EFRC Training Workshop
Foundation design for reciprocating compressors

Soil Foundation Interaction

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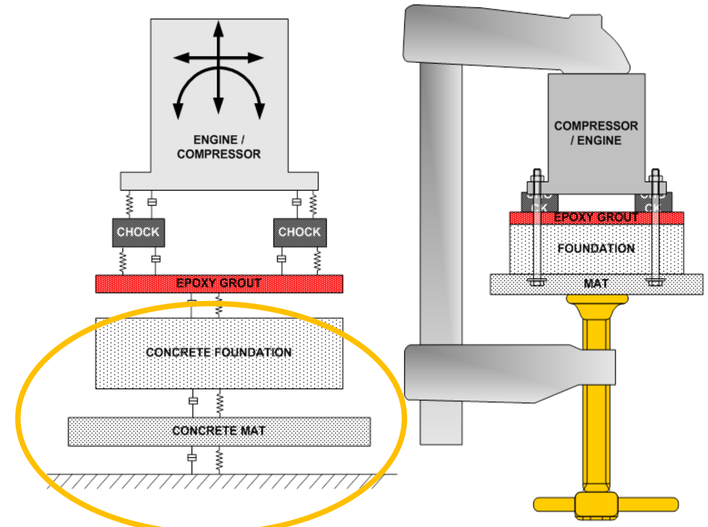
TNO innovation for life

Introduction Foundation Design

- Compressor and foundation must form a tightly rigid (monolithic) structure
- According to API 686 “RP for Machinery Installation and Installation Design”:
  – A static structural analysis <u>and</u> a dynamic analysis for reciprocating compressors for powers > 150 kW shall be carried out



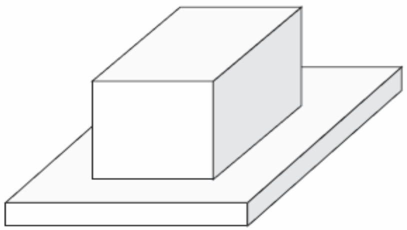
Different elements of a foundation and its mounting system (source: ITW)

Introduction Foundation Design

- An adequate foundation design consists of:
  - interaction of soil, piles, block and equipment mounted on block
- Key words in static structural foundation design:
  - High block strength & stiffness, low and even settlement, reinforcement, centre of gravity, maximum compressive strength
- Keywords in dynamic foundation design
  - Non-resonance condition, (separation from excitation frequencies and MNF's), acceptable vibration levels (≈3 mm/s rms), dynamic soil/pile/block interaction

Introduction Foundation Design

Source of pictures: GMRC



BLOCK ON MAT

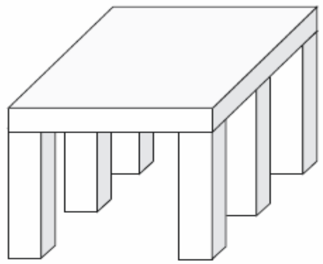
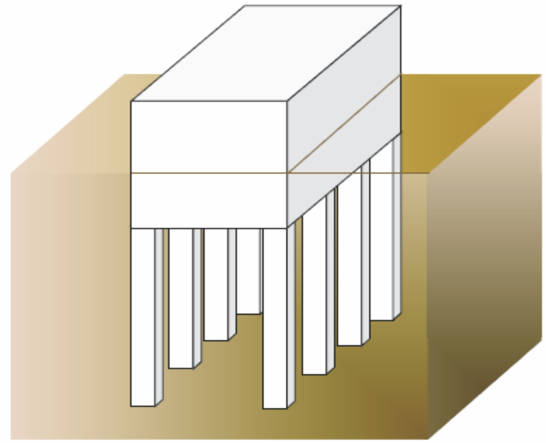
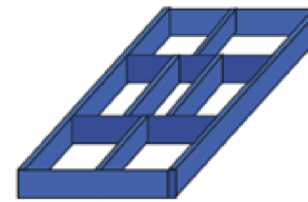


