Engineering Standard

SAES-Q-007 4 April 2009
Foundations and Supporting
Structures for Heavy Machinery

Saudi Aramco DeskTop Standards

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1 Scope

1.1 This standard covers mandatory requirements governing the design of foundations and support structures for heavy machinery.

It pertains to foundation and support structure designs governed by dynamic loadings due to machinery vibrations. Foundations and support structures designed for machinery vibrations must also be capable of withstanding all other loadings to which they may be subjected (wind, piping forces, etc.), with stresses not exceeding those permitted by the applicable Saudi Aramco Standards.

Commentary Note 1.1:

Foundations for reciprocating compressors greater than 150 kilowatts (200 brake horsepower) and all table-top special purpose equipment shall be dynamically analyzed. If the analysis predicts a resonance, then the mass of the foundation should be increased (if possible) to overtune it. Foundations for general purpose equipment do not generally require specific dynamic or vibration related design, but it is recommended that these foundations comply with Sections 6.1.2 & 7 of this standard and PIP REIE686/API RP 686, Chapter 4.

1.2 The basic design objectives as prescribed in this Standard are:

a) The suppression of vibration amplitudes to meet the limits specified in the applicable Saudi Aramco Standards.

b) The determination of the machine-foundation system natural frequencies to ensure that the separation margins specified in the applicable Saudi Armco Rotating Equipment Standards are met for the relevant excitation sources.

c) The provision of sufficient strength and rigidity to maintain equipment alignment and to prevent failures due to fatigue or overstressing.

d) The provisions for adequate foundation bearing capacity and acceptable settlements.

2 Conflicts and Deviations

2.1 Any conflicts between this standard and other applicable Saudi Aramco Engineering Standards (SAESs), Materials System Specifications (SAMSSs), Standard Drawings (SASDs), or industry standards, codes, and forms shall be resolved in writing by the Company or Buyer Representative through the Manager, Consulting Services Department of Saudi Aramco, Dhahran.

2.2 Direct all requests to deviate from this standard in writing to the Company or Buyer Representative, who shall follow internal company procedure SAEP-302 and forward such requests to the Manager, Consulting Services Department of Saudi Aramco, Dhahran.

3 References

The selection of material and equipment, and the design, construction, maintenance, and repair of equipment and facilities covered by this standard shall comply with the latest edition of the references listed below unless otherwise noted.

3.1 Saudi Aramco References

Saudi Aramco Engineering Procedure

SAEP-302 — *Instructions for Obtaining a Waiver of a Mandatory Saudi Aramco Engineering Requirement*

Saudi Aramco Engineering Standards

SAES-A-113 — *Geotechnical Engineering Requirements*

SAES-A-114 — *Excavation and Backfill*

SAES-M-100 — *Saudi Aramco Building Code*

SAES-Q-001 — *Criteria for Design and Construction of Concrete Structures*

SAES-Q-005 — *Concrete Foundations*

SAES-Q-011 — *Epoxy Grout for Machinery Support*

Saudi Aramco Engineering Reports

SAER-5659 — *Guidelines for Setting Acceptance, Alarm and Shutdown Vibration Limits*

Saudi Aramco Materials System Specification

09-SAMSS-097 — *Ready-Mixed Portland Cement Concrete*

12-SAMSS-007 — *Fabrication of Structural and Miscellaneous Steel*

3.2 Industry Codes and Standards

American Society of Mechanical Engineers

ASME B 73.1 — *Specification for Horizontal End Suction Centrifugal Pumps for Chemical Process*

American Concrete Institute

ACI 207.2R	*Effect of Restraint, Volume Change, and Reinforcement on Cracking of Massive Concrete*
ACI 318	*Building Code Requirements for Structural Concrete and Commentary (ACI 318R) Errata*
ACI 504R	*Guide for Sealing Joints in Concrete Structures*

