Reciprocating compressor foundation design with driven steel piles

By

Debarshi Das, MSc, PEng
Team Lead – Civil Engineering and Structural Analysis
Wood
Calgary, Canada
debarsi.das@woodplc.com

Kelly Eberle, BSc, PEng
Principal Consultant – Vibration, Dynamics and Noise
Wood
Calgary, Canada
kelly.eberle@woodplc.com

Mehdi Arjmand, MSc, PEng
Senior Engineer – Field Engineering and Troubleshooting
Wood
Calgary, Canada
mehdi.arjmand@woodplc.com

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Abstract

A sound foundation is a key factor in a successful reciprocating compressor application. Conventional concrete block foundations provide a reliable design, but the cost can be significant. Driven steel pile foundations are a good alternative that has been used successfully even for very large reciprocating compressor packages. A steel pile foundation has the advantage of lower cost and shorter installation time compared to concrete block foundations.

The steel pile foundation design must consider static loads, which is a well-understood process. Reciprocating compressors also generate dynamic forces as part of their normal operation which must be considered in the pile foundation design along with the static loads. A dynamic analysis of pile foundations requires specific approaches and practices, and the package design must include special considerations when a pile foundation is used. The best-designed pile foundation will not be successful if the reciprocating compressor package design is not executed properly.

This paper will outline the design practices used by Wood’s structural vibration specialists to create safe and economical driven steel pile foundations. Topics include:

- Definition of soil properties
- Pile arrangement and design goals for pile foundation designs
- Design practices for reciprocating compressor packages considering pile foundation
- Pile-to-skid connections
- Local skid reinforcements
- Analysis requirements for skid and foundation design

Case studies will be used to demonstrate the discussed design principles. One case study will illustrate how small changes in the skid structural design resulted in significant improvements. The second case study looks at field measurements and design work to show that excessive foundation and skid vibration is the result of pulsation shaking force acting on the cylinder in the vertical direction in combination with a foundation resonance. The third case study will demonstrate a successful design for a large (6000 HP), high-speed compressor.
Introduction

Driven steel pile foundations have been successfully used for reciprocating compressor packages of 6,000 HP and more for many years. Vibration problems may occur on the foundation and compressor package if the design and installation of the foundation do not consider the complexities of the dynamic requirements for these applications. The design of steel pile foundations for static requirements is well understood. Reciprocating compressors generate dynamic forces which present unique challenges to manage as compared to static forces.

Reciprocating compressor package basics

Reciprocating compressor packages are equipment packages composed of a steel baseplate or skid with the necessary equipment to allow for gas compression. Figure 1 is an image of a typical package showing the usual equipment such as the reciprocating compressor, driver (engine, in this case) as well as the vessels and piping equipment required for delivering gas and auxiliary equipment to operate the compressor and engine. Most medium and high-speed reciprocating compressors are installed in packages such as this, to allow for a more cost-effective assembly in a shop environment compared to assembling the reciprocating compressor components at site. The equipment package is then shipped to site as a whole assembly and installed on the foundation.

Figure 1. Typical compressor package

Owners and operators of reciprocating compressors are always looking for cost-effective and short-timeline approaches for their machinery foundations. Driven steel pile foundations are a much more cost-effective approach than concrete block foundations. Driven steel pile foundations for static considerations are well understood. Calculation of soil properties, bearing loads, settlement and other static design requirements for pile foundations are used in many applications. The design considerations of driven steel piles for dynamics, that is control of vibration, are very different to static considerations. A brief discussion of structural dynamics and vibration relating to reciprocating compressors is necessary before discussing the specifics of pile foundations.
The typical approach to the fundamentals of vibration starts with consideration of a single-degree-of-freedom mechanical system as shown in Figure 2. The mechanical system is comprised of a mass (m), spring (k) and damper (c).

\[ m\ddot{x} + c\dot{x} + kx = p(t) \]  

(1)

Figure 2. Model for the single degree-of-freedom mechanical system

A time-varying force \( p(t) \) acting on the mass results in a time-varying displacement \( x(t) \) or vibration of the mass. Equation 1 shows the relationship between the force and the motion of the mass.