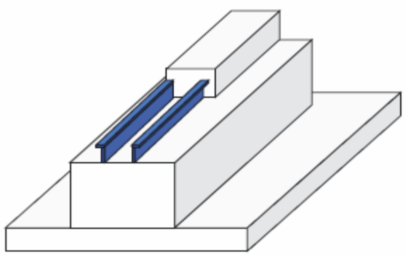
TABLE TOP



BLOCK ON PIERS

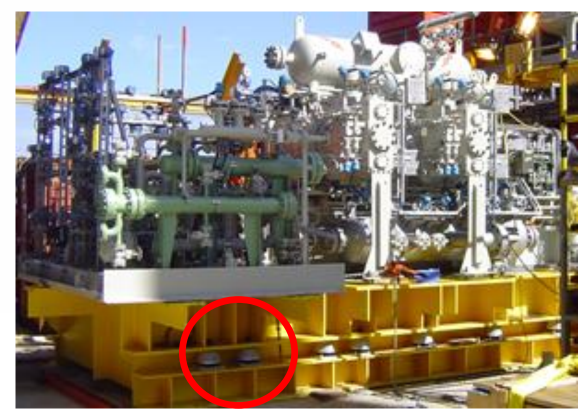


STEEL SKID



HYBRID

SKID ON DRIVEN STEEL PILINGS (USA)



BLOCK OR MACHINE MOUNTED ON ANTI VIBRATION MOUNTS (AVM'S)

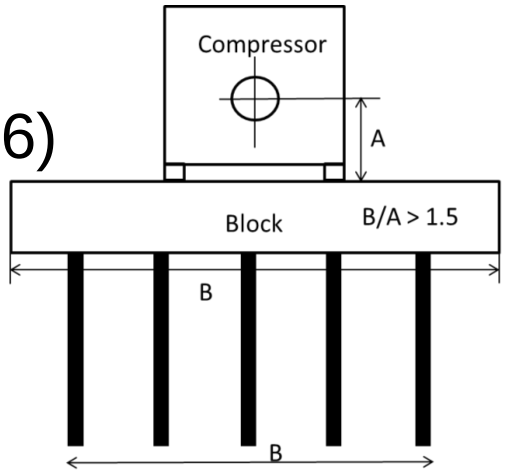
Summary of loads to be used in a foundation design

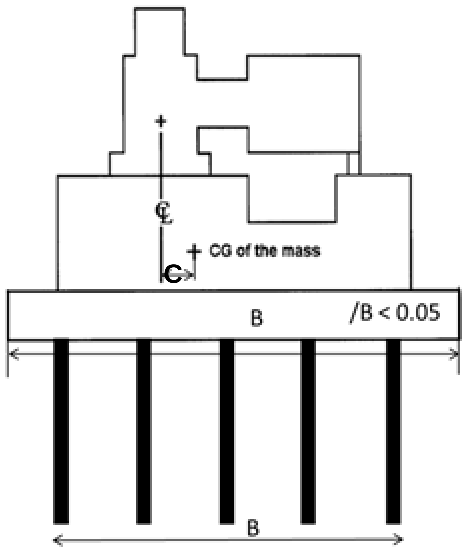
- Summary of static loads:
  - Dead weight of compressor & driver, skid, pulsation dampers, coolers, separators, piping, etc.
- Summary of dynamic loads:
  - Global loads shall be used (vector summation)
  - Pulsation-induced shaking forces,
  - Unbalanced free forces and moments
  - Torque variations

Foundation Block Design Rules

Source of pictures: GMRC

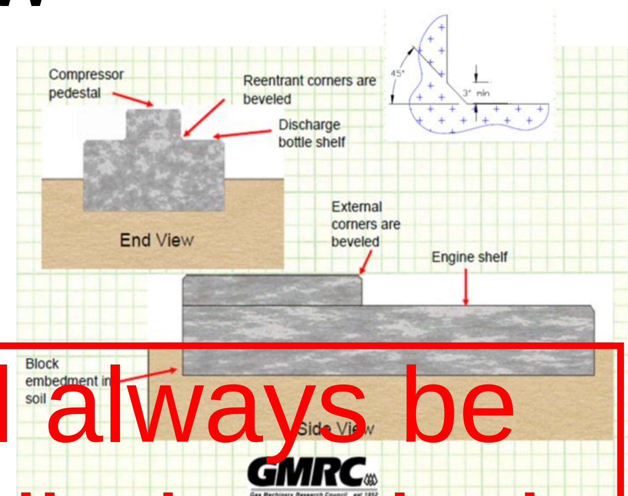
- Preliminary design rules
  - block/compressor weight: 5-10 (API 686)
  - B/A >1.5
  - minimum 50% of the block thickness shall be embedded in the soil
  - finished foundation shall be >100 mm above the floor slab (prevention of damage of the machinery from runoff or wash-down water)
  - C/B < 0.05 to prevent torsional effects





