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MACHINE FOUNDATIONS: A REVIEW OF FAILURES

Priya Jose¹, Ravi S. Jakka² and Ashok D. Pandey³

¹M.Tech Student, Department of Earthquake Engineering, Indian Institute of Technology, P.O. Box 247667, Roorkee, email: priyajosevithayathil@gmail.com

²Associate Professor, Department of Earthquake Engineering, Indian Institute of Technology, P.O. Box 247667, Roorkee, email: rsjakka@gmail.com

³Assistant Professor, Department of Earthquake Engineering, Indian Institute of Technology, P.O. Box 247667, Roorkee, email: adpanfeq@gmail.com

ABSTRACT

Foundation failures are relatively uncommon where these support static loads. However, the potential for failure is greatly increased where foundations support machinery or equipment which applies dynamic excitation. The term ‘failure’, when applied to machine foundations does not necessarily infer damage to the foundation block itself; nor unacceptable static deformation; it more often relates to unacceptable levels of vibration resulting from inadequate design or functioning of the machine in a manner not accounted for in design. Abnormally high machine foundation oscillations are a serious concern for any enterprise since they cause excessive wear and bearing, damage to machine components and supply pipes, loosening of fasteners, electrical and electronic malfunctions in the equipment, damage of foundation structures and undesirable soil deformations. The paper reviews case studies where foundations have failed due to intolerable vibrations and various aspects of analyzing; diagnostics and monitoring of these vibrations are described.

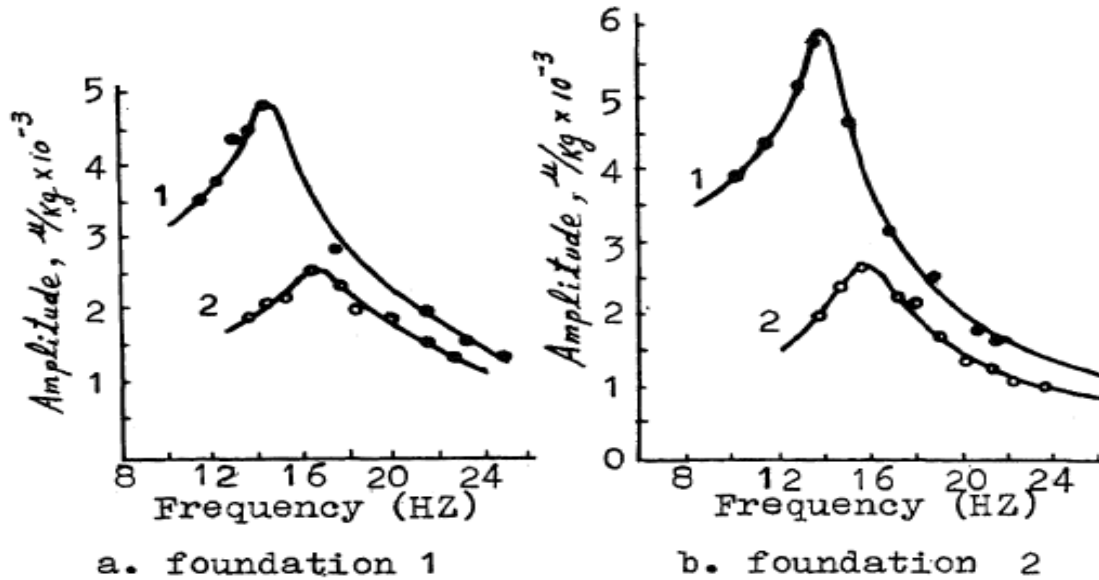
INTRODUCTION

Machine foundations are special type of foundations built for supporting machines, machine tools and heavy equipments which have wide range of speeds, loads and operating conditions. These foundations are subjected to dynamic loads in addition to static loads due to the weight of machine and foundation. Thus they require special attention of a foundation engineer. The basic philosophy behind design of machine foundations is that: a) the dynamic forces of machines are transmitted through the foundation to the soil in such a way that all kinds of damaging effects are removed and the amplitudes of vibration of the machine as well as that of foundation are well within the specified limits, b) foundation should be structurally safe to resist all static and dynamic forces generated by the machine. The amplitude of motion of a machine at its operating frequency is the most important parameter to be determined in designing machine foundation. High amplitudes can cause either serviceability and malfunctioning problems reducing people’s comfort, or safety problems with danger of failure. When excessive motions of an existing foundation obstruct the operation of the supported machinery, analysis is necessary to understand the causes of the problem and hence to guide appropriate remedial action. The paper reviews various vibration problems grouped under different types of machine foundations and the different schemes by which the foundations were revived.

