Using reinforced soil systems in hammer foundations

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Forging hammers produce powerful short-period impact loads. A mounting system or a properly designed foundation could be used to transmit the shock to the soil and lessen its effects on the surroundings. The supporting foundations must be designed to reduce the vibration amplitude and the forces transmitted to the soil medium in order to meet serviceability and stability requirements. Soil reinforcement may be used to improve the performance of the foundations supporting shock-producing equipment. This paper investigates the effect of soil reinforcement on the performance characteristics for different configurations of shock-absorbing foundations. The results demonstrated the efficiency of soil reinforcement in improving the performance of foundations subjected to impact load. A parametric study was conducted and a set of charts was established as practical guidance for the design of soil reinforcement schemes.

1. INTRODUCTION

The act of hammering is a basic industrial process encountered in such diverse activities as the breaking up of scrap and the forging of metal. Hammers, presses and other types of shock-producing machines generate powerful dynamic effects that are quite short in duration and can be characterised as pulses. Only a part of the shock energy is utilised in the intended machine function and the rest is dissipated in the foundation causing intense vibration. Shock-absorbing foundations such as mounting systems are now used to support hammers and to reduce the transmission of the impact force to the soil.

The shock is transmitted through the mounting system and foundation to the soil and surroundings. Heavy shocks imparted to the foundation can cause alignment problems (i.e. reduce operating life), neighbour complaints and prohibit proper operation of adjacent equipment. Therefore, the main objectives of the design of a foundation supporting shock-producing equipment are to reduce the vibration amplitudes and the forces transmitted to the soil and/or to minimise any disturbance to the neighbourhood and surroundings.

Current practice is to install die forgers and hammers on layered elastomeric isolators or viscous spring isolators. The foundation system for forging hammers using elastomeric and spring isolators is shown in Figure 1.

The impact force created by each blow of the forging hammer is absorbed by the vertical motion of the machine through viscous damping. The layered elastomeric foundation systems, as shown in Figure 1(a), and the viscous spring isolator mounting systems, as shown in Figures 1(b) and (c) are designed to allow the motion of the machine to decay below a certain level before the next impact.

To ensure satisfactory performance of the machinery, the mounting system and/or the foundation should be designed such that the vibration amplitudes do not exceed the values given in Table 1 (Novak, 1983).

A number of dynamic models have been developed to analyse the response to pulse loading of one-mass and two-mass foundations with springs and dampers. Using these models, the influence of various parameters of the isolator mounting system was studied (e.g. Chehab and El Naggar, 2003, 2004;
El-Hifnawy and Novak, 1984; Heydari et al., 2008; Novak and El-Hifnawy, 1983; Wang and Dong, 2006). Novak and El-Hifnawy (1983) examined two methods based on energy consideration and a complex eigenvalue approach to incorporate damping in the analysis of the response of one-mass and two-mass hammer foundation systems. The effect of the anvil pad flexibility on the foundation response was examined. They studied the undamped and damped responses of two-mass foundation systems to pulse loading. Chehab and El Naggar (2003) investigated the efficiency of impact isolation for different anvil and machine configurations considering two-mass foundation systems. A parametric study was conducted to reveal the influences of stiffness and damping of a mounting system on the dynamic behaviour of hammer foundations. The effects of the pulse shape and pulse duration on the dynamic response of the one-mass hammer foundation system have also been investigated (Chehab and El Naggar, 2004). A new method for performing design optimisation of a viscous spring isolator mounting system for a forging hammer was introduced (Wang and Dong, 2006). Heydari et al. (2008) investigated the extent of efficiency of soil reinforcement on the dynamic responses of a machine foundation under vertical vibration for different vibration isolation systems.

Mounting systems may not always achieve satisfactory performance. The optimum use of mounting systems depends on the intended purpose, the mass arrangement and the dynamic characteristics of foundation. Thus, the dynamic soil properties can be altered to improve the performance of foundations supporting shock-producing equipment.