Foundation Block Design Rules

- Minimum block depth:
  - 1.2-1.5 m for drivers less than 1840 kW
  - 1.8 m for drivers of 1840-3680 kW
  - 1.8-2.5 m for drivers > 3680 kW
- Sharp corners should be avoided to avoid fatigue cracks

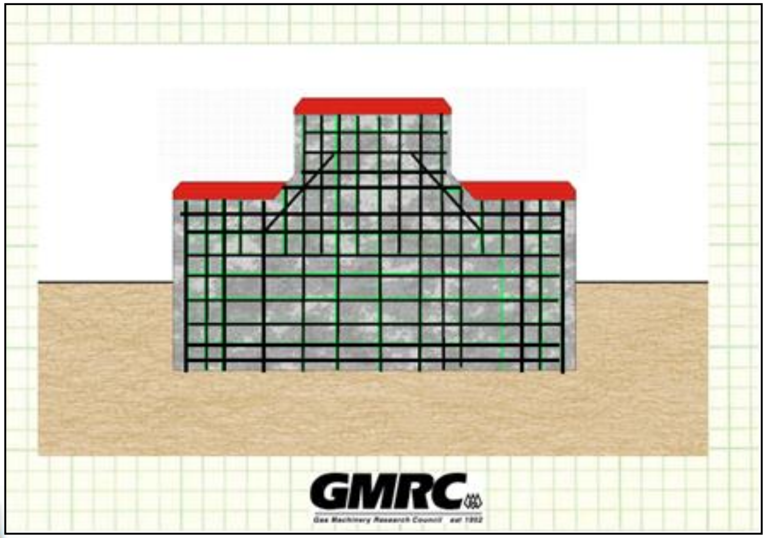


The final design shall always be determined with a detailed analysis

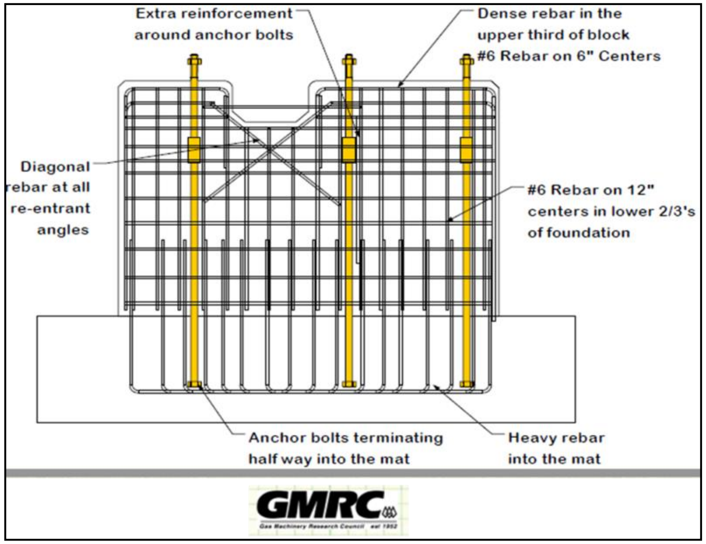
Concrete Block: Reinforcement

Why reinforcement:

- Concrete has a high compressive strength but has a very low tensile strength
- Reinforcement reinforces the concrete and gives it increased tolerance to tensile stresses.



Dense reinforcement cage of modern designs



Typical modern block design for a reciprocating compressor

Concrete Block: Reinforcement

Foundation rebar matrix for anchor bolts (source GMRC)

Recommended density:

- In equipment pedestal area:
  - 150-300 mm horizontal centres
- The vertical distance between the reinforcement:
  - 150 mm near the top
  - 250 mm in the middle
  - 300 near the bottom
- Reinforcement should be covered with concrete:
  - 75 mm at the top and bottom and 50 mm elsewhere

