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BASE ISOLATION FOR FOUNDATION

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ABSTRACT

The paper presents the basic principles of Base Isolation (Earthquake/Vibration) in brief. Transmissibility could be reduced either by shifting the phase between the moving element and the foundation block or by increasing the absorption of energy in the propagating medium. Salient points in Mechanical and Geodynamic Isolation have been reviewed. Utilisation of liquefaction potentiality of sand to decrease the transmissibility of earthquake tremor to the superstructure has been included. Practical and economically feasible methods of base isolation have been illustrated.

INTRODUCTION

One of the most important tasks of a Civil Engineer is to reduce as far as possible the effect of vibrations on structures. Satisfactory performance of structures are expressed in terms of the limiting amplitude of vibration at a particular frequency or a limiting value of peak velocity or peak acceleration. Depending upon the importance of the structure and its expected performance, this limit of acceptable vibration varies. Many times, not only the safety of structure but, physiological or psychological effect dictates the term. Thus in base isolation the attempt is made to reduce the effect of vibration by adopting suitable remedial measures either on the structure or in the supporting soil.

Isolation of vibration or shock may be based upon the temporary storage of energy in the isolator and its subsequent release with different time relation. The principle of isolation is not primarily dependent on absorption or dissipation of energy, though sometimes, dissipation of energy enhances isolation as a secondary beneficiary effect. In principle there are two aspects of isolation : (1) isolation of force and (2) isolation of motion.

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Sources and the task may be identified as :

Source	Task
1. Propagated noise from Operating Machine in Industrial Complex	Take action on the source to reduce the effect on neighbouring structure
2. Incoming noise from neighborhood	Take action on the object to reduce the level of its vibration

The principal objective in the first mentioned aspect is the reduction in the magnitude of the force transmitted to the support of the object (e.g. machinery). In the second aspect, the principal objective is a reduction in vibration amplitude so that the mounted object (e.g. building or equipments) will be subjected to vibration of less severity than the supporting structure. Although the ultimate objectives and the test for effectiveness of isolations are different in these two cases, the same engineering principle applies to both. This principle, in general terms, is to mount the object upon resilient supports or isolators in such a manner that the natural frequency of the object-isolator system is substantially lower than the frequency of the vibration to be isolated.

MECHANICAL ISOLATOR

In mechanical isolator remedial measures are taken on the structural element. These are basically used for machine foundations. The most simple method adopted for the analysis of a mechanical isolator is a single degree of freedom idealization of the machine isolator system (Fig. Ia and Ib). Strictly speaking, this analysis is applicable where the resiliently supported body is free to move only in one direction. Depending upon the mounting arrangement, a resiliently supported rigid body may have from one to six natural modes of vibration. The motion in each mode may or may not be independent of the motions of other modes (Fig. Ic) and in each mode the system will have a natural frequency. If the centre of the supports are located unsymmetrically with respect to the center of gravity of the body, certain translatory and rotational modes may be coupled. When the modes are coupled a vibration in one mode will induce motion in the other coupled mode also. This induction of motion in the other mode depends upon the location and stiffness of the isolator and on the mass distribution of the supported machinery.

A substantial simplification could be brought in the analysis when the mounted body and the isolators have parallel axes of intertia. The degree of simplification depends on the degree of symmetry involved. If this symmetry exists with respect to the principal plane of intertia, the natural frequencies could be determined by solving a cubic equation. The complete analysis of a general six degree of freedom system needs the solution of a sixth order determinant which is too complicated for a routine checking in any industrial complex without any access to a computer. By decoupling certain mode of vibration, either with a proper arrangement of the isolators or with some suitable assumptions, an engineering judgement about the performance of the system can be arrived at using an undamped single degree of freedom idealization of the system with the knowledge of : (1) Mass of the mounted bodies, (2) Stiffness of the isolator, (3) Magnitude and frequency of the excitation. Decoupling of modes not only reduces the mathematical complexities but also allows the designer to excercise control over each motion separately, without affecting other motions.

The purpose of providing a vibration isolator for a system, as mentioned before, is to reduce the transmission of a force, F, applied by the body to its support through the isolator of stiffness, Ky. The effectiveness of isolation is defined by Force Transmissibility, T_F, obtained as the ratio of the force transmitted by the isolator to the force applied on the mass and the essential requirement is that T_F should be less than one.

In a single degree of freedom system [3]
Transmissibility, $T_F = 1/[1 - (w^2/W1^2)]$
and the displacement $y = [(F_0/Ky)\ \text{Sin}\ wt]\,[1 - (w^2/W1^2)]$

The transmissibility, T_F, depends upon the ratio of operating frequency w of the forcing function, F, and the natural frequency W1 of the isolator with stiffness Ky.

