



DESIGN CHARTS FOR MACHINE FOUNDATIONS

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ABSTRACT

The problems of design of machine foundations for the special case of vertical mode of vibration for block foundation are presented in this paper. The empirical design method is used to get the results using a computer program **MATCAD** dealing with the parameters related to the machine. Design charts that are prepared to be a guide for the designer engineer are drawn. The design charts are based on the variables limitations including the properties of the soil, machine and foundation. The design charts are based on three displacements which are acceptable for design of the machine foundation.

الخلاصة

يتضمن البحث دراسة المشاكل التي تتعرض لها اسس المكينن بالاتجاه العمودي للاسس الكتلية . لقد استخدمت الطريقة الوضعية للحصول على النتائج بمساعدة برنامج حسابي (**MATCAD**) والذي يتعامل مع حدود ترتبط مع الماكنه . لقد تم اعتماد جداول للتصميم كمرشد للمهندس المصمم في الموقع . جداول التصاميم اعتمدت محددات المتغيرات والتي تتضمن خواص كل من التربة، الماكنة والاساس. حيث اعتمدت على ثلاث ازاحات والتي تعتبر مقبولة من ناحية التصميم.

KEY WORDS:Machine foundation, Design charts, Empirical methods.

INTRODUCTION

The design of machine foundations is a trail-and-error procedure involving three interrelated steps (Gazetas and Roesset, 1979):

- 1) Establishment of desired foundation performance (design criteria),
- 2) Determination of magnitude and characteristics of the dynamic loading,
- 3) Estimation of anticipated translational and rotational motion of machine-foundation-soil system.

The design of a machine foundation is more complex than that of a foundation which supports only static loads. In machine foundations, the designer must consider, in addition to the static loads,

the dynamic forces caused by the working of the machine operation. These dynamic forces are, in turn, transmitted to the foundation supporting the machine (Srinivasulu and Vaidyanathan, 1976).

DESIGN LIMITS OF MACHINE FOUNDATION FOR EMPIRICAL METHODS

The design of block foundation for centrifugal or reciprocating machine starts with preliminary sizing of the block, which has been found to result in acceptable configuration as (Arya et al., 1979):

1. The bottom of block foundation should be above water table. It should not be resting on back filled soil nor on a special sensitive soil.
2. The mass of rigid foundation equals (2-3) times the mass of supported machine (for centrifugal), while the mass of rigid foundation equals (3-5) times the mass of supported machine (for reciprocating).
3. The top of block is usually kept (0.3 m) above finished floor or pavement elevation to prevent damage from surface water run off.
4. The vertical thickness of block should not be less than (0.61 m). The thickness seldom less than one-fifth the least dimension or one-tenth the largest dimension.
5. The foundation should be wide enough to increase damping in the rocking mode. The width should be at least (1-1.5) times the vertical distance from the base to machine centerline.
6. The combined center of gravity should coincide with the center of gravity of the foundation.
7. For large reciprocating machines, it may be desirable to increase the embedded depth in soil such that 50% to 80% of the depth, this will increase the lateral restraint and damping ratio for all modes of vibration.
8. Static bearing capacity Q_{all} : proportion of footing area for 50% of allowable soil pressure, which means that the actual soil pressure should be less than 50% of static bearing capacity Q_{all} . The actual soil pressure equals to the weight of machine and foundation divided by the base area of footing as shown:

$$\text{Actual soil pressure} = \frac{W_{mach.} + W_{fou.}}{L_f \cdot B_f}$$

9. Static settlement must be uniform; center of gravity of footing and machine load should be within 5% of each linear dimension from the foundation center.
10. Bearing capacity: static plus dynamic loads. The sum of static and modified dynamic loads should not create bearing pressure greater than 75% of allowable soil pressure given for static load condition Q_{all} .
11. The magnification factor (M) should preferably be less than (1.5). The magnification factor can be defined as the ratio of dynamic displacement to the static displacement as shown in **Table (1)**.
12. Vibration amplitude (Y), at operating frequency is shown in **Fig. (1)**. The maximum amplitude of motion for the foundation system should lie in zones A or B.
13. The velocity which equals ($2 \pi f$ x displacement amplitude) compares with the limiting value in **Table (2)** and **Fig. (1)**.
14. The acceleration which equals ($4 \pi^2 f^2$ x displacement amplitude) should be tested for zone B in **Fig. (1)**.
where:



$$f = \text{Operating speed of machine} = \frac{\omega}{2\pi}$$

15. Resonance: the acting frequencies of machine should have at least a difference of $\pm 20\%$ with the resonance frequency of **Table (1)**.

$$0.8 f_{mr} \geq f \geq 1.2 f_{mr}$$

16. The horizontal translation and the rocking mode needs not be coupled if:

$$\sqrt{f_{nx}^2 + f_{n\psi}^2} / f_{nx} \quad (f_{n\psi} \leq 2/3 f)$$

where:

f_{nx}^2 = natural frequency in the x- direction, rpm.

$f_{n\psi}$ = natural frequency in the rocking direction, rpm.

Table (1) – Summary of derived expressions for a single-degree-of-freedom system (Arya et al., 1979).

Expression	Constant Force Excitation F_0 Constant	Rotating Mass-type Excitation $F_0 = m_i e \omega^2$
Magnification factor	$M = \frac{1}{\sqrt{(1-r^2)^2 + (2Dr^2)^2}}$	$M = \frac{r^2}{\sqrt{(1-r^2)^2 + (2Dr^2)^2}}$
Amplitude frequency f	$Y = M(F_0/k)$	$Y = M_r(m_i e/m)$
Resonance frequency	$f_{mr} = f_n \sqrt{1-2D^2}$	$f_{mr} = \frac{f_n}{\sqrt{1-2D^2}}$
Amplitude at resonance frequency f_r	$Y_{\max} = \frac{F_0/\kappa}{2D\sqrt{1-D^2}}$	$Y_{\max} = \frac{(m_i e/m)}{2D\sqrt{1-D^2}}$
Transmissibility factor	$T_r = \frac{\sqrt{1+(2Dr^2)^2}}{\sqrt{(1-r^2)^2 + (2Dr^2)^2}}$	$\bar{T}_r = \frac{r^2 \sqrt{1+(2Dr^2)^2}}{\sqrt{(1-r^2)^2 + (2Dr^2)^2}}$

where:

$$r = \omega/\omega_n$$

ω_n = Natural circular frequency rad / sec.

ω = Frequency of excitation force = $\sqrt{(k/m)}$, rad / sec.

k = Spring constant, kN /m

m = Mass of machine and foundation, kg

m_i = Rotating mass, kg

D = Damping ratio = C/C_c

C = Damping

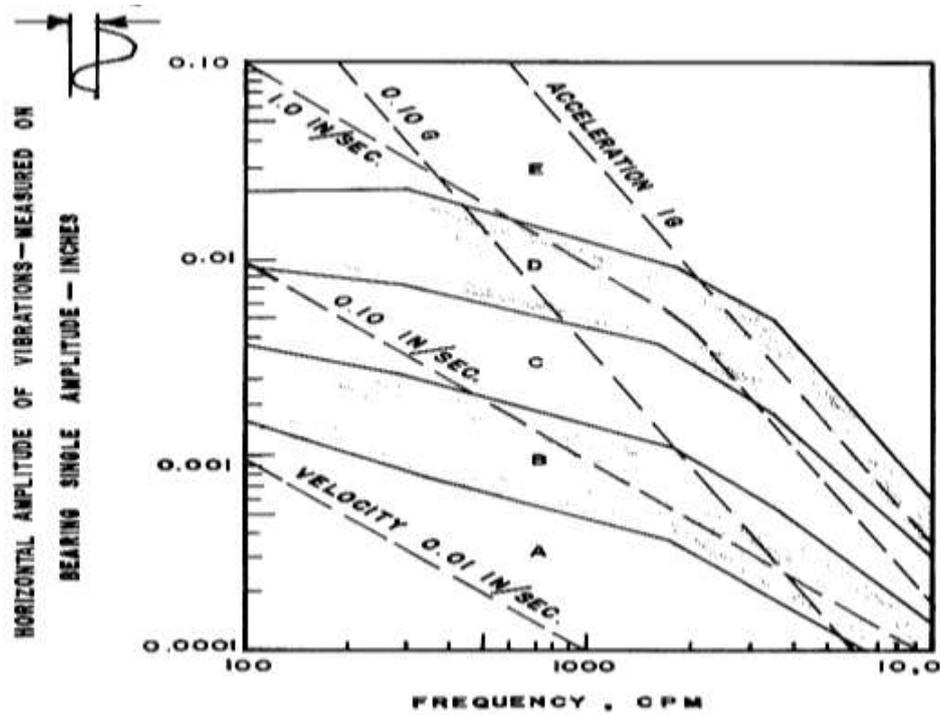
C_c = Critical damping = $2\sqrt{km}$

e = Eccentricity of unbalance mass to axis of rotation at operating speed, m

f_n = Natural frequency, rpm

f_{mr} = Resonant frequency for rotating mass-type excitation, rpm

- M = Dynamic magnification factor
- M_r = Magnification factor
- F_0 = Amplitude of excitation force, kN
- T_r = Force transmitted / F_0
- $\overline{T_r}$ = Force transmitted / $m_i e \omega_n^2$
- Y = Amplitude at frequency f



Horizontal Peak Velocity (m/sec.)	Machine Operation
<0.00013	Extremely smooth
0.00013-0.00025	Very smooth
0.00025-0.00051	Smooth
0.00051-0.00101	Very good
0.00101-0.00203	Good



0.00203-0.00406	Fair
0.00406-0.008	Slightly rough
0.008-0.016	Rough
>0.016	Very rough

- Fig. (1): Vibration performance of rotating machines (Harr, 1966).**
- A No faults. Typical new equipment.**
 - B Minor faults. Correction wasted dollars.**
 - C Faulty. Correction within 10 days to save maintenance dollars.**
 - D Failure is near. Correct within two days to avoid breakdown.**
 - E Dangerous. Shut it down now to avoid danger.**

Table (2) —General machinery-vibration-severity data (Richart et al., 1970).