Founding a footing on a suitably reinforced soil medium can lead to considerable improvement of its bearing capacity and significant reduction of its settlement (Shin et al., 2002). Jones (1985) proposed a model for the confinement effect of reinforcement and used it for the analysis of a reinforced foundation bed. The confinement effect is quantified in terms of the average increase in confining pressure due to the reinforcement, which is used to evaluate the modified shear stiffness of the granular soil surrounding the reinforcement (Ghosh and Madhav, 1994). Furthermore, soil reinforcement improves the dynamic properties of the soil (Montanelli and Recalcati, 2003; Shuwang et al., 2004), increases the stiffness of piled foundations (El Naggar and Abdel-Meguid, 1997) and has been found to improve the response of footings to harmonic loading (El Naggar and Wei, 1997). Al-Dobaissi (1990) examined the resistance of reinforced soil to impact loading of different magnitudes in a laboratory testing programme. The test results revealed the superior performance of reinforced soil.

Reasonable determination of shear modulus of the supporting medium is necessary for the design of satisfactory and reliable foundations subjected to low strain vibrations (e.g. machinery, traffic, paper mills and compressor stations). The elastic modulus of soil (and its shear modulus) can be increased by reinforcement and the settlement of the reinforced soil can be noticeably decreased (Al-Dobaissi, 1990). Therefore, a reasonable estimate of the response of a reinforced soil foundation can be made by determining the increased value of homogenised shear modulus of the reinforced soil. It is important, however, to realise that the magnitude of shear modulus of reinforced soil is a function of several parameters.

The non-linear elastic model for fibre-reinforced soils under cyclic loading at small strain were introduced and the effects of geofibre, confining pressure and loading repetition on the elastic shear modulus of reinforced soil were studied and analysed (Li and Ding, 2002). Das and Maji (1994) and Das et al. (1998) conducted laboratory model tests to study the settlement of a square foundation supported by geogrid-reinforced sand and subjected to transient load. They found that the geogrid reinforcement reduced the settlement of the foundation. The ultimate settlements due to the transient loading for both reinforced and unreinforced soils were calculated and their ratio was defined as the settlement reduction factor, \( R \); and found to be a function of reinforcement depth. More recently, the effect of the location and the number of reinforcement layers on low strain stiffness and bearing capacity of shallow foundations was studied. The results of both laboratory and numerical tests indicate that the soil stiffness at low strain levels and bearing capacity can be greatly improved with reinforcement layer(s) placed underneath the foundation at the critical and most effective location(s). It was concluded that soil reinforcement can also be used to reduce low strain vibrations of foundations (Chung and Cascante, 2007).

Soil reinforcement is therefore considered a potentially advantageous technique to enhance the performance of hammer foundation systems under impact loads. In the present study, the effect of soil reinforcement on the foundation response was examined for different configurations of shock-absorbing foundation. The results were used to provide some guidance for the design of an appropriate reinforced foundation with shock-absorbing system for a given application.

2. REINFORCED SOIL FOUNDATION

The use of geosynthetics to improve the bearing capacity and settlement performance of shallow foundations has proved to be a cost-effective foundation system. A reinforced soil foundation (RSF) consists of one or more layers of a geosynthetic reinforcement and controlled fill placed below a conventional spread footing to create a composite material with improved performance characteristics. A composite reinforced soil foundation (CRSF) is an RSF that also includes a geosynthetic fabric separating native soil from the fill used to construct the RSF. Reinforced soil foundations may be used to construct shallow foundations on loose granular soils, soft fine-grained soils, or soft organic soils. Most RSFs are constructed with the reinforcement placed horizontally; however, there are cases in which vertical reinforcement may be used. The reinforcement may consist of geogrids, geofabrics, geocells or other geosynthetics.

Considerable advances have been made into the understanding of the behaviour of reinforced soil foundations and on the applications and limitations of using geosynthetics to improve the performance of shallow foundations. Detailed investigations have been performed using small- and large-scale model footings to evaluate the performance of RSFs and to develop rational methods for design.
The fill placed between layers of reinforcement is usually a clean coarse road-base material that is compacted to a minimum relative density of about 75%, but may also consist of compacted sand. A number of factors may influence the performance of an RSF, including: (a) type of reinforcement; (b) number of reinforcing layers in the zone of influence, \( N \); (c) depth below the footing to the first layer of reinforcement, \( u/B \); (d) spacing between reinforcing layers, \( h/B \); (e) width of reinforcement layers, \( b/B \); (f) total depth of reinforcement, \( d/B \); (g) type of imported loads; and (h) type and placement of the fill. Some of these parameters for geogrid-reinforced sand are shown in Figure 2.