American Petroleum Institute

API STD 610	*Centrifugal Pumps for Petroleum, Heavy Duty Chemical and Gas Industry Services*
API STD 611	*General Purpose Steam Turbines for Petroleum, Chemical, and Gas Industry Services*
API STD 612	*Special Purpose Steam Turbines for Petroleum, Chemical, and Gas Industry Services*
API STD 613	*Special Purpose Gear Units for Petroleum, Chemical, and Gas Industry Services*
API STD 616	*Gas Turbines for Petroleum, Chemical, and Gas Service Industries*
API STD 617	*Centrifugal Compressors for Petroleum, Chemical, and Gas Service Industries*
API STD 618	*Reciprocating Compressors for Petroleum, Chemical, and Gas Industry Services*
API STD 672	*Packaged, Integrally Geared Centrifugal Air Compressors for Petroleum, Chemical, and Gas Industry Services*
API STD 674	*Positive Displacement Pumps - Reciprocating*
API STD 676	*Positive Displacement Pumps - Rotary*
API STD 677	*General Purpose Gear Units for Petroleum, Chemical, and Gas Industry Services*
API RP 686	*Recommended Practice*

International Organization for Standardization

ISO 2631-1	*Mechanical Vibration and Shock Evaluation of Human Exposure to Whole-Body Vibration-Part 1: General Requirements*

ISO 2631-2	*Evaluation of Human Exposure to Whole-Body Vibration-Part 2: Continuous and Shock-induced Vibration in Buildings (1 to 80 Hz)*

Process Industry Practices

PIP REIE686	*Recommended Practice for Machinery Installation and Installation Design*
PIP STC01015	*Structural Design Criteria*

4 Definitions

Heavy Machinery: Any machinery having rotating or reciprocating masses as the major moving parts (such as compressors, pumps, electric motors, diesel engines and turbines).

Machine Support/Foundation System: A system consisting of the machinery (train) including baseplate and the foundation, support structure plus all piers, equipment and process piping supported on the foundation or machinery. The supporting soil, piling or structure shall be considered part of the machine foundation system.

Support/Foundation: The part of the machine support not supplied by the equipment manufacturer as part of the machinery (train). This may include but is not limited to piers, concrete mat or block, pilings, steel structures, anchor bolts and embedded foundation plates.

Base Plate (also called Mounting Plate or Skid): Common steel machine support supplied by the machinery manufacturer for mounting the entire machinery (train) on.

Grout: An epoxy or cementitious material used to provide a uniform foundation support and load transfer link for the installation of rotating machinery. This non-shrink material is typically placed between a piece of equipment's concrete foundation and its mounting plate.

Equipment User: The person or organization charged with the operation of the rotating machinery. In general, but not always, the equipment user owns and maintains the rotating machinery after the project is complete.

Equipment Train: Two or more rotating equipment machinery elements consisting of at least one driver and one driven element joined together by a coupling.

General Purpose Equipment Trains (Definition as per PIP REIE686): Those trains that have all general purpose elements in the train. They are usually spared, relatively small in size (power), or are in noncritical service. They are intended for applications where process conditions will not exceed 48 bar gauge (700 psig) pressure or 205°C

(400°F) temperature (excluding steam turbines), or both, and where speed will not exceed 5000 revolutions per minute (RPM).

Commentary Note:

> *General purpose equipment trains have all elements that are either manufacturer's standard or are covered by standards such as the following: ASME B.73.1 for horizontal pumps, API STD 610 for pumps, API STD 611 for steam turbines, API STD 672 for air compressors, API STD 677 for general purpose gears, API STD 674 for reciprocating pumps, API STD 676 for rotary positive displacement pumps, and NEMA frame motors.*

Special Purpose Equipment Trains (Definition as per PIP REIE686): Equipment trains with driven equipment that is usually not spared, is relatively large in size (power), or is in critical service. This category is not limited by operating conditions or speed.

Commentary Note:

> *Special purpose equipment trains will be defined by the user. In general, any equipment train such as an API STD 612 turbines, API STD 618 reciprocating compressors, API STD 613 gear, API STD 616 gas turbines, API STD 617 centrifugal compressors, or equipment with a gas turbine in the train shall be considered to be special purpose.*

High-Tuned System: A high-tuned system is a machine support/foundation system in which the operating frequency (range) of the machinery (train) is below all natural frequencies of the System.

Low-Tuned System: A low-tuned system is a machine support/foundation system in which the operating frequency (range) of the machinery (train) is above all natural frequencies of the System.

Mixed System: A Mixed System is a Machine Support/Foundation System having one or more of its natural frequencies below and the rest above the operating frequency (range) of the machinery (train).

