# Analyze your engine foundations

**User, contractor, and foundation engineer should understand the importance of simple preliminary checks if the engine (or compressor) is to run well. Alignment and material problems can shed light on related topics**

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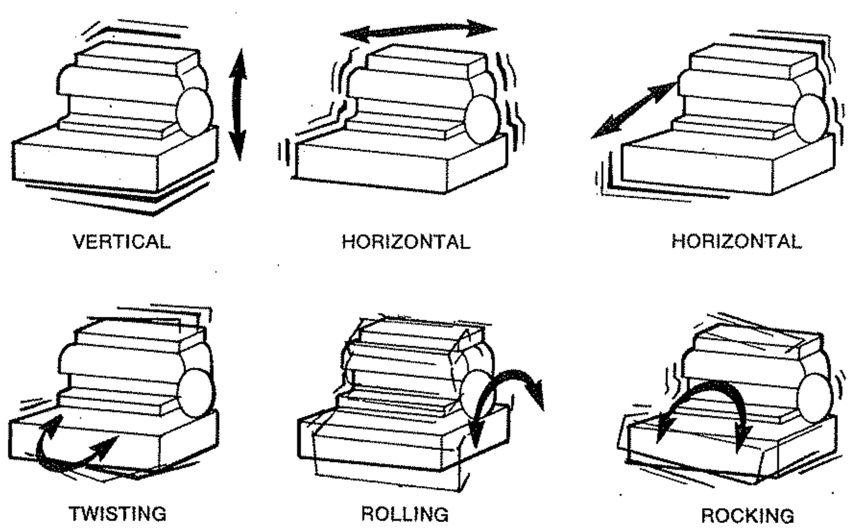
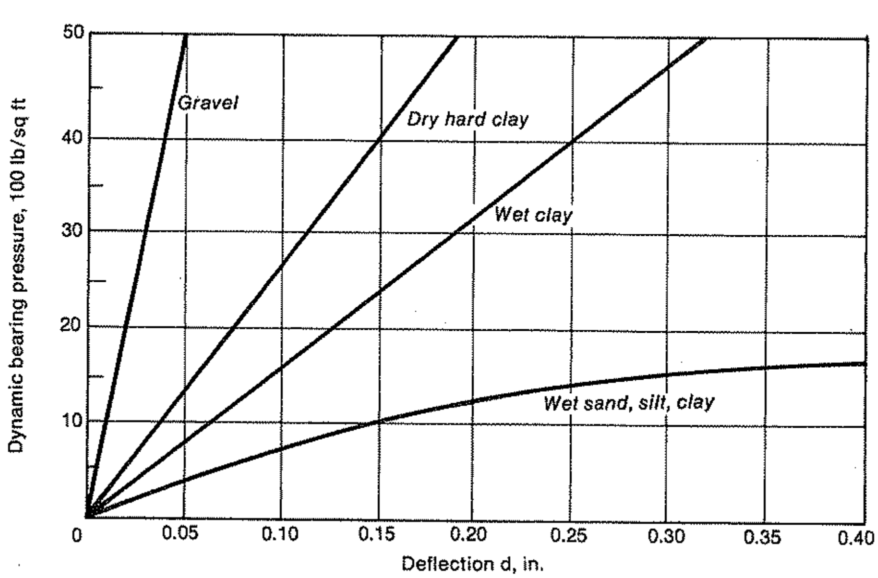
Analysis of engine foundations must go into the details of some of the topics mentioned in the article, "Set guidelines for engine foundations" (POWER, October 1977). We will start here with a look at the soil under the foundation.

Present design methods recognize the importance of the natural frequency of the soil in elastic systems comprising engine foundation and supporting soil or piling. Vibration is induced by a periodic force, and here frequency is that of system vibration measured in cycles per minute. When the disturbing force in the engine or compressor, say from primary or secondary imbalance, is at the same frequency as that of the combined foundation and soil system, serious vibration occurs.




**Six degrees of freedom are possible** for vibrating foundation block freely supported on soil. Because of shape and comparative stiffness, block itself is assumed to be rigid




**Typical frequencies for various soils,** deriving from early test results, are a function of static-deflection characteristics and have proved out in many installations

Foundation-block vibration modes are shown at left. Frequencies that, in resonance, excite large amplitudes of these motions will cause serious settlement or transmission to the building or adjacent dwellings.