FORMULATION OF THE PROBLEM

The objective is to provide a clear image of design for machine foundation by using empirical methods. The empirical method, which is dependent on the theory of elastic half-space, the parameters of machine foundation and soil required for analysis are first obtained.

In this theory the footing is assumed to rest on the surface of the elastic half space and to have simple geometrical areas of contact, usually circular, but other shapes such as rectangular or long strip are possible (Arya et al., 1979). This theory includes the dissipation of energy throughout the half-space by "geometric damping" and allows calculation of finite amplitude of vibration at the "resonant frequency". The method is an analytical procedure, which provides a rational means of evaluating the spring and damping constants for incorporation into lumped-parameter, mass-spring-dashpot-vibrating systems.

The parameters of machine include the weight of machine depending on its type, which may be reciprocating compressor that is relatively heavy machine and generate vibrating forces of substantial magnitude at low operating frequency. It is also important to know the primary and secondary compressor speed in (rpm) and the primary and secondary forces and moments.

The parameters of soil on which the footing is assumed to rest on are obtained considering the surface of elastic half space and to have simple contact area. For the present case, the footing is rectangular with dimensions of $L_f \times B_f \times h$ (depending on limits or experience of the designer).

The type of soil is also considered, which is in this problem silty sand gravel (medium dense) including the density of soil (γ), shear modulus (G) and Poisson's ratio (ν). The allowable bearing capacity q_{all} and the permanent settlement of the soil (S_{tt}) are also considered.

EQUATIONS OF THE MACHINE FOUNDATION

The foundation of machine when designed requires knowledge of the dimensions for design; these dimensions are supplied by the manufacturer of the machine or depending on the experience of the designer. The dimensions of the foundation are considered as (L_f, B_f, h) in which the weight of the foundation equals to:

$$W_{foun} = L_f \times B_f \times h \times \gamma_c$$

where:

$$\gamma_c = \text{the unit weight of concrete} = 23.5 \text{ kN/m}^3$$

The effect of the shape of foundation is approximately considered by equivalent radius (r_o). So for rectangular foundation, the equivalent radius is:

$$r_{0z} = \sqrt{\frac{B_f \times L_f}{\pi}} \quad (1)$$

To calculate the equivalent spring constant for the vertical direction, the spring constant embedment factor in vertical direction and the spring coefficient have to be specified as follows:

$$\eta_z = 1 + 0.6(1 - \nu) \cdot \frac{h_0}{r_{0z}} \quad (2)$$

where: h_0 is the effective depth of embedment of the foundation.

The spring coefficient for vertical direction (β_z) is obtained from **Fig. (2)** (Srinivasulu and Vaidyanathan, 1976) as below:

$$\kappa_z = \frac{G}{1 - \nu} \beta_z \sqrt{L_f \times B_f} \eta_z \quad (3)$$

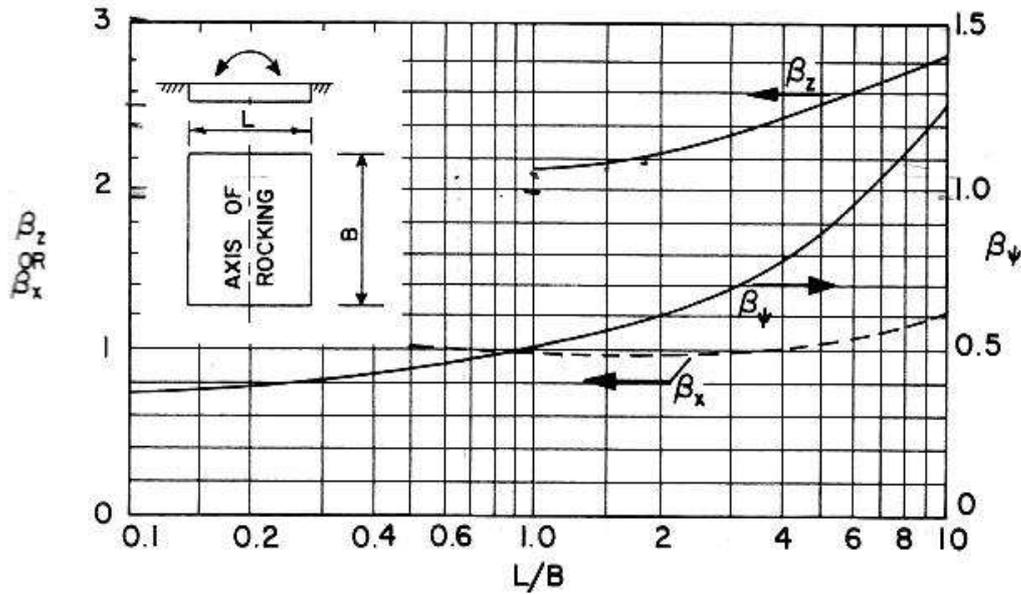


Fig. (2) – Coefficient β_z, β_x and β_ψ for rectangular footing (after Whitman, 1966).

To calculate the geometric damping ratio for vertical direction D_{g_z} , the damping ratio embedment factor for vertical direction $\alpha_{(z)}$ and mass ratio for vertical direction (B_z) have to be specified, while internal damping ratio (D_i) equals approximately (0.05) as follows (Das, 1983):

$$\alpha_{(z)} = \frac{1 + 1.9(1 - \nu) \frac{h_0}{r_{oz}}}{\sqrt{\eta_z}} \tag{4}$$

$$B_z = \frac{(1 - \nu) W_t}{4\gamma (r_{oz})^3} \tag{5}$$

$$D_{g_z} = \frac{0.425 \alpha_{(z)}}{\sqrt{B_z}} \tag{6}$$

The summation of geometric and internal damping gives total damping which contributes to the calculation of resonance frequency if resonance is possible or not depending on the term $(2D^2)$ in the equation of resonance frequency eq. (7b) after calculating natural frequency eq. (7a) as given below (Das, 1983):

$$f_{nz} = \frac{1}{2\pi} \sqrt{\frac{\kappa_z}{m_t}} \tag{7a}$$

$$f_{m_z} = \frac{f_n}{\sqrt{1 - 2D^2}} \quad (7b)$$

After the resonance conditions are defined, the magnification factor (M_z) should be calculated. The magnification factor is defined as the ratio of a steady-state displacement response caused by dynamic force (A_{\max}) to the displacement caused by an equivalent static force of amplitude equals to the amplitude of the dynamic force (A_s) **Fig. (1)**:

$$M_z = A_{\max} / A_s \quad (8a)$$

$$\text{or } M_z = \frac{1}{\left(\left(1 - \left(\frac{\omega}{\omega_n} \right)^2 \right)^2 + \left(2D \frac{\omega}{\omega_n} \right)^2 \right)^{1/2}} \quad (8b)$$

where (ω/ω_n) is the ratio of operating frequency to natural circular frequency (rps) in vertical direction which is calculated from:

$$\omega = 2\pi f \quad (9a)$$

$$\omega_n = 2\pi f_n \quad (9b)$$

in which f and f_n are the operating frequency of machine and natural frequency, respectively.

After all that, the displacement which occurs as a result of vibration is calculated depending on the vibration force obtained from the force diagrams that are usually supplied by the manufacturer of the machine as follows:

$$Z = \frac{M_z F_o}{K_z} \quad (10)$$

where: F_o is the amplitude of excitation force.

Then the transmissibility factor (T_r), which is defined as, “the ratio of the magnitude of the force transmitted to that of the impressed force”, is calculated as follows (see **Fig. (3) and (4)**):

$$T_r = \frac{\sqrt{1 + (2Dr^2)}}{\sqrt{(1 - r^2) + (2Dr^2)}} \quad (11)$$

In the final step for design criteria, the transmitted force P_v is calculated as follows:

$$P_v = T_r F_o \quad (12)$$



These calculations will be carried out using the computer program MATHCAD. The results obtained by this procedure have to be compared with the design limits as shown in Fig. (3) in order to get the appropriate decision of design.

The permissible amplitudes of a machine foundation is governed by the relative importance of the machine and the sensitivity of neighboring structures to vibration. These limits are summarized in Table (3).

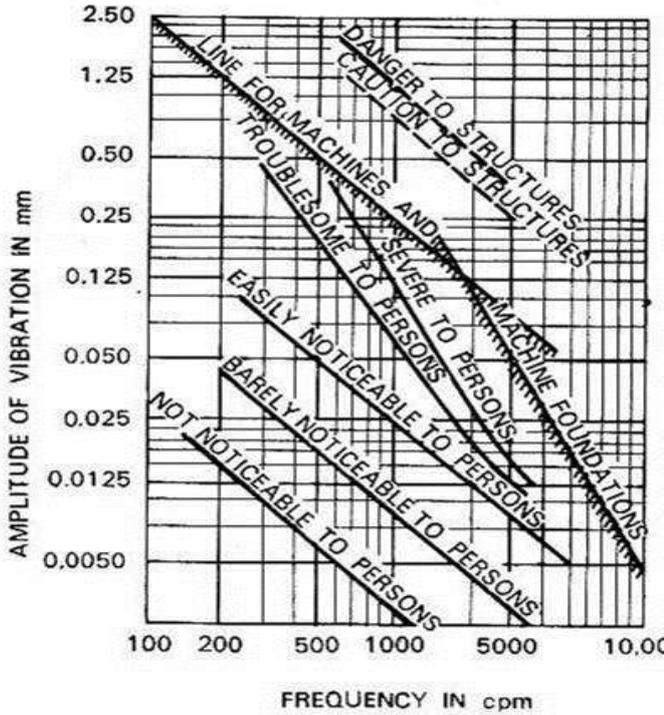


Fig. (3) – General limits of vibration amplitude (Richart, 1960).