The terms \( \ddot{x}, \dot{x}, \) and \( x \) represent the acceleration, velocity and displacement of the mass. Equation 1 accurately represents the physics of the mass motion in precise mathematical format. A less rigorous but more intuitive form of Equation 1 in terms of understanding vibration is given by the following expression.

\[ V = P_D \times F_D \]  

(2)

Where \( V \) is the vibration, \( P_D \) is the dynamic load and \( F_D \) is the dynamic flexibility. Minimizing vibration requires minimizing the dynamic load or the dynamic flexibility. Underlying this simple relationship are many details that must be considered for reciprocating compressor foundations. Application of Equation 2, colloquially called the vibration equation, to obtain a fundamental understanding of vibration, and control of vibration, can be a powerful tool.

The dynamic loads for a typical engine-driven reciprocating compressor are shown graphically in Figure 3. The dynamic loads include both forces and moments. Dynamic forces and moments from unbalanced reciprocating and rotating inertias are present in all reciprocating compressors and engines to some degree. These unbalanced forces and moments are often the highest dynamic loads and most important when considering the foundation design. However, other dynamic loads such as the crosshead guide forces and the pulsation shaking forces can result in significant skid and foundation vibration if the forces, or the effect of the forces, is not properly managed. Therefore, it is important that designers include all these forces in the dynamic study of the pile foundation to ensure the final design will operate in a safe, reliable manner. As demonstrated in the vibration equation, minimizing these dynamic forces will minimize vibration on the compressor package and foundation.
The second term in the vibration equation is *dynamic flexibility*. Minimizing vibration on a skid and foundation requires minimizing the dynamic flexibility. The dynamic flexibility is defined by three general properties being the static stiffness, damping and mass. The dynamic flexibility varies with time or frequency as noted in the more rigorous form of the vibration equation in Equation 1. The chart in Figure 4 shows a typical response curve that illustrates the variation in dynamic flexibility with frequency. The maximum dynamic flexibility occurs at the natural frequency, $f_n$. This means that if the compressor operates at the natural frequency of the foundation, vibration will be high. Operating at the natural frequency, also called resonance, should generally be avoided if possible. If the package must be operated at resonance, only changing the damping will affect the vibration, however, increasing damping to reduce vibration is difficult. The more typical approach to control skid and foundation vibration is by changing the static stiffness or mass. Either changing the mass or stiffness will be effective, however, when considering the vibration on a skid and foundation, the mass and stiffness of the foundation and soil must be included. The dynamic flexibility of a driven steel pile foundation is a function of the steel piles as well as the soil properties. Proper characterization of the soil dynamic properties is key to understanding the dynamics of the foundation and the overall reciprocating compressor package vibration.
Soil properties

An understanding of the site soil properties is key to the design of driven steel pile foundations. Driven steel pile foundations can be used in almost any soil type, however, the design of pile foundation and skid may require special considerations. For example, a driven steel pile foundation and compressor skid design for a heavy clay soil will be much different from that in a swampy or muskeg soil type. Similarly, for expansive or swell-type soil, special foundation designs must be considered. A thorough understanding of the site soil conditions will allow for the proper design to be determined.

A geotechnical survey of the reciprocating compressor site is an important first step to characterize the soil conditions. Typically, borehole samples are taken to define soil strata (layers) that characterize the soil types. There may be published information or work from past projects that can be used to describe the soil dynamic properties based on these soil types. The key soil dynamic properties that are required for the foundation analysis are the density, damping and shear wave velocity.

It is often best to conduct site-specific tests to measure the soil dynamic properties. There are several approaches for measuring the soil dynamic properties. Two recommended approaches are the Seismic Cross Hole Test (SCHT) and Seismic Cone Penetration Test (SCPT).

A seismic cross-hole test is performed as per ASTM D4428 specification. In the SCHT method (Figure 5), two vertical boreholes are drilled. A signal generator is placed in one hole, and a sensor is placed in the other hole. An impulse signal is generated in one hole, and then the time (t) the shear wave takes to travel from the signal generator to the sensor is measured (h). The distance divided by the travel time yields the shear wave velocity as shown in Equation 2. The cross-hole method can be used to determine the shear modulus (G) at different depths (Equation 3).

\[
V_s = \frac{h}{t} \quad (3)
\]

\[
G_0 = \rho V_s^2 \quad (4)
\]

where:

- \(V_s\) – shear wave velocity [m/s],
- \(h\) – distance between source and receiver
- \(t\) – travel time between source and receiver [s].
Seismic cone penetration test (SCPT) is performed as per ASTM D5778 specification. A schematic of SCPT is shown in Figure 6. The SCPT cone is equipped with two geophones located at 1 m apart which permit measuring the shear wave velocity in a 1 m layer. An impulse signal is generated at ground level. When the impulse arrives at the upper geophone, the oscilloscope starts and the impulse which is traveling to the lower geophone is being recorded. The travel time obtained from the oscilloscope readings and the distance between geophones allows for estimating the shear wave velocity using Equation 3. During each SCPT test, the cone penetration is stopped every 1 m to measure shear wave velocity at 1-m intervals. Shear modulus can be calculated from Equation 4 from the measured shear wave velocity.
Design approach for a pile foundation design

