Reciprocating compressor foundation design with steel piles

By

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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 pile and helical or screw pile foundations are good alternatives that have been used successfully, even for very large reciprocating compressor packages. A pile foundation has the advantage of lower costs and shorter installation time compared to concrete block foundations.

The pile foundation design must consider static loads, which is a well-understood requirement. 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. There are also some differences between driven pile and helical pile foundations that must be considered.

This paper outlines the general design practices for driven and helical pile foundations for reciprocating compressors. The advantages and disadvantages of pile foundations and concrete block foundations are discussed. Case studies for reciprocating compressor packages are presented to demonstrate the use of pile foundations and the need for a dynamic foundation analysis.
Introduction

Driven and helical (screw) steel pile foundations have been successfully used for many years to support buildings, pipe racks, overhead power transmission towers and other structures. The ease of installation and effectiveness of the foundations in a wide variety of applications have made steel pile foundations an attractive approach. The continual drive to reduce construction schedules and costs led to the use of driven and helical pile foundation for reciprocating compressor packages rather than using conventional concrete block foundations. The challenge with using a pile foundation for a reciprocating compressor package is that high dynamic forces and moments generated by the normal reciprocating compressor operation must be controlled. Controlling the dynamic response requires understanding the dynamic properties of the piles and soil as well as the reciprocating compressor package. These dynamic properties require a different analysis approach as compared to the well-understood static analysis.

Foundation types

Foundations are classified into two general categories: shallow and deep. As implied by the name, the difference in the foundation is the depth at which it is installed and how the loads are transferred from the reciprocating compressor package to the soil.

Shallow foundations

A shallow foundation is one in which the foundation is installed in the upper layers of the soil. The use of shallow foundations relies on subgrade soils that can sustain or distribute the package static and dynamic forces.

A concrete block foundation is the most commonly used shallow foundation for reciprocating compressor foundations. The large mass of the concrete is needed to control the static and dynamic response of the machinery. The dynamic response of concrete block foundations is well understood and have been used successfully for many years. The main drawback to a concrete foundation is the cost, particularly for sites that are remote from concrete mixing plants. There are also significant timelines for the installation and curing of concrete foundations that are unattractive for fast-track projects.

A second type of shallow foundation used for reciprocating compressor applications is a gravel pad foundation. A gravel pad foundation is an engineering foundation that has been used most commonly on fleet reciprocating compressor packages in the less-than-1,000 HP range. The gravel pad is a compacted mixture of aggregate with a range of sizes to ensure good compaction and retention of the foundation profile and mechanical properties. A gravel pad foundation is attractive due to the low cost and easy installation. Recently, gravel pad foundations have been used in 2,000 HP to 4,000 HP applications. One of the key factors in a successful gravel pad foundation is ensuring full contact between the skid beams and foundation. A thin sand layer is often used to
avoid gaps under the skid due to an uneven or irregular profile of the bottom flanges of the skid beams. The foundation must be protected from damage due to rain and surface water that can cause degradation of this top layer.

Deep foundations

A deep foundation is used or required in cases where the lower or deep soil layers must be engaged to make an effective foundation. The three common types for reciprocating applications are driven piles, helical or screw piles and cast-in-place piles.

Driven pile foundations have been used for many years in North America's oil and gas industry, especially at locations where concrete is not accessible or economical. Structural members are driven into the ground to provide a foundation. The pile lengths are typically 20 feet to 35 feet. The piles for reciprocating compressor packages are most commonly steel pipes in the 6” to 12” diameter range. Piles are installed or driven into the soil by a hydraulic or drop hammer. The piles are driven until refusal, that is, the pile penetration into the soil does not increase with subsequent hammer blows. The typical maximum pile driving energy is 5000 BTU/yd² (630 J/cm²) to prevent damaging the pile.

Helical or screw pile foundations have become popular in recent years. A helical pile is similar to a driven pile except the helical pile includes one or more helixes on the pile lead section that provide additional load-carrying capability. The helical pile is installed by a
hydraulic power head that applies torque to the pile. The helix section pulls the pile into the soil. Monitoring the torque applied gives a reliable method of determining when the pile has been sufficiently installed.

The main advantages of helical piles are:
- Easier and quicker installation
- Economical
- Immediate load carrying capacity
- Verification of load capacity during Installation
- An extension can be added to increase pile length for greater load capacity
- A battered pile (a pile driven at an angle) can be easily installed for lateral capacity

The main disadvantages of helical piles are:
- A weak zone around helical piles is created during installation that can result in lower dynamic stiffness
- Not suitable for gravel and cobble deposit soil types. Helical piles are generally not appropriate for shallow bedrock soils.