Machine Bearing Axis: An axis drawn between the geometric centers of two bearings supporting the machine rotor or shaft. For machinery trains with an offset gearbox, an equivalent machine bearing axis shall be determined, parallel to the individual axes and in the position of the resultant of the in-phase dynamic forces.

Transient Dynamic Force: Any dynamic force which is short term in nature such as starting torques or short circuit moments in electrical machinery, hydraulic forces, resonance forces of low-tuned or mixed systems during start-up or shut-down.

Steady-State Dynamic Force: Any dynamic force which is periodic in nature and generated during normal operating conditions, such as centrifugal forces due to unbalances in rotating machinery or piston forces in reciprocating machinery.

Table Top: Reinforced concrete structure supporting elevated machinery.

Acceptance Level (as per SAER-5659): This is the vibration level (displacement, velocity, or acceleration) at which a machine can run indefinitely without inducing vibration related maintenance.

Alarm Level (as per SAER-5659): This is the vibration level at which a machine is considered to have developed a defect that will result in related downtime. This level is usually higher than the acceptance level to allow for conservatism and machinery variance and is currently recommended as 1.5 times the acceptance level but may be varied, depending on specific experience or operational requirements.

Nomenclature:

L Length of foundation parallel to the machine bearing axis in meters

B Width of foundation in meters

D Depth of foundation in meters

FC Compressive strength of concrete after 28 days in MPa (psi)

ED Dynamic Modulus of elasticity of concrete in MPa (psi)

A Maximum permissible peak-to-peak vibration amplitude in µm (mil)

rpm Machine speed in revolutions per minute

f Operating frequency of the machinery (train) in Hertz

f(n) Natural frequency of Machine Foundation System in Hertz

FD Magnitude of dynamic force in kN (kip = 1000 lb)

W Total mass of rotating parts in kg (kip)

5 Design Requirements

5.1 General

5.1.1 Support structures or foundations for centrifugal rotating machinery greater than 500 horsepower shall be designed for the expected dynamic forces using dynamic analysis procedures. For units less than 500 horsepower, in the absence of a detailed dynamic analysis, the foundation weight shall be at least three times the total machinery weight, unless specified otherwise by the Manufacturer.

5.1.2 For reciprocating machinery less than 200 horsepower, in the absence of a detailed dynamic analysis, the foundation weight shall be at least five times the total machinery weight, unless specified otherwise by the Manufacturer.

5.1.3 To maintain equipment alignment and to minimize relative deflections, all coupled elements of the machinery train shall be mounted on a common foundation or support structure.

Commentary Note 5.1.3:

> *Coupled elements are the driver (e.g., diesel engine, gas turbine, electric motor), gear-box, if any, and driven equipment (e.g., pump, compressor, generator). Auxiliary equipment such as lube oil or seal oil pumps and reservoirs need not be installed on the same skid.*

5.1.4 Foundations for heavy machinery shall be independent of adjacent foundations and buildings. Concrete slabs or paving adjacent to the foundation shall have a minimum 12 mm isolation joint around the foundation using an approved elastic joint filler with sealant on top.

Commentary Notes 5.1.4:

> *Foundations for heavy machinery shall be independent of adjacent foundations, concrete slabs, paving or buildings because the adjacent mass may restrain the equipment foundation building up stresses for which it was not designed or conversely the equipment may cause unwanted stresses or vibrations in adjacent structures.*
>
> *Joint filler material shall be an expansion joint material, see ACI 504R "Guide for Sealing Joints in Concrete Structures". Preformed expansion joint filler shall be of the full thickness and depth of the joint with splicing only on the length.*

5.1.5 The clear distance in any direction between adjacent foundations for heavy machinery shall be large enough to avoid transmission of detrimental vibration amplitudes through the surrounding soil or the foundations shall be protected in other ways. Transmissibility of amplitudes shall be limited to 20% between adjacent foundations, unless otherwise agreed by the Manager, Consulting Services Department.

Commentary Note 5.1.5:

> *Foundation spacing is intended to ensure that the soil response of adjacent foundations is independent as far as possible. A spacing of 2.5 times the width of the smallest foundation is recommended, because the volumes of soil under stress from adjacent foundations will not overlap in that case. In instances where this spacing cannot be accomplished, calculations have to be made to prove that the transmissibility is*

acceptable. Otherwise, consideration must be given to applying soft board on the adjacent sides of the foundations or the installation of slurry walls or sheet piles between the foundations. The choice depends on the calculated vibration amplitudes and the expected behavior of the soil.

