Replacement of rigid soil by an elastic material for the reduction of sensitive machine vibrations

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Abstract

Elastic mountings are necessary for reducing the effect of environmental vibrations on sensitive machinery. The common method is the application of artificial polymeric, fibrous materials or metal springs as elastic mountings. Such mountings necessitate control and maintenance. It is much more attractive to use materials that do not deteriorate over time, at least for a few decades. This is due to the fact that in order to get the effect of "mass-spring" response, a heavy mass that supports the sensitive system is laid over an elastic material. At least a partial solution can be obtained by soil replacement of the rock underneath the foundation. However, it is illustrated here numerically that the result is strongly dependent on the spectrum of the system response, and in certain cases incorrect design may even cause weakening of the isolation.
Keywords: soil mechanics, elastic isolation, soil replacement, vibrations, spectral response.

1 Introduction

Regular design of foundations isolation considers the natural properties of the existing ground. However, under certain circumstances, the ground, on which the foundation is intended to be built, is too hard and/or non-uniform. In the first case the protected machine may suffer severe vibrations that are beyond its capacity, or may lead to damages, such as defects in the products of the machine. In the second case, the non-uniformity of the ground under the foundation can lead to differential settlement, cracks in the structure and even instabilities. A change in the mechanical properties of the soil under the foundation can be used

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in order to form an elastic mounting suitable for obtaining vibration isolation as needed.

The underlying principle that the paper uses is the concept of "base isolation", widely used in structural engineering applications and known within geotechnical engineering, for example, when liquefaction occurs and vibrations are damped out.

There are many examples of various areas of application of this approach. One example is the isolation of vibrations caused by trains passing over bridges. It is attained by putting a ballast mat under the ballast. The ballast mat is a resilient layer of an elastomer, the thickness of which is about 25 mm, and it is laid under the ballast that separates the structure from the gravel in bridges. This combination proves to be very effective.

Another example is the use of a sand layer under terrazzo floors, in order to reduce the transmission of impact noise on their upper surface into the rooms beneath. In order to obtain significant results the thickness of the sand should be above a certain value (e.g., 8 cm), and it should be clean of rigid obstacles (caused for example by penetration of cement water during construction). Those rigid bodies may cause sound and vibration "bridges" that spoil the isolation. Since acoustic isolation standards and regulations become more demanding every year (and so are the claims for compensation to be paid by the contractors), and structures that use modern materials are getting lighter, the importance of this kind of isolation is growing.

In the present paper we are interested in the use of natural ground as replacement to the rigid ground that exists there already and is not suitable for the isolation needs. The age of nano-electronics and even micro-electronics is characterized by higher sensitivity to vibrations, which demands better isolation of machinery. Existing machines in the hi-tech industry are subject to severe limits on penetration of external vibrations in order to avoid damage to production and to the control of the products. A typical example to such a limitation is 0.000001 g (one millionth of gravity acceleration on earth) or other data, in accordance with the manufacturer's specification.

Another kind of problem is the occurring of differential settlements of the foundation due to the non-uniformity of the properties of the ground underneath. Take for example a whole building with one side built on solid rock, while the other one is built on soft soil. The deflection of the building over the soft ground will be higher than that on the rigid ground, which may in turn cause inclination of the building and dangerous bending moments. See Rosenhouse et al. [1] and Burland et al. [2].

Soil replacement of the right thickness for gaining the expected vibration isolation, can be obtained by digging the hard rock (soil) and filling the void by material such as calcareous sandstone. Other solutions that apply metal springs and layers of polymeric or fibrous materials can be used. However, such solutions require more control and maintenance, while natural ground materials are less sensitive to long-term influences.

In this paper we show theoretical computerized estimates that illustrate various cases, using the finite difference method. The materials involved (existing soil, the soil replacement and concrete) will be considered elasto-plastic. The domain of the analysis is modeled by a "half space" that is "cut" by vertical and horizontal boundary conditions into a rectangle for 2-D analysis.

2 The method of calculation

A comprehensive theoretical examination of the effect of soil replacement on vibration isolation is available in Rosenhouse et al. [1] and Kirzhner et al. [3] about the protection of sensitive structures against excessive vibrations. An example to source of vibrations is transportation on roads. Such isolation can help at least partially in vibration reduction, if properly designed.