Determining a pile layout is the goal of the pile foundation study. Industry practices and “rules of thumb” have been developed as a starting point to assess a pile foundation design. These “rules of thumb” include:

- The weight of the pile cap should be 2.5 times and 4 times the weight of the rotating and reciprocating machine, respectively. The term pile cap, in general, refers to all the equipment (skid, machinery, piping, etc) mounted on top of the piles.
- Minimum width of skid or concrete pile cap (if applicable) should be 1.5 times the vertical distance from the machine centerline to the bottom of the foundation block.
- Pile center spacing should be kept as three times the diameter of the pile.
- Plan view eccentricities between the COG of the combined machine-skid-pile system and the center of resistance (center of stiffness or COG of piles) should be less than 5% of the plan dimensions of the cap.
- Maximum stress in piles should not exceed 50% of allowable stress due to static loading.
- For reciprocating compressor packages, the pile shaft diameter should not be less than 8” to have adequate lateral stiffness.

These rules of thumb are a starting point to design the pile foundation, however, an in-depth analysis is required to ensure the foundation meets the static and dynamic requirements. There are well-established practices and expertise in pile design for statics. The approach for static analysis will not be discussed in this paper. In general, the approach includes ensuring the bearing pressure of the piles from static loads (weight and environmental loads) must not exceed the allowable soil bearing pressure that is described in the geotechnical report.

The next step of the pile foundation design is an evaluation of the dynamic response. The dynamic response needs to consider both the overall response of the package and foundation as well as localized dynamic effects on the package. A comprehensive model of the soil, pile foundation and compressor package must be developed to calculate the dynamic response. Simulation of the soil and foundation dynamics requires special consideration of the soil properties, soil profile (layers) and pile properties such as length, diameter, arrangement (group effects) and pile end conditions. A complete description of the background and theory on this topic is beyond the scope of this paper. Interested readers are encouraged to read work done by Novak (Ref 5) and El Nagger (Ref 6). Specialized pile software or specialized techniques using general purpose finite element analysis software are necessary to accurately calculate the soil and foundation dynamic response. One important factor that most specialized software overlooks or assumes is that the pile cap, in this case, the compressor package mounted on the piles, is rigid. Most compressor packages are not rigid relative to the stiffness of the pile foundation. The pile foundation analysis must be done including the flexibility of the compressor skid as well as the many different dynamic forces that act on the skid and can cause vibration. A finite element model of the compressor package, piles and soil dynamic properties as shown in Figure 6 is the typical analysis approach.
The primary design objective for the dynamic pile foundation analysis is to minimize vibration. The typical approach to achieve this is to minimize the foundation flexibility by avoiding resonance. It is often seen in dynamic foundation design specification or client specification to avoid resonance at 1X operating speed by a separation margin of ±20%. Some of the highest dynamic forces occur at 1X operating speed, so this is a reasonable approach. However, when considering the flexibility of the compressor skid as well as the variable-speed operation of most modern reciprocating compressor packages, achieving this goal is not practical. As discussed earlier, there are many dynamic forces acting on the compressor package and foundation, and these forces can be significant at 2X operating speed. Should resonance at 2X be avoided with ±20% separation margin? From an ideal design approach, yes, but from a practical standpoint, this goal is not achievable. It becomes impracticable to avoid all mechanical natural frequencies that fall in the range of 1X and 2X operating speed for a variable-speed package that runs at 600 to 1200 RPM. Even units that operate over a small speed range, for example, 900 to 1200 rpm, are not practical to avoid 1X and 2X when a 10% or 20% tolerance is applied to the speed range. A harmonic forced response analysis should be performed to calculate the expected vibration and dynamic stress levels. The fact that a mechanical natural frequency occurs in the range of 1X or 2X does not necessarily mean that vibration will be excessive. The dynamic forces may be low, or the particular mechanical natural frequency may not be responsive to a particular dynamic force, so the result will be acceptable vibration.