Several model studies have been conducted on shallow foundations to determine the optimum values of \( u/B, d/B, h/B \) and \( b/B \) in order to obtain the maximum benefit of soil reinforcement (e.g. Guido et al., 1987; Omar et al., 1993). The model test results have shown that, for given values of \( u/B, h/B \) and \( b/B \), the magnitude of \( d/B \) for consideration of the stress influence as related to bearing capacity and settlement is about 1-5 for square foundations, and increases to about 2 for strip foundations. Similarly, for given values of \( u/B, h/B \) and \( d/B \), the magnitudes of the ultimate bearing capacity and settlement of foundation improve with \( b/B \) to an approximate maximum that was reported to be 4 to 4.5 and remains constant thereafter. Uchimura et al. (2006) evaluated the stiffness and residual deformation of a geosynthetic-reinforced soil structure subjected to sustained concentrated vertical loading and a long-term vertical cyclic loading history. They found that the effects of reinforcement stiffness were utterly insignificant on the behaviour during unloading and reloading for the range of the examined limit of reinforcement stiffness.

3. DYNAMICS OF HAMMER FOUNDATION SYSTEM

The dynamic performance of isolated foundations can be modelled mathematically using either analytical or numerical approaches. The key factors that determine the response of isolated foundation systems are: the dynamic characteristics of isolator; duration, magnitude and shape of pulse loading; size and mass of foundation; and the soil conditions. These factors are reflected in the system stiffness and damping values.

3.1. Mathematical model

Several components of shock-absorbing foundation such as hammer, anvil, machine frame, viscous spring isolator, foundation block and the underneath soil should be considered in the model. With centric blows and a symmetrical arrangement, the mathematical model of hammer systems similar to those shown in Figure 1 has two degrees of freedom as shown in Figure 3. The governing equations of the system are

\[
\begin{bmatrix}
 m_1 & 0 \\
 0 & m_2
\end{bmatrix}
\begin{bmatrix}
 x_1 \\
 x_2
\end{bmatrix}
+ \begin{bmatrix}
 c_1 & -c_1 \\
 -c_1 & c_1 + c_2
\end{bmatrix}
\begin{bmatrix}
 f_1 \\
 f_2
\end{bmatrix}
+ \begin{bmatrix}
 k_1 & -k_1 \\
 -k_1 & k_1 + k_2
\end{bmatrix}
\begin{bmatrix}
 r_1 \\
 r_2
\end{bmatrix}
= \begin{bmatrix}
 f(t) \\
 0
\end{bmatrix}
\]

where \( m_1 \) is the mass of the machine (Figure 1(a) and (c)) or the mass of the machine plus foundation block (Figure 1(b)). The mass \( m_2 \) is the mass of the foundation block and all the parts attached to it (e.g. Figure 1(a)) or the mass of the trough (Figure 1(b) and (c)). The stiffness and damping constants \( k_1 \) and \( c_1 \) represent the stiffness and damping of the spring and dashpot of the shock-absorbing system; similarly, \( k_2 \) and \( c_2 \) are the stiffness and damping coefficients representing the foundation. The anvil (or machine) and foundation block (or trough) responses are \( x_1(t) \) and \( x_2(t) \). Finally, \( f(t) \) is the impact force acting on the anvil.

3.2. Stiffness and damping constants of the system

The prediction of the response of the hammer foundation requires the description of the stiffness and damping of the foundation and the isolators.
3.2.1. Isolator stiffness and damping. When the foundation block or the anvil rests on a pad of viscoelastic material, the dynamic characteristics of the pad can be computed and expressed as

\[ K_1 = \frac{E_p A_p}{d}, \quad C_1 = \frac{\tan \delta_p k_1}{\omega_0} \]

where \( E_p \) is the Young’s modulus of the pad material; \( A_p \) and \( d \) are the cross-sectional area and the thickness of the pad, respectively; \( \tan \delta_p \) is the pad material damping ratio; and \( \omega_0 \) is the anvil natural frequency expressed in radians per second.

Mounting systems offer the greatest degree of vibration and shock isolation because they are relatively soft when compared with elastomeric isolation systems. The stiffness and damping constants of viscous spring isolators are supplied by their manufacturers.