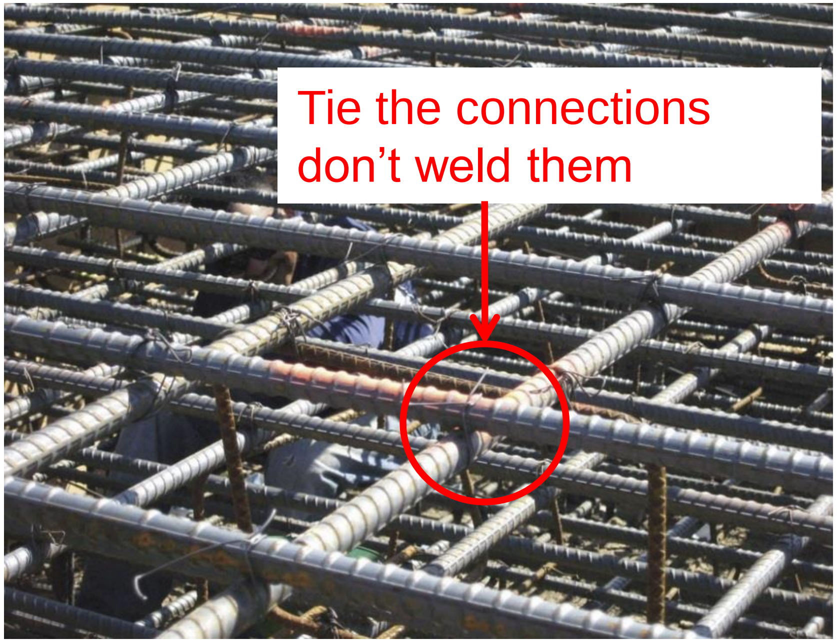
Recommended material:

- minimum yield strength of 414 MPa (Grade 60)

Recommended diameter:

- maximum 16 mm

Concrete Block: Reinforcement



Reinforcement Matrix Showing Tied Connections (source GMRC)

Facts & Figures of Concrete

- Commercially attractive
- Consists of a composite material that consists essentially of a binding medium (cement & water) within which are embedded particles or fragments of aggregate
- Hardens by an exothermal process of hydration
- Most of its strength in the first month, typically referred to as the 28-day strength
- Strength is a function of: water content (primarily), size and type of aggregate, additives, air entrainment
- Is very strong in compression, but weak in tension
- The low tensile strength of concrete is reason for tendency to crack

Facts & Figures of Concrete

- Typical density of 2400 kg/m3
- Typical Young's modulus of 20.7 GPa (≈0.1 times that of steel, 2 times that of epoxy grout)
- Coefficient of thermal expansion is similar to that of steel
- Tensile strength of ≈ 10% of the compressive strength, must be downgraded by a factor of 2 under dynamic loads:
  - for a concrete with a compressive strength of 28 MPa the allowable tensile strength is only 1.4 MPa
- Shear strength ≈ 5% of its compressive strength

Facts & Figures of Concrete

- Compressive strength > 28 MPa (API Std. 618 refers to API RP 686)
- Design bearing strength of 10 MPa
- (EN 1993 Eurocode 3 “Design of Steel Structures)
- When epoxy grout is used:
  - concrete must have a tensile strength of not less than 2.4 MPa to reduce the possibility of edge lifting. This will be fulfilled is a concrete is used with a minimum compressive strength of 28 MPa


Concrete with a too low compressive strength

Soil & Piles

- A foundation should never be installed without a thorough characterization of the underlying soil.
- One-size-fits-all foundation designs are a recipe for trouble.
- Some locations are totally unsuitable for reciprocating compressor installations.
- Many locations require additional measures (excavation and backfill, pilings, etc.) for a successful installation.
- Geophysical soil surveys are essential for a successful foundation (type of soil determines the type of foundation)
- Samples and shear wave velocity measurements are required