All dynamic forces that are discussed in Figure 3 must be included in the forced response analysis. It is important that the complete operating speed range and the complete range of operating conditions be simulated in the analysis. The dynamic forces are a vector quantity meaning the force has a magnitude and phase. The phase relationship for the forces within the compressor or driver are known, however, the phase relationship between the compressor and driver is not known. The forced response analysis for the compressor forces must be done separately from the driver. The results from the two simulations must be added in a scalar manner to determine a conservative, worst-case scenario response.

Even the best foundation design will result in some residual vibration that can’t be eliminated. Vibration guidelines
have been established to qualify the final design. When discussing vibration guidelines, it is important to distinguish between spectral and overall vibration measurements. Spectral vibration guidelines define the allowable vibrations at different frequencies. Overall vibration guidelines define the total allowable vibration that is the sum of all spectral vibration for a specific frequency range. There are pros and cons to using each of these guidelines. The particular guideline that is used is generally not the critical factor. The important factor is understanding how the guideline is to be used or applied. Vibration guidelines should generally not be taken as a strict pass or fail criteria. The vibration guideline is meant to give a measure of the relative reliability or risk of fatigue failure. An understanding of the vibration amplitude, phase relationship, impact of the foundation vibration on components the foundation is supporting, and operating scenarios is needed to determine the acceptability of a vibrating foundation.

A general industry spectral guideline for skid and foundations in a reciprocating compressor application is 0.1 in/sec-peak (2.5 mm/sec 0-peak). Figure 8 shows the European Forum Reciprocating Compressors (EFRC) overall (OA) screening guideline for different areas of a reciprocating compressor. The design goal would be to keep vibration levels of all components in Zone A which is shown by the green color. Allowable vibration for a foundation supporting a reciprocating package is 0.15 in/sec-pk as per PIP STC01015 structural engineering specification. Another foundation guideline proposed by Irish and Walker (Ref 4) is often used in the industry, and allowable vibration in vertical and horizontal direction is given as 0.05 in/sec-pk and 0.1 in/sec-pk, respectively.

![EFRC Vibration Screening Guidelines for Reciprocating Compressor Packages, Converted to pPk OA](image)

**Figure 8.** EFRC vibration guidelines converted to pseudo peak overall velocity
It is essential to recognize that vibrations can get amplified as they move from the foundation to the skid and the components attached to it. Lowering skid and foundation vibration amplitudes will lower vibration of all attached components. High stress due to repetitive dynamic loads can cause fatigue failure. Dynamic stress in skid beams and other components (machinery, piping, vessels, etc) attached to it should be kept low. A typical dynamic stress guideline is 1500 psi peak (unintensified stress). If dynamic stresses are less than the fatigue limit, vibration over the guideline can be acceptable.

The outcome from the compressor package and foundation dynamic analysis generally includes recommendations from additional piles to those that were determined from the static analysis. Figure 7 shows a typical pile arrangement for a reciprocating compressor package considering both the static and dynamic requirements.
Design practices for reciprocating compressor packages considering pile foundation

The previous section described the general approach for the design of a driven pile foundation for a reciprocating compressor. There are several general characteristics or best practices regarding the design and implementation of a pile foundation that are recommended to ensure a sound foundation design. Following are several of these design practices based upon the authors’ experience.

Compressor and driver dynamic forces are in general controlled or dissipated by trying to move a large foundation mass (skid, in this case). The size of the foundation, as well as the path by which the machinery loads are transferred from the machinery to the foundation (load path), are key to controlling vibration. The vibratory energy created by the operating machinery must have a continuous load path into an appropriate foundation. If a skid is not properly supported by piles at key locations discussed earlier, there is no load path, and the unbalanced forces cannot move into the foundation to be dissipated. If the skid is not stiff enough, it will not dissipate and distribute the dynamic loads. High unbalanced forces that are not dissipated by the skid into the foundation can excite the natural frequencies of other components and cause instrumentation failures, small-bore piping failures, pressure vessel nozzle failures, fastener loosening and other problems. These can result in unscheduled shutdowns and safety hazards.

Appropriate design of the compressor and motor pedestal, skid and skid connection to the foundation are key to ensuring a proper load path between the machinery and soil. Figure 10 shows a schematic of a poor load path and appropriate load path design. Anchor bolts and supports for the compressor and driver should be located as close to the web of the pedestal and skid beams as possible. Local reinforcements with gussets are recommended to improve the load path. It is a good practice to fill the pedestal with concrete.