5.1.6 Where practical and economical, the machine foundation system shall be proportioned to be low-tuned.

Commentary Notes 5.1.6:

For heavy, high-speed machinery the foundation geometry is typically such that the primary natural frequencies will be lower than machine operating frequency. Since the natural frequency is a function of the square root of (stiffness/mass), the mass required to satisfy static loading conditions alone will tend to produce a low natural frequency for the foundation system.

Another reason to prefer low-tuned systems can be found in the fact that, for similarly tuned systems, a low-tuned system will have smaller vibration amplitudes than a high-tuned system.

5.1.7 High-tuned machine foundation systems shall be used only when a low-tuned system is not practical or economical; e.g., for low-speed or variable-speed machinery.

Commentary Note 5.1.7:

Where it is not practical to design a rigid foundation with high mass, the natural frequency of the system will be increased. This higher natural frequency in conjunction with a lower machine operating frequency will often result in high-tuned systems being more economical for low-speed machinery.

5.1.8 For elevated machinery, the flexibility of the entire support structure must be considered in the dynamic analysis.

Commentary Note 5.1.8:

For elevated machinery, like a machine on a table top or a blower in a steel structure, the flexibility of the entire structure must be taken into consideration. This is different from a machine on a mass concrete foundation, where the foundation with machine is usually considered as one mass point.

5.1.9 The foundation design shall be capable of resisting all applied dynamic and static loads specified by the machinery manufacturer, loads from thermal movement, dead and live loads as applicable or as specified in SAES-M-100, wind or seismic forces, any loads that may be associated with installation or maintenance of the equipment, and fatigue. For fatigue, the dynamic loads shall be increased by a factor of 1.5.

Commentary Note 5.1.9:

The dynamic forces are equal to the unbalanced forces multiplied by the applicable magnification factor. This section requires the design for dynamic forces to be multiplied by a fatigue factor of 1.5 and applied as quasi-static loads. The loads specified above shall be combined to produce the most unfavorable effect on the supporting foundation. The effects of both wind and seismic activity need not be considered to act simultaneously. Design load combinations may be as specified in ACI 318.

5.1.10 Design shall be such that buried cables, pipes, etc., will not be incorporated in the foundation, and be protected from the influence of foundation stresses.

Commentary Note 5.1.10:

Cables and pipes shall be sleeved if incorporation in the foundation cannot be avoided, e.g., if they are essential to the operation of the machinery supported from the foundation.

5.1.11 Where practicable, miscellaneous steel structures, such as operator platforms, shall be independent from the main machinery carrying structure(s), to avoid operator discomfort. Also, machinery loads shall be supported directly by the foundations and not by access platforms.

Commentary Note 5.1.11:

Sometimes operator platforms attached to the main supporting structure can be subject to vibration that causes serious discomfort to operators. In that case, it is necessary to keep the platforms independent from the main structure so that vibrations will not be transmitted to the platform.

5.1.12 The designer should refer to the general guidance given by ISO 2631-1 and ISO 2631-2 on human response to building vibration and weighting curves of frequency responses for equal annoyance of humans together with measurement methods to be used. Methods of quantifying whole-body vibration in relation to human health and comfort, the probability of vibration perception, and the incidence of motion sickness are presented in these standards.

5.2 Special Provisions for Reinforced Concrete

5.2.1 The structural design of all reinforced concrete shall be in accordance with SAES-Q-001, and ACI 318.

5.2.2 The minimum compressive strength of concrete at 28 days shall not be less than 27.6 MPa (4000 psi).

Commentary Note 5.2.2:

The minimum compressive strength is what is required by 09-SAMSS-097.

5.2.3 All faces of concrete shall be reinforced bi-axially. For deformed bars, the reinforcement in each direction shall not be less than 0.0018 times the gross area perpendicular to the direction of reinforcement.

Exception:

In the event that a foundation size greater than 1.20 meters (48 inches) thick is required for stability, rigidity, or damping, the minimum reinforcing steel may be as recommended in ACI 207.2R with a suggested minimum reinforcement of 22 mm (#7) bars at 30 centimeters (12 inches) on center.