CASE STUDIES ON BLOCK FOUNDATIONS

Compressor Foundation Subjected to High Horizontal Vibrations (Wang, 1984)

Foundations under 3 compressors rested on clay base. The horizontal vibration velocity reached 8.96 mm/s exceeding the permissible limit, affecting normal production and work in neighboring offices. The author was asked to rectify the problem without interrupting production. Firstly, two foundations (N-1 and N-2) were tested under horizontal forced vibration. Test results are shown in Figure 1. From the figure, the natural frequency was found to be 14.2 Hz for N-1 and 14 Hz for N-2.



**Figure 1. Response of amplitude under horizontal exciting force: (1) Before treatment
(2) After treatment (Wang, 1984)**

The secondary exciting frequency being 13 Hz, the ratio of operating frequency of machine to natural frequency of the system was 0.92 – 0.93, clearly indicating resonant vibrations. Various treatment schemes were available. Since the foundations were lying close to one another, it would be helpful to connect the foundations so as to increase the rigidity as a whole. Thus combined foundation was employed; base plates of foundations were combined using a reinforced concrete ground beam as shown in Figure 2. to increase elastic resistance, damping ratio and resonance frequency of base.

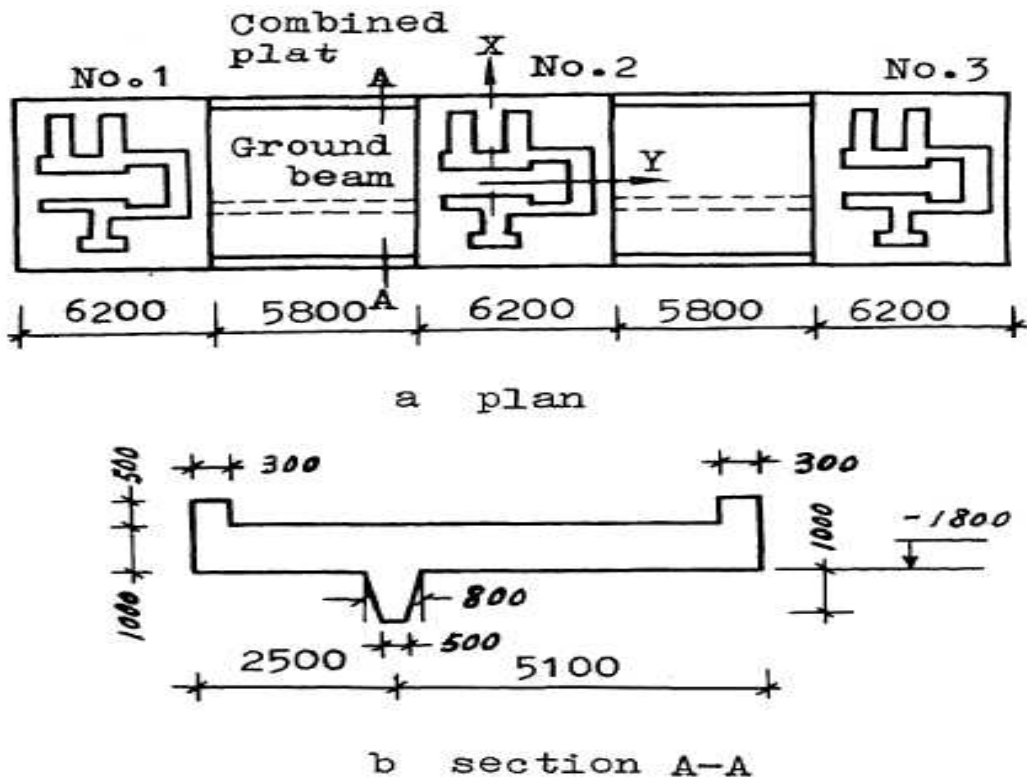


Figure 2. Diagrams of combined foundations (Wang, 1984)

A forced horizontal vibration test was repeated after hardening of ground beams, results of which are given in Figure 1. It can be seen that the amplitude of vibrations has significantly decreased and the frequency of N-1 increased from 14.2 to 17 Hz while that of N-2 from 14 to 16 Hz. This can be attributed to increase in stiffness of base with an increase in mass participating in vibration.

