A very challenging engineering problem was presented by an existing massive concrete foundation that was in continuous resonance with the operating speed of the supported engine/compressor unit. This problem became even more difficult for the following reasons:

- the resonance occurred as a torsional mode of vibration, about the vertical axis of the foundation,
- the building did not provide space to accommodate any reasonable solution,
- complications arose when the owner could not allow the required full shutdown time of the gas engine/compressor, and
- workers were not permitted to use any construction or welding equipment inside the building. These last two restrictions were necessary in order to continue plant production and to avoid any sparks that may ignite gas or create the potential for an explosion hazard.

The original foundation design did not take into account all possible modes of vibration (vertical, horizontal, rocking and torsional) of the soil-foundation interaction system. As a result, the resonance/vibration problems ensued. This article presents the analysis, construction, and problems associated with the proposed corrective measures to increase the torsional stiffness of the deficient foundation. It was concluded that increasing the foundation torsional stiffness was the only solution that could be adopted and implemented in order to eliminate torsional resonance and to significantly reduce the problem vibration levels.

The Problem

Equipment

In 1981, a reciprocating engine/compressor package with a total weight of about 375 tons (340 Mg) was installed at one of the major compressor stations operated by ANR (American Natural Resources Pipeline Company, a subsidiary of the Coastal Corporation). The installed engine generates 11,000 horsepower at 330 rpm and occupies a 15 x 38 ft (4.6 x 11.6 m) plot area. Twenty power cylinders are used to drive five 18 in. (457 mm) bore reciprocating compressor cylinders. A general view of this unit is shown in Fig. 1. The engine/compressor compresses a natural gas flow of 700 MMSCF/D — million standard cubic feet per day — (19,820 Ml/d).

Dynamic Forces

The unbalanced primary and secondary forces and moments exerted on the foundation by the engine/compressor are shown in Table 1. The primary and secondary forces and moments are associated with the operating speed of 330 rpm. Examination of the dynamic forces indicates that the predominant exciting forces that the foundation would experience occur about the foundation vertical axis (torsional) at 5.5 Hz and about the foundation's longitudinal axis (rocking) at 11.0 Hz.

These dynamic forces act at the intersection of the center line of the crank-shaft and the center line of compressor

Table 1 — Unbalanced dynamic forces and moments of the engine/compressor unit

<table>
<thead>
<tr>
<th>Force (lbs.)</th>
<th>Moment (ft-lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal</td>
<td>Vertical</td>
</tr>
<tr>
<td>Primary</td>
<td>Secondary</td>
</tr>
<tr>
<td>2000</td>
<td>0</td>
</tr>
<tr>
<td>178,445</td>
<td>915</td>
</tr>
</tbody>
</table>
Table 2 — Dynamic characteristics of the supporting soil

<table>
<thead>
<tr>
<th>Soil Depth Below Mat (ft)</th>
<th>Soil Type</th>
<th>Unit Weight (lbs/ft^3)</th>
<th>Average Shear Modulus (psi)</th>
<th>Poisson's Ratio</th>
<th>Material Damping (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 to 4.5'</td>
<td>Fine to Medium Sand</td>
<td>115</td>
<td>4,700</td>
<td>0.25</td>
<td>5</td>
</tr>
<tr>
<td>4.5' to 12'</td>
<td>Stiff Clay</td>
<td>125</td>
<td>20,000</td>
<td>0.45</td>
<td>5</td>
</tr>
<tr>
<td>12' to 26'</td>
<td>Very Stiff Clay</td>
<td>135</td>
<td>30,000</td>
<td>0.45</td>
<td>5</td>
</tr>
<tr>
<td>26' and below</td>
<td>Shale Bedrock</td>
<td>135</td>
<td>&gt;30,000</td>
<td>0.3</td>
<td>5</td>
</tr>
</tbody>
</table>

cylinder #3. These forces are transferred to the center of gravity of the foundation with a large amplification factor, which should be taken into consideration in the vibration analysis.

**Soil condition**

The soil report indicated that the problem foundation is resting on 4.5 ft (1.4 m) of sand and backfill, underlaid by 7.5 ft (2.3 m) of stiff clay, and 14 ft (4.3 m) of very stiff clay with bedrock shale encountered at 26 ft (7.9 m) below the bottom of the mat. The dynamic characteristics of the supporting soil are shown in Table 2. These dynamic characteristics of the soil play a major role in determining the dynamic response of the existing foundation and in the success of any proposed corrective measures.