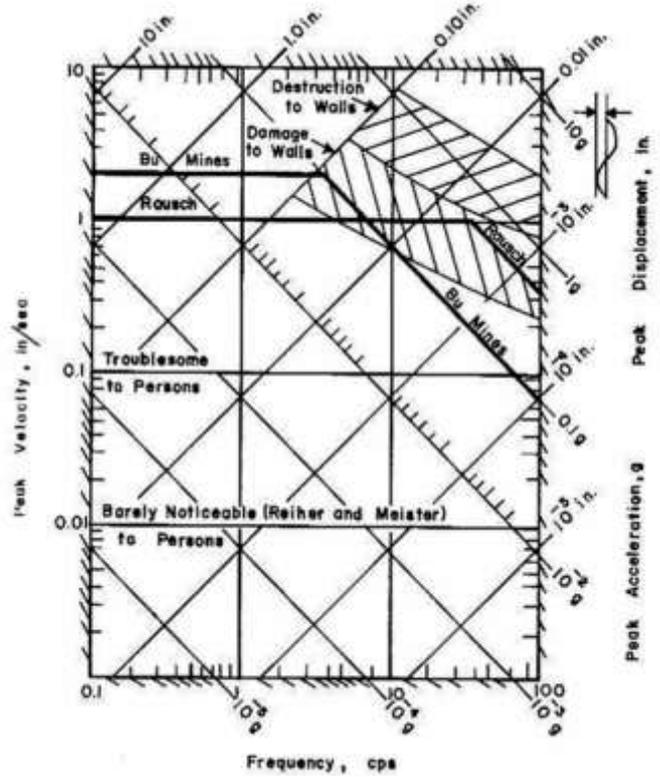


Fig. (4) – Response spectra for allowable vibration (Richart et al., 1970).

Table (3) – The permissible amplitudes of the machine foundation (Srinivasulu and Viadyanathan, 1976).

Type	Permissible amplitudes (m)
Low-speed machinery (500 rpm)	0.0002 to 0.00025
Hammer foundations	0.001 to 0.0012
High -speed machinery:	
a. (3000 rpm)	0.00002 to 0.00003
b. (1500 rpm)	0.00004 to 0.00006

THE COMPUTER PROGRAM MATHCAD

In order to apply the empirical method, the design equations need to be used more than one time for a given data. So to solve these equations with a little effort, time, and high accuracy, it is preferred to use assistant program. The computer software MATHCAD is used for this purpose.

MATHCAD program is a professional quality tool being increasingly used by many of scientists and engineers in the visualization and application of mathematics (Desrués, 1997). It is

the industry standard calculation software for technical professionals, educators, and college students. By using **MATHCAD** in calculating, the results become easy to understand.

DESIGN CHARTS FOR MACHINE FOUNDATIONS

To use of the solution presented in equations of machine foundation by the empirical method, design charts are prepared to be a guide for the designer engineer. The selected values used in these charts were limited based on the conditions considered in **Table (4)** as well as the limitations considered in the limitations of machine foundation. The design charts are selected based on three displacements which are acceptable for design of machine foundations as considered in **Fig. (3)** (Bowles, 1988).

Table (4): The parameters of the empirical method.

Parameters	Basic values	Range of values	Units
$W_{mach.}$	1444.905	60-620	kN
f	585	50-1000	rpm
γ	18.33	18-22	kN/m ³
G	96365	25000-190000	kN/m ²
ν	0.35	0.3-0.45	–
D_i	0.05	0.05-0.15	–
L_f	8.39	2-20	m
B_f	4.80	2-20	m
h	1.52	0.6-2.2	m
$W_{fou.}$	1443.95	$(3-5)W_{mach.}$	kN

For these displacements, the analysis is carried out using the computer program MATHCAD and the results are presented in the form of a relationship between $(G / \gamma L_f)$ (y-axis) and frequency (rpm) (x-axis), for different ratios of the weight of the foundation to the weight of the machine $((W_f / W_m) W_f = \text{weight of foundation, } W_m = \text{weight of machine})$ ranging between (3-5).

The selected displacement values ranged between (2.5×10^{-6}) m to a maximum value of (125×10^{-6}) m.

The charts are used to design the dimensions of the footing by the empirical method depending on the weight of the machine, the operating frequency of the machine and the properties of the soil including (shear modulus, Poisson's ratio and unit weight of the soil). In this paper we will take the effects of the minimum displacement $= (2.5 \times 10^{-6})$ m on the design charts.

MINIMUM DISPLACEMENT = 2.5×10^{-6} m:

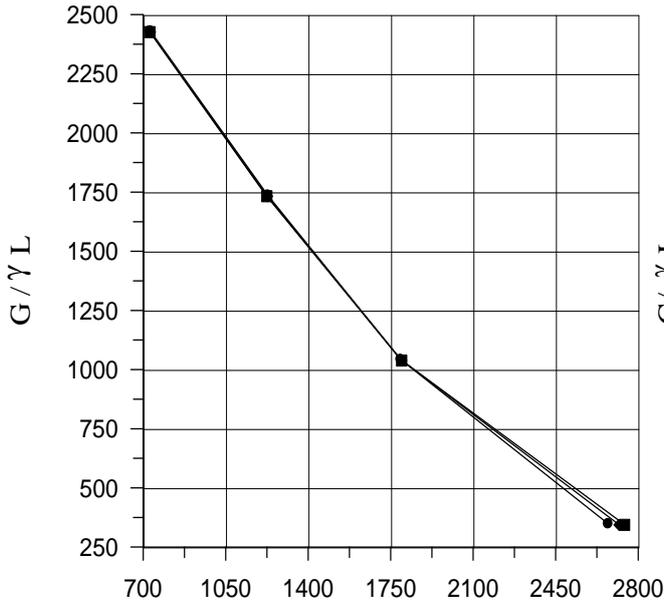


This displacement is considered for general limits of vibration which is not noticeable to persons as shown in Fig. (3). Fig. (5) is drawn for the foundation dimensions ratio $L_f/B_f = 1$, Poisson's ratio, $\nu = 0.35$, and different soil unit weights, $\gamma = 18, 20$ and 22 kN/m^3 .

From these figures, it is apparent that the frequency is inversely proportional to the values of $(G/\gamma L_f)$. The curves of these relationships for different values of (W_f/W_m) coincide with each other especially at frequency level (500-1750 rpm). After this limit of frequency, the effect of the weight ratio can be pronounced.

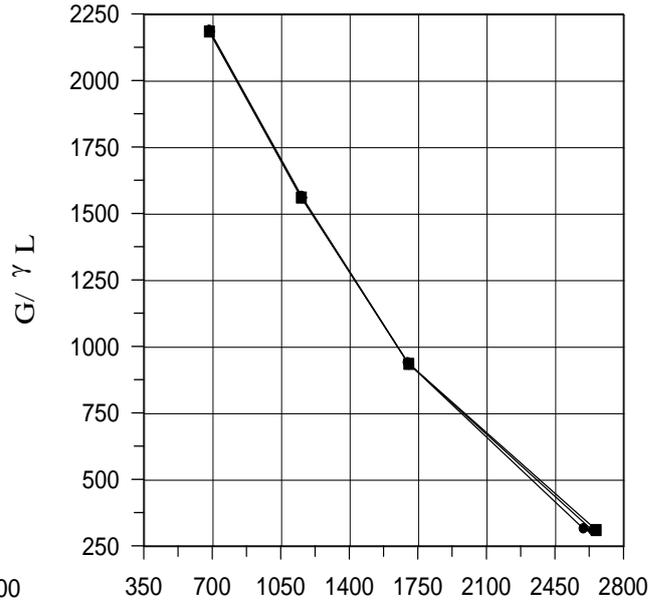
The values of the shear modulus (G) used in these figures ranged between

$(25 \times 10^3 \text{ and } 175 \times 10^3) \text{ kN/m}^2$.



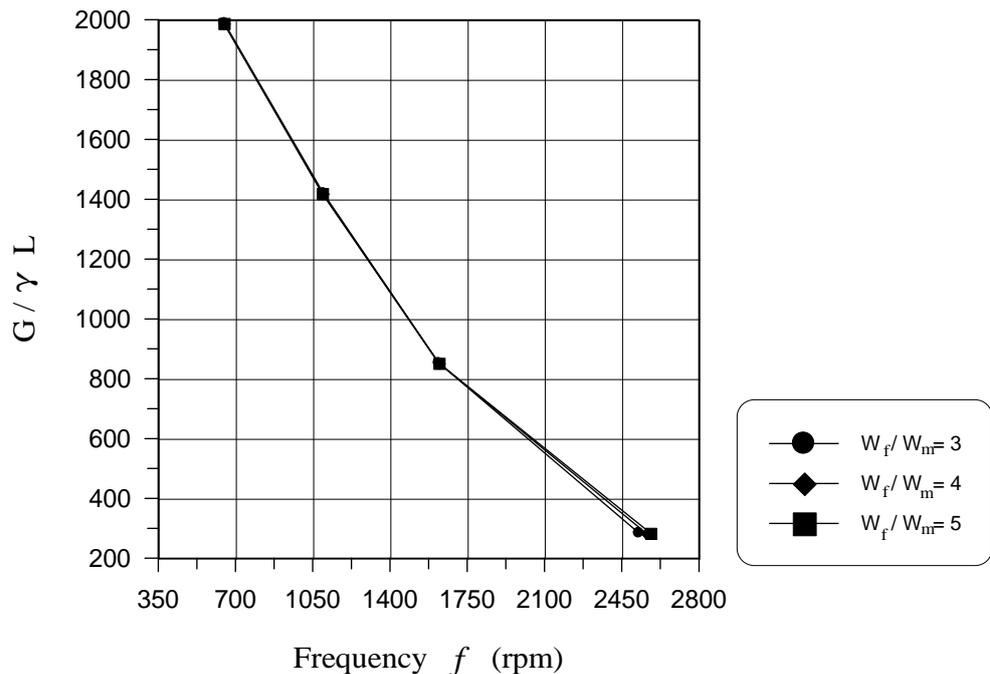
Frequency f (rpm)

a) $\gamma = 18 \text{ kN/m}^3$



Frequency f (rpm)

b) $\gamma = 20 \text{ kN/m}^3$



Frequency f (rpm)

Fig. (6) is drawn for the foundation dimensions ratio $L_f/B_f = 2$, Poisson's ratio, $\nu = 0.35$, and different soil unit weights. $\gamma = 18, 20$ and 22 kN/m^3 .