The third type of pile foundation is a cast-in-place foundation. The pile design includes drilling a hole in the soil to create a form for the pile. Reinforcing bar is installed in the pile hole and concrete added to create the pile.

A cast-in-place is usually used in applications where large equipment is being supported. The number of piles is fewer, and the diameter is larger for cast-in-place piles compared to steel pile foundation. The relatively large diameter of the pile results in significantly higher lateral capacity compared to steel piles. The common application for a cast-in-place foundation is where bedrock is close to the surface.
Design approach for a pile foundation design

The previous section gave a general overview of different foundation types that are available. The focus of the remainder of this paper is on driven and helical pile foundations for reciprocating compressor packages.

Static design

The static design of pile foundations is well understood by civil and structural engineers. The static loads that a pile can carry, or are designed for, are vertical loads. The resultant downward vertical load \( P_r \) is distributed between load carried by the end of the pile interacting with the soil as well as the outer surface or skin friction between the pile outside diameter and the soil. The diameter and length of the pile can then be selected if downward and uplift forces are known as well as the soil end bearing pressure and skin friction pressure are known. The site geotechnical investigation and report will include a description of these pile capacities for the different soil layers.

\[
P_r = P_{\text{Skin Friction}} + P_{\text{End Bearing}}
\]

![Figure 5: Cast-in-place pile installation](image)

![Figure 6: Driven pile static load design](image)

The static design for a helical pile is somewhat similar to a driven pile. The skin friction of the shaft is included. The bearing capacity is also included, but instead of the bearing capacity being limited to the pile diameter, the helix diameter is used. The larger diameter of the helix increases the static capacity of the pile. The helix bearing capacity must also be considered in the uplift capacity as the helix

\[
P_r = P_{\text{Skin Friction}}
\]
bearing area acts when the pile load is downward or upward. The uplift capacity is also increased by the soil counterweight load or weight of the soil that must be lifted by the helix and the pile. As is seen by comparing the design of the driven and helical piles, the helical pile offers increased static capacity assuming the same pipe diameter is used for each.

![Figure 7: Helical pile static load design](image)

The helical pile may include more than one helix. The helical pile capacity increases due to increased bearing capacity for multiple helixes. Also, when the helixes are closely spaced, the cylinder of soil trapped between the helixes results in an increased load capacity due to shearing resistance between this soil cylinder between the helixes and the surrounding native soil.

**Dynamic design**

The dynamic design of the pile foundation must consider the overall dynamic response of the compressor package and foundation. A pile foundation design that is done without considering both the flexibility and inertia of the compressor package will not result in a design that reflects the actual compressor package and foundation response. Even though the compressor package may include large beams or sections of the skid structure that are filled with concrete, the dynamic flexibility of the skid structure is relatively high, and resonance of the compressor package and foundation at 1x or 2x operating speed are likely. A foundation design that assumes the compressor package is rigid or very stiff as compared to the foundation is not appropriate.

An approach that has been used successfully for simulating the dynamics of the compressor package and the pile foundation is using a finite element model, as shown in Figure 8. A finite element model of the compressor package is generated based on the design provided by the packager. The model of the pile foundation is somewhat more complicated. The steel pipes for the piles can be easily simulated with beam elements, however, characterizing the dynamic properties of the soil and interaction of the piles and soil is complex. The soil stiffness and damping properties are frequency dependent. The soil may have several different layers with different properties along the length of the pile. Also, the effect of pile grouping and interaction between piles must be considered. Calculations of the soil impedance are done using specialized software to characterize the dynamic impedance. The concept of dynamic impedance is better understood when one starts with the concept of static stiffness, $k$. The static stiffness is defined by

$$k = P/x$$

Where $P$ is the static force, and $x$ is the displacement. The dynamic impedance, $K(\alpha)$, takes the same general form as the static stiffness.
The force and displacement vary with time. The dynamic impedance is a complex number that varies with the mode of vibration, that is, the relative shape displacement between different parts of the foundation at a particular frequency. The dynamic impedance is typically written as

\[ K_i(\omega) = k_i + i\omega c_i \]

Where \( i \) represents the \( i \)-th mode of vibration. The real part of the dynamic impedance is the dynamic stiffness. The imaginary part is the damping (viscous and/or radiation). A complete description of the background and theory of pile and soil dynamic impedance is beyond the scope of this paper. Interested readers are encouraged to read work done by Novak(3) and El Nagger(4). This approach of using general pipe elements to simulate the piles with additional soil dynamic impedance parameters applied to the foundation has been successfully used for evaluating the dynamic response of the foundation.