Analysis of Compressor Station before Completion of Work (Kvasnicka et al., 1988)

A compressor station consisted of eight compressors. Measurements were taken before the whole station was completed and only 3 compressors were in operation. Analyses were performed considering three soil profiles:-

- Soil profile modeled as clay stratum ($G= 50 \text{ MN/m}^2$) over sand half space ($G=100 \text{ MN/m}^2$).
- Foundation on half space with $G= 100 \text{ MN/m}^2$ (thus neglecting the clay sub layer).
- Foundation stratum with average modulus $G=80 \text{ MN/m}^2$ over half space with sand properties ($G= 100 \text{ MN/m}^2$).

The calculated amplitudes of vibrations for the above soil profiles are given in Table 1.

Table 1. Calculated amplitudes of vibrations at corners of foundation (Kvasnicka et al., 1988)

Case	Longitudinal (μm)	Vertical (μm)	Radial(μm)
a)	1,1	4,2	23,2
b)	0,6	2,3	5,9
c)	0,8	2,7	11,3

From the table, the amplitudes were found to be high when clay was direct foundation supporting soil. Therefore it was decided to replace clay above ground water level with one meter thick densified gravel layer. After treatment, measurements were taken in the middle (M) and at corners (C) of the foundation for three compressor foundations as shown in Table 2. Substituting clay by gravel layer has significantly lowered the amplitudes. This accounts to the increased stiffness of soil supporting the foundation.

Table 2. Measured values of amplitudes (Kvasnicka et al., 1988)

		Longitudinal (μm)	Vertical (μm)	Radial (μm)
C1	(M)	0,4	0,8	1,8
	(C)	0,4	1,25	1,33
C2	(M)	0,9	1,2	2,19
	(C)	0,9	1,2	2,5
C3	(M)	1,2	1,7	2,5

Compressor Foundation Producing Excessive Vibrations (Arya et al., 1978)

During the operation of a four stage BPCL air compressor in the oxygen plant of Central forge plant of M/s BHEL, Haridwar excessive vibrations occurred necessitating check in the design of foundations of the air compressor. Natural frequencies and amplitudes in different modes were computed using the linear elastic weightless spring method from the given design data. Amplitudes of vibration of the compressor foundation were also determined by measuring in horizontal and vertical direction at different locations. From the computed results, it was found that the natural frequency in yawing mode coincided with the operating frequency and the vertical frequency was only slightly different from the operating frequency. The higher natural frequency due to combined rocking and sliding approached the second harmonic. Both the observed and computed amplitudes were much higher than the permissible amplitude. The foundation was therefore considered inadequate. It was suggested to adopt appropriate remedial measures such as attachment of special slabs to reduce the vibration amplitudes.

CASE STUDIES ON HAMMER FOUNDATIONS

Intolerable Vibrations due to Hammer Foundation (Svinkin, 1993)

Five storey apartment building was situated at a distance of 500 m from the vibration isolated foundation under a forge hammer. Measured vibrations of the building were intolerable when the

natural frequency of the foundation was 3.1 Hz. For diminishing intolerable resonance building vibrations, it is necessary either to reinforce building structures or change the frequency of the vibration isolated foundation. Changing the frequency of block vibrations is much simpler and more economical than the first measure. This can be accomplished by decreasing vibroisolator stiffness by eliminating a part of them from work. Since springs are accounted from condition of strength, it is possible to diminish only dashpot amount. Thus the frequency of the foundation was decreased to a value of 2.9 Hz by eliminating a few dashpots. Buildings usually have narrow resonance range and a small change in the frequency of block vibrations gives good result.

High Oscillations of a Hammer Foundation in Turkey (Arsoy, 2008)

Unwanted vibrations were arising from a forging facility in Turkey, causing trouble to surrounding facilities within a radius of 300 meters. The solution lies in reducing vibrations at source or employing active or passive vibration barriers. A vibration barrier at other structures could not be requested. Effectiveness of vibration isolation employing open or filled trenches was questionable for the site. Therefore it was not considered. The best solution was to increase the stiffness of soil using piles as foundation support. However, the owner wanted cost effective rapid solution of unwanted vibrations. The short term solution opted was to use reverse vibration absorber approach by reducing the foundation amplitude by allowing the machine to have higher amplitudes; the machine acted as a vibration isolator block by protecting foundation from vibrations. This was carried out by reducing the springs between the foundation and the machine. The disadvantages were absorbed by taking additional measures on the lifeline connections of the machine.