Figure 10. Recommended pile locations from static and dynamic consideration

- Pile location for static requirements
- Pile location for dynamic requirements
Adding concrete in the skid in key locations can significantly reduce vibration on the skid and equipment mounted on the skid. Concrete increases the local static stiffness and adds mass and damping to help control vibration. Typical locations for adding concrete are below the compressor, driver and suction scrubbers as shown in Figure 11.

Special attention must be given for pile-to-skid connections, as it is a critical joint that transfers loads from skid to
the foundation. A steel plate (pile cap) is commonly used. There are several drawbacks to this approach such as gaps between pile cap and skid beam, the pile cap may not be parallel to the skid beam flange, and sometimes the pile is not centered on the beam flange. Figure 12 shows an example of installed piles that have large gaps between the cap and skid beam which means the skid beams at that two locations are not supported. Also, note the large off-center location in the pile on the right relative to the skid beam. A large gusset has been installed between the pile and cap. The gap may be filled with shim material, but the connection stiffness will be compromised.

![Gap](image1.png)

**Figure 13. Gaps between pile cap and skid beams**

During pile installation, caution should be taken to identify the correct pile location from the construction drawing, and installation should be performed as per the installation specification. Poorly installed piles as indicated in Figure 13 can cause flexibility and lead to potential vibration problems. The picture on right side of Figure 13 and Figure 14 shows poorly installed piles where the skid beam is getting little stiffness from the pile. Figure 14 also shows another example of a poor load path, where the pile is welded to a belly pan rather than a skid beam. Situations like these should be avoided during pile installation especially if the mounting detail is steel cap plate. Consult with a vibration specialist to determine mitigation approaches in cases where the pile installation is not according to the specification.

![Gusset between pile and cap](image2.png)

**Figure 14. Poorly aligned piles**
A recommended practice for attaching skid beams to steel piles is shown in Figure 15. This is sometimes called a split ring collar type connection which replaces the pile cap. As discussed, gaps often exist between the top of the pile and the bottom flange of the skid beam, making welding difficult and impractical. A split ring collar can be used to connect the pile to the skid beams rather than a steel plate pile cap. The collar provides a simple way of filling gaps between the pile and the skid beam and ensures a strong connection between the pile and the beam.
Sometimes cylinder head-end supports are not recommended during the design stage. Changes in operation or site conditions over time may require cylinder head-end supports to be installed. Head-end supports that do not have a pile foundation are ineffective as there is no direct load path between the compressor and the foundation. It is normally recommended that additional piles be installed below the head end of the cylinders as a precautionary measure, as shown in Figure 7. Two piles are recommended for each cylinder to allow for installation of an A-frame-type support. Installing additional piles for an existing package is a difficult and costly exercise. The small cost for extra piles during the construction phase is a low-cost insurance policy against future vibration problems.

Screw piles vs driven piles

Driven piles are a proven technology for reciprocating compressor foundations. The focus of this paper is driven piles, however, a brief discussion about screw piles or helical piles is worthwhile. A screw pile is made of a circular or square steel shaft and a single or multiple helices that are welded to the shaft. Helices can be press-formed to a specified pitch. Figure 16 shows a typical screw pile being installed. Due to the advantages of quick installation time and cost over driven piles, they are often considered as a foundation option for reciprocating compressor packages. There are many successful installations with screw piles for reciprocating compressor packages, particularly for units of less than 2,000 HP. The shaft of the screw pile provides lateral stiffness similar to that of a driven pile. The helices of the screw piles provide additional vertical restraint as compared to a driven pile of the same shaft diameter. In large part, the dynamic behavior of screw pile foundations is the same as driven pile foundations. The horizontal motion of either pile is identical (Ref 2). Screw piles do offer additional challenges and limitations as compared to drive piles. During the installation of screw piles, a weak zone around the helix may be developed especially for cohesive (clay) soil. The effect of the weak zone should be taken into consideration in the design as it reduces stiffness.

Case study 1 – mitigating a vibration problem by small changes to the skid design

This case study is about high vibrations experienced on a 2400 HP reciprocating compressor unit. The 4-throw, 2-stage compressor was being driven by an engine running at 750 to 1000 RPM. The skid is broken into three parts: main skid
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and two wings for size limitation during transportation. Both wing skids mainly support the discharge piping and outboard supports. The package is surrounded by an enclosure and mounted on driven piles about 2 ft above the grade. High vibration on a wing skid beam and discharge piping, along with multiple clamp failures for the discharge lines were experienced. A few clamps were replaced, but this did not help reduce the vibration problem which indicated high skid vibration resulting from skid flexibility was the source of problem.