**Foundation**

The engine/compressor foundation shown in Fig. 2 consists of a 46 x 30 x 5 ft (14 x 9 x 1.5 m) mat and 15 vertical concrete piles, 30 in. (762 mm) diameter, extending from the mat down 32 ft (9.8 m) to bedrock shale. Reviewing the original design calculations revealed that the dynamic analysis of the soil-foundation only addressed the vibration response in the vertical direction. These calculations indicated that the natural frequency of the foundation system in the vertical direction is higher than the operating speed of the equipment. Therefore, it was originally concluded that resonance or vibration of the supporting foundation system would not be a potential problem. Torsional, rocking and horizontal frequency calculations would have pointed to serious vibration problems in this foundation design.

A standard soil-foundation vibration torsional analysis indicated that there was a definite need for additional torsion stiffness in order to increase the natural frequencies about the foundation's vertical axis. This additional torsional stiffness exceeds that provided by the vertical concrete piles alone. Additional torsional stiffness can be achieved by providing battered or sloped piles in addition to the vertical piles.

**Early operation problems**

During the early stages of operation, the engine/compressor unit exhibited
serious vibration problems. Periodic vibration measurements indicated that the two main gas connections, inlet and outlet piping, at the north end of the unit, and all other service piping, ducts, conduits, stairs, platforms, and railings were experiencing substantial vibration levels. The foundation was moving back and forth in the east-west horizontal direction (short direction), up to 21 mils peak-to-peak at the operating speed of 330 rpm. It was also noted that the vibration levels in the horizontal direction were higher at the south end compared to the north end of the mat. The combination of these vibration levels and frequency, when plotted on the standard machinery vibration severity chart, extrapolated into the "rough" zone. The frequency domain response due to the sweep test indicated that the existing foundation system was experiencing continuous resonance, at operating speed, about the foundation vertical axis.

In order to maintain the station operation, the unit’s operating speed was reduced. This reduction in the operating speed was imposed in order to reduce the vibration levels from 21 to 5 mils peak-to-peak. By restricting the maximum speed to 315 rpm the power and throughput of the engine were obviously reduced. Foreseeing the need to utilize and restore the unit to full operating capacity — by running the engine at 330 rpm — several engineering investigations were launched. The most practical and economical solution to the resonance problem must meet all the safety regulations and be feasible within the limited construction space and shutdown-time constraints.

**Potential solutions**

Initial thoughts were that the engine was out of balance due to misalignment. The unbalanced reciprocating counterweights and an unbalanced crankshaft torsional damper were investigated. Unfortunately, after each of these areas were tested and adjusted, the vibration levels were not mitigated. This particular unit produces significant unbalanced forces and moments. These forces and moments are considered inherent to the engine/compressor unit.

It was concluded that the foundation would have to be redesigned and modified to accommodate the unbalanced forces and moments.
Preliminary vibration/stiffness calculations indicated that the existing foundation system was very poor in providing adequate torsional stiffness. As a result, the fundamental torsional frequency of the foundation was exactly matching that of the unit's operating speed.

Therefore, the existing foundation needed to be modified in such a way as to increase the torsional natural frequency to account for the unbalanced dynamic forces and moments. Execution of an engineered solution proved to be quite a daunting task as the unit could not be brought down during remedial construction. It was imperative that the ANR unit continue operation.

One primary concern was the space limitation. The engine/compressor package is housed in a 61 x 56 ft (18.6 x 17.1 m) steel building which was to remain intact and adequately supported during construction. This obviously limited the options for foundation modification to those which could be conducted outside the building unit. Due to the amount of heavy equipment located immediately adjacent to the south wall as well as suction and discharge gas piping positioned just outside the north wall, any access to the engine mat for the purpose of modifying the foundation was limited to the east and west wall.

Although the eastern access was unrestricted, the west side has a small motor control center (MCC) building that occupied approximately a 12 ft (3.7 m) portion of the compressor building. Fortunately, this MCC building was situated along the midpoint of the west wall allowing access to both ends of the existing mat. Access to the west wall required the rerouting of conduits.

Initial proposals for remedial action included considerations of pre-tensioned cables and rock bolts installed at 45° from the engine mat down to the shale stratum. The possibility of replacing the rock bolts with steel pipes filled with concrete for adequate torsional stiffness was considered. Neither design was deemed a viable option due to the fact that OSHA (Occupational Safety and Health Administration) requirements would mandate that the excavation ditch to be at least 60 ft (18.2m) wide in each of the four locations proposed. Due to OSHA excavation slope standards, the potential of undermining the existing vertical sup-
Fig. 7 — Horizontal vibration levels of the foundation due to proposed corrective measures.

Corrective measures

Three different alternative measures were proposed and analyzed using the finite element method. The first solution evaluated was to install a total of 12 concrete piles at 16 in. (406 mm) diameter. Four sets, each consisting of three piles, would be connected to the existing mat through a reinforced concrete beam (Fig. 3) 6 ft wide by 4 ft deep (1.8 by 1.2 m). The second solution proposed was to utilize six 4 to 6 ft (1.2 to 1.8 m) diameter caissons connected to the existing mat (Fig. 4). The third solution proposed using four 8 ft (2.4 m) diameter caissons connected to the existing mat by 8 ft wide by 6 ft deep (2.4 by 1.8 m) girders (Fig. 5).