3.2.2. Foundation stiffness and damping. In a reinforced foundation bed under dynamic loading, it is imperative that the effect of the presence of geosynthetics is properly included. Kavazanjian and Matasovic (1995) showed that ignoring the effect of geosynthetics leads to overestimating the accelerations. The slip deformations that may occur along geosynthetic interfaces experiencing dynamic loading can limit the acceleration transmitted through the interface to the soil (Yegian and Harb, 1995). Yegian et al. (1998) modelled the geosynthetic interfaces using an equivalent soil layer and represented its stiffness and damping using an equivalent spring and dashpot system to simulate the behaviour of the geosynthetic–soil interface. The dynamic parameters of the equivalent layer (i.e. equivalent mass, stiffness and damping) would depend on the soil layer thickness, soil modulus, and material damping ratio. Shuwang et al. (2004) employed this approach to analyse the soil–geogrid interaction under automobile loading.

The foundation block for a hammer can be situated on top and directly supported by the soil. However, it is usually embedded to increase the damping provided through the soil layers adjacent to the foundation sides. For embedded foundations in a deep homogeneous stratum (halfspace), the stiffness and damping coefficients can be calculated by (Novak, 1974; Novak and Beredugo, 1972)

\[ K_2 = G r_0 \left( C_n + \frac{G_s}{G_r} s_n \right) \]

\[ C_2 = r_0^2 \sqrt{\rho G} \left( C_{v1} + s_{v2} \frac{\rho G_s}{\rho G} \right) \]

where \( G \) is the soil shear modulus, \( r_0 \) is the base radius for circular bases or the equivalent radius \( (r_0 = \sqrt{A / \pi} \) for non-circular bases), \( \rho \) is the soil density, \( L \) is the embedment depth, and \( G_s \) and \( \rho_s \) are the shear modulus and density of the side layers (backfill) respectively.

The dimensionless stiffness and damping parameters \( C_{v1} \) and \( C_{v2} \) depend on the dimensionless frequency, where \( \omega_0 \) is the system natural frequency and \( V_s \) is the soil shear wave velocity. \( S_{v1} \) and \( S_{v2} \) are the dimensionless stiffness and damping parameters for the side layer. The values of \( C_{v1} \), \( C_{v2} \), \( S_{v1} \) and \( S_{v2} \) for most foundation types are given in Table 2 (Das, 1992).

The first set of parameters in Table 2 is used in the analysis reported herein. The effect of reinforcement is included in the analysis by substituting into Equation 3 the homogenised shear modulus, \( G_1 \), and homogenised density, \( \rho_1 \), of the reinforced soil. The geogrid could have a density between 1200 and 1700 kg/m³, which is close to the common values of soil density. Therefore, the equivalent density of reinforced backfill may change only slightly, such that it can be assumed to remain constant.

3.2.3. Determination of homogenised shear modulus. Soil reinforcement may increase the magnitude of homogenised shear modulus of reinforced soil. Studies on the mechanical behaviour of reinforced soil are relatively recent. Li and Ding (2002) conducted cyclic shear tests using a conventional triaxial apparatus to investigate the non-linear behaviour of geofibre-reinforced soil at small strain. They reported that the elastic shear modulus of geofibre-reinforced soil increases with the increase of fibre content and confining pressure, and decreases with the increase of loading repetition. The magnitude of the shear modulus of soil, reinforced with geosynthetics, is a function of several parameters as discussed in Section 2. Based on previous studies, typical design parameters for the use of reinforcement layers are \( u/B = h/B = 0.15–0.03 \), \( h/B = 2.0–3.0 \), \( N = 2–3 \), and maximum recommended values are \( u/B = h/B = 0.5 \), \( h/B = 5 \) and \( N = 5 \) (Chung and Cascante, 2007). Chung and Cascante (2007) summarised the results of past laboratory studies using soil reinforcement on shallow foundations and performed a number of meticulous laboratory tests to investigate the effect of reinforcement on the low strain stiffness of shallow foundations. The slope of the linear part of the load–displacement curve for a reinforced foundation was used to determine the low-strain stiffness and normalised with the corresponding slope in the unreinforced case. A dimensionless factor, called stiffness improvement factor (SIF), was defined to evaluate the improvement in the low-strain stiffness of the system. The effects of the number of reinforcement layers (\( N \)) and reinforcement location were studied by conducting a set of load tests on shallow square foundations on dry sand. Their results identify a critical zone between 0.3 and 0.5B for

