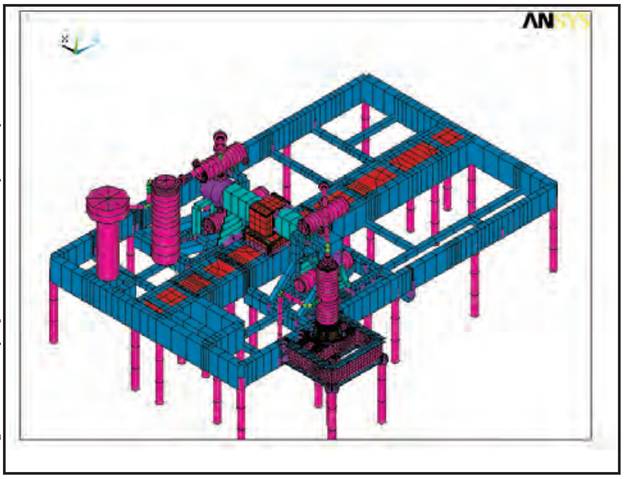
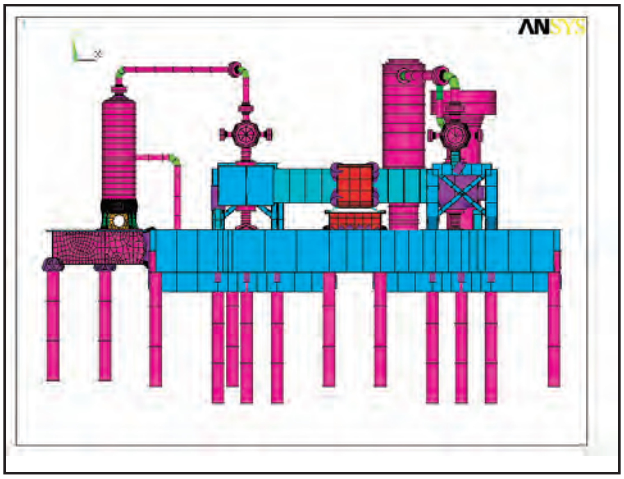
Images courtesy of Beta Machinery Analysis.





■ **Dynamic foundation analyses are prepared to provide recommendations for pile locations and foundation stiffness. Through the completion of these analyses the likelihood of resonance by the equipment is reduced, which results in reduced vibration within the package.**

FOUNDATION ANALYSIS AND DESIGN FOR RECIPROCATING AND ROTATING EQUIPMENT

The Lack of Proper Foundations Can Create Disastrous Results

By Neil Purslow

Editors Note — *This article has been created to provide one perspective on the need for adequate analysis and design for proper foundations for reciprocating and rotating equipment. In completing the article,* **COMPRESSOR***Tech*^Two *interviewed three Calgary-based companies involved in foundation design, construction and inspection services.*

Beta Machinery Analysis (Brian Howes, chief engineer), Primus Engineering (K. Pak, president) and Accurata Inc. (Frank Zahner, compression consultant) were interviewed, with each providing insights and experiences in compressor foundations. Although the companies and individuals perform many more services than mentioned in this article, their comments have been limited to certain areas for brevity.

There are a number of factors that cause gas compression equipment to vibrate, and eventually break down — and poor foundation design is one of them. Recent discussions with industry consultants revealed that many challenges in designing and implementing effective foundations exist. One challenge includes the lack of industry specifications to guide equipment users in the design of foundations where dynamic loads will be used. As a result, many equipment purchasers lack a consistent approach to foundation design, thereby decreasing the reliability of their facilities. In some cases, the lack of proper foundations can create disastrous results.

Why worry about vibration? Vibration is one of the leading causes of high-frequency maintenance and failure of compression equipment. The damage it causes may be obvious and easy to detect, such as the loosening of oil lines and other attached equipment. But it can also be insidious, including fatigue of equipment components and piping that may go unnoticed until failures occur. In both instances, excess vibration leads to higher operating costs, and failures in pressure containment systems can result in gas leaks and serious safety concerns.

Several important elements are in-

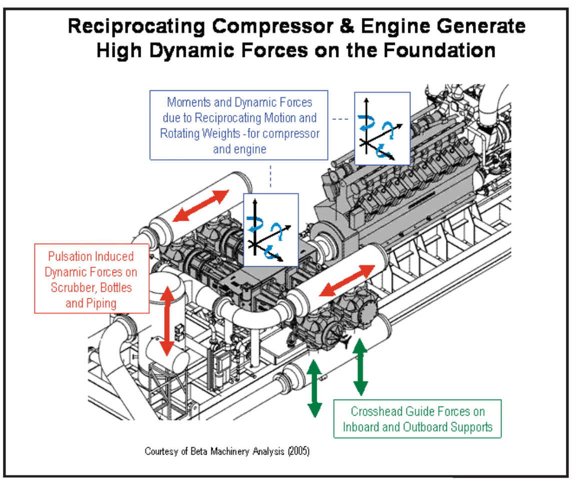


Image courtesy of Beta Machinery Analysis.