Fig. (5) – Design charts for machine foundations ($L/B = 1, \nu = 0.35$) and displacement = $2.5 \times 10^{-6} \text{ m}$.

From these figures, it is apparent that the frequency is also inversely proportional to the values of $(G / \gamma L_f)$. The curves of these relationships for different values of (W_f / W_m) coincide with each other especially at frequency level (200-900 rpm). After this limit of frequency, the effect of the weight ratio can be pronounced.

The values of the shear modulus (G) used in these figures ranged between $(25 \times 10^3$ and $125 \times 10^3)$ kN/m² because in the case of shear modulus equals to (175×10^3) kN/m², the resulted displacements were out of the limit of (2.5×10^{-6}) m.

Fig. (7) is drawn for the foundation dimensions ratio $L_f/B_f = 3$, Poisson's ratio, $\nu = 0.35$, and different soil unit weights, $\gamma = 18, 20$ and 22 kN /m³.

From these figures, it is apparent that the frequency is inversely proportional to the values of $(G / \gamma L_f)$. The curves of these relationships for different values of (W_f / W_m) coincide with each other especially at frequency level (200-1750 rpm). After this limit of frequency, the effect of the weight ratio can be pronounced.

The values of the shear modulus (G) used in these figures ranged between $(25 \times 10^3$ and $175 \times 10^3)$ kN/m² except for $\gamma = 18$, the shear modulus (G) ranged between $(25 \times 10^3$ and $125 \times 10^3)$ kN/m².

Fig. (8) is drawn for the foundation dimensions ratio $L_f/B_f = 1$, Poisson's ratio, $\nu = 0.4$, and different soil unit weights, $\gamma = 18, 20$ and 22 kN /m³.

As in the previous figures, it is apparent that the frequency is inversely proportional to the values of $(G / \gamma L_f)$. The curves of these relationships for different values of (W_f / W_m) coincide with each other especially at frequency level (400-2000 rpm). After this limit of frequency, the effect of the weight ratio can be pronounced.

The values of the shear modulus (G) used in these figures ranged between $(25 \times 10^3$ and $125 \times 10^3)$ kN/m² except for $\gamma = 18$ kN/m³, the shear modulus (G) ranged between $(25 \times 10^3$ and $175 \times 10^3)$ kN/m².

Fig. (9) is drawn for the foundation dimensions ratio $L_f/B_f = 2$, Poisson's ratio, $\nu = 0.4$, and different soil unit weights, $\gamma = 18, 20$ and 22 kN /m³.

The same relationship between the frequency and the values of $(G / \gamma L_f)$. The curves of these relationships for different values of (W_f / W_m) coincide with each other especially at frequency level (400-1000 rpm). After this limit of frequency, the effect of the weight ratio can be pronounced.

The values of the shear modulus (G) used in these figures ranged $(25 \times 10^3$ and $125 \times 10^3)$ kN/m².

Fig. (10) is drawn for the foundation dimensions ratio $L_f/B_f = 3$, Poisson's ratio, $\nu = 0.4$, and different soil unit weights, $\gamma = 18, 20$ and 22 kN /m³.

From these figures, it is apparent that the frequency is inversely proportional to the values of $(G / \gamma L_f)$. The curves of these relationships for different values of (W_f / W_m) coincide with each other especially at frequency level (500-700 rpm). After this limit of frequency, the effect of the weight ratio can be pronounced.

The values of the shear modulus (G) used in these figures are $(25 \times 10^3$ and $75 \times 10^3)$ kN/m².

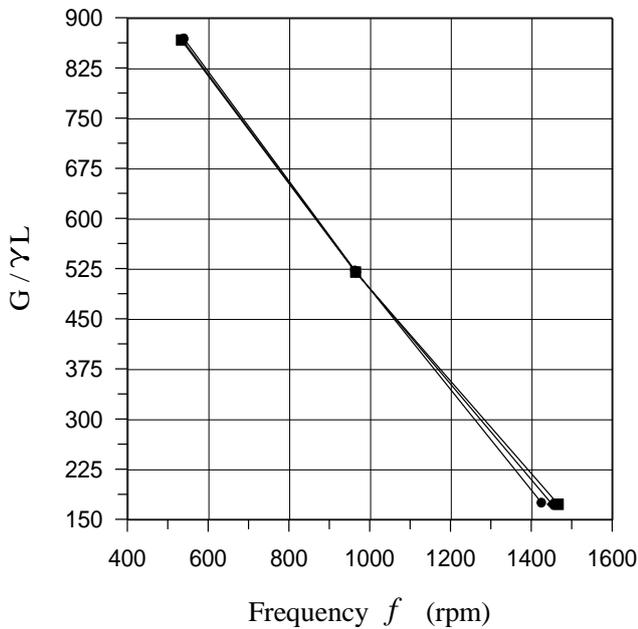
Fig. (11) is drawn for the foundation dimensions ratio $L_f/B_f = 1$, Poisson's ratio, $\nu = 0.45$, and different soil unit weights, $\gamma = 18, 20$ and 22 kN /m³.

From these figures, it is apparent that the frequency is inversely proportional to the values of $(G / \gamma L_f)$. The curves of these relationships for different values of (W_f / W_m) coincide with each

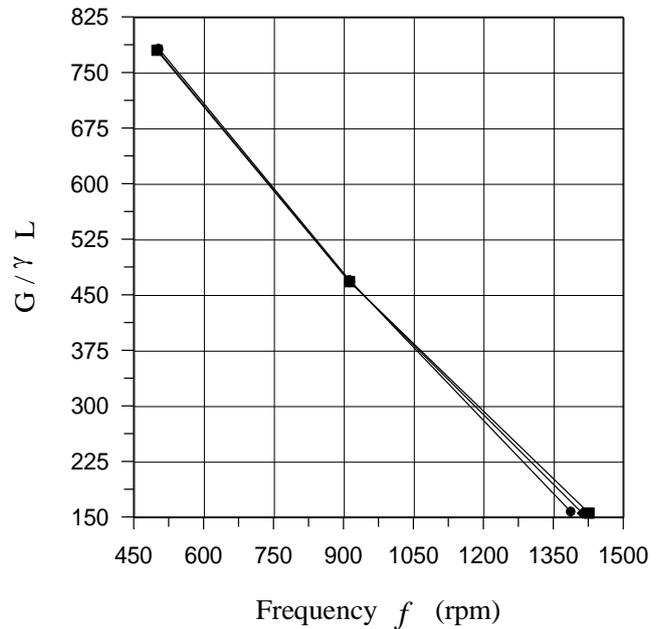


other especially at frequency level (250-2000 rpm). After this limit of frequency, the effect of the weight ratio can be pronounced.

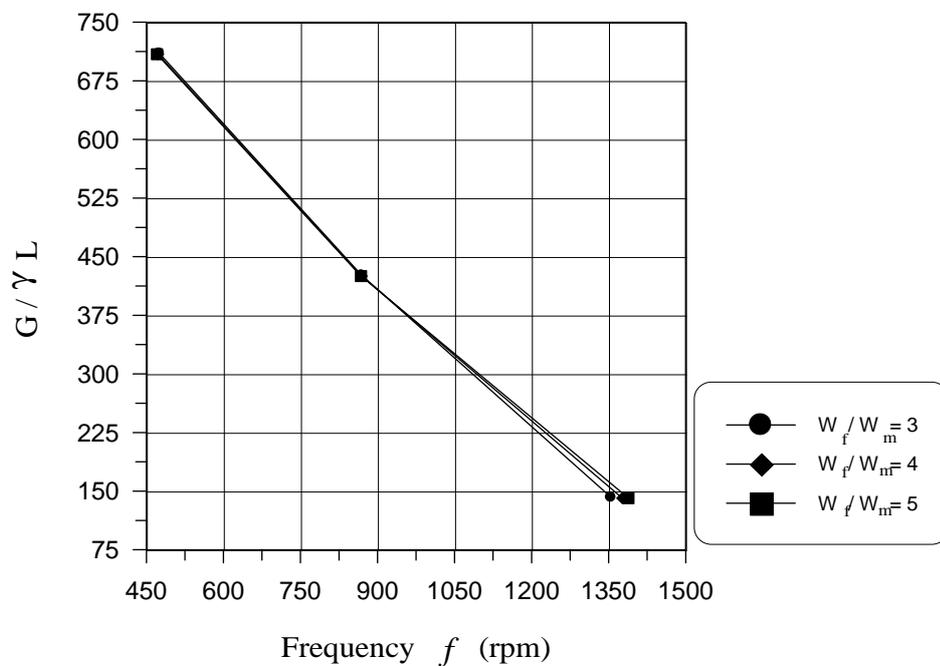
The values of the shear modulus (G) used in these figures ranged between (25 x 10³ and 175 x 10³) kN/m².