<table>
<thead>
<tr>
<th>Soil</th>
<th>Halfspace (deep stratum)</th>
<th>Side layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poisson's ratio, ( \mu_s )</td>
<td>( C_{v1} )</td>
<td>( C_{v2} )</td>
</tr>
<tr>
<td>0.0</td>
<td>3.9</td>
<td>3.5</td>
</tr>
<tr>
<td>0.25</td>
<td>5.2</td>
<td>5.0</td>
</tr>
<tr>
<td>0.5</td>
<td>7.5</td>
<td>6.8</td>
</tr>
</tbody>
</table>

Table 2. Practical stiffness and damping parameters for hammer foundation.
maximising the benefits of soil reinforcement. The use of multiple layers of reinforcement is effective only if the first reinforcement layer is placed at the critical depth and the spacing between reinforcement layers is smaller than \( h = 0.3B \). When the reinforcement is located at a depth of \( 1.0B \) below the foundation, the effect of reinforcement tends to disappear. It was revealed that the effect of location and number of reinforcement layers is interrelated. A summary of their laboratory results is presented in Table 3. These experimental results are valid for coarse or cohesionless material with a linear increase in strength as a function of depth.

Using the results obtained from Table 3, a non-linear regression is carried out to derive an expression that relates the SIF only to the number and location of reinforcement layers

\[
SIF = \left( \frac{N^{0.74}}{1.13} \left( \frac{u}{B} \right)^{0.84} + 0.31 \left( \frac{h}{B} \right)^{0.48} \right)
\]

In the above equation, the effects of width and tensile stiffness of the reinforcement layers are not considered. It should be noted that SIF increases with an increase in the tensile stiffness of the reinforcement (Chung and Cascante, 2007). Further study is needed to determine the optimum values of \( u/B, b/B, h/B \) and tensile stiffness of the reinforcement in order to derive the maximum benefit for improving the shear modulus of the reinforced soil below the foundation.

Cyclic plate load tests can also be carried out to evaluate the variation of the shear modulus of the reinforced soil. For the same maximum depth of reinforcement, the shear modulus increases with the number of layers in place. Cyclic plate load tests performed in the field can be used to determine the modulus of elasticity of soil \( (E_s) \) supporting the foundation. The soil shear modulus \( G_s \) can then be calculated from

\[
G_s = \frac{C_z(1 - \mu_s^2)}{2.26} \sqrt{A}
\]

The magnitude of \( C_z \) is proportional to the square root of the area of the test plate. The theoretical relationship for \( C_z \) is of the form (Prakash, 1981)

\[
C_z = 1.13 \frac{E_s}{1 - \mu_s^2} \frac{1}{\sqrt{A}}
\]

Combining Equations 5 and 7 yields

\[
G_s = \frac{C_z(1 - \mu_s^2)}{2.26} \sqrt{A}
\]

The field cyclic plate load tests are conducted by applying step loads to a test plate as a sequence of unloading and reloading. In this manner, the elastic rebound of the soil, \( S_e \), at any stress level \( \Delta \sigma \) can be determined as shown in Figure 4. The variation of \( \Delta \sigma \) with \( S_e \) can be used to calculate the effect of elastic uniform compression, \( C_z \), of the soil as (Figure 5)

\[
C_z = \frac{\Delta \sigma}{S_e}
\]
In most cases, the magnitude of $G_s$, as determined by Equation 8 will be for a strain level about $10^{-4}$ to $10^{-3}$ (Prakash, 1981). This strain level is representative of the elastic settlement of shallow foundations. The dynamic response of shallow foundations supported by granular material is not sensitive for Poisson’s ratio, $\mu_s$ (i.e. where $\mu_s$ is less than 0-4), thus its value can be reasonably assumed.