We were contacted to mitigate the vibration issue. The original foundation design was conducted by a third party. The proposed pile layout is shown in Figure 17. Following a site inspection and initial review of the project, it was noticed that there were no piles supporting big span (45 ft) of two back-to-back channels at the interface between main and wing skids (refer the orange boxes in Figure 17). These beams are only connected at the ends and supported by two piles (red circles in Figure 17) at each end of the channels, and the channels are bolted at 4 ft on center. Some bolts were missing at a few locations around the discharge bottle area during the site visit.

The design study was performed using computer simulations of the soil, foundation and compressor package. The geotechnical report did not have any soil dynamic parameters, so soil parameters were estimated from other relevant parameters given in the report and based on published literature. A picture of the finite element model showing the skid package is shown in Figure 18. Analysis results predicted high vibration on the wing skid beams (about 0.5 in/sec-pk) which are in line with the initial findings. Unfortunately, no field data was available to compare to the calculated vibration.
Several iterations were done to determine a recommendation considering the existing constraints. The proposed modifications are as shown in Figure 19. The recommendations included:

- Adding channel sections to stiffen the wing skids
- Welding along the full length of the top and bottom flanges for the two channels rather than intermittent fillet welding
- Bolting the channels’ web together at 2 ft center spacing
- Supporting the channels from the pile near the head ends of the cylinder (blue circles in Figure 17) using gusset plates

All proposed recommendations were implemented, and vibration was reduced significantly. This case study demonstrates how small changes to the skid design can mitigate significant vibration problems.
Case study 2 – high foundation and skid vibration due to pulsation shaking forces

The following case study involves the troubleshooting of high vibration on a 2-throw, 4-stage compressor package on a driven steel pile foundation. The package owner had experienced high vibration on the compressor cylinders, bottles and piping when operating at speeds around 1,080 RPM. Figure 20 shows a plan view of the compressor package.

Site testing was done to assess vibration on the package. A vibration survey on the compressor package determined excessive vertical vibration on the compressor cylinders at 2X compressor speed. Vibrations were measured to be 4.7 ips pk on the head end of both cylinders. Normally, vibration levels for a compressor cylinder such as this would be about 0.7 ips pk, about 1/7 of the measured vibration. It was observed that the cylinder vibration was in-phase, that is the cylinders were vibrating vertically up and down with each other. Typically, the cylinders would be vibrating out of phase.

Further testing was done to evaluate the odd vibration behavior. The vibration survey of the compressor crankcase and skid around the compressor and engine found excessive vibration that was well over guideline. Vertical vibrations on the compressor skid were found to be 0.56 ips-pk at 36 Hz. A typical skid vibration guideline is 0.1 ips pk. Refer to Figure 21 for a plan view of the skid showing the measured skid vibrations.
The excessive vibration measured on the skid beams in the vertical direction lead to the initial conclusion that there may have been a poor connection of the skid to the pile. Measurements on the top of the pile and bottom of the skid were taken as shown in Figure 22. The time trace of the vibration at the top of the pile and bottom of the skid almost exactly follow each other. This indicates the skid is well connected to the pile, and more importantly, the pile is vibrating vertically almost six times higher than what is normally acceptable. The pile foundation is clearly unsuitable for this particular application.
Impact testing of the skid and compressor cylinders was done to identify if mechanical resonance was playing a factor in the high vibration. Measurements found the compressor cylinders had a resonance in the vertical direction at approximately 36 Hz corresponding to the frequency of the high vibration. Mechanical resonance of the compressor cylinders was also a factor in the high vertical vibration.

Impact testing on the skid found the skid and foundation had a resonance at approximately 36 Hz. The combination of a compressor cylinder and foundation resonance at the same frequency was a major factor in the extreme vertical vibration. However, there was still uncertainty as to what force was driving the structural resonances, in particular, what forces would cause in-phase motion of the compressor cylinders.

The in-phase vibration of the compressor cylinder led to the theory that shaking forces from pressure pulsations may be causing the vibration. The compressor does generate vertical forces from mechanical unbalance and crosshead guide forces, but these forces tend to cause out-of-phase cylinder vibration. The compressor cylinders are identical and loaded in the same manner so the pulsation shaking forces would be in-phase. A pulsation model of the suction and discharge systems was created.