a) $\gamma = 18 \text{ kN/m}^3$



b) $\gamma = 20 \text{ kN/m}^3$



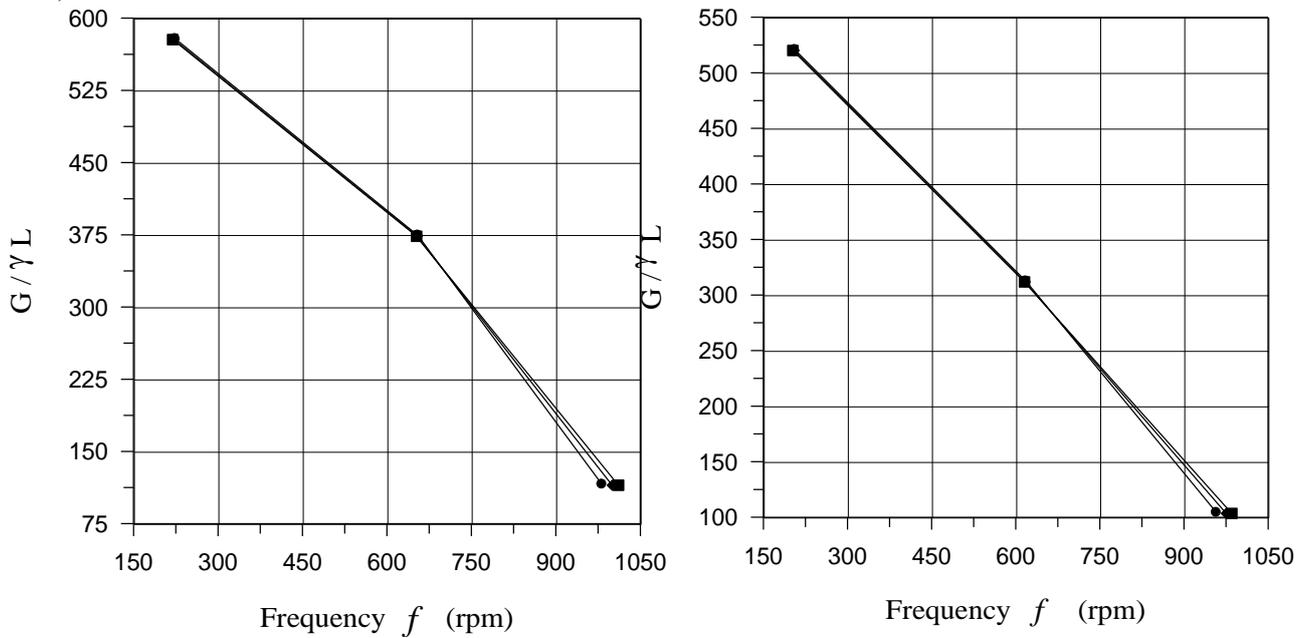
c) $\gamma = 22 \text{ kN/m}^3$

Fig. (6) — Design charts for machine foundations ($L/B = 2, \nu = 0.35$) and displacement = $2.5 \times 10^{-6} \text{ m}$.

Fig. (12) is drawn for the foundation dimensions ratio $L_f/B_f = 2$, Poisson's ratio, $\nu = 0.45$, and different soil unit weights, $\gamma = 18, 20$ and 22 kN/m^3 .

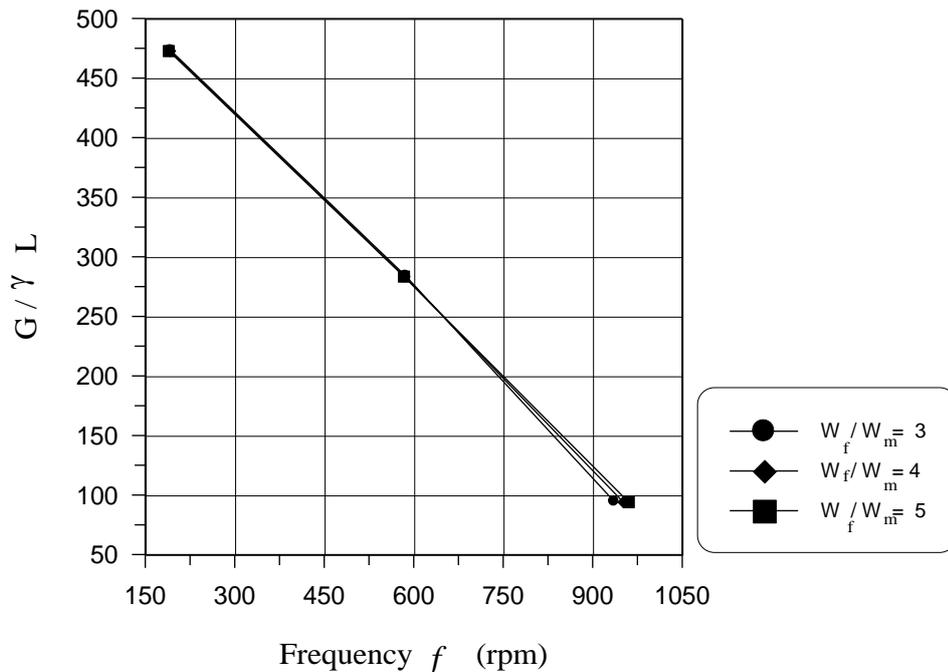
From these figures, it is apparent that the frequency is inversely proportional to the values of $(G/\gamma L_f)$. The curves of these relationships for different values of (W_f/W_m) also coincide with each other especially at frequency level (200-1000 rpm). After this limit of frequency, the effect of the weight ratio can be pronounced.

The values of the shear modulus (G) used in these figures ranged between $(25 \times 10^3 \text{ and } 75 \times 10^3) \text{ kN/m}^2$.



a) $\gamma = 18 \text{ kN/m}^3$

b) $\gamma = 20 \text{ kN/m}^3$



c) $\gamma = 22 \text{ kN/m}^3$

Fig. (7) — Design charts for machine foundations ($L/B = 3, \nu = 0.35$) and displacement = $2.5 \times 10^{-6} \text{ m}$.



Fig. (13) is drawn for the foundation dimensions ratio $L_f / B_f = 3$, Poisson's ratio, $\nu = 0.45$, and different soil unit weights, $\gamma = 18, 20$ and 22 kN/m^3 .

From these figures, it is apparent that the frequency is inversely proportional to the values of $(G / \gamma L_f)$. The curves of these relationships for different values of (W_f / W_m) coincide with each other especially at frequency level (500-650 rpm). After this limit of frequency, the effect of the weight ratio can be pronounced.

The values of the shear modulus (G) used in these figures are $(25 \times 10^3$ and $75 \times 10^3) \text{ kN/m}^2$.