3.3. Impact load
During normal operations, the hammer usually impacts on the anvil for a few milliseconds resulting in a transient load, $f(t)$. As the exciting force due to a hammer operation is stochastic in nature, the load–time history can not be defined exactly. However, it is commonly modelled as a half-sine pulse, triangular pulse or rectangular pulse (used in the current study). The duration and maximum size of impact are specified (with an initial triangular pulse or rectangular pulse (used in the current study). However, it is commonly modelled as a half-sine pulse, triangular pulse or rectangular pulse (used in the current study). The duration and maximum size of impact are specified (with an initial

$$\sigma(t) = \begin{cases} 
\frac{m_1 v_1}{\tau} & 60i/n < t \leq 60i/n + \tau \\
0 & 60i/n + \tau < t \leq 60(i+1)/n 
\end{cases}$$

where $\tau$ is the collision time and $n$ is the number of impacts per minute.

3.4. Method of analysis
The governing equilibrium equations of a two-mass system can be solved using the direct approach, by means of modal analysis, or numerically using a computer program. The direct approach involves substituting a particular solution into the basic differential equations and solving the resulting equation exactly using Kramer’s rule. In the modal analysis, modal shapes and natural frequencies are also obtained as well as the amplitudes. The accuracy of model analysis deteriorates for highly damped systems (Novak and El-Hifnawy, 1983). On the other hand, computer-encoded numerical methods can easily be used to solve differential equations. The accuracy of the solution is highly noticeable for simple linear systems. In the current analysis, the equilibrium equations are solved using a central difference method with $dt = 1/500$ to obtain displacement and velocity time histories. The force transmitted through the mounting system can then be calculated as

$$f_{1(t)} = k_1(x_1 - x_2) + c_1(x_1 - x_2)$$

and the force transmitted through the soil is

$$f_{2(t)} = k_2 x_2 + c_2 x_2$$

4. PARAMETRIC STUDY
A comprehensive parametric study was conducted to investigate the effect of soil reinforcement on the foundation and anvil response and the force transmitted through the mounting system and foundation to the surroundings. The different mass ratios ($m_1/m_s$) are representatives of different configurations of isolated foundations. For small hammers where the anvil sits on an industrial pad and the frame is attached to the block, as shown in Figure 1(a), the mass ratio may vary from 0-11 to about 0-33. For larger presses, the entire press is supported by a mounting system that sits on a trough, as shown in Figure 1(b) and (c), and the mass ratio varies between 0-43 and 3. In the former case, using a pad is useful as long as pad stiffness, $K_1$, is less than about 0-04K. In the other cases, the mounting system can be useful as long as the stiffness $K_1$ is less than about 0-30K. The damping of the isolators is usually selected to be about 5 to 10% of the foundation damping – that is, $C_1/C_2 = 0.05 - 0.1$ (Chehab and El-Naggar, 2003).
In order to establish the design charts for reinforced foundation with shock-absorbing system, the results are presented in a dimensionless form. The stiffness and damping of the foundation (\(K_i\), \(C_i\)) are normalised by the stiffness and damping of the reinforced foundation (\(K_2\), \(C_2\)). The vibration amplitudes of the anvil and the foundation block in the two-mass foundation system (\(A_1\), \(A_2\)) are normalised by their vibration amplitudes in the two mass reinforced foundation systems (\(A_{1r}\), \(A_{2r}\)). Similarly, the maximum amplitudes of the forces transmitted through the mounting system and the base in the two-mass foundation system (\(F_1\), \(F_2\)) are normalised by the maximum amplitude of the forces transmitted through them in a two-mass reinforced foundation system (\(F_{1r}\), \(F_{2r}\)).