CASE STUDIES ON FRAMED FOUNDATIONS

Sudden Rise in Vibrations of Foundation under Cone Crusher (Svinkin, 1993)

Two cone crushers were mounted on two separate identical framed foundations. The vibrations of these crusher foundations were in tolerable limits for long time. However, the vibration of one foundation surged all of a sudden and the amplitude reached 1 mm. Such vibration level was inadmissible and could be attributed to changes in any part of machine-foundation-soil system. Steps were undertaken to diagnose the vibration problem. Impulse loads cannot be suddenly increased and the unbalanced forces can only increase gradually. Crusher as a source of vibrations was ruled out for these reasons. The crusher foundation didn't have any visible damage and cracks and therefore it was not responsible for high vibrations. The soil below crusher foundation was limestone with sandy and clayey interlayer's. Crushing being wet process production, water penetrated and reversed the soil properties. Changes in soil moisture resulted in low stiffness of soil, causing a change in the frequency of the system and correspondingly the amplitudes of motion. The viable solution was to reduce the moisture content by pumping out water.

Excessive Horizontal Vibrations of Foundation under Centrifugal Pumps

On initial installation of 3600 RPM horizontal centrifugal pumps in petroleum refinery, the pumps were found to exhibit high levels of horizontal vibrations. Suspecting a resonance condition, 'bump test' was performed in the horizontal direction on the pump bearing. The horizontal natural frequency of the pump bearing was found to be of same order from the test.

Thus resonance was confirmed as the cause for excessive vibrations. The best solution to solve a resonance problem is to separate the natural frequency from the exciting force frequency. This can be done by changing the natural frequency by increasing or decreasing mass or stiffness, or by increasing or decreasing exciting force frequency. However, these changes are not possible or cost-effective. Another possible solution is to install a dynamic absorber (auxiliary mass vibration neutralizer). The dynamic absorber is usually a spring-mass system installed in series with the resonant system to create an out of phase exciting force to effectively curb the initial excitation force. In this case, plant engineering opted for dynamic absorber approach to solve the problem.

CASE STUDY ON MAT FOUNDATION

Offset Printing Press Subjected to High Levels of Vibration (Vlad, 2010)

An offset printing press was installed in a steel industrial building in Romania. Some undesirable transverse vibrations began to occur when the speed of operation was increased. After a detailed instrumental investigation and evaluation, the source of occurred vibrations was found to be the printing press itself. During operation, ink is distributed to the printing plates by rollers which rotate about an axis transverse to the longitudinal direction of the press. This transverse excitation produced by ink distributing rollers was very close to the Eigen frequency of the first swaying mode of the ensemble. Thus the performance of ink rollers paved way for excessive vibrations. The solution proposed was to change the inking roller gears so that they wouldn't reach a frequency ratio greater than 0.6. This case study showed how at higher speeds, an unbalanced force can cause undesirable vibrations.

CONCLUSIONS

The effects of excessive vibrations range from annoyance for local population and disturbance of working conditions for sensitive devices, to diminution of structure serviceability and durability. Therefore there is an increasing need to analyze, monitor, diagnose and retrieve machine foundations from intolerable vibrations. Various schemes are available for remedying vibration problems.

- Firstly, the machine is checked for unbalance. **Balancing** is done by minimizing eccentricities in rotary parts or by applying a counter-force/moment.
- **Structural measures** like increasing base area or mass of the foundation, attaching a slab to the foundation, and using auxiliary spring-mass system are resorted to achieve largest possible difference between natural frequency and operational frequency of machine, i.e. during resonance.
- **Stabilization of soils** results in an increase in the rigidity of base and consequently reduces vibrations.
- Effective isolation can be achieved by **proper location** of vibration causing machinery. For example, foundations on sound, deep-seated bedrock will experience smaller vibration amplitudes than foundations on weathered materials or soils subjected to same excitation.
- Transmission of waves generated by machine foundations can be minimized by placing a suitable **wave barrier** in the ground before the structure. Open trenches, in-filled concrete or bentonite trenches, sheet pile walls, concrete core walls or row of piles can be effective wave barriers.

The solution therefore lies in identifying the cause for vibrations and taking remedial action in the concerned direction.

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