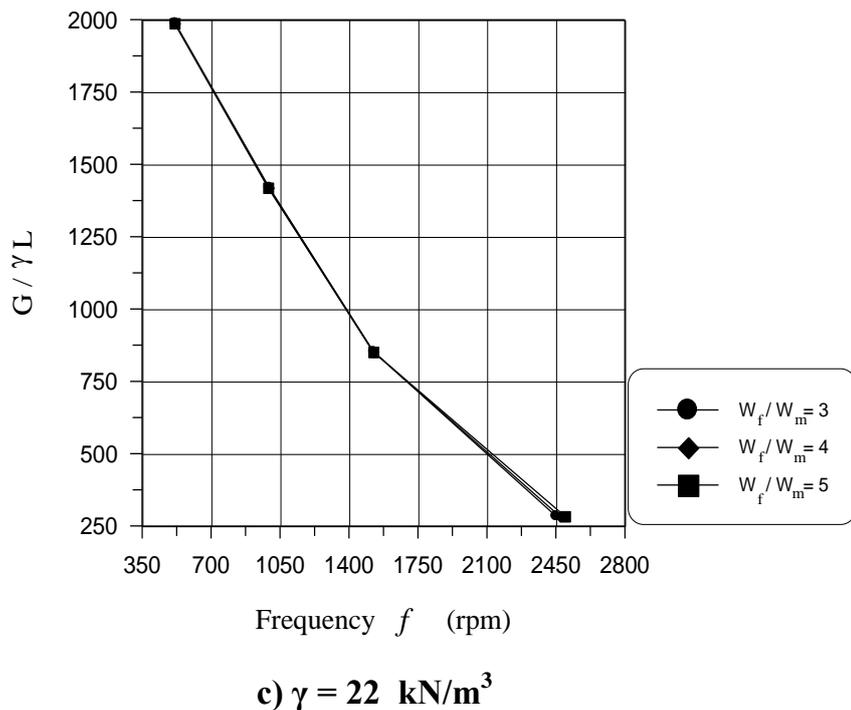
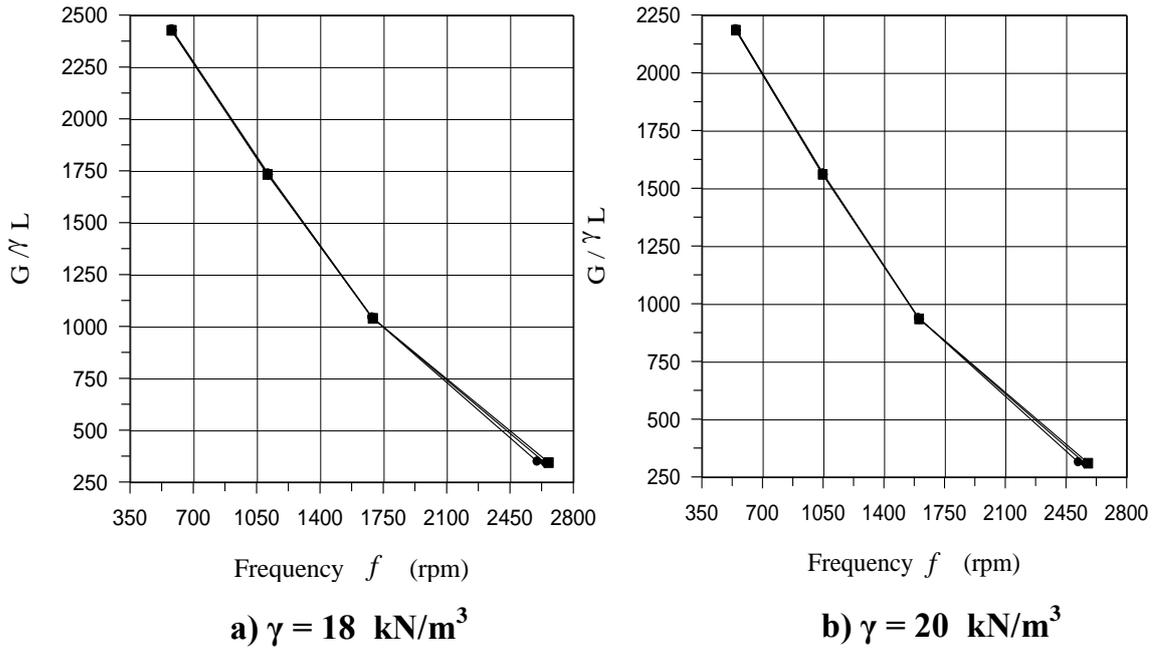
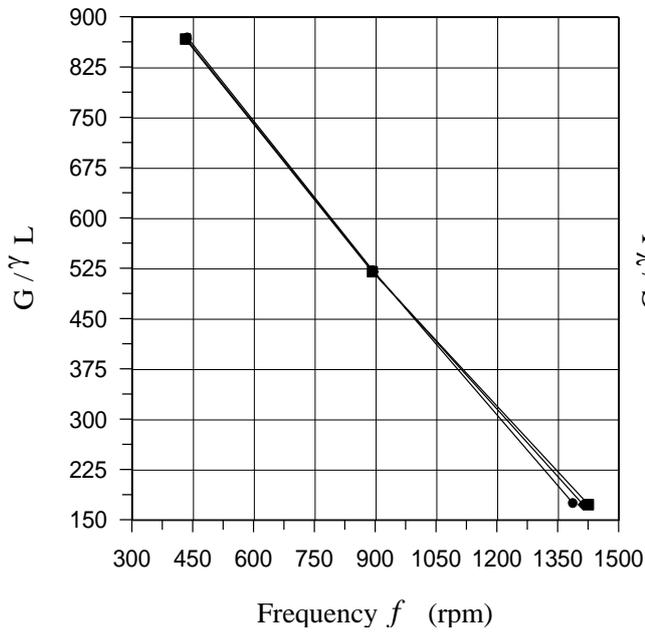
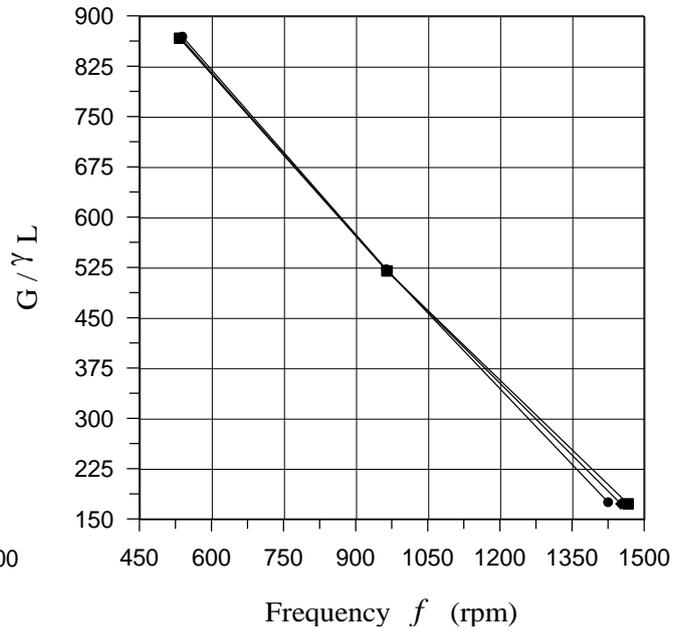


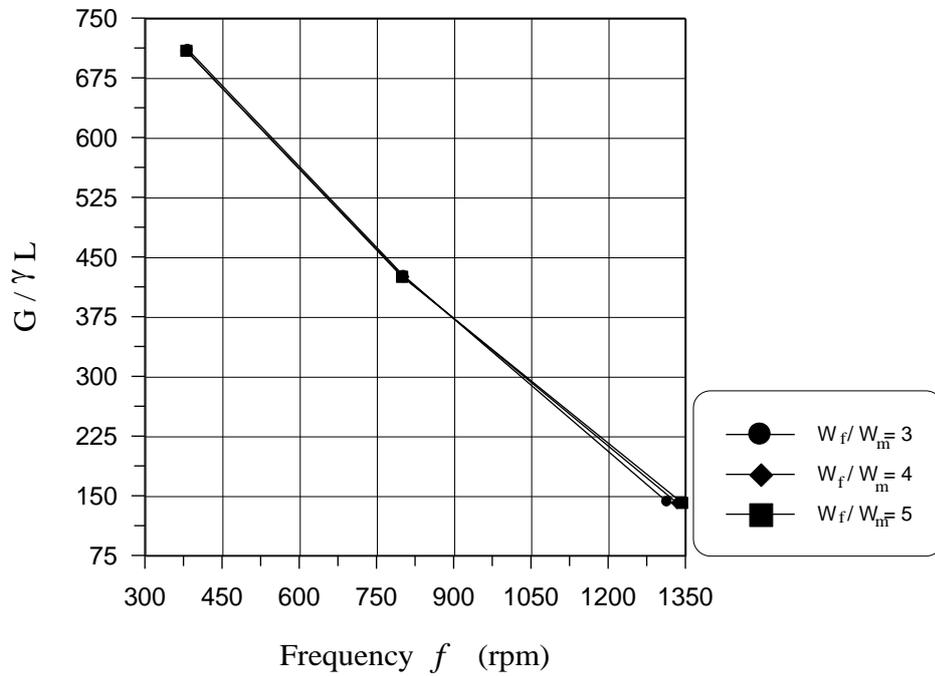
Fig. (8) – Design charts for machine foundations ($L/B = 1, \nu = 0.4$) and displacement = $2.5 \times 10^{-6} \text{ m}$.