Pulsation-generated shaking forces are calculated in the piping system and pulsation bottles. One shaking force that is often overlooked is the shaking force in the vertical direction that is generated between the compressor cylinder and pulsation bottle as shown in Figure 23. A net force in the vertical direction results from the difference in dynamic pressure at the suction bottle outlet nozzle at the shell and the area projection on the gas passage. A shaking force is generated between the suction bottle and cylinder as well as between the discharge bottle and cylinder. These two forces add to create a total shaking force on the cylinder. The calculated shaking force acting on the compressor cylinder for the field test condition is as determined by the pulsation model shown in Figure 24. The force is quite high, up to 4,000 lb pk-pk at 2X compressor speed. A typical guideline used by Wood for these types of compressor is 1,000 lb pk-pk. This shaking force is excessive and the likely cause of the high cylinder and foundation vibration.

The compressor is a single-stage operation with both cylinders equally loaded so the pressure pulsations and shaking forces acting on the two cylinders will be nearly the same. The pressure pulsation and shaking forces will also be in-phase. The in-phase vibration measured during the field test is therefore a likely result of these in-phase vertical shaking forces acting on the cylinders.
Design work was undertaken to determine if the model could calculate the observed behavior and then be used to determine possible solutions to reduce vibration. A model of the existing compressor package and foundation was developed as shown in Figure 25. The model included simulation of the pile and soil dynamic properties, skid structure, detailed model of the compressor, bottles and piping, motor and cooler. All the dynamic forces generated by the compressor including unbalance, crosshead guide forces, internal cylinder gas forces and pulsation shaking forces were applied to the model. Figure 26 shows a vector plot of the calculated vibration at 36 Hz. The model results agree well with the field measurements in both the frequency of the highest vibration as well as amplitude. The computer simulation is shown to be an effective model of the real system so design modification could be evaluated.
Many modifications to change support for the bottles and compressor cylinders were evaluated, but none were effective. Approaches for adding mass to detune the mechanical resonances were investigated, but none were effective. The fundamental problem remained with high vibration due to resonance of the pile foundation and soil. Design modifications to the foundation were then evaluated. It was determined that a concrete block foundation of at least 5 ft deep would be required to shift the foundation resonance away from 2X compressor speed. After the foundation problem was solved, the vertical resonance of the compressor cylinders at 2X compressor speed remained. Head-end cylinder supports were required to increase the cylinder resonance above 2X compressor speed.
The combination of the concrete block foundation and cylinder head support would be effective in reducing vibration to guideline levels. The concrete block foundation is a somewhat costly modification. As an alternative to changing the foundation resonance, designing modifications to reduce the pulsation-generated shaking between the compressor cylinder and bottles were investigated. Many modifications including different orifice plates, bottle designs and resonators in the gas passage were evaluated. None of these modifications were effective in reducing the 2X shaking force between the compressor cylinder and bottles. The 2X shaking force is largely due to the design of the compressor cylinder gas passage and the compressor operating conditions. Changes to the cylinder design or selecting a different compressor cylinder would be required. Changing the compressor cylinder is a significant modification to the package.

The compressor package owner is currently considering which approach to take to either install a large concrete block foundation or change the compressor cylinders. The owner decided to conduct some field trials to try to add more stiffness to the foundation. Temporary supports were added below the compressor using jack supports. A number of jacks were installed, and vibrations were measured. The jacks were found to have virtually no impact on the vibration. The soil properties are not suitable for simple vertical jack or pile type supports. This case study highlights the importance of doing a dynamic foundation study when designing a pile foundation. The dynamic foundation study must include all dynamic forces at 1X and 2X operating speed, including shaking forces from pressure pulsations.

**Case study 3 – how to create a successful design for a large high-speed compressor**

This case study involves the design of a driven steel pile foundation for five large variable-speed compressors. The application includes a 6-throw, 3-stage horizontal separable compressor. The design was relatively challenging given the large size, approximately 6,000 HP, and variable-speed motor drive operating over a speed range of 600 to 900 RPM. The large size of the compressor and multiple compressors being installed for a critical application warranted a comprehensive design of compressor package and foundation.

The initial design of the driven steel pile foundation was conducted for static considerations as well as best practices based on experience. A geotechnical survey of the site was undertaken to determine the soil dynamic properties. A review of the geotechnical report and soil properties indicated that a driven steel pile foundation could be acceptable for this site.

The design process progressed to the next stage of conducting computer simulations of the soil, foundation and compressor package. The initial dynamic simulation determined small changes to remove a few piles that were redundant and add a few piles in locations to provide dynamic support for the compressor. A more-comprehensive finite element model of the complete compressor package and pile foundation was undertaken as a final step in evaluating the dynamic response. An image of the finite element model is shown in Figure 27. The model includes the pile foundation, compressor skid, a detailed 3D model of the compressor, motor, pulsation bottles and scrubbers. Dynamic forces from compressor unbalance, gas forces and pulsation forces were applied to the model as shown in Figure 28.