Commentary Note 5.2.3:

The required reinforcing steel necessary to resist the internal forces and moments is relatively small in the majority of block foundations because of their massive size. Therefore, the minimum quantity of steel will likely be controlled by the amount of steel necessary to meet temperature and shrinkage requirements. Although ACI 318 does not specifically address the required steel in a block foundation, the requirement of 0.0018 of the cross-sectional area of the concrete may be used as guidance for the amount of temperature reinforcing steel in a foundation using grade 60 reinforcing.

5.2.4 Main reinforcement in piers shall not be less than 1% nor more than 8% of the cross-sectional area of the piers. Main reinforcement in pedestals shall not be less than ½%.

5.2.5 Minimum tie size in piers shall be 12 mm.

5.2.6 Maximum tie spacing in piers shall be the smallest of 8-bar diameters, 24-tie diameters or 1/3 the least dimension of the pier.

5.2.7 Slabs with the thickness of 500 mm or more shall be provided with shrinkage and temperature reinforcement in accordance with ACI 318.

5.2.8 When foundation thickness is greater than 1200 mm (48 in) thick, the designer should consult ACI 207.2R and other ACI mass concrete requirements for concrete mixes and installation.

5.3 Additional Requirements for Foundations for Vertical Pumps

5.3.1 In contrast to the design practice for horizontal shaft machinery, vertical pumps cannot be considered infinitely rigid. Therefore, to properly analyze the dynamic behavior of the Machine Foundation System, it is necessary to consider the flexibility of the vertical pump as well.

Commentary Note 5.3.1:

> *Foundation designers tend to assume that the machinery is infinitely stiff and represent the machinery by one or more points in space with the correct mass, mass moment of inertia, etc. This approach cannot be used for vertical pumps where the machinery is flexible enough to significantly influence the calculation results.*

5.3.2 As a minimum, the pump shall be simulated by four lumped masses, respectively for the driver, for the pump part above the top of the outer barrel including suction and discharge piping, for the barrel and for the pump part inside the barrel. The mass of the fluid inside the barrel shall be considered as well.

5.4 Additional Requirements for Table Tops

5.4.1 Forces due to a short circuit moment shall be increased by 100% and shall be considered in both directions for design purposes.

Commentary Note 5.4.1:

> *Forces due to short circuit shall be analyzed for a clock-wise and counter clock-wise moment.*

5.4.2 Any structural component not subject to dynamic forces shall be designed for a quasi-static load of 50% of the dead weight of the component in any direction in addition to the static design load(s).

Commentary Note 5.4.2:

> *In order to achieve some safety against stray or unexpected vibrations, it is required to design each structural component, not subject to (significant) dynamic loads, for a quasi-static force equal to 50% of the weight of the component plus anything supported from the component. This quasi-static load must be assumed separately in positive and negative X-, Y- and Z-direction and should be taken in addition to any static loads.*

5.4.3 Temperature effects due to uniform heating/cooling or temperature differentials through the material shall be considered.

5.4.4 In addition to the foundation stiffness requirements given in paragraph 6.1.3, foundation slabs for table tops shall have a depth of at least 1/10 of the length of the slab.

5.5 Anchor bolts

Anchor bolts shall be in accordance with SAES-Q-005. When specified, the diameter, steel quality, projection and installation method shall be as required by the machine manufacturer. Requirements for anchor bolt coating and double nuts shall be in compliance with 12-SAMSS-007 and SAES-Q-005 respectively. It is the responsibility of the foundation design engineer to verify the capacity of any vendor furnished or detailed anchor bolts.

Unless otherwise specified by the equipment user, equipment shall be installed on mounting plate(s), and the direct attachment of equipment feet to the foundation using the anchor bolts shall not be permitted. Mounting plates shall be of sufficient strength and rigidity to transfer the applied forces to the foundation.

5.6 Grouting

Grouting shall be in accordance with SAES-Q-011 and machine manufacturer's instructions.

6 Stiffness Requirements

6.1 Reinforced Concrete Structures

6.1.1 For foundations and piers constructed with normal weight concrete, the dynamic modulus of elasticity shall be taken as:

$$ED = 6560 * (FC)^{0.5} \quad (MPa) \text{ or,}$$

$$ED = 79000 * (FC)^{0.5} \quad (psi)$$

Commentary Note 6.1.1:

The dynamic modulus of elasticity is higher than the static modulus.