In order to simulate numerically solution alternatives we have used a 2-D dynamic FLAC program [4] that has two main schemes:

1. Non-reflective boundaries.
2. Free boundaries.

The choice of boundary conditions scheme follows the type of the problem to be solved.

3 The model for the dynamical problem

Assume that a vibrating machine is located above a concrete foundation, as shown in figure 1. The machine vibrates the foundation and generates a prescribed excitation spectrum. The foundation is cast over a rocky ground (we took the Young moduli of the concrete and the rock alike).

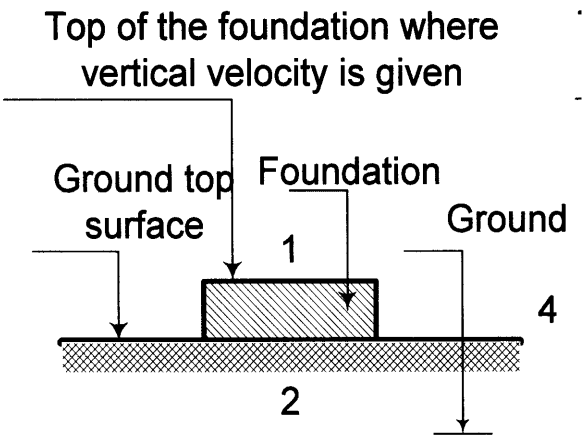

Figure 1: A rigid foundation supporting a machine over a rocky half space.

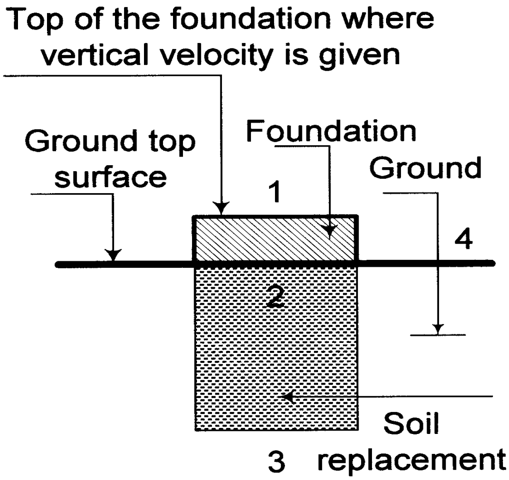

Figure 2: A rigid machine foundation isolated by ground replacement in a rocky half space.

Thus, in the absence of additional isolation, the vibrations will spread outside the foundation body into the ground. The vibrations may be of high amplitude when passing through point 4 in figure 1. In order to reduce the escape of high mechanical energy at point 4, if it is excessive, a part of the rock mass under the foundation is removed, and replaced by material that is much more elastic, for example, calcareous sandstone. The depth of the replacement **reaches** the needed depth – point 3 in figure.

In the inverse problem, the dynamic load is located outside the foundation, in or over the ground, and the vibrations reach the machine via the foundation.

The depth of the replacement and difference between elastic properties of the road and rock and those of the elastic replacement affect the extent to which isolation against vibration can be achieved. Therefore, the properties of the materials involved should be known. Table 1 summarizes the symbols of the physical parameters of the air, road, and elastic replacement layer.

The system shown in figure 2 yields multiple reflections. However, for the sake of simplicity we can focus first on the interface as in figure 3a. The effect of the impedance mismatch between the road and the soft replacement layer follows the diagram of the pressure load, shown in Figure 3b and a model that gives the effect of absence of vibration bridges ("mass-spring" model) is shown in figure 3c. This last model suits the situation in figure 2, where the elastic replacement layer totally separates the foundation from the ground to avoid vibration bridges. We assumed here plane strain for a foundation strip of 1 m width, and a cross-section as in figures 1 and 2. The limitation to a single degree of freedom of the spring is justified, since the first mode takes most of the vibrational energy.

Table 1: Notation of physical parameters.

PARAMETER	AIR	ROAD (ROCK)	ELASTIC REPLACEMENT
Density	ρ_0	ρ_1	ρ_2
Young's modulus	-	E_1	E_2
Poisson's ratio	-	ν_1	ν_2
Propagation velocity of vibrations	C_0	c_1	c_2

The effects of the impedance mismatch and the effect of the mass-spring model join together and they can be used for interpretation of the numerical results.