5. RESULTS AND DISCUSSION

Figures 6 and 7 present the results for cases representative of small hammers where the anvil sits on an industrial pad and the frame is attached to the block directly. Figure 6 presents the variation of the anvil and foundation amplitudes of a foundation on RSF with the stiffness ratio \(K_1/K_2\) and a mass ratio \(m_1/m_2 = 0\cdot11\), for different initial stiffness and damping ratio \(K_i/K_2\) and \(C_i/C_2\), respectively. Figure 6(a) shows that the anvil amplitude was slightly reduced, and Figure 6(b) shows that the foundation amplitude decreased significantly (up to 80\%) as the stiffness of the RSF increased relative to the native soil. On the other hand, the force transmitted to the foundation increased slightly, and the force transmitted to the RSF either increased significantly (up to 60\%) for higher \(C_1/C_2\) or decreased slightly (for low \(C_1/C_2\)) as the stiffness of the RSF increased, as can be noted from Figure 6(c) and (d), respectively. It is evident that the change in foundation responses and the forces transmitted through the system to the RSF as the stiffness ratio \(K_1/K_2\) increased was mainly dependent on the value of initial damping ratio \(C_1/C_2\). Figure 7 shows the variation of responses of a hammer foundation and forces transmitted to the supporting RSF with the stiffness ratio \(K_1/K_2\) for \(m_1/m_2 = 0\cdot33\). Similar observations can be made in this case. Comparing Figures 6 and 7, it can be seen that the beneficial effects of RSF increased and the adverse effects diminished as \(m_1/m_2\) increased. The responses of the foundation system, the forces transmitted to foundation and the forces transmitted to RSF (for lower \(C_1/C_2\)) were improved slightly as the mass ratio \(m_1/m_2\) increased. For higher \(C_1/C_2\), the adverse effect of increasing the force transmitted to the RSF reduced significantly (from 60 to 30\%) as the mass ratio \(m_1/m_2\) increased.

Figures 8 to 11 present the variation of the vibration amplitudes of the foundation system and the forces transmitted to RSF with the stiffness ratio \(K_1/K_2\) for larger presses, where the entire press is supported by a mounting system that sits on a trough. In this case, the mass ratio \(m_1/m_2\) typically varied between 0-43 and 3. Figure 8(a) shows that the anvil amplitude was slightly reduced, and Figure 8(b) shows that the foundation amplitude decreased significantly (up to 80\%) as the stiffness of the RSF increased relative to the native soil. On the other hand, the force transmitted to the foundation increased (up to 10\%), and the force transmitted to the RSF either increased (up to 15\% for higher \(K_1/K_2\)) or decreased slightly (for lower \(K_1/K_2\)) as the stiffness of the RSF increased, as can be noted from Figure 8(c) and (d), respectively. It is noted that the variation in the foundation responses and forces transmitted.

![Figure 6. Variation of hammer foundation response and forces with stiffness of reinforced soil foundation (for m1/m2 = 0·11): (a) anvil amplitude, A1; (b) foundation amplitude, A2; (c) force transmitted to foundation, F1; (d) force transmitted to RSF, F2.](image-url)
Figure 7. Variation of hammer foundation response and forces with stiffness of reinforced soil foundation (for $m_1/m_2 = 0.33$): 
(a) anvil amplitude, $A_1$; (b) foundation amplitude, $A_2$; (c) force transmitted to foundation, $F_1$; (d) force transmitted to RSF, $F_2$

Figure 8. Variation of hammer foundation response and forces with stiffness of reinforced soil foundation (for $m_1/m_2 = 0.43$): 
(a) anvil amplitude, $A_1$; (b) foundation amplitude, $A_2$; (c) force transmitted to foundation, $F_1$; (d) force transmitted to RSF, $F_2$
through the system to the RSF with the stiffness ratio $K_2r/K_2$ depended mainly on the value of initial stiffness ratio $K_1/K_1$.

Figure 9 shows the variation of responses of a hammer foundation and forces transmitted to the supporting RSF with the stiffness ratio $K_2r/K_2$ for $m_1/m_2 = 1$. Figure 9(a) and (b) demonstrate trends similar to those noted in Figure 8(a) and (b), in terms of the variation of anvil and foundation amplitudes, $A_1$ and $A_2$, respectively. Figure 9(c) and (d) show the variation of forces transmitted to the foundation, $F_1$, and to the RSF, $F_2$, respectively.
amplitudes with the stiffness ratio $K_{2r}/K_2$ while the amplitude responses improved slightly. Although the force transmitted to the foundation may increase, as can be noted from Figure 9(c), its adverse effect either increased (for higher $K_1/K_2$) or slightly decreased (for lower $K_1/K_2$) in comparison with Figure 8(c). Furthermore, comparing Figures 8(d) and 9(d), it is clear that the adverse effect of increasing the force transmitted to RSF decreased (about 10% for higher $K_1/K_2$).