A system can be adjusted to the soil conditions in various ways. Changing the block mass, increasing area of the support mat, reducing unit soil-load pressure, and reducing unbalanced forces will all increase mass-soil frequency. The shape of the loaded undersurface of block or mat and the distribution of soil loading pressure, too, affect vibration.

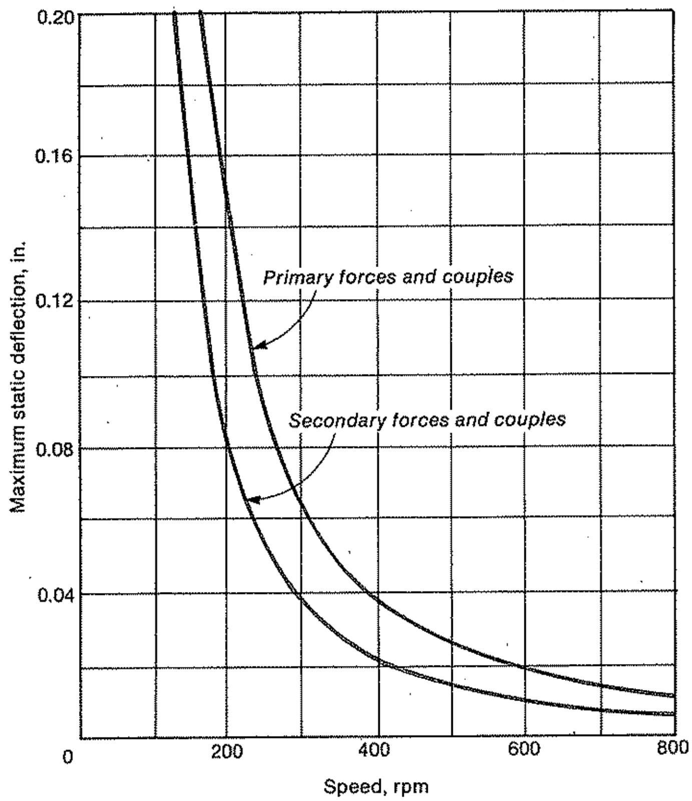
## Check soil dynamics

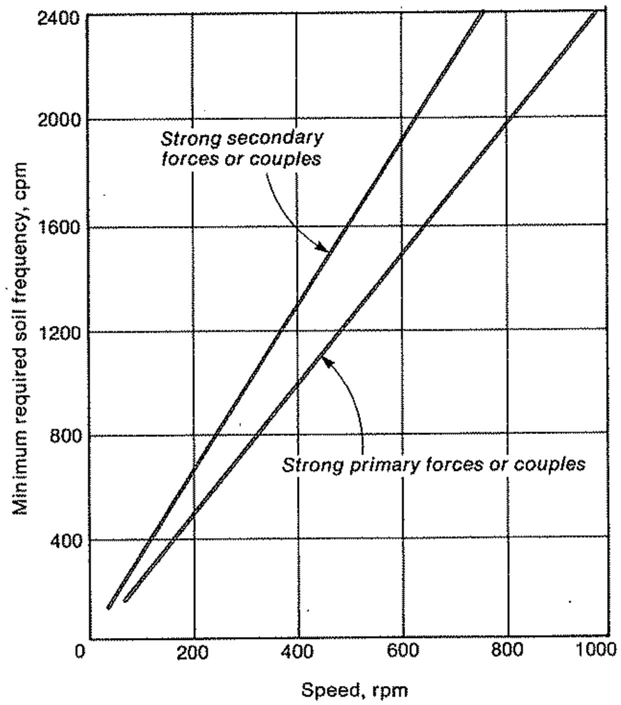
Natural frequency of the soil can be calculated from soil deflection, impact tests, or mechanical-oscillator data. Accuracy will vary. The chart (lower left) gives frequencies for various soils.

Tests show that soil frequencies also depend on other factors, to an extent that can alter values by over 20%. Area of mat, intensity as well as frequency of dynamic loading, and proximity of other foundations or building supports are some of these factors. Although neither static nor dynamic load tests will give highly accurate determinations, the outlined method is valuable as an approximation, or index.

The "gravel" curve of the chart can be used for good subsoil, and the "wet clay" curve for doubtful soil and clay/sand mixtures. The nature of the soil is directly related to its inherent frequency. The two basic soil types are noncohesive and cohesive.