The incident vibrational pressure is given by:

$$p_i = p_{i0} \exp[j(\Omega t - k_1 x)], \quad j = \sqrt{-1} \tag{1}$$

where p_{i0} is the pressure amplitude, Pa; k_1 is the wave number of the foundation, m^{-1}, Ω is the angular frequency, radian/s; t is time, s; x – distance inside the elastic isolation layer from its upper surface, m.

Only when the foundation isolation excludes the possibility of lateral vibration bridges, as shown in Figure 2, a mass-spring model becomes relevant. See Figure 3c, following the addition of a viscous damper. The equation of motion for this model is:

$$M\ddot{x} + c\dot{x} + kx = F_0 \sin(\Omega t), \tag{2}$$

where, M - mass of foundation, kg; k - spring constant N/m; c – coefficient of viscous damping, Ns/m; Ω -excitation frequency, radian/s; F_0 – amplitude of the applied force F, N.

According to this model, the ratio T_r, of transmitted force to incident force takes the following form

$$T_r = \frac{\sqrt{1+4\gamma^2 r^2}}{\sqrt{(1-r^2)^2 + 4\gamma^2 r^2}}; \; \gamma = \frac{c}{c_{cr}}; \qquad r = \frac{\Omega}{\omega_n}; \; \omega_n = \sqrt{\frac{k}{M}}; \; c_{cr} = 2\sqrt{kM}, \tag{3}$$

where ω_n denotes the natural radian frequency of the "mass – spring – damper" system.

A typical description of T_r (transmissibility) is given in Kinsler and Frey [5] and Kirzhner et al. [3]. If a substantially low transmission of vibration is desirable, then high values of Ω/ω_n and viscous damping should be used.

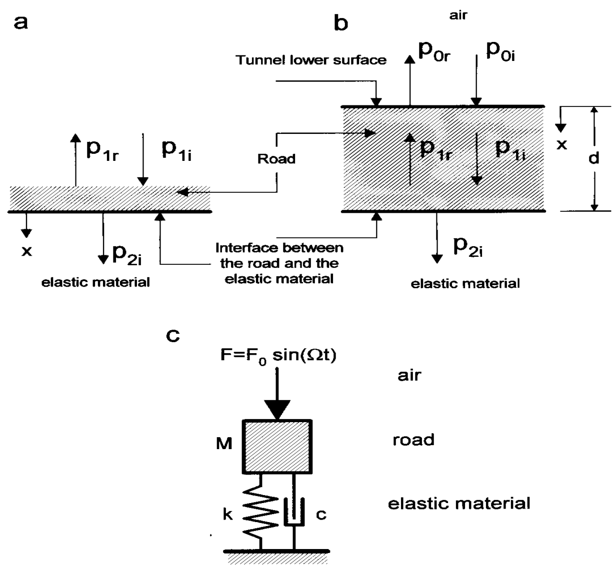

Figure 3: a. Interface between the road and elastic material; b. Transmission of vibrational load to the elastic replacement material; c. Mass-spring-damper model.

The incident pressure is partially transmitted into the elastic layer, while the other part is reflected back, as shown in figure 3a. The ratio of transmitted to incident intensity, which is defined as the vibration power transmission coefficient, is given by Kinsler and Frey [5] (see Table 1 for notation):

$$T_{12} = \frac{4\rho_1 c_1 \rho_2 c_2}{(\rho_1 c_1 + \rho_2 c_2)^2}. \tag{4}$$

Given the excitation frequency f = 100 Hz, $\rho_2 c_2 = 0.1\,\rho_1 c_1$ the transmission coefficient is $T_{12} = 0.33$, whereas at f =100 Hz, $\rho_2 c_2 = 0.01\,\rho_1 c_1$, T_{12} decreases to 0.0392.