Soil & Piles

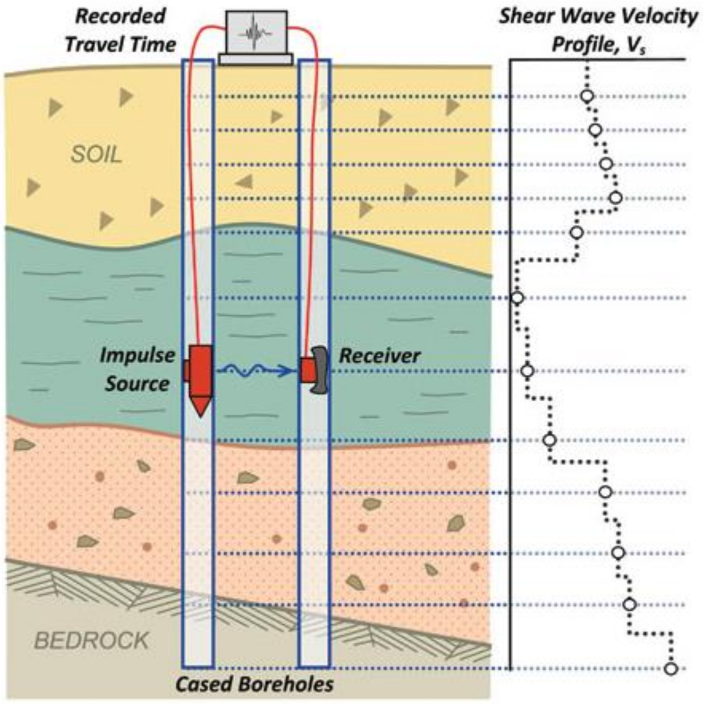
- Specialized geotechnical testing is required to measure the soil dynamic properties:
  - shear wave velocity, damping, density and Poisson’s ratio
- Soil has different layers of different compositions:
  - Wet clay can expand and contract, causing settlement and uplift.
  - Dry sand has no cohesion and low to moderate bearing capacity.
  - Slightly moist mixtures of clay and sand have moderate to high load bearing capacity, good stiffness, and are desirable.
  - Rock, shale and limestone are extremely dense (hard) and form good bedrock.

Soil & Piles

- With a cross-hole wave propagation test the shear modulus of soil can be determined for different layers with:

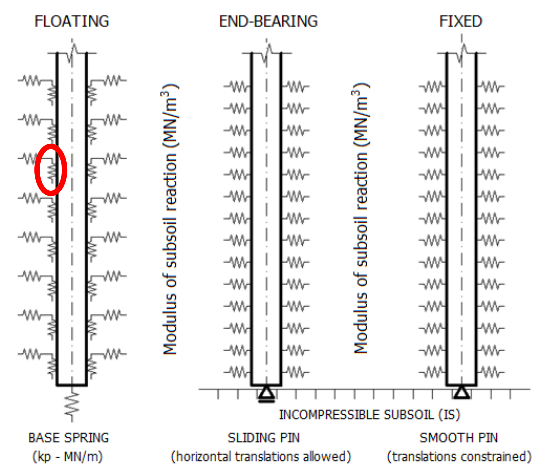
$$G = \rho v^2 \ \ (\text{N/m}^2)$$

- G= shear modulus (N/m^2)
- ρ= density (kg/m^3)
- v= shear wave velocity (m/s)



Soil & Piles

- Piles are required when the soil is:
  - too soft to support the combined dead weights of machinery and foundation so that the design soil bearing capacity (< 72 kPa) or the limits for settlement (≈10 mm) are exceeded
  - the soil isn't stiff enough to resist vibration forces and deflections
  - water table is too high or variable to assure consistent soil properties over time.
- The stiffness of the piles is based on friction between the soil and sides of the piles and by the end-bearing pressure.



Different types of pile bearing capacities

Soil & Piles

- The foundation stiffness is dependent upon pile group stiffness and cap attachment of the piles to the block
- Fixation of the piles into the cap will increase lateral (factor of 2) and rotation stiffness
- The minimum vertical embedment distance of the top of the pile into the cap required for achieving a fixed connection is 2 times the pile diameter or width
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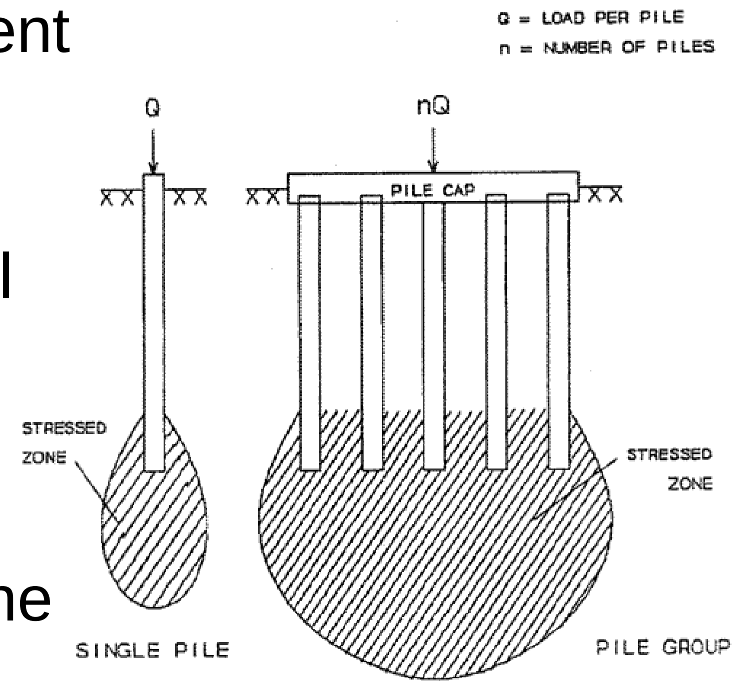