Noncohesive soils include sands and gravels of loose or dense consistency. Cohesive soils include complex structures typical of clays. Porosity of sands ranges from 30% for dense to 50% for




**Block-mass calculations** start with operating speed vs soil deflection (left). Minimum required soil frequency (above) goes up with speed. Reduction for soil deflection raises frequency

loose structures. Cohesive soils vary from 20% to 90% in porosity.

Dense sandy soils tend to resist settlement. Loose, noncohesive soils will settle considerably under compacting forces, because of distortion and shear of sand grains into void areas. With clay soils, although vibration may not alter them, long-term settlement occurs because of moisture content and distortion of particles in the agglomerate. In such cases, piling supports driven to refusal would be advisable.

Experience with other structures in the area may be a good start in review of conditions. Dry sample borings will indicate soil composition from the rate of penetration. Where water table is high and sands excessively loose, or soft and wet, a consultant's services may be advisable. A foundation expert may recommend compacting by vibroflotation, or he may suggest pilings. Pressure injection of grout is also effective, as discussed below.

## Early foundation decisions

Foundations for engines or horizontal reciprocating compressors must be designed during the planning stage for the facility building. Suitable soil loading for the foundation will determine the area necessary. If basements are needed for the building, their level may establish minimum height of the block. Isolate foundations from building footings or floors by at least 1 in., and fill the gap with watertight mastic material.

Two basic types of foundation are block (or box) and rigid frame. The block foundation adapts well to engine-generator sets and reciprocating compressors. The frame foundation serves turboblowers, where piping and intercoolers go under the machine.

Differences of opinion exist on pouring of block foundations. While one pour is recommended by some, other experts recommend a three-section pour to overcome heat effects. Where a single pour is not possible, suitable locking in by rebars is needed to prevent cracking.

Soil-load calculations will be simplified if the slab bottom is flat. Depth of slab or mat is determined from shear stress of the section adjoining the block, including rebars. For large engines, the depth is 18 to 24 in; small units have 8 to 12 in. of mat under the block.

## Engine unbalance effects

Balanced reciprocating engines with 6 or 8 cylinders in line, or V-12 and V-16 four-cycle engines, are not critical if guidelines are followed. An odd number of cylinders produces inherent couples tending to rotate the block. Angle gas compressors have both primary and secondary forces and couples. Horizontal balanced-opposed compressors have both vertical and horizontal couples.

Impressed-force vibration amplitude is:

$$\Theta = 91FD \div I(rpm)^2$$

where $\Theta$ is the angular displacement in radians, F the force (primary or secondary), D the distance from center of gravity of engine or compressor to foundation bottom, I the mass moment of inertia of machine and foundation about an axis adjacent to foundation bottom, and rpm the engine speed in revolutions per minute. For secondary force, multiply rpm by 2.

Where rocking couples exist, there is a tendency to rotate about the combined center of gravity of machine and foundation. Here, the equation becomes:

$$\Theta = 91C \div I(rpm)^2$$

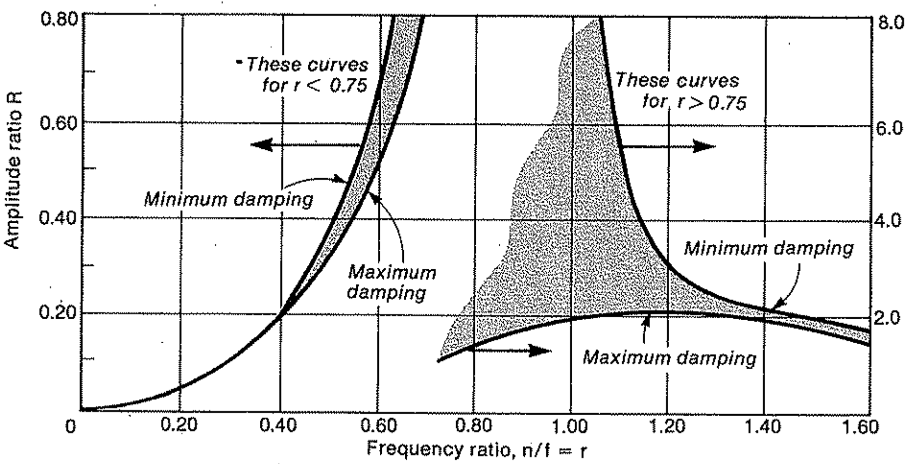
where C is the rocking couple. The center of gravity tends to remain stationary.