Similar observations can be obtained from Figures 10 and 11 that show the variation of responses of the foundation system and forces transmitted to the RSF with the stiffness ratio $K_{2r}/K_2$ for $m_1/m_2 = 2$ and 3, respectively. Generally, the variations of the anvil and foundation amplitudes with the stiffness ratio $K_{2r}/K_2$ are likely to be the same as the mass ratio $m_1/m_2$ increases. Figures 10(c) and 11(c) show that for this range of the mass ratio (2 to 3) the force transmitted to the foundation remains almost unchanged. Figures 10(d) and 11(d) show similar trends for the variation of the force transmitted to the RSF whereas the force transmitted increased slightly as the mass ratio increased. However, by comparing Figures 10(d) and 11(d) with Figure 9(d), it is noted that increasing the mass ratio has a slight effect on the force transmitted to RSF.

6. DESIGN PROCEDURE

The design of foundations for vibrating equipment is usually governed by displacement considerations. The displacement of foundations subjected to impact load depends on the type and geometry of the foundations, the flexibility of the supporting ground and characteristics of pulse loading. The main objective of the design is to limit the response amplitudes of the foundation to the specified tolerance and minimise the maximum impact force transmissibility under design constraints, using the stiffness and damping coefficients of the isolator, mass of the foundation block and support area of soil as design variables.

The design of a machine foundation subjected to impact load involves a trial-and-error procedure. After establishing the soil profile and evaluating the soil properties required for the dynamic analysis (shear modulus, mass density, Poisson’s ratio and material damping ratio), based on experience, the type and trial dimensions of the foundation should be selected. The maximum displacement and force transmitted to the soil of the one-mass foundation system (without a mounting system and soil reinforcement) under specific pulse loading can be computed easily (Chehab and El Naggar, 2004) and then compared with the performance criteria. If the response is not satisfactory, the force transmitted to the foundation and the vibration of the foundation (and consequently the disturbance to the surrounding medium) could be reduced by choosing the optimum configuration of mounting system and soil reinforcement using the foregoing design charts.

For small hammers, considering Figures 6 and 7, the designer should select the minimum stiffness of the mounting system, with its damping as small as possible. The soil reinforcement can then be designed to achieve satisfactory performance. The stiffness and damping of reinforced soil can be calculated as discussed in Section 3.2.2. The different parameters defining the geogrid-reinforcement can be varied to achieve the desired stiffness ratio $K_{2r}/K_2$ required to realise a certain reduction in the response. For example, stiffness ratio $K_{2r}/K_2 = 3$ yields a reduction in the foundation amplitudes of up to 60%. On the
other hand, the force transmitted to the RSF remained unchanged as the lowest damping ratio was used. However, if the mounting system is chosen such that damping ratio \( C_1/C_2 = 0.1 \), the force transmissibility increases up to 30%. The adverse effect of increasing the force transmitted to the RSF can be reduced significantly as the mass ratio \( m_1/m_2 \) increases. Thus, selecting an appropriate configuration of the mounting system or modifying the foundation dimensions to reach a higher mass ratio can be used as an effective option to reduce the force transmitted to the supporting RSF.

For the foundation of larger presses on RSF, the designer has to select the minimum stiffness of the mounting system while its damping ratio can have any value between 0-05 and 0-1 as can be stipulated from Figures 8 to 11. Similar to the case of small hammers, choosing the soil reinforcing scheme can provide a higher stiffness ratio \( K_{ds}/K_d \) and using a proper configuration of the mounting system or modifying the foundation dimensions to achieve a desirable mass ratio. These two options together can be used effectively to satisfy the performance criteria.

7. SUMMARY AND CONCLUSIONS
The effect of soil reinforcement on the performance characteristics for different configurations of shock-absorbing foundations was investigated. Soil reinforcement can be used to increase the stiffness of the supporting medium. This increase can be designed to achieve a superior dynamic performance for shock-producing equipment when the mounting system alone cannot achieve a satisfactory design. A parametric study was conducted and a set of charts was established as practical guidance for the design of soil-reinforcement schemes. It was shown that for small hammers, the reinforced soil foundation can reduce the foundation response amplitude by up to 80%. For large hammers and presses, the reinforced soil foundation can be designed to reduce the foundation response by up to 60% of the case of no soil reinforcement.

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