6.1.2 For concrete foundations, the weight of the foundation for reciprocating equipment shall not be less than 5 times and, for rotary equipment, shall not be less than 3 times the weight of the machinery, including its baseplate and the piping supported from the foundation, unless analysis demonstrates that a lesser value will perform adequately.

Commentary Note 6.1.2:

The minimum mass ratios 3:1 and 5:1 are traditional empirical values for foundation mass to equipment mass that should be used unless a lesser amount can be demonstrated to perform adequately. Although the mass ratio design approach has been a good rule of thumb, in certain *installations a dynamic analysis of the concrete foundation may be necessary to adequately predict its behavior.*

6.1.3 The minimum thickness of the concrete foundations shall not be less than the following:

0.60 + L/30 (meters)

2.0 + L/30 (feet)

Commentary Note 6.1.3:

A foundation must have a certain minimum thickness to allow the designer to assume that the foundation has sufficient rigidity to be represented by a single mass point.

6.1.4 The foundation must be of sufficient width to prevent rocking and adequate depth to permit properly embedded anchor bolts.

Commentary Note 6.1.4:

The width of the foundation should be at least 1.5 times the vertical distance from the base to the machine centerline, unless analysis demonstrates that a lesser value will perform adequately.

6.1.5 Piers shall not be used unless absolutely required by operation or maintenance or if required by machine vendor specifications.

6.1.6 Block foundations for reciprocating machines (compressors, and so forth) should have a minimum of 50% of the block thickness embedded in the soil, unless otherwise specified by the equipment user.

Commentary Note 6.1.6:

It is desirable to have at least 50% of the total depth of the foundation embedded in the soil to increase the lateral restraint and the damping ratios for all modes of vibration.

6.2 Steel Structures

6.2.1 It is difficult to identify specific stiffness requirements for steel structures. Normally, the machinery train will be supplied on a very stiff base plate, which in turn has to be supported by the steel structure. It is essential that support locations that are assumed by the machinery train manufacturer will be accurately provided.

6.2.2 If the manufacturer assumed continuous support for his base plate it is recommended that the supporting members of the steel structure will have at least 3 times the stiffness of the base plate.

Commentary Note 6.2.2:

General stiffness requirements for dynamically loaded steel structures are not available, and the design of a structure is based on trial and error. The flexibility of the structure must be accounted for in the design. However, the support conditions assumed by the machinery manufacturer must be accurately provided. In general, the manufacturer will assume that the base plate support is infinitely rigid. Flexibility of the support immediately underneath the base plate will result in misalignment of the machinery train. Supports that is 3 time stiffer than the base plate seems therefore a minimum and may not be stiff enough in certain cases.

7 Allowable Eccentricities for Concrete Foundations with Horizontal Shaft Machinery

Commentary Note 7:

The reason to limit eccentricities is to minimize secondary moments that could significantly influence the natural frequencies of the foundation. e.g., if a foundation is subject to a vertical unbalanced force that is not in line with its elastic support point, the force will cause rotation in addition to vertical displacement. These two-coupled movements will cause two natural frequencies possibly significantly different from the single natural frequency if no eccentricity exists.

7.1 The horizontal eccentricity, perpendicular to the machine bearing axis, between the center of gravity of the machine foundation system and the centroid of the soil contact area (or in case of piled foundations, the elastic support point of the pile group) shall not exceed 0.05 times B.

7.2 The horizontal eccentricity, parallel to the bearing axis between the center of gravity of the machine foundation system and the centroid of the soil contact area (or in the case of piled foundations, the elastic support point of the pile group) shall not exceed 0.05 times L.

7.3 The machine bearing axis and the centroid of the support (soil contact area, or pile group) shall lie in a common vertical plane.

7.4 Piers and columns shall be proportioned in such a manner that the centroid of their vertical stiffness lies in the same vertical plane as the bearing axis and center of gravity of the machinery.