A summary of the maximum vibration for 1X and 2X operating speed is shown in Figure 29. The results are presented as a percentage of the guideline for the particular components. The vibration of the skid was calculated to be about 60% over the design guideline at the top of 1X compressor speed. The vibration on all other components mounted on the package was well below the guideline. Closer inspection of the operating deflection shape in Figure 30 shows the vibration was limited to the inner rails of the compressor skid around the motor. Vibration on the motor was calculated to be well below guidelines as represented by the black diamonds in Figure 29. Therefore, the decision was made to proceed with the foundation design.

A vibration survey was conducted on the compressor package as part of the commissioning stage. Vibration was measured on the compressor, motor, piping and all vessels mounted on the skid. All vibrations were found to be acceptable. Unfortunately, vibration measurements on the skid beams or piles were not recorded. However, the vibrations on the compressor frame and motor are shown in Figure 31 as a percentage of the vibration guideline. As shown by these field measurements, the driven steel pile foundation was effective and suitable for this application, resulting in compressor frame and motor vibrations that were less than 30% of guideline.
Figure 28. Compressor package and foundation finite element model

Figure 29. Dynamic forces applied compressor model
Figure 30. Summary of maximum vibration

Compressor Package maximum vibration 0.47 ips pk
Skid beam maximum vibration 0.09 ips pk

Figure 31. Maximum vibration results at 16.3 Hz

Figure 32. Measured compressor frame and motor vibration
Conclusions and recommendations

A sound pile foundation design can eliminate potential vibration problems. As a starting point, “rules of thumb” and other recommendations such as key pile locations discussed in this paper can be used for preliminary foundation sizing. The preliminary pile foundation size thus achieved must be verified by performing a detailed static and dynamic analysis. The foundation static design of the pile arrangement must consider static and quasi-static forces. All dynamic forces discussed in the paper must be considered in the pile foundation dynamic analysis. The pile foundation dynamic analysis must consider the flexibility of the compressor package mounted on the piles. A detailed finite element analysis is required to evaluate skid and pile foundation integrated analysis for dynamic loads. A geotechnical site survey is required as the dynamic behavior of foundation is greatly influenced by the soil layers supporting the foundation. The same package mounted on two different sites might show completely different behavior if soil parameters are significantly different. A local geotechnical or dynamic specialist should be consulted. The foundation and/or package design may require slight modifications to suit the new site soil parameters.

The highest amplitude dynamic forces on a reciprocating compressor are the unbalanced forces acting on the compressor frame, as well as cylinder horizontal gas forces, vertical crosshead guide forces and pulsation shaking forces. Generally, these forces are highest at 1X and 2X operating speed. Avoiding structural natural frequencies in the range of 1X and 2X operating speed is always the goal to minimize vibration. In many cases, particularly variable-speed compressors, avoiding resonance at 1X and 2X is not practical. A forced response analysis to calculate vibration and dynamic stress is required to determine an acceptable pile foundation design.

The dynamic forces can only be controlled if the load path from their sources to the foundation is as direct and stiff as possible. Filing the skid and pedestal with concrete under the compressor, throws and driver is strongly recommended as concrete adds local stiffness, mass as well as damping. The skid to pile connection is critical, and a solid connection must be ensured. A collar-type connection should be used to overcome the drawbacks of steel plate pile caps.

Reciprocating compressor packagers often request a skid dynamic study. The skid dynamic behavior is greatly influenced by the type of foundation and soil supporting the foundation. This is particularly true for driven steel pile foundations. The skid dynamic analysis without considering the pile foundation and surrounding soil is not accurate. An integrated analysis of skid and foundation using site-specific dynamic soil parameters is required. It is recommended that one engineering company performs both static and dynamic analysis of the pile foundation.

All equipment owners and packagers need to be aware of the importance of pile foundation design, including dynamic analyses and field installation practices. Responsibility for foundation design should be clearly outlined in the contracts between the parties involved in the project. If not contractually stated, the responsibility generally falls to the owner. Owners and packagers should use the services of companies who specialize in foundation designs in the absence of dynamic foundation specifications for equipment. The information given in this paper demonstrates that tools and techniques are available to mitigate the risks of vibration and fatigue failures for reciprocating compressor packages installed on driven steel pile foundations.

References

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