Finite element analysis

A detailed finite element model considering the soil-foundation interaction was developed to investigate the vibration response of the existing foundation design and the three proposed corrective measures. The developed three-dimensional model, shown in Fig. 6, simulated the existing conditions of the foundation system, the engine/compressor unit, and the soil contribution, in resisting the specified dynamic forces and moments. The unbalanced forces and moments were applied to the computer model at different speeds ranging from 240 to 450 rpm. The results of this analysis are shown in Fig. 7.

It was clear that solution #3 would provide the required additional torsional stiffness. This solution would result in a significant decrease in the anticipated horizontal vibration levels at the operating speed — to about 2.0 mils. Therefore, the decision was made to implement solution #3 as the best corrective measure to solve the resonance and vibration problem. This remediation plan was very attractive to the owner as most of the construction activities would be conducted outside the compressor building. Limiting the construction to the exterior of the unit minimized unit downtime, eliminated many hazards, and complied with OSHA standards.

Fig. 8 — Cross-section details of proposed solution.
Construction of the selected approach

As presented, it was concluded that the most appropriate modification to provide adequate lateral and torsional stiffness would be achieved by constructing four vertical caissons coupled with four large horizontal beams rigidly connected to the existing mat. This solution minimized downtime and did not require adjacent excavations as the caissons would be drilled. This remediation plan also allowed for the preservation of the existing vertical support of the engine and building. Construction detail of this solution is shown in Fig. 8.

A total of four 8 ft (2.4 m) diameter vertical caissons were constructed and embedded into shale. The caissons were positioned just outside the building wall at each corner and connected to the engine mat via 8 x 6 ft (2.4 x 1.8) horizontal concrete beams. These beams were considered the most critical piece of this modification since a void of approximately twenty-thousandths of an inch (0.051 mm) between the existing engine mat and the new caissons would render the whole design useless. Any gap between the mat and the concrete caissons would allow continued horizontal vibration.

In order to ensure this critical tight fit, Type K expansive cement was incorporated in the concrete design mix. Type K cement is shrinkage compensating, providing an efficient way to minimize the drying-shrinkage cracking normally associated with standard portland cements.

The use of Type K cement along with the appropriate reinforcement significantly reduces internal tensile stresses which normally develop due to drying-shrinkage because of its controlled expansion. The specification of the concrete mix for the foundation modification included a 0.42 water/cement ratio, a slump of 4 in. (100 mm), air entrainment of approximately 5 percent and a minimum strength of 4000 psi (28 MPa) at 3 days.

Construction commenced with building four separate isolated work areas. This allowed the contractor to work inside the compressor building yet not pose any potential danger — such as exposing the Class I Div. II area to any type of ignition source. Fig. 9 shows one of the working areas prepared to accommodate the caisson and the beam. The next step was to cut the compressor building floor and excavate in each of the four isolated areas where the horizontal beams were to be located. The connection of the new beams to the existing engine mat required mechanically coupling new reinforcing steel to the existing reinforcing steel. The mat was then chipped back to expose the existing reinforcing steel at each of the four locations. Once the excavated areas were shored, the outside drilling of the caissons began.

Care was taken to pinpoint the center line of each caisson for drilling. Each of the caissons were required to be embedded into 5 ft (1.5 m) of shale, which was accomplished by drilling to a depth of 28 to 35 ft (8.5 to 10.7 m) below grade level. Drilling had to be tightly controlled in order to conform to ACI 336.1-79, as adopted in 1989, for Cate-
gory C plumness. Fig. 10 shows the placement of the reinforcement cages for one of the four caissons.

Once the first of the four corners was completely excavated, a reinforcing cage was placed for both the caisson and the connecting beam (Fig. 11). Next, plain concrete was poured to within 6 ft (1.8 m) of the top of the caisson while the next caisson was being drilled. This construction sequence continued until all four of the caissons were placed. After three days’ curing time, the beams were then cast, with the remaining portion of each caisson utilizing a Type K cement. A special bonding agent was applied to the face of the existing foundation mat. It was only during this period that the engine was shut down and remained so — for approximately three days while the concrete cured.

The total amount of concrete used for the vertical caissons was approximately 225 cy (172 m³) and approximately 110 cy (84 m³) for the horizontal connecting beams. Fig. 12 shows the final step in constructing one of the caissons and its connected beam.

The last step of the construction phase of the project was to disassemble the temporary work areas and restore the compressor building to its original condition. The total cost of the foundation modification was approximately $400,000.

Acknowledgment

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Selected for reader interest by the editors.

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