When $(w/W1) > 1$, the ratio $y/F_0 < 1$, which indicates that the force experienced by the support is out of phase with the applied force on the body and the maximum downward force on the support occurs simultaneously with the maximum upward force on the mass as the reaction from isolator. Thus in principle adjustment of the stiffness of the isolator helps decrease the transmissibility and increase the isolation. The isolation of a single degree of freedom system increases as the natural frequency of the isolator decreases. For a multi degree of freedom system the same trend is usually obtained. To estimate the possibility of resonant condition, it is desirable to determine the natural frequencies of the system which indicates the probable effectiveness of the isolators. If possible, designers try to maintain all natural frequencies substantially below the frequency of the principal vibration to be isolated. Symmetry in the system helps decoupling the mode of vibration. Decoupling of modes in a Non symmertical body may be achieved by suitable positioning and proper selection of the softness of individual isolators.

The task of a designer gets often complicated by the fact that the physical characteristic of a machine or of a structure have been predetermined and any change in the configuration is not permissible. The weight distributions and shapes of many machines may be such that effective vibration isolation may not be possible. The designer of the machines hardly put any foresight regarding the need for a vibration isolation which may subsequently appear after its mounting and to many, the philosophy of vibration isolation detailing, is of little importance. At the planning stage a detailed consideration regarding (i) geological condition (ii) location of water table, (iii) drainage and (iv) seasonal variation of the site could avoid many complicacies.

The design of isolator systems for an existing and operating equipment is to choose a system such that its natural frequency is much lower than the frequency of vibration that is to be isolated. For calculating the natural frequencies the following informations are essential :

(1) Weight distribution of the mounted body.

(2) Stiffness of each isolator in different mode.

(3) The radii of gyration with respect to various principal intertia axes.

(4) Horizontal distance of principal inertia axes from the respective isolators.

(5) Vertical distances of the isolators from the centre of gravity of the mountings.

The weight distribution, shape and the radii of gyration are predetermined parameters established by the equipment designer much before the need of isolation is felt. From the workability constraints of the shop floor, not much scope is left with the adjustment of vertical and horizontal distances as mentioned in (4) and (5) above. The one characteristic that usually is left to be determined, and freedom in this respect is sometimes restricted by other considerations, is the stiffness of isolators in several modes. When the ratio of horizontal to vertical stiffness of the isolator is low, for any height to width ratio of the mounted body, both of the coupled natural frequencies tend to become a minimum. Thus a low horizontal stiffness of the isolator, though sometimes may be a liability, mounted below the mounting body may offer the desirable low natural frequency of the system. Sometimes advantages may be derived by placing the principal axes of the isolators in an inclined direction (Fig. 1d) with respect to that of the machine. Proper orientation of the isolators helps decoupling the modes. Then vibration in one mode does not excite the vibration in other modes. This decoupling of modes greatly simplifies the isolation problem. The necessary conditions for decoupling are : (1) The resultant of the forces applied to the mounted body by the isolators when the mounted body is displaced in translation must be a force directed through the center of gravity. (2) The resultant of the couples applied to the mounted body by the isolators when the mounted body is displaced through a rotation must be a couple about an axis through the center of gravity. The most practical method of solution, where the designer works for the selection of optimum isolator characteristics and location, is to assume the required physical parameters and to compute the natural frequencies by a trial and error method.

A machine that produces a shock type of impact causing the structure to vibrate in a transient manner and in many natural modes simultaneously makes the problem of isolation exceedingly complex. The single degree of freedom idealization may be considered reasonable since the cushioning effect offered by the isolators reduces the suddenness of the force and the motion and thus reduces the contribution from the higher modes of vibration. If the ratio of the natural frequencies of the element and that of the isolators is more than 2, the provision of the shock isolator will reduce maximum acceleration experienced by the element and this reduction is not much influenced by the degree of damping property of the isolators. On the otherhand, if the said ratio is less than 2, the maximum acceleration experienced by the element will be increased and this detrimental magnification is highly influenced by the damping. Designers are perplexed by the fact that most of the equipments consist of numerous elements having a wide range of stiffness and the selection of some stiffness for the isolators may bring benefits for some stiff elements but at the same time this may push the softer elements in danger. In a shock isolator the damping property helps save the softer elements. The damping property of the isolator helps reduce the excessive vibration of high speed machinery when it crosses the resonant frequency of the system. Thus an engineering judgement is very essential to determine the overall effectiveness of the isolators. Most commonly used materials for the design of isolators [11] are Metal Springs, Rubber, Felt, Cork, Sponge Rubber, Rubber pad bonded between two metal plates, Double shear sandwitch rubber pad, bonded rubber bushing (Fig. 1c-1g, Fig. 2), Air below mounting [6].

Highly filled natural rubber offers excellent bilinear visco elastic behaviour against dynamic loading. The bearings are made by vulcanisation bonding of sheets of rubber to thin steel reinforcing plates. These bearings are very stiff in the vertical direction and very flexible in the horizontal direction. As the shear strain increases the shear stiffness of rubber decreases and at 50% shear strain the shear modulous drops down to 20% of the initial shear modulous. But at a very high strain, greater than 100%, shear stiffness once again begin to increase. Damping also decreases to 0.1, from its initial value of 0.2 at small strain level, and at very high shear strain level damping starts increasing. Thjs very desirable self adjusting property has made the rubber a popular isolating material. Advancement in rubber technology has made this material durable, long standing, resistant to various environmental hazards and safe against fire.