8 Soil Bearing Pressures, Pile Capacities and Settlements

8.1 A geotechnical investigation shall be carried out in accordance with SAES-A-113 to determine soil and groundwater conditions based on a sufficient number of boring results and in-situ and laboratory testing. Foundation adequacy for static bearing capacity and settlement considerations shall be checked. In addition, effect of dynamic loading on foundation soil (i.e., densification of loose cohesionless soil, or liquefaction of loose saturated cohesionless soils) shall be investigated. If necessary, treatment of the in-situ foundation soils to improve their condition shall be considered. Compaction shall be in accordance with SAES-A-114. In-situ or laboratory testing to establish appropriate dynamic parameters of the foundation soils, whether in-situ treated or untreated, or compacted fill, shall be carried out. If a requirement for piles is established, appropriate dynamic parameters for the piles shall be determined.

Commentary Note 8.1:

The geotechnical report should give insight to the expected dynamic behavior of the soil or piles. As a minimum the report should give the density, poisson's ratio and the shear modulus (G) for soils, or the equivalent fixate level of piles. A dynamic modulus of sub-grade reaction or dynamic pile spring constant may also be required in support of the foundation dynamic analysis.

8.2 Unless foundation settlement calculations for dynamic loads show otherwise, the allowable soil bearing pressures shall be limited as indicated below:

For high-tuned foundations: soil bearing pressures shall not exceed 50% of the allowable bearing pressure permitted for static loads.

For **low-tuned foundations**: bearing pressures shall not exceed 75% of the allowable bearing pressure permitted for static loads.

Commentary Note 8.2:

The allowable soil bearing pressure must be reduced for heavy machinery foundations to provide a factor of safety against excessive settlement due to vibration.

9 Loads and Forces

9.1 General

All sections shall be proportioned to resist the sum of the static loads and dynamic forces as described in the following paragraphs. See Section 5 for fatigue factors.

9.2 Static Loads

Static loads shall consist of all dead and live loads on the foundation, etc., thermal and fluid forces from process piping, loads due to temperature differentials, wind loads and any other sustained loads.

9.3 Transient Dynamic Forces

a) If not specified by the equipment manufacturer, transient forces consisting of vertical, lateral, and longitudinal forces equal to 25% of the total weight of the machine train and acting through the center machine bearing axis shall be used in design.

b) The forces per Section 9.3.a above need not be considered to act concurrently.

c) For purposes of strength design, the forces in Sections 9.3.a and 9.3.b shall be treated as quasi-static loads.

In general no dynamic analysis is required for these forces.

However, for low-tuned systems, dynamic load effects due to transient resonance during machine start-up or shut-down shall be considered.

Commentary Notes 9.3:

For low-tuned systems, transient resonant vibrations will occur as the machine accelerates or decelerates through the system natural frequencies. For transient resonance calculations, damping effects should be included to avoid unrealistically high results as the frequency ratio passes through the 0.7 to 1.3 range.

It is generally accepted that, unless foundations or structures or connecting piping are unusual, resonance due to transient dynamic forces will cause no problems and need not be evaluated.

9.4 Steady State Dynamic Forces

9.4.1 Information on steady state dynamic forces shall be furnished by the equipment manufacturer(s). For this purpose the manufacturer shall supply the following information depending on the type of equipment;

9.4.1.1 Reciprocating Machinery

a) The weights of the machine and all auxiliary equipment with exact location of centers of gravity.

b) Number of revolutions per minute. (Operating speed or range of operating speeds).

c) Diagrams showing:

All primary forces
All secondary forces
All primary moments
All secondary moments

d) Curves of free forces and moments against crank angle degrees.

9.4.1.2 Rotating Machinery

a) The weights of the machine, rotor and auxiliary equipment with exact location of centers of gravity.

b) The range of operating speeds.

c) Possible unbalanced forces and points of application (for operating conditions based on alarm level).

Commentary Note 9.4.1.2:

Steady state dynamic forces should be based on operating conditions at alarm level for vibration velocity calculation purposes. Machinery operation is normally maintained until alarm condition is reached and may operate at or around this level for an extended period depending on operational requirements, therefore the alarm vibration level should be considered as per SAER-5659.

9.4.2 In the event that there is no manufacturer information available, the steady state dynamic force for rotating machinery can be estimated as follows:

$$FD = Factor * W * (rpm/1000)^{1.5}$$

where

Factor = 0.001 for SI units
Factor = 0.1 for imperial units
W = Total mass of the rotating part in kg (kip)
FD = Steady state dynamic force in kN (kip)

10 Permissible Frequency Ratios

10.1 To avoid the danger of excessive vibration, the ratio between the operating frequency of the machinery, f, and each natural frequency of the machine foundation system, f(n) shall not lie in the range of 0.7 to 1.3. Accordingly, for high-tuned systems, f/f(n) shall be less than 0.7 and for low-tuned systems f/f(n) shall be greater than 1.3.

