, specially those used in high pressure piping (for example, low density polyethylene) process applications.

The operating frequencies of reciprocating machines may lie very close to the natural frequencies of the supporting structure in several of the vibrating modes, thus creating possible resonance conditions in the machine-foundation system. The absolute magnitude of vibration amplitude at the resonance condition becomes a controlling criteria because of the closeness of operating and natural frequencies. In order to achieve acceptable vibration amplitudes it becomes necessary to make the structure very rigid so that the fundamental frequency of the structural system increases to a value above the operating machine frequency. The difference between the fundamental frequency and the operating frequency should be substantial say, a difference of at least 20 but preferably 50 percent. In addition, the ratio of the deflections in the structure caused by the dynamic force to the equivalent static load deflections (magnification factor) as well as the maximum velocity, should be within acceptable limits. This design approach requires that modeling of the foundation structure be as close to the real structure as is consistent with the available tools of analysis so that differences between the model and prototype structure behavior be minimized.

Contrary to other structural systems, dynamic-sensitive structures are difficult to retune and any modification or replacement will result in substantial financial losses not only due to repair costs but also to production losses. Therefore, to guard against uncertainties and to assure proper functioning of the structure, it is imperative that suitable analytical procedures be developed and used which not only provide more accurate dynamic response values but also formally use the latest available analysis techniques. Some of these techniques are lumped parameter model analysis (1-3), soil structure interaction (2-4), elastic half- space theory (3-6) and the latest computer programs available to the profession (7,8). This paper illustrates integration of current knowledge in these areas for the design of elevated structures supporting reciprocating compressors.

Modeling of the real structure, machine and the supporting soil is of critical importance in obtaining results that will approach the actual performance of the combined soil-structure interactive medium (9, 10). A comprehensive analytical approach using four different models of the type of foundation under study are presented and discussed in this paper. Two of the models are developed according to conventional classical procedures while the other two models are analyzed by using current concepts developed in the fields of structural dynamics and soil dynamics. The relative advantages and disadvantages of these models are discussed.

A complete design for a structure supporting a reciprocating machine will include the following steps:

a) Obtaining all information including machine characteristics, center of gravity, unbalanced forces and moments, excitation frequencies, geometry and special clearance and height requirements.

b) Geotechnical conditions at the site and evaluation of soil design parameters.

c) Preliminary design of the supporting structure.

d) Static and Dynamic analysis.

e) Checking the proposed design for acceptability. If not acceptable, the design is modified and the analysis repeated.

These steps are considered in detail in reference 10. An example problem illustrating the use of suggested analysis techniques for the design of an elevated reciprocating machine is presented. The paper also includes a discussion of alternate modeling techniques.

FOUNDATION LAYOUT

The design engineer either by himself or with the help of the geotechnical consultant should establish the layout for the foundation structure. There are two common types of foundations used: concrete block footing placed directly on the soil or rock, and concrete footing supported by piles or piers. The preference of one system over the other should be decided by taking into consideration: relative economy, settlement, bearing capacity of the soil, vibration isolation, and the level of the underground water table. Pile or pier-supported footings are the exception and are used only where poor soil conditions are found.

Preliminary sizing and geometrical member arrangement consitutes the initial and often, the most tedious design phase for elevated foundations. Although this preliminary phase is partly based on the experience of the designer, suggested guidelines can be useful in arriving at a satisfactory final design. It should be emphasized that the general guidelines for trial sizing are only useful in the initial phase and are no substitute for a thorough dynamic analysis and check as described later. These general guidelines include the following (10):

1. The designer should carefully analyze equipment size and clearance requirements to assure that sufficient space is allocated to equipment, anchor bolts, piping and clearance for installation, maintenance and operation. That is, physical space limits and requirements should be clearly identified and considered.

2. The bottom of the foundation mat should be placed no higher than the minimum founding depth recommended by the soil consultant. This generally includes considering the location of adequate bearing strata, water table, depth of frost penetration, paving elevation and special local soil conditions. However, in very poor soils, the geotechnical consultant may recommend the use of piles.

3. The top of the footing should be kept a minimum of 0.3 m (1 ft.) above the finished floor or pavement to prevent damage from surface water runoff.

4. The minimum thickness of the foundation slab is seldom less than one-fifth the least slab dimensions or one-tenth the largest slab dimension.

5. Increased damping in the rocking mode is recommended, thus, the width perpendicular to the axis of rocking should be 1.5 times the vertical distance from the bottom of the slab to the machine center of gravity. The additional damping is recommended in view of the degree of uncertainty in some of the design parameters.