■ **A variety of dynamic forces from a reciprocating compressor package will affect the analysis and design of the package's foundation. It is the action of the pistons that causes the biggest vibration concern when designing foundations because the pistons create unbalanced forces and couples in the compressor.**

Image courtesy of Primus Consulting.

Gravel pads are generally cheap to install. However, they often don't provide good, solid contact between the skid package and the gravel pad for transmitting vibration into the ground. Gaps between the two surfaces, as shown in this picture, can only be fixed by removing the skid and fixing the gravel pad.

cluded in a foundation analysis and design process to reduce the likelihood of vibration in reciprocating and rotating compressors. First, a site and equipment analysis must be completed. Second, a dynamic foundation analysis should be performed to identify where foundation stiffness is required to avoid resonance of machine components. And finally, field implementation must be carefully managed to ensure foundations are properly installed and connected to the package's skid members.

When Primus performs a foundation analysis, a series of factors are taken into consideration. First, testing is performed to determine the properties of the soil at the proposed site. Next, data on the type of equipment to be used at the site are gathered. All of this information is required to determine the dynamic response of the foundation system.

In a package using a reciprocating compressor, for example, the model of compressor, the number of throws, cylinder sizes and the speed of the equipment determines the dynamic forces and couples produced during operation. In the majority of larger compressors, opposing pistons are mounted horizontally and offset (i.e., the center line of the pistons do not line up). Since opposing pistons are connected to the same crankshaft and travel in and out together, the forces they create almost cancel each other. But even though the forces are minimal, the pistons create torque as they travel outward, and create torque in the opposite direction when they travel inward.

It is this action by the pistons that creates unbalanced forces and couples in the compressor, and it is these forces that cause the biggest vibration concern when designing foundations. Besides mechanical causes, unbalance forces can also be induced by pulsating gas in the system, counterweights on the crankshaft and crosshead forces in the compressor, said Pak and Howes. Other types of vibration may also arise, such as vibrating cylinders, scrubbers, bottles and piping. These are often the result of poor support or the equipment being operated at or near their resonance.

These forces and their location on the skid are then incorporated into a dynamic analysis, which can be performed by Beta or Primus. The result is a recommended design that resists forces and adds stiffness in areas supporting key machine components. The required stiffness is critical to avoiding resonances in certain areas, such as scrubber bases and cylinder assembly supports.

The foundation design may entail the construction of an engineered gravel pad. "Pads are normally cheap to install, but do not always provide good solid contact between the package skid and the gravel pad that is necessary to transmit vibration into the ground," said Pak. "It becomes a painstaking process to ensure proper contact between the two surfaces. There is no easy way to fix a gap, since shims and grouting are not suitable options. The only way to fix a gap is to remove the package and fix the pad."

Using pile foundations is another option. Piles are effective at suppressing vertical movement, but are weak at dampening horizontal movement, said Pak. Many compressor packages in Western Canada are installed on metal piles, which generally consist of 8, 10 or 12 in. (203, 254 and 305 mm) pipe or I-beam, added Howes. Steel pipe is the most common because it is fast to install and can be used immediately, whereas concrete piles require time to cure. Metal piles are often used in remote locations because of the difficulty of obtaining concrete.

Primus recommends that if piles are used, a pre-cast concrete slab be installed on top of the piles. This option provides a more forgiving design while offering a large contact surface to support the skid package. Steel plates can be embedded onto the top of the concrete and used for welding the skid to the slab. As well, plates can be installed for welding the skid under scrubbers, pipe clamps, bottles and building columns to the concrete base.

After the piles have been driven to their designed depth, they should be cut to the proper elevation and capped. Pile stick-up above the ground should be minimized wherever possible, since the amount of stick-up adversely affects the lateral stiffness of the piles. When compressor skids are welded directly onto metal piles, the

Image courtesy of Beta Machinery Analysis.

In this field project, the foundation was modified. A beam was added under the skid and welded to the existing piles. By adding an extra beam, stiffness was provided midspan to support the equipment above it. If a foundation analysis and design had been completed before construction, a pile would have been installed at that location.

Image courtesy of Primus Consulting.