a) $\gamma = 18 \text{ kN/m}^3$

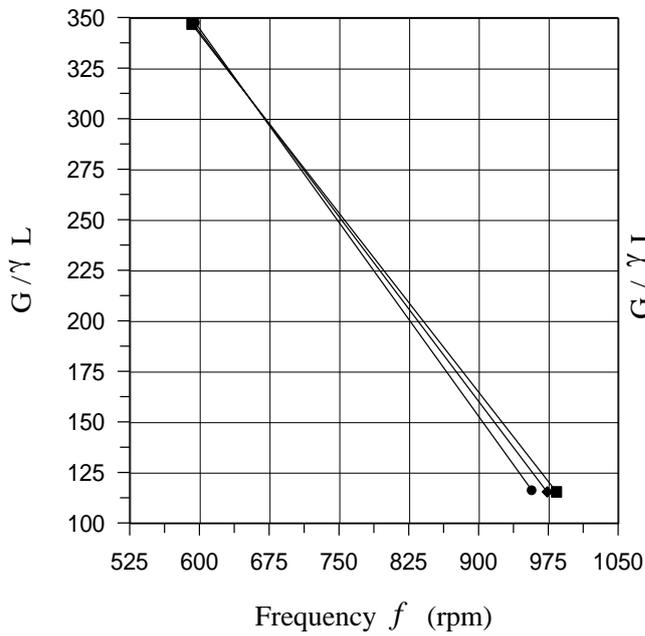


b) $\gamma = 20 \text{ kN/m}^3$

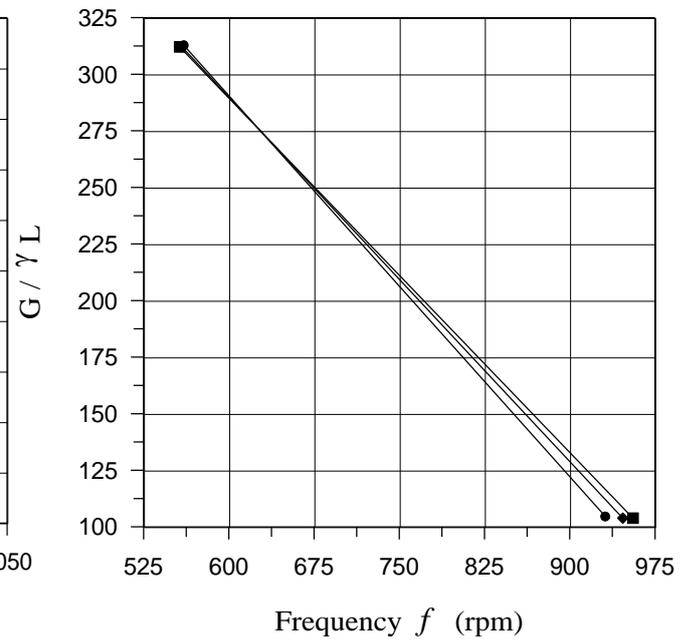


c) $\gamma = 22 \text{ kN/m}^3$

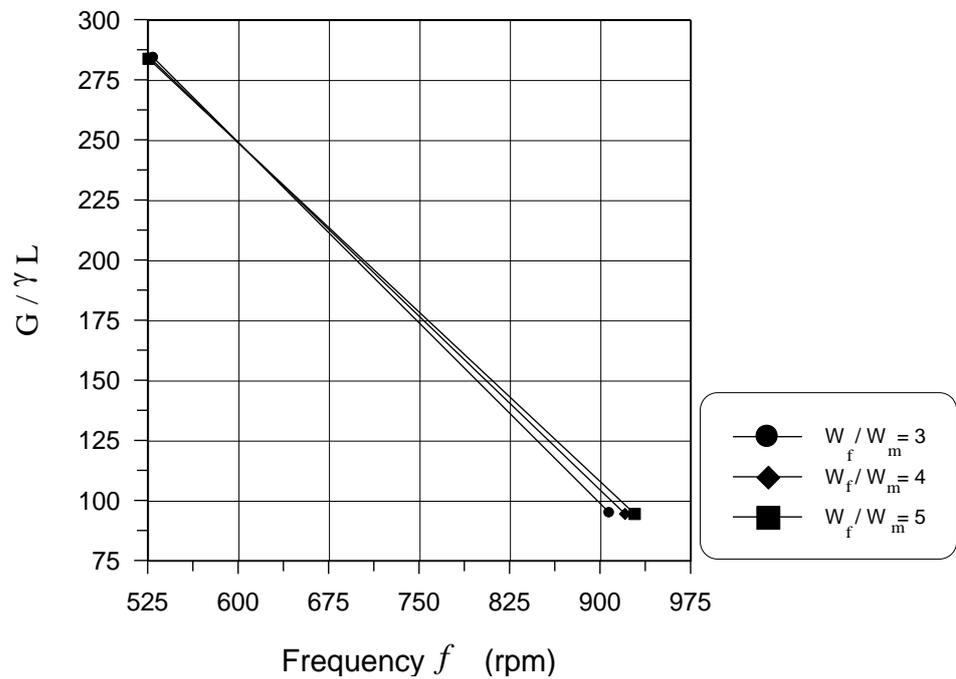
Fig. (9) – Design charts for machine foundations ($L/B = 2$, $\nu = 0.4$) and displacement = $2.5 \times 10^{-6} \text{ m}$.



a) $\gamma = 18 \text{ kN/m}^3$

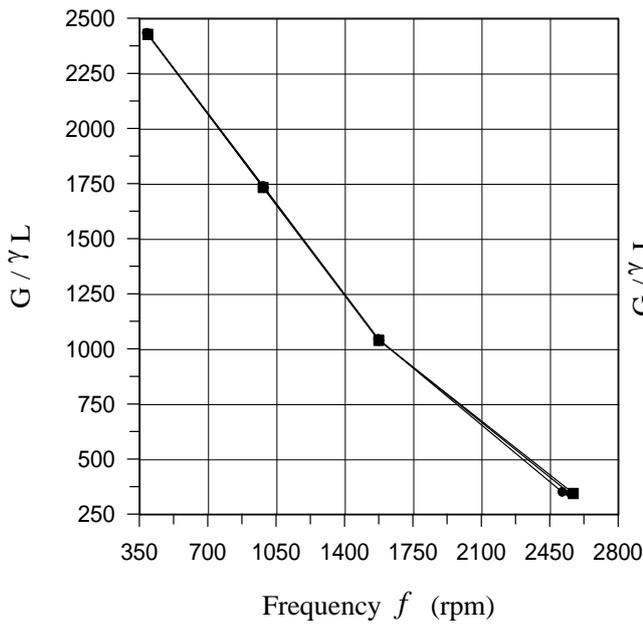


b) $\gamma = 20 \text{ kN/m}^3$

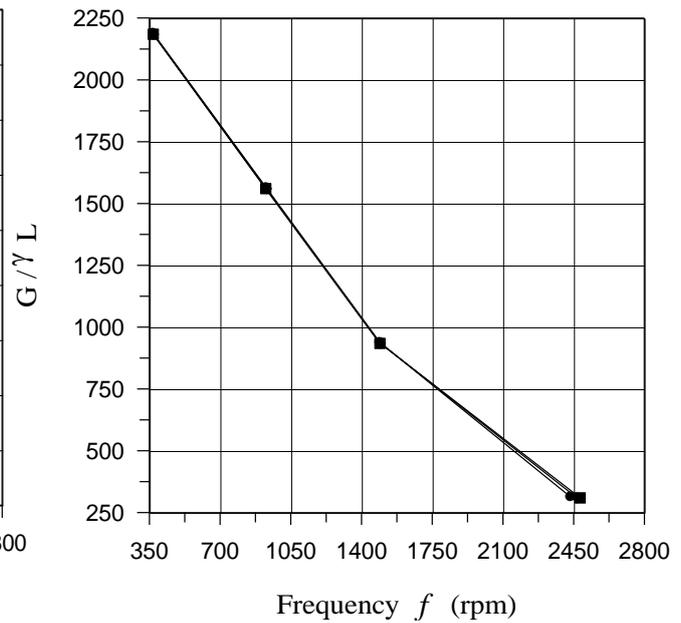


c) $\gamma = 22 \text{ kN/m}^3$

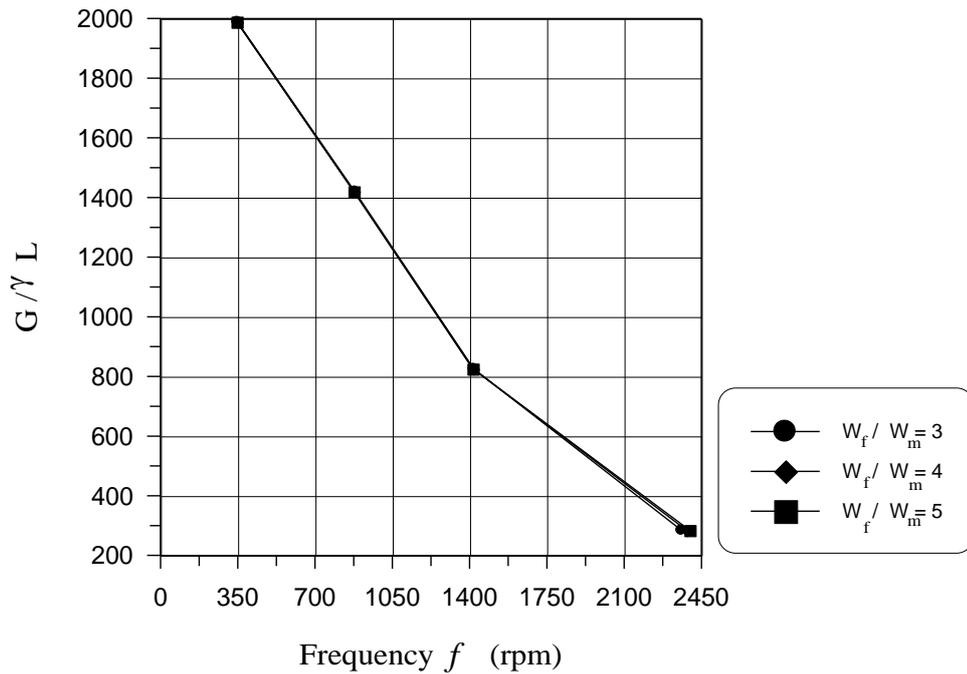
Fig. (10) – Design charts for machine foundations ($L/B = 3, \nu = 0.4$) and displacement = $2.5 \times 10^{-6} \text{ m}$.