With these equations and the figures above, the estimate of foundation-block mass can be made. In the left chart, one curve is for strong primary forces or couples, and another curve for secondary forces or couples. Allowable soil deflection decreases as speed increases. The manufacturer's installation prints will usually show unbalanced forces and couples.

## Resonant frequency and mass

The method outlined above is applied starting from a desirable soil frequency, engine speed, and foundation bearing area. Foundation specialists appreciate that there is a magnification effect where resonance exists between soil frequency and forcing frequency, or periodic force, in the reciprocating machine.

Need for economy in foundation design will impose limits to block mass.



**Amplitude calculation,** beginning with engine speed, foundation bearing capability, and desirable soil frequency, must include amplitude ratio, or magnification factor, R

For preliminary calculations, a value of at least twice that of the machinery mass can serve. Dynamic soil load, the load in lb/sq ft of the combined machinery and foundation on the contact area of block or mat bottom should not exceed one-quarter of static load test of the soil. A nominal value of 1500 lb/sq ft can serve for soil frequencies in the 1500-1700-cycles/min range.

Vibration amplitudes allowable at the machine center of gravity depend on the engine speed. For operating speed below 250 rpm, 0.004 in. is allowable. Speed from 250 to 450 rpm reduces the allowable to 0.003 in.; above 450 rpm, the limit is 0.002 in. In general, borderline conditions can be expected between 0.004 and 0.008 in., with real difficulty above 0.008 in.

If foundations are embedded firmly in the soil, maximum amplitudes about 50% higher than the allowables given above offer no appreciable discomfort to personnel.

Spring mounting changes the picture somewhat, since these units are permitted as much as three times the allowable values above. Flexible piping to and from the equipment is needed here.

High-speed machines on poor soil call for extreme care in design. Primary forces with frequency over 1000 cycles/min, or secondary forces of units operating at 500 rpm and above, fall into the high-speed classification.

## Typical problem

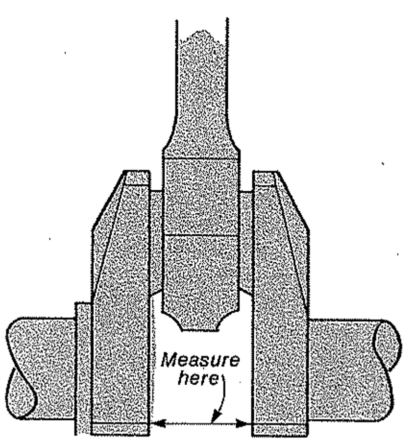
A five-cylinder, 175-hp vertical diesel engine operates at 600 rpm and has a primary rocking couple of 7200 lb-ft. Weight of engine and foundation is assumed to be 57,000 lb, with moment of inertia of 25,000. If the soil is dry firm gravel, the allowable static pressure is 6000 lb/sq ft, and the allowable dynamic load is 25% of this, or 1500 lb/sq ft. Contact area is then 57,000/1500, or 38 sq ft.

Upper curve in upper left figure on preceding page gives static deflection, d, of 0.016 in. at 600 rpm. The upper right figure gives the desired frequency as 1500 cpm. The assumed frequency f is calculated from:

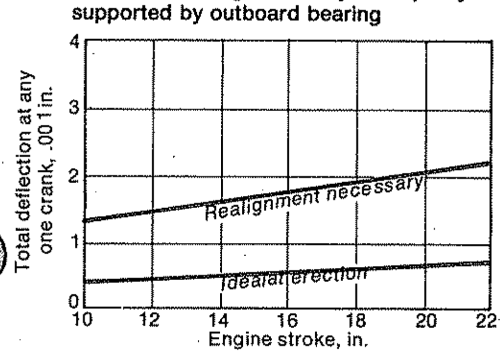
$$f = (35{,}400/d)^{0.5}$$

So if d = 0.016 in., the frequency is 1490 cycles/min.

Frequency ratio r is n/f, or 600/1490 = 0.403. In the chart above, this value gives a magnification factor R of 0.20 for the primary vertical couple. Actual amplitude at the foundation end, 72 in. from the center of gravity, will be the free amplitude, times the magnification factor. Angular displacement, Θ, must be found first. This is 91C ÷ I(rpm)$^2$, or 91 × 7200 ÷ [25,000 × (600)$^2$], which is 0.0000747 radians. At the foundation end, 72 in. from the center of gravity, the free amplitude is Θ × 72, or 0.0054 in. The expected actual amplitude is this amplitude multiplied by magnification factor R, or 0.00108 in. The maximum allowable amplitude at 600 rpm is 0.002 in., so the operation will be satisfactory.