The model in Figure 3b represents transmission through a road into the elastic layer. In this case, the vibration power transmission coefficient takes the following form:

$$T_{12} = \frac{4R_2 R_0}{(R_0 + R_2)^2 \cos^2(k_1 d) + (R_1 + R_2 R_0 / R_1)^2 \sin^2(k_1 d)}, \tag{5}$$

$$k_1 = \frac{2\pi f}{c_1},\ R_0 = \rho_0 c_0,\ R_1 = \rho_1 c_1,\ R_2 = \rho_2 c_2,$$

d denotes the elastic layer thickness. If f=100 Hz, d=0.5 m, $\rho_2 c_2 = 0.1\,\rho_1 c_1$, $\rho_0 c_0 = 0.001\,\rho_1 c_1$ and c_1=3000 m/s, then we obtain T_{12}=0.02.

4 Illustrations

4.1 Example 1

A relatively simple model is that of a harmonic excitation. However it is important to perform spectral analysis and to define the isolation effect in the frequency domain as we do in the present example.

A machine that is sensitive to vibration is anchored to the surface area over a given foundation, as shown in figure 4.

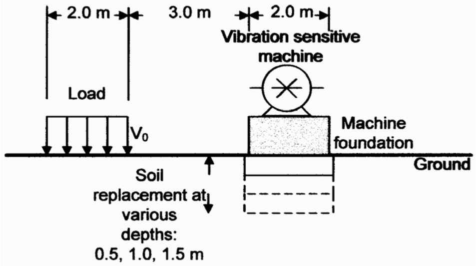

Figure 4: A cross-section through the foundation and the nearby vibrational source.

A nearby line source radiates mechanical vibrations (e.g. transportation). The dynamic input is expressed in terms of a vertical surface velocity, V:

$$V = V_0 \exp(j\Omega t); \Omega = 2\pi f. \tag{6}$$

A typical velocity amplitude V_o, in the y-direction, was set at 0.1 m/s. The self frequency of the rock mass was taken as 40 Hz, and the excitation frequency was set at 100 Hz. Mechanical data of rocks, for the numerical analysis is given in Table 2.

Table 2: Mechanical data of rocks.

Type of rock	Density, kg/m^3	Young modulus, MPa	Poisson ratio
Limestone	2400	20,000	0.3
Calcareous sandstone	2000	20	0.2

The response to the vibration was examined under the center of the foundation – point 2 in figures 1 and 2. First, the response was analyzed in the absence of replacement soil in the range of frequencies, f = 10-200 Hz. The domain that includes the source and foundation was chosen to be big enough as to avoid at the control point the effect of fictitious reflections from the artificial boundaries. The natural frequency of the ground was taken as 40 Hz. A light hysteretic damping of 5% was taken for the ground in all cases.

The results of the calculation are given in figure 5, and we observe that without soil replacement there is no significant resonance, with the maximum amplitude at about 120 Hz.

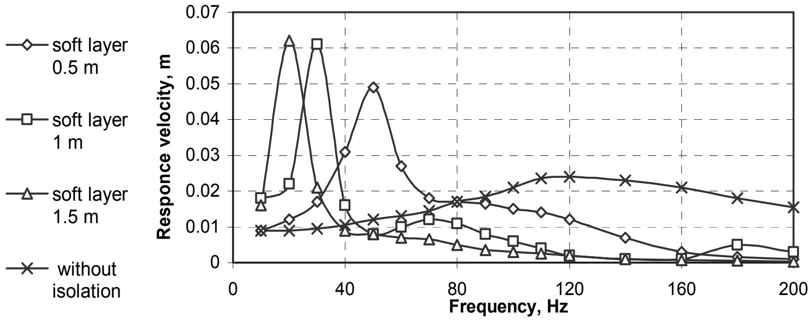

Figure 5: The vibration under the foundation, without isolation and with isolation by replacement soil at the depths of 0.5 m, 1.0 m and 1.5 m.

Next, analyses with soil replacements of 0.5 m, 1.0 m and 1.5 m depth (see figure 4), were performed. With the results that appear at figure 5 the following conclusions can be drawn:

1. At the examined frequency domain (10-200 Hz) and lack of soil replacement, a large amount of vibrations is transferred through the rock into the foundation. The attenuation in this case is mostly geometrical, and it is due to the distance of propagation of the vibration from the source to the center of the foundation. At certain frequencies, the response has reached 20% of the vibration at the source.
2. When the rock is replaced three main domains of response are distinguished. At the lower frequency range – up to 80 Hz, for the specific example, clear resonances appear as a result of the numerical analysis (see the model in the example in section 4.2). Hence, in this range, soil replacement even weakens the isolation. The second domain is in the range 80-160 Hz, where the soil replacement significantly improves the isolation and the depth of the layer is influential. The last domain ranges from 160 Hz, where a depth of replacement of 0.5 m is sufficient, and additional depth does not help. In this domain the isolation reduces the amplitude of vibration under the foundation to a tenth as compared with vibration without isolation.