6. For large reciprocating machines, the authors recommend that the embedded depth in soil be increased so that 50 to 80 percent of the slab is soil-embedded. This will result in increased damping for all modes of vibration. Increased damping will minimize the amplitude of vibrations even close to the resonance condition and is considered an additional preventative measure to avoid undesirable displacements.

7. The total mass of the structure including the mat should preferably be no less than 5 times the mass of the machine for reciprocating-type machines. For centrifugal machines, the ratio is usually no less than 3.

8. The maximum static bearing pressure for soil-supported foundations should not exceed one-half of the allowable static soil pressure. For pile-supported foundations, the heaviest loaded pile should not carry over one-half of its allowable load.

9. The center of resistance of the soil should be within 5 percent of the side measured parallel to the eccentricity of all superimposed loads for soil-supported foundations. For pile-supported foundations, the centroid of the piles should also be within 5 percent of the side measured parallel to the eccentricity of the superimposed loads.

10. The columns or piers should be checked for individual member resonance with the machine acting frequency. The lowest natural frequency of the columns or piers is approximately given by

$$f_n = \frac{44800\,(f'_c)^{1/4}}{\sqrt{pL}}$$

Where f'_c is the concrete strength in psi (1 psi = 6895 Pa), p is the actual column or pier axial stress in psi and is usually in the 40-300 psi range (276-2070 kPa), L is the column or pier height in inches (1 in. = 25.4 mm) and f_n is in cycles per minute. The formula above is obtained by substituting the axial deformation in a column $\delta = pL/E$ into the formula giving the natural frequency of a single degree of freedom system with no damping:

$f_n = (g/\delta)^{1/2}/(2\pi)$ with $E = 57000\ (f'_c)^{1/2}$ psi and $g = 386.4$ in/sec/sec.

MODELING OF IDEALIZED SYSTEM

A sketch for a proposed foundation structure is shown in Figure 1 and may be represented by four models. Models A and B are conventional engineering practice models, while Models C and D are models which give a more realistic representation of the prototype system behavior.

Model A

This model consists of a single-lumped mass supported by linear and rotational springs. The total mass is equivalent to the sum of the masses of machines, piers and the foundation. The entire system is assumed to be a perfectly rigid body (block-type foundation) resting on soil and, therefore, the elastic-half-space theory is applicable. An idealized model for the system is shown in three parts, Figure 2 (a), (b) and (c), each representing independent modes. These are the only possible modes of vibration because the excitation forces are acting in the given direction.

Model B

This model only considers the superstructure and assumes that the mat slab is massive and, therefore, the piers in Figure 1(c) will function as cantilevers having full fixity at their base, see Figure 3. The superstructure is modeled as a multi-lumped system with each mass having three linear degrees of freedom. Excitation forces are applied at the joints. The influence of the soil is not considered, except for proportioning of the slab based on an allowable bearing capacity. The natural frequencies and response values for individual members of the superstructure are obtained in this model.

Model C

This model is an improvement over Model A, see Figure 4. The model includes a two lumped-mass system with six possible degrees of freedom for each mass. The mass corresponding to the upper half of the superstructure plus machines is lumped at joint 1 while the mass corresponding to the lower half of the superstructure and the mat slab is lumped at joint 2. The element connecting the two masses represents the equivalent stiffness of the superstructure. The soil spring constants are attached to each of the joints and represent the equivalent six soil stiffnesses supporting the mass at joint 2. This model assumes that the superstructure and the foundation are rigid and their masses and stiffnesses can be represented by equivalent lumped parameters (lumped masses and springs). This model provides overall information with regards to the lowest natural frequencies and also yields the response values at the machine attachment point and at the foundation levels which are the usual points of interest. However, the model does not provide complete dynamic results at various points of machinery support and foundation level.

Model D

This model is an improvement in relation to the previous models, not only with respect to degree of reliability of results but also with regards to availability of sufficient information at all points of interest. The approach is based on lumping the masses at the nodes. The foundation slab is modeled using finite element procedures and is supported by soil-springs at the node points, see Figure 5. There are other methods which account for the stiffness of the foundation slab and provide equally good results, such as "Equivalent Frame Method" as described in the American Concrete Institute Building Code, Requirements for Reinforced Concrete (ACI-318). The interaction of the soil's stiffness with the foundation structure is obtained through the use of the elastic half-space theory. The calculation of stiffness for the structure is quite complex and is generally done through the use of computer programs. This model yields comprehensive results not only about the dynamic behavior of the structure but also of the foundation (9). In addition, through various mode shapes, it is possible to determine the distress situation that may occur at various points of interest. This model is highly recommended for large reciprocating machines supported on elevated piers and is used in the example problem presented in this paper.