**Crankweb deflection** (left) is measured over a complete revolution. Chart (below) is for vertical engine with flywheel partly supported by outboard bearing




## Pressure grouting

Soil instability can be a serious problem after a unit enters service. Horizontal reciprocating compressors and angle-engine compressors are more troublesome here because some engine imbalance is inherent. Even though counterweights, firing-order alterations, and compressor crank-angle selection may help reduce unbalanced forces and couples, the residual forces and moments will compact unstable soils.

Core samples will usually locate the unstable zone, which may be as deep as 10-40 ft below the mat. Pressure grouting, injection of portland cement fortified with an intrusion aid to keep cement particles in suspension, has successfully compacted the soil. In one case, grout injection lifted the entire engine, foundation, and mat back to its initial elevation.

Alteration of soil properties by injection of chemicals can make soil impervious and cohesive, preventing seepage, but special techniques are required. Analysis of soil samples at various depths when soil instability is present will determine the static bearing load at the foundation support level. If the water table is high, or if soft wet silt and clay occur, piling carried down to refusal is recommended. Concrete-filled steel-pipe piling has been installed for this purpose.

## Crankshaft alignment

Crankshaft alignment is related to foundation design. Manufacturers have set up crankweb-deflection limits for each type and size of unit. The reading is taken, as shown at left, by a dial indicator between webs at a distance from shaft centerline prescribed by the manufacturer. The outboard bearing at the generator end can be adjusted to align flywheel end crank, but all other crankwebs are aligned by wedges, shims, or adjusting screws under the base flanges before grouting.

Wedges, if used, are placed close to the foundation bolts and are removed after grout has set. The void is then filled with grout. If adjusting screws are the choice, they thread directly into the base flange and are removed after grout hardens.

Deterioration of grout by leaking oil will cause the base to separate from its support and to distort enough to disturb the initial alignment. Damaged bearings and ultimately a broken crankshaft will result unless the unit is promptly regrouted.

Warping of the foundation block can also occur from excessive drying during adverse climatic conditions. Distortion of this type on long foundations can be checked, if reference plugs or bench marks are set. Other factors in warping are impure water, improper aggregate, freezing, and inadequate rebar reinforcement.

## Alkali-aggregate danger

Recently, alkali aggregates have been found to cause serious crankshaft misalignment. In one case, mill tests showed variation from 0.49% to 0.79% alkali content in a block. Excessive distortion had been experienced and detected by checks during six years.

Chemical reaction of free alkali and amorphous silica will expand the concrete. The reaction takes place with as low as 0.40% alkali content, but becomes critical above 0.60%. Siliceous rocks, amorphous silica, and potassium oxides will start alkali aggregate reaction. Test bars expand at normal atmospheric conditions, indicating a 0.50% change in block dimensions. A growth of as little as 0.025 in. will give 0.005 in. crankweb deflection.

Reactive pozzolans are added to the concrete mix to control this. Specifications for concrete should provide for these additives if there is any possibility of alkali aggregate. Innocuous aggregates and low-alkali cement are recommended. Reactivity tests follow ASTM C227 method.

## Bolt repairs

Breakage of foundation bolts can result from foundation growth; this usually occurs in the bottom thread of the nut end of the bolt. Improper installation and excessive tightening also contribute to the problem.

Weld a new threaded extension to the broken bolt, install a short sleeve, and add new grout to fill the opening. If the bolt is definitely cocked, provide additional bolt length for an adjustable spherical washer under the nut.

## Differential temperature

Don't underestimate the importance of temperature distribution in concrete foundation blocks, since distortions result in broken foundation bolts. In one case of broken bolts, none of the causes related to foundation growth appeared. Aggregate was low in alkali, and the water was sulfate-free. Tests on the grouted base showed 0.08 in. humping at engine center after 700 hr operation under severe cold-weather conditions. The engine base showed a 0.045 in. hump, of which only 0.029 in. came from temperature rise in the metal. This indicated that the engine base was resisting the foundation distortion. Although the foundation bolts had been torqued to 400 lb-ft, their release torque was 900 lb-ft with the engine warm.