4.2 Example 2

An approximate calculation of the resonance frequency of the filling-mass is shown by this example, taking into account the data of table 2 for calcareous sandstone. For this purpose we assume that the mass of the foundation, including the effect of the filling causes a load of 160000 N/m^2, concerning deflection. See figure 6. If the foundation area is 1 m, the depth of the filling is L=1 m and its Young modulus is E, the "spring" constant of the filling is defined as:

$$k = \frac{EA}{L}; \ N/m. \tag{7}$$

Hence, the static deflection of the surface of the filling is:

$$\delta = \frac{P}{k} = \frac{PL}{EA} = \frac{1 \times 1.6 \times 10^5}{2 \times 10^7} = 8 \times 10^{-3} \ m = 8 \ mm. \tag{8}$$

And natural frequency of the calcareous sandstone upper surface becomes:

$$f_n = \sqrt{\frac{g}{\delta_{st}}} = \sqrt{\frac{9.8}{8 \times 10^{-3}}} = 35 \ Hz. \tag{9}$$

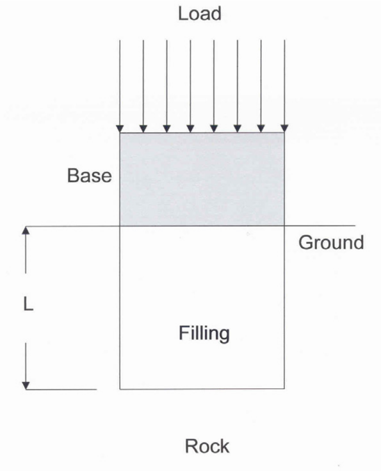

Figure 6: A simple model for an approximate estimation of the resonance frequency of the filling.

5 Conclusions and comments

Soil replacement of rock for better vibration isolation is possible, as was demonstrated numerically in the present paper.

Two main mechanisms of vibration reduction were identified. Those are a "mass-spring" system and the impedance mismatching. Those mechanisms can act simultaneously if vibration bridges are avoided. This conclusion is supported by the first example in section 4.

The choice of depth and mechanical properties of the soil replacement material should be subject to careful design. It should take into account the relevant frequency range in order to optimize the response. Wrong decisions can lead to negative effects due to the use of soil replacement. In practice it is recommended to perform experiments to define the filling response before any decision is taken. The approach suggested here concerning vibration isolation involves also economical consideration. There are cases when the excavation for the soil replacement will be very large, and hence, too expensive, for example, in coating a pipe buried deep in the ground by elastic replacement. In such cases open excavation might be impossible and the excavated volume will be huge.

An important factor in the suggested method is that it does not demand as much maintenance as elastic mountains made of steel and other kinds of elastic mountings, even if the target is decades of years of use.

Acknowledgment

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References

[1] Rosenhouse, G., Kirzhner, F., Zimmels, Y., The effect of ground replacement on control of underground vibrations and differential settlements of structures, *Computational Methods in Contact Mechanics*, WIT Press, C.A. Brebbia (ed.), Southampton, pp. 3-13, 2003.

[2] Burland, J., Jamiolkowski, M., Viggiani, C., Preserving Pisa's treasure, *Civil Engineering*, 72(3), pp.42-49, 2002

[3] Kirzner, F., Rosenhouse, G., Zimmles, Y., Environmental protection against underground propagation of vibration by elastic barriers, *Proc. NARMS-TAC 2002, Mining and Tunneling Innovation and Opportunity Conference*, Hammah et al. (eds), University of Toronto, pp 727-732, 2002.

[4] Itasca Consulting Group, FLAC – Fast Lagrangian Analysis of Continua, Version 3.4, 1996

[5] Kinsler, L. E., Frey, A.R., *Fundamentals of Acoustics*, 2nd ed. John Wiley, 1962.