For exceptions, refer to Sections 10.2 and 10.3.

Commentary Notes 10.1:

As the ratio f/f(n) approaches 1, a rapid increase of the vibration amplitude occurs. In order to provide some safety factor against resonance vibrations, a range of unacceptable frequency ratios has been specified.

Outside the range of 0.7 to 1.3, the maximum dynamic response of the system is limited to values only slightly greater than the static deflection value.

10.2 The limiting frequency range per sect. 10.1 can be waived by the Manager, Consulting Services Department, Dhahran, upon submittal of evidence that the indicated frequency range cannot realistically be avoided and that an acceptable alternative is available (see also Section 10.3).

Commentary Notes 10.2:

In certain cases, like foundations for variable speed machinery or in case of steel structures, it is very difficult if at all possible to avoid the frequency range indicated in Section 10.1.

In general the Manager of Consulting Services Dept. will waive the limiting frequency range, if the designer can provide evidence that the frequency range cannot realistically be met (e.g., extremely heavy foundation) and that the calculated vibration velocities comply with Section 11.1.

10.3 For complex structures (like steel structures) it is often impossible to avoid natural frequencies in the range indicated in Section 10.1. In such cases, the Design Contractor shall submit detailed information on modal shapes in the limiting frequency range through the Company Representative for review and acceptance by the Manager, Consulting Services Department, Saudi Aramco.

A modal shape (and its associated natural frequency) will in general be acceptable, if:

1 The location(s) of dominant vibration amplitude(s) are sufficiently away from other machinery to avoid resonance ("whipping") effects.
2 Dominant vibration amplitude(s) do not occur at major structural components.
3 Calculated maximum vibration velocities comply with Section 11.

Commentary Note 10.3:

Steel structures have a number of frequencies equal to the degrees of freedom which is for spatial structures almost equal to 6 times the number of nodes (mass points). For a structure with 100 nodes this will result in almost 600 natural frequencies. It will be clear that several of these frequencies will inadvertently lie in the frequency range given in Section 10.1. If one changes the design to move those frequencies outside the limiting range other frequencies will end up inside the range. It is therefore accepted that certain frequencies will be inside the limiting frequency range as long as the designer can provide information that the associated modal shapes are acceptable as explained in Section 10.3.

11 Permissible Vibration

11.1 Machinery foundations shall be designed in accordance with PIP REIE686 Chapter 4, equipment Manufacturer's recommendations, and published design procedures and criteria for dynamic analysis. If Manufacturer's vibration criteria are not available, the maximum velocity of movement during steady-state normal operation shall be limited to 0.12 inch per second for centrifugal machines and 0.15 inches per second for reciprocating machines per PIP STC01015.

11.2 For rocking and torsional mode calculations the vibration velocities shall be computed with the dynamic forces of the machinery train components assumed in phase and 180 degrees out of phase.

12 Drawing Information

12.1 In addition to the structural information necessary to construct the foundation, the drawings must clearly indicate the elevation of the top of the finished (poured) foundation and the bottom of the soleplate, the locations and type of the anchor bolts and sleeves, the anchor bolt diameter, the depth of embedment into the foundation of the anchor bolts, the length of the anchor bolts threads, and the length of the anchor bolt projections.

Commentary Note 12.1:

The above information should be clearly marked on the drawing in order for it to be readily identified during the final checks before concrete placement.

12.2 The required 28-day minimum compressive strength of the concrete foundation and the yield strength of the reinforcing steel shall be clearly specified on the structural drawings.

Commentary Note 12.2:

Not only is this information necessary for construction of the foundation, it may be necessary in the future to identify the material properties for possible modifications or investigations of the foundation. Placing this information on the drawings will permit its permanent retention with the foundation structural details.

12.3 The anchor bolt material shall be specified on the structural drawing.

12.4 The soil bearing capacity shall be specified on the structural drawings.

Revision Summary

4 April 2009 Revised the "Next Planned Update". Reaffirmed the contents of the document and reissued with editorial revision.