These engines had a flat-bottom integral-oil-sump base. A unit of this type would be vulnerable to high thermal dissipation to the upper concrete surface. Steel rails under the engine gave an effective solution, providing insulating air space as well as allowing shimming of individual bearing supports in the base structure.

Mounting of diesel and dual-fuel engines on rails, ground parallel top and bottom, and sized to impose about 400 lb/sq ft on the grout, is common. Steel shims between rails and chocks atop the rails give proper alignment of the engine crankshaft.

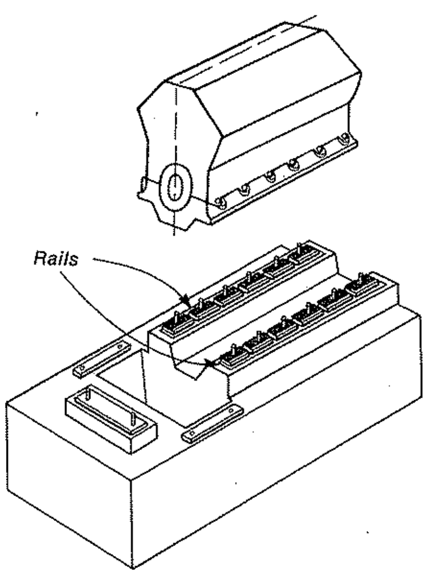
## What pulsation does

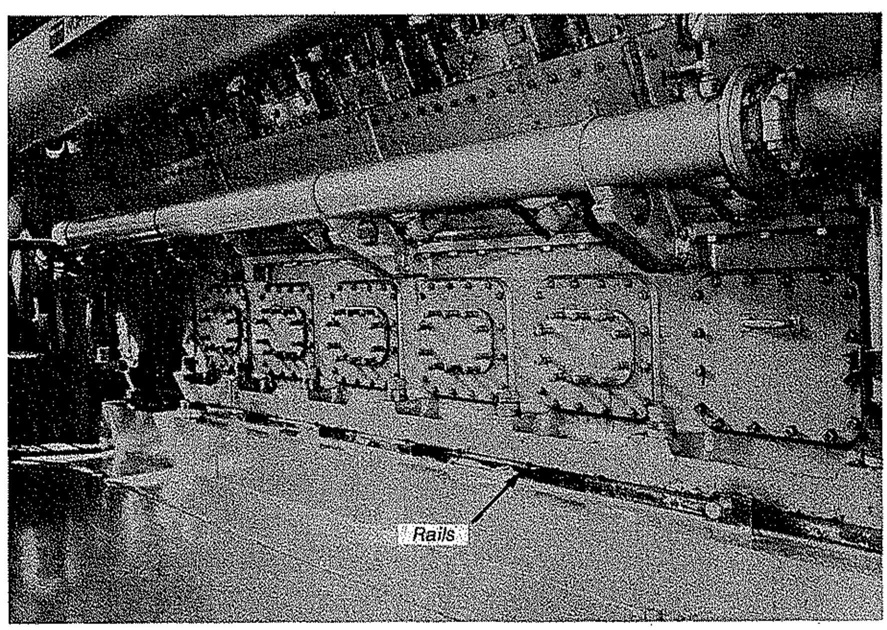
In many cases of vibration problems with horizontal reciprocating compressors, the foundation has been blamed when gas pulsations in the suction or discharge piping have been the real cause. In complex systems, an analog study is needed to determine the resonant frequency and location of maximum amplitudes.

For a quick check to see if pulsation is responsible, remove the suction valves from the compressor and run the unit. If vibration is absent, the fault is in the piping. If vibration still occurs, then the disturbance is from unbalanced forces in the machine.

In the final analysis, much information is still needed to handle the complex problems of piling and structure flexibility, which have become specialized engineering techniques. The engine builder's responsibility can perhaps be summed up by a note like this on the foundation plan: "This foundation design is for good soil only, with a minimum allowable static load of 800 lb/sq ft. In case of poorer soil, a competent foundation engineer should be employed."

**Edited by William O'Keefe**




**Rail-mounting** of large high-output engines is now widely accepted. Flat bars, 2 to 4 in. thick, distribute engine weight to grout. Chocks—short steel plates, ground parallel and about 1 in. thick—may be interposed between rails and engine base