The general goal for controlling the dynamic response or vibration for a reciprocating compressor package is to avoid resonance. Resonance is the coincidence of dynamic forces with a mechanical natural frequency of a component. The compressor package installed on a pile foundation will have many mechanical natural frequencies. The compressor and driver also generate many dynamic forces. The highest forces occur at 1x and 2x compressor speed. Therefore, the general design goal of avoiding resonance would be to have all mechanical natural frequencies tuned to avoid 1x and 2x compressor speed. In practice, avoiding all resonances is not possible or at least not practical, particularly for high-speed reciprocating compressors operating over a wide speed range. The foundation design must include a forced response analysis to calculate the expected vibration on the piles, skid and equipment installed on the skid. Including the dynamic impedance that represents the pile and soil flexibility and damping properties is a key step in performing an accurate analysis. The soil damping properties can be quite high when compared to structural steel with equivalent damping ratios of more than 5% as compared to damping ratios of 1% to 2% for piping and steel structures. This means that even though there may be resonances of the pile foundation and compressor package in the range of 1x and 2x, the vibration is often within acceptable limits.

The previous discussion of the static design for driven piles and screw piles highlighted the differences between the two designs. The dynamic design for driven and helical piles are typically very similar. The key factor in the dynamic design of pile foundation is the lateral stiffness. The lateral stiffness of the pile controls the horizontal translation and twisting dynamic response of the compressor package, as shown in Figure 9. The lateral dynamic stiffness of a pile as noted by Elkasabgy(2) is typically described by the length of the
pile that is 10 to 12 pile shaft diameters below grade. The design of a driven pile and helical pile foundation are identical for the upper portion of the pile embedded in the soil. Differences between the driven pile and helical pile only occur in the lower section of the helical pile. The lower section of the pile has essentially no influence on the lateral response of the pile foundation, so the lateral dynamic response of driven piles and helical piles are essentially the same.

Horizontal mode

Twisting mode

Figure 9: Typical reciprocating compressor package and pile foundation mode shapes

The vertical pile stiffness of driven piles and helical piles can be different due to the impact of the helixes. A helical pile is typically stiffer in the vertical direction that a driven pile. More than one helix can be installed on the pile to increase the vertical stiffness. The vertical dynamic stiffness is generally not an important factor in the reciprocating compressor package design if the pile foundation has been adequately designed for static vertical loads.

The process of installing a helical pile does result in some disturbance of the soil around the pile that can impact the pile foundation flexibility. This soil disturbance can create a weak zone around the pile, particularly for cohesive (clay) soil, that should be taken into consideration in the design. A region of soil with lower stiffness is one approach to account to the disturbed soil. The amount of soil disturbance can be minimized by the helix shape. The helix must be a true helix shape formed by a pressing operating. Some helical piles use a helix section that pulls a cut section to the plate to form a helix-like shape often referred to as a “duck-bill” shape. A pulled helix shape can result in excessive soil disturbance which reduces the load capacity and causes excessive settling with the potential for surface water being introduced next to the pile shaft. All these factors reduce the pile's effectiveness. It should be noted that the disturbed soil around the pile can “heal” or return to its original state and stiffness over time, but this process may take nine months or up to two years (Elkasabgy2). Efforts must be made to minimize soil disturbance to maximize foundation effectiveness. A true helical shape of the blade welded to the pile will greatly reduce soil disturbance.

Soil properties

An understanding of the site soil properties is key to the design of 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. A thorough understanding of the site soil conditions will enable a proper pile design.
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. The geotechnical report will always provide sufficient information for the static pile design. The dynamic pile design requires specific information such as the soil density, damping and shear wave velocity. 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. It may be necessary to conduct specific testing to determine the soil dynamic properties.

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. One of the more common approaches is the seismic cross hole test (SCHT), as described in ASTM D4428. In the SCHT method (Figure 10), 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. The distance (Δx) 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 2).

\[ V_s = \frac{\Delta x}{t} \]  
\[ G_0 = \rho V_s^2 \]

where:
\( V_s \) – shear wave velocity [m/s],
\( \Delta x \) – distance between source and receiver
\( t \) – travel time between source and receiver [s].