Soil & Piles

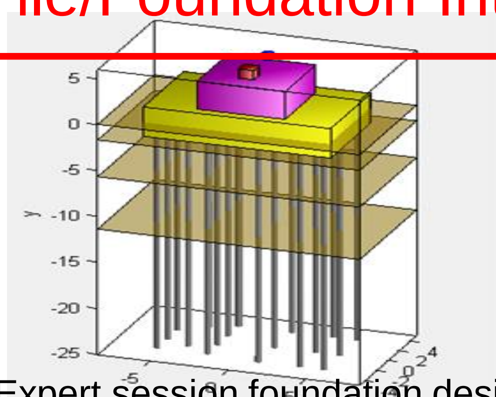
- According to the “GMRC Guidelines for high speed reciprocating compressor Packages for Natural Gas Transmission & Storage Applications, 2013”:
  - The plan area of the pile group should be made as large as practical
  - Piles to be installed below the compressor crankcase as well as under the crosshead guide supports.
  - The pile spacing should be at approximately the same distance from the compressor centreline to the top of the skid or foundation block.
  - If there are multiple throws on one side of a compressor frame, the typical number of piles is equal to the number of throws plus one.

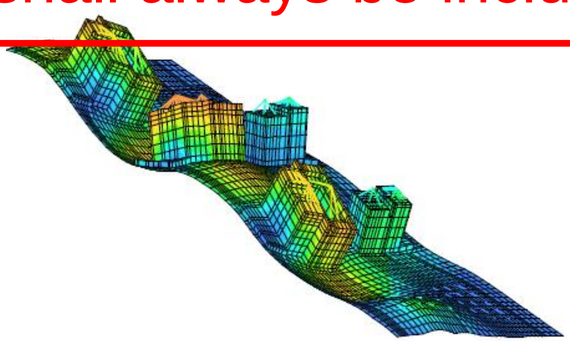
Concluding Remarks:

An adequate foundation design will lead to acceptable vibrations ensuring the long term integrity, safety and reliability of the complete system

Static & Dynamic foundation design shall be determined with a detailed analysis by a specialised civil engineer

For an adequate foundation design:
Soil/Pile/Foundation Interaction shall always be included





Thank you

Any Questions ?

References

References on block:

1.GMRC Technical Report TR-97-2 “Foundation Guidelines”, January1997

2.API Recommended Practice 686 “Recommended Practices for Machinery Installation and Installation Design”, PIP REIE 686, Second Edition 2009

3.GMRC Course “Foundation Design & Repair, The Bolted Joint”, May 12-14, 2009

4.GMRC Guidelines for high speed reciprocating compressor Packages for Natural Gas Transmission & Storage Applications, 2013

References on concrete material:

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3.ACI Title No. 94-M49, The Influence of Aggregate on the Compressive Strength of Normal and High Strength Concrete

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2.GMRC Course “Foundation Design & Repair, The Bolted Joint”, May 12-14, 20

3.“GMRC Guidelines for high speed reciprocating compressor Packages for Natural Gas Transmission & Storage Applications, 2013

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References on soil:

1.API Recommended Practice 686 “Recommended Practices for Machinery Installation and Installation Design”, PIP REIE 686, Second Edition 2009

2.“GMRC Guidelines for high speed reciprocating compressor Packages for Natural Gas Transmission & Storage Applications, 2013