Pre-cast concrete slabs can be constructed with steel plates embedded onto the top of the concrete. These plates are used for welding the skid onto the slab. Plates are also installed for welding the skid under scrubbers, pipe clamps, bottles and building columns. Before the concrete is poured, the plates are positioned to match the corresponding skid members where tie-downs are required.

amount of stick-up must provide sufficient crawlspace to accommodate proper welding from below. Some pre-cast concrete slabs come with welding sleeves embedded into the concrete, which allows for the slab's installation close to the ground and accommodates welding from atop the slab.

The installation of enviropans on compressor packages has caused other challenges, said Howes. The inclusion of these pans requires packages be installed higher to provide welders access to the pilings from below. This additional height increases the likelihood that resonance will occur in the foundation and add to future foundation concerns.

"Good foundation designs are important for minimizing vibration," said Zahner, "but so is sound construction. It is very important to ensure that equipment and foundations are installed correctly." Zahner cited a number of examples where improper construction resulted in vibration in operating equipment.

In one situation, a skid package had been built on a wide flange for installation at a particular site. When the package was installed, it was not shimmed before being welded to the piles. This resulted in the welds only occurring along the tips of the wide flange, thereby creating a diving board effect and vibration in the package.

In another case, a compressor package had been fabricated with a solid main skid in the center containing all the major equipment components. Along the two lengthwise sides were removable wings that contained a small amount of process piping. The wings had been properly fastened to the center skid, but the foundations under the wings had been reduced. It was believed that because of the wing's lighter weight, the foundation under the wings could be diminished. The result was a package that resembled a bird in flight, with the movement in the wings causing vibration throughout the package.

"It is important that all construction activities be adequately supervised," said Zahner, "and that the proposed foundation be delivered precisely as designed. All alterations should be adequately analyzed and their effect on the operation of the package determined, before any alterations are undertaken. Construction deficiencies not only cost money and time to fix, but generally result in equipment downtime and lost production, which can add up quickly."

"We're often asked to determine why a customer's equipment shakes and vibrates," said Howes. "If a customer is fortunate, the exciting element can be calmed down by merely adjusting or making small repairs to the equipment, or by making a minor modification to the package. If not, the problem may involve more extensive repairs to the foundation or stiffening of the skid."

One solution used to decrease vibration in a package is to add a beam along the bottom of a skid using the existing piles. By installing an additional beam, stiffness can be provided midspan to support the equipment above it, which reduces the resonance and resulting vibration. The beam is slid under the package and lifted. It is deformed by jacking up the middle, then welded into place. All repairs occur while working in the crawlspace between the package and the ground. This solution is generally used when there are not enough piles or the existing piles are incorrectly located, plus, there must be enough space under the package to enable this type of repair. These repairs are generally expensive to complete.

Vibration tends to be less of a problem with screw and small reciprocating compressors because of smaller forces, but nonetheless, problems still exist. Beta recently completed an analysis of two electric-driven screw compressors that were vibrating and causing a number of operational issues. Even though the units had been mounted on a concrete pad and piles, analysis showed that the piles were installed in the wrong places and there were not enough of them, resulting in a skid that was too flexible.

These examples illustrate the challenges that exist in analyzing and designing proper foundations for compression equipment. To assist equipment users, the following recommendations were identified by the consultants.

All equipment users need to be aware of the importance of foundation design, including dynamic analyses and field installation practices.

Responsibility for foundation design

Vertical pipe sleeves can also be embedded into the pre-cast concrete slab. Each sleeve is placed in the slab to fit over an installed pile. After the slab is in place, the sleeves are welded to the piles from atop the slab.

Image courtesy of Primus Consulting.

Image courtesy of Primus Consulting.

After the piles have been driven to their designed depth, they are cut to the proper elevation and capped. The need for a crawlspace beneath the slab for underside welding can be eliminated when slabs are welded from the top using vertical pipe sleeves. When stick-up is kept to a minimum, the lateral stiffness of the piles is increased.

should be clearly outlined in the contracts between the parties involved in the project. When not contractually stated, all consultants agreed that the producer/owner is responsible. Since it is the owner who is responsible for all facets of a project, then, by default, they are responsible for foundation design.

In the absence of dynamic foundation specifications for equipment, users should use the services of companies who specialize in foundation designs. Many facilities are installed using similar foundation designs, regardless of soil and the forces and stiffness associated with the installed equipment. Companies with years of experience and developed expertise in geotechnical engineering should be consulted to reduce the likelihood of equipment vibration.

One common theme for all was that once a producer experiences a vibration problem with a compressor, they quickly realize the need for proper engineering for each project, including the foundation. It is important to get the foundation right, they said, since the last thing an owner wants to do is fix a problem after the package is installed. Producers can either pay upfront to complete a proper foundation analysis, design and implementation, or pay later to fix a vibration problem. The latter is generally more costly. The other alternative is to do nothing and live with the vibration, safety issues, higher maintenance cost and shortened equipment life.