Figure 10: Schematic of seismic cross-hole test. Source: (Hussain, 2016)
Pile layout

The pile layout for a compressor package involves using some general rules of thumb as well as the previously described static and dynamic considerations. Following are several criteria that are typically used as shown for the package in Figure 11.

- Locate piles below significant components on the package or locations where high dynamic loads act. For example:
  - Drive end and non-drive end of the compressor and driver
  - Compressor crosshead guide
  - Head end of the compressor cylinders
  - Scrubbers, separators and secondary volumes
- At least two piles are recommended for the head end of the cylinder in the case that outboard supports are required
- Pile center spacing should not be less than three times the diameter of the pile or three times the helix diameter in the case of helical piles
- 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 package outline
- Maximum stress in piles should not exceed 50% of allowable stress due to static loading
- The pile shaft diameter should not be less than 8” to have adequate lateral stiffness. If less than 8”, more piles may be required
- Install piles for large diameter suction pipe supports near risers to separators and below large valves

![Figure 11: Typical pile arrangement (red circles)](image)

Pile connection to package skid

The best pile foundation design will not be effective if the details of the pile connection to the skid and equipment connection to the skid are not executed properly. One way of conceptualizing this concept is that the energy and dynamic forces that are generated by the equipment must be transmitted as directly to the soil as possible. The load path or energy path must follow the shortest path. The components in that path must be as stiff as practical.
The first area in ensuring a direct load path is the connection of the pile to the skid. The common approach used for pile connections is to use a pile cap, which is essentially a flat plate welded to the pile. The skid is placed on the pile cap and welded in place. The drawback to this approach is that the pile cap and bottom flange of the skid are not flat and true. There will not be complete contact between the two surfaces. This requires shims or spacers to be added, but they are generally not 100% effective in eliminating the gaps. Any remaining small gaps will add flexibility in the joint that will make the pile foundation less effective. The recommended approach to connect the pile to the skid is to use a split ring collar, as shown in Figure 12. The split ring collar allows for a stiff connection between the pile and skid.

![Figure 12: Pile connection detail](image)

The second area of ensuring a direct load path is in the equipment connection through the equipment support to the bottom of the skid. Figure 13 shows an example of a compressor crosshead guide support. The poor load path design includes a relatively tall crosshead guide support located on the edge of a flange of a relatively small skid beam. The skid beam is offset on the top of the pile. There will be significant flexibility in the guide support and skid beam. A better design would use a shorter, stiffer guide support that is located over the web of a large section skid beam. The skid beam web is located on the centreline of the pile. There is a direct load path between the high forces generated on the crosshead guide and the pile making this a much better connection.
Case studies

Case study 1: helical pile design for reciprocating compressor package

This project included the design of a helical pile foundation for a reciprocating compressor package located in West Texas. The geotechnical report classified the soil as a dense to very dense, with primarily a caliche or silty sand composition. The soil is well-suited to a helical pile foundation.

The compressor package includes an engine-driven reciprocating compressor that is a two-stage, four-throw configuration. Photographs of the compressor package while loaded on the truck trailer bed for shipping are shown in Figure 14.
The main challenge with this pile foundation design is the wide operating speed range. The compressor operates over a speed range of 750 rpm to 1,000 rpm. This speed range corresponds to a 1x and 2x frequency range of 12.5 Hz to 16.6 Hz and 25 Hz to 33.3 Hz. There is a very narrow frequency range between 1x and 2x to tune the mechanical natural frequencies of the package and foundation to minimize vibration.

One factor that made the foundation design simpler is that all four compressor cylinders were the same size even though the compressor was operating in a two-stage configuration. The reciprocating and rotating weights for the compressor are well balanced, so the resulting horizontal and vertical forces and couple are particularly low. The primary and secondary forces were perfectly balanced, so there was no net unbalanced force. The primary horizontal and vertical couples were 6.7 kip-ft and 11.3 kip-ft. The horizontal couple is often the dynamic load that excites the foundation mode with twisting about a vertical axis, so a low amplitude horizontal couple will make the foundation design simpler to meet the design guideline. The vertical couple, although higher amplitude than the horizontal couple, is easily transferred through the skid into the piles. The vibration due to vertical couple is usually well controlled.

A model of the compressor package and foundation was created, as shown in Figure 15. The compressor package and piles were simulated using finite elements. A model of the pile and soil was created based on the site geotechnical report to determine the dynamic impedance of the foundation.