STATIC AND DYNAMIC ANALYSIS

After a trial configuration is selected, the structure is modeled as discussed above, an actual static and dynamic analysis is performed and the predicted behavior is compared to certain admissible performance guidelines. These may include: design for the equivalent (conservative loads), natural frequencies of the structure for possible resonance, maximum amplitude of deformation due to the application of the dynamic loads and checking the structure and foundation for the effect of the dynamic loads.

The availability of electronic digital computers having great calculating speed and analytical power has resulted in substantial advancement in designing complex machine foundations. Structural software packages predict the natural frequencies, the deformations and the forces in the structure (7, 8). In many cases, the structure or soil parameters are not exactly known. For example, the shear modulus of the soil, G, may vary by ± 25% or more at points below the foundation even for a careful well-designed field investigation (10). The effect of this variation in G may be considered by changing one input parameter and re-running the program. Thus, the soil-structural behavior may be predicted for possible ranges of G. This is a most convenient feature of computer use. A flow chart summarizing the steps that occur during a computer analysis is given in Figure 6 and is typical of all structural software packages commercially available. The flow chart depicts specific stages using the ICES-STRUDL software package (7, 8).

ACCEPTABILITY AND FINAL DESIGN

The computer results must be checked against certain acceptable performance criteria. These include:

1-Static Conditions

a) The maximum soil pressure or pile load should not exceed 50% of the allowable capacity.

b) Settlement must be uniform, i.e., the center of gravity of all static loads should be within 5% of any linear dimension (and preferably coincide) with the footing or pile group centroid.

c) The combined center of gravity of the static plus dynamic loads should be within 0.5% of any linear dimension from the footing or pile group centroid. The axis of rocking should coincide with a principal axis of the footing. The total settlement should be less than the permissible deflection for attached piping (very small for high pressure piping).

2-Dynamic Conditions

a) Resonance - The acting machine frequencies should differ by at least ± 20% and preferably ± 50% for reciprocating machines from the 10 lowest natural frequencies of the structure.

b) Maximum Vibration Amplitude - The maximum amplitude must fall in an acceptable range for the acting machine frequencies, for example in zones A or B of Figure 3-3 of Reference 10 or Figure 10-2 of Reference 4. A number of other acceptable vibration amplitude charts are available (10-13).

c) Velocity - The maximum resulting velocity is also checked. The velocity may be calculated from

$$v = 2\pi f \text{ (cps)} \times \text{(displ. amplitude)}$$

Acceptable velocities are given in Table 10-4 of Reference 4 and Table 3-2 of Reference 10. Maximum horizontal peak velocities in excess of 4 mm/sec. (0.16 in./sec.) are generally, to be avoided.

d) Acceleration - The maximum resulting acceleration as calculated from

$$a = 4\pi^2 f^2 \text{ (cps)} \times \text{(displ. amplitude)}$$

is checked, for example, using Figure 3-3 of Reference 10 or Figure 10-2 of Reference 4. However, if the maximum vibration amplitude and velocity (b) and (c) above are acceptable, an acceleration check is not required.

e) The ratio of the deflections caused by the dynamic forces to the deflections caused by the equivalent static loads (the magnification factor) should be less than 1.5.

EXAMPLE PROBLEM

The elevated structure shown in Figure 1 is analyzed using the four previously described Models A-D. The structure and soil parameters and the machine unbalanced dynamic forces, see Figures 7 and 8 required for the analysis of these models are:

Soil:	G (shear modulus)	=	165.5 MPa
	υ (Poisson's ratio)	=	0.40
	γ (density)	=	179.6 kg/m^3
Structure:	E (mod. of elast.)	=	21525.4 MPa
	υ (Poisson's ratio)	=	0.17
	γ (density)	=	245.0 kg/m^3

Machine: Unbalanced dynamic forces (see Figures 7 and 8):

Fy (vertical) Primary:	6619 sin ωt N
Fx (horizontal) Primary:	39746 cos ωt N
Fx (horizontal) Secondary:	102970 cos $2\omega t$ N
My (vertical) Primary:	37412 sin ωt N-m
Mx (horizontal) Primary:	444938 cos ωt N-m
Mx (horizontal) Secondary:	80395 cos $2\omega t$ N-m