a) $\gamma = 18 \text{ kN/m}^3$

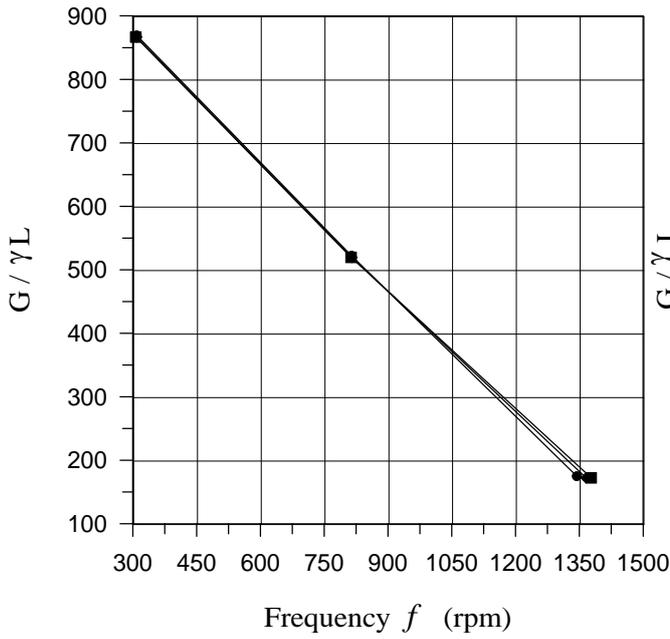


b) $\gamma = 20 \text{ kN/m}^3$

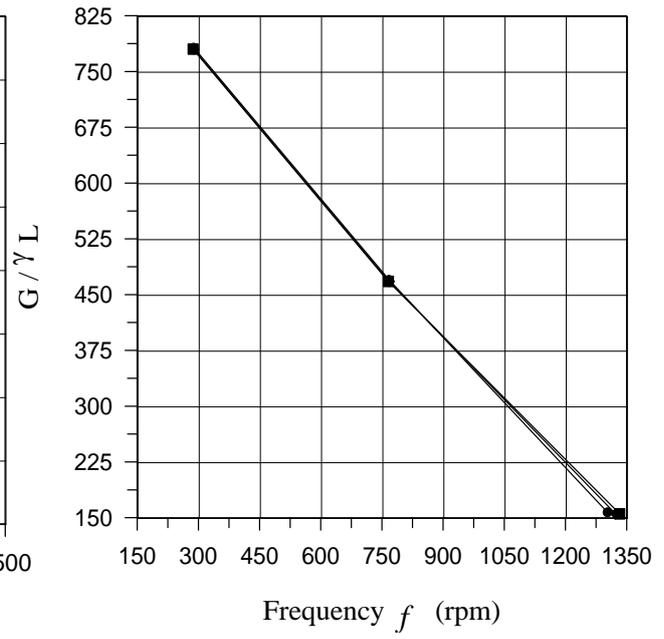


c) $\gamma = 22 \text{ kN/m}^3$

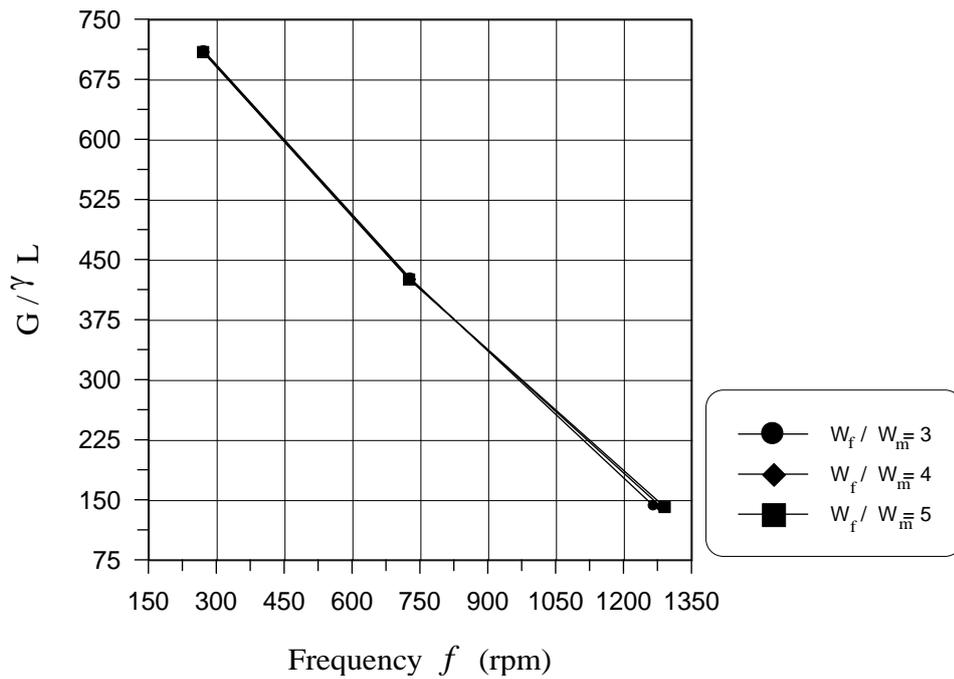
Fig. (11) – Design charts for machine foundations ($L/B = 1$, $\nu = 0.45$) and displacement = $2.5 \times 10^{-6} \text{ m}$.



a) $\gamma = 18 \text{ kN/m}^3$

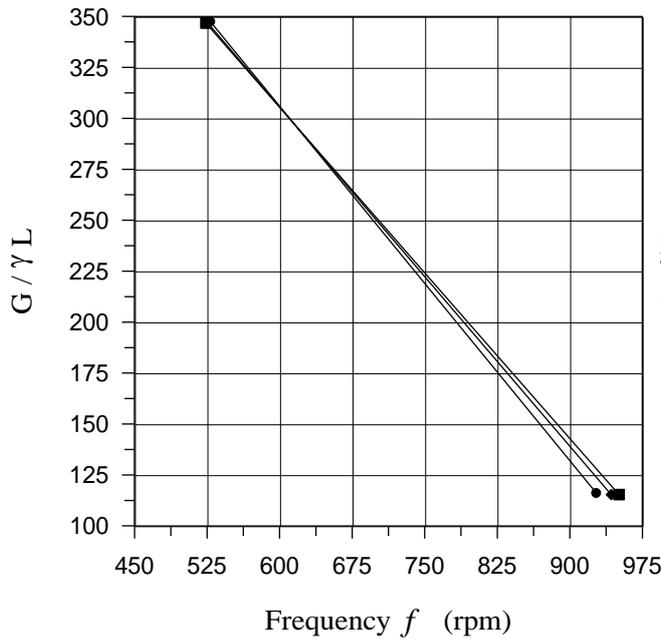


b) $\gamma = 20 \text{ kN/m}^3$

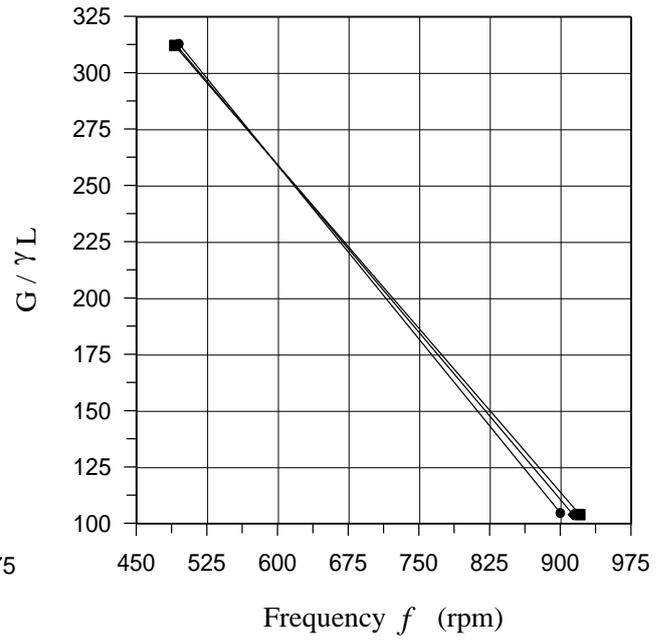


c) $\gamma = 22 \text{ kN/m}^3$

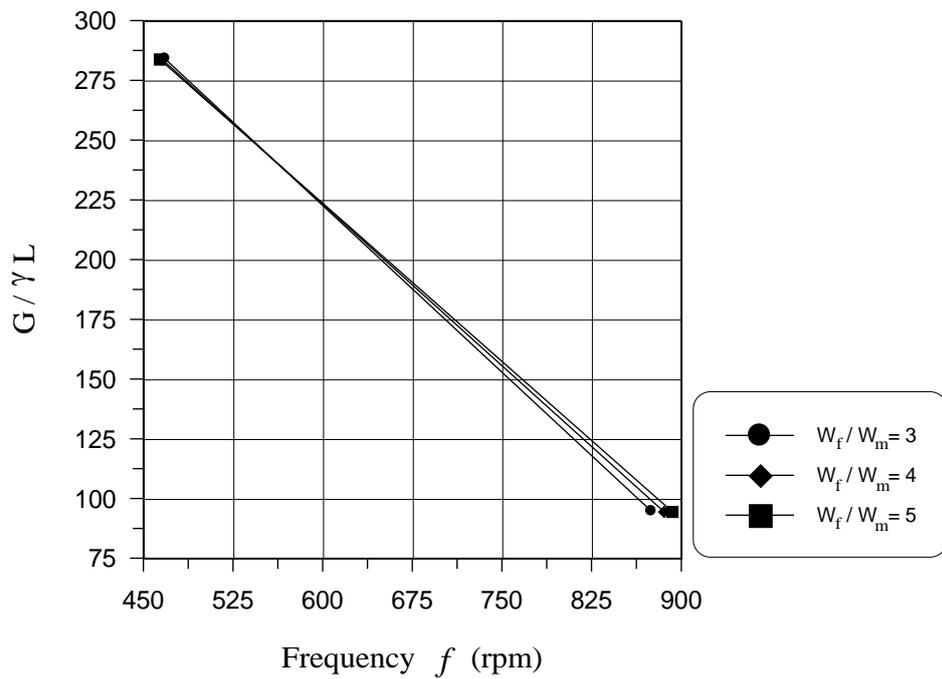
Fig. (12) – Design charts for machine foundations ($L/B = 2, \nu = 0.45$) and displacement = $2.5 \times 10^{-6} \text{ m}$.



a) $\gamma = 18 \text{ kN/m}^3$



b) $\gamma = 20 \text{ kN/m}^3$



c) $\gamma = 22 \text{ kN/m}^3$

Fig. (13) – Design charts for machine foundations ($L/B = 3$, $\nu = 0.45$) and displacement = $2.5 \times 10^{-6} \text{ m}$.



CONCLUSIONS

It was found that the most important variable affecting the problem of machine foundations is the shear modulus of the soil. Considering the shear modulus as state variable, it was found that by the empirical method, the maximum displacement decreases when the shear modulus increases as the type of soil is sand; and the maximum displacement is smaller than the case when the type of soil is clay. For the cone model method, the maximum displacement decreases when the shear modulus increases when the shear modulus is less than 200 kN/m² for the range of soils analyzed in this study, while when the shear modulus is more than 200 kN/m², the maximum displacement increases with the increase of the shear modulus.

The maximum displacement decreases with the increase of machine operating frequency, soil unit weight, shear modulus, Poisson's ratio and internal damping.

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