![Figure 15: Model of a reciprocating compressor package with helical pile foundation](image)

The first step of the analysis was to conduct the modal analysis to calculate the mechanical natural frequencies (MNF). The problematic modes of a typical reciprocating compressor on a pile foundation are those where the package translates in the horizontal direction or twists about a vertical axis as noted earlier. The dynamic forces tend to excite these modes and cause high vibration. Figure 16 shows these modes at 5.3 Hz, 5.4 Hz and 7.3 Hz. These modes are tuned well below the compressor minimum operating speed of 12.5 Hz (750 rpm). Although other modes of the vessels and piping are calculated in the range of 1x and 2x, these do not involve significant participation of the skid and foundation. All higher-order skid and foundation modes were calculated to be above 2x. Therefore, the skid design is stiff enough to avoid local resonances in the 1x and 2x frequency range. This modal result is an indicator that vibration is likely to be acceptable.
The next step of the analysis was to calculate the vibration amplitude on the package. The dynamic loads were applied to the model for the 1x and 2x frequency range. The maximum vibration for this frequency range is extracted and presented in Figure 17. The 1x and 2x frequency range is indicated by the shaded areas. The vibration at 1x operating speed is well below guidelines. The primary package and foundation modes are well below the compressor operating speed, so the vibration is low. Figure 18 shows the operating deflection shape at 16.7 Hz. The results at 2x show high skid vibration at 31.4 Hz. Figure 19 shows the operating deflection shape at this frequency. Close inspection of this result shows that vibration is only over guideline at the edge of the skid flange beam where the discharge bottles are clamped to the skid. The general vibration of the skid structure is less than the skid vibration guideline of 0.1 ips pk. The 2x vibration on the compressor frame, cylinders, piping and vessel are well below guideline. The design is considered acceptable based on this analysis.

The helical piles were installed in the fall of 2018. The compressor package was installed and commissioned at the end of 2018 and has since been operating without any vibration problems. Site vibration testing has not yet been completed as a final verification of the analysis, however, the smooth, trouble-free operation of this package is a clear indicator of the effectiveness of the helical pile foundation.
Figure 18: Operating deflection shape at 16.7 Hz

Figure 19: Operating deflection shape at 31.4 Hz

High vibration only on edge of beam flange
Case study 2: high vertical vibration on a skid

This case study involves the unusual vertical vibration on a reciprocating compressor package. The package is a two-throw single-stage compressor with an engine driver on a driven steel pile foundation. An image of the compressor package finite element model is previously shown in Figure 8. The package owner reported high vibration on the compressor cylinders, bottles and piping when operating at speeds around 1,080 RPM.

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 at 2x as the 2x vibration is normally driven by crosshead guide forces.

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 20 for a plan view of the skid showing the measured skid vibrations.

Figure 20: Summary of vibration on skid (ips-pk)
The excessive vibration measured on the skid beams in the vertical direction led 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 21. 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 what is normally acceptable. The pile foundation is clearly unsuitable for this 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.

Field modal testing on the skid found the skid and foundation also 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 the 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 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 evaluated. The shaking force is generated between the suction bottle and cylinder as well as between the discharge bottle and cylinder was calculated to be as high as 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.

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 8. The model included simulation of the pile and soil dynamic properties, skid structure, detailed model of the compressor, bottles and piping, motor and cooler. The model calculated a mechanical natural frequency at 36 Hz as well as excessive skid and compressor cylinder vibration. Figure 22 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 modifications could be evaluated.
Many possible modifications to the 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. However, the concrete block foundation would be a 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 conducting 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.

**Conclusions and recommendations**

A pile foundation, whether the piles are driven or helical piles, can be effective for reciprocating compressor applications. The pile foundation design process must consider static and dynamic forces generated by the compressor and driver. Local flexibilities in the compressor skid and connection of the compressor skid to the foundation must be minimized to ensure the pile foundation is effective.
The dynamic analysis of the foundation requires simulating the interaction of the piles and soil to evaluate the flexibility and damping characteristics. A site-specific geotechnical survey to determine the soil dynamic properties is a necessary step to ensure the pile foundation design is appropriate.

There will be interaction of the pile foundation dynamic response with the compressor package. The design of each must not be done independently. A simulation integrating both the foundation and package is necessary to ensure the reciprocating compressor installation will operate in a safe and reliable manner.

**References**

1. GMRC Guideline for High-Speed Reciprocating Compressor Packages for Natural Gas Transmission and Storage Applications