The problem of mechanical isolation discussed in the preceding section deals basically with two cases; (1) The isolation of the support from a force that is created within a machine, (2) The isolation of an equipment from the vibration of the support. A situation may arise where, because of some constraints, mechanical isolation is not feasible or it may not bring a sufficient degree of reduction in the noise level. In such difficult situation geodynamic isolation where preventive measure is taken in the foundation soil may provide adequate protection.

GEODYNAMIC ISOLATION

In geodynamic isolation most commonly followed methods are : (i) Open trenches, (ii) Backfilled trenches, (iii) Sheetpiling as barriers and, (iv) Provision of some compacted zones. It is usually recommended to place the barrier around the source of vibration which is termed as active isolation. Barriers near the receiver, known as passive isolation, is adopted for moving or distant and unapproachable vibration source.

Trenches and sheet pile walls [7,8] have been used for many years in attempts to isolate foundations of machine and structures from vibratory energy but have not always been successful. Engineers in their exasparation declared, "Experience with various barriers has shown that they are often of no use at all or their effect is very small" (Barkan, 1962). This frustration comes from the lack of understanding of the theory of surface wave propagation in nonlinear earth medium in the presence of barriers on the surface. The physics of elastic wave propagation in a half space is of prime importance to read the behavior of barriers in the isolation of foundations. In the analysis of seismic wave propagation it is assumed that the propagating medium, the earth, can be idealised as a homogeneous, isotropic and linearly elastic half space. Lamb (1904), Kolsky (1953), Ewing, Jardetzky and Press (1957), Grant and West (1965) and others have developed the theory of wave propagation in an Elastic Half space.

Elastic waves originate from earthquake, explosion, pile driving operation, vibrating machine foundation, etc. The source may be within the half space (e.g. earthquake tremor) or on the surface (e.g. machine foundation). Since most footings or buildings and machineries are located on or near the surface of the earth, waves generated by the surface sources are of importance in the foundation isolation studies. The physics of the wave propagation informs that the Rayleigh wave which travels along the surface is responsible for carrying the major part of the noise from the source [2]. The other parts of the energy transmission takes place through Compressional wave and Shear wave. The distribution of energy among these waves, as has been computed by Miller and Pursey (1955) for the case of elastic half space for a Poisson's ratio of 0.25, excited by a vertically oscillating circular disk on the surface of the half space, have been shown in the Fig. 3a. The Body wave propagate along a hemispherical wave front but the Rayleigh wave propagate along a cylindrical wave front with geometric damping decay rate of $1/r$ and $1/r^{0.5}$ respectively. The Rayleigh wave with retrogradory elliptic orbital motion of particle on the surface decays with depth. The fact that the Rayleigh wave decays much more slowly on the surface and carries approximately 66% of the input energy it is of primary concern for foundation isolation problems.

The presence of a barrier (Fig. 3b) creates diffraction of the wave propagation and a screened zone (Fig. 3c & 3d) or a shadow zone is formed behind the screen where the amplitude of vibration reduces drastically. Outside this shadow zone the propagation of the wave continues. The depth of the screened zone decreases as the distance from the screen increases. The volume occupied by the screened zone depends upon the wavelength, length and depth of the screen. Apparently width of the screen does not have much effect. The effectiveness of the presence of the screen is measured by the Amplitude Reduction Ratio (ARR) which is defined as the ratio of the amplitude at a point, when the screen is present, to the amplitude at that point when no screen was present. For a plane undamped wave ARR continuously increases, as the distance from the barrier increases, from a minimum just behind the screen to unity at a distance greater than or equal to the depth of the barrier. At any particular point within the shadow zone, the ARR decreases as the length of the barrier increases. For a sufficiently large length of the screen, the ARR at or around the central portion of the screened zone (Fig. 3e) may be equal to zero. Though the Rayleigh wave travels along the surface its depth of penetration is approximately of one wavelength. So to bring adequate reduction in the noise level the depth of the barrier should be a minimum of one wave length. A long barrier on the surface with inadequate depth may be totally ineffective. Along with diffraction a a barrier may produce magnification of wave amplitude in front of the barrier, that is between the source and the barrier.

SLEEVED PILE

In a difficult subsoil condition engineers usually opt for pile foundation for building. The embedded length of the pile increases the stiffness of the base and the quantum of seismic energy transferred to the building through the piles gets increased substantially. This undesirable effect could be reduced substantially by housing the pile inside a cylindrical sleeve, driven in the ground, which reduces the contact area of the load bearing pile with soil. The space between the sleeve and the pile allows a certain amount of lateral movement of pile and reduces the horizontal stiffness of the pile. The outside sleeve acts as a fail safe arrangement against severe tremor.

SLIDING BASE MECHANISM

The presence of a sliding layer at the foundation level helps isolate the building from seismic forces. A thin layer of specially screened sand is laid on the sliding surface and the building is constructed on this. These sliding joint mechanisms, which add flexibility in the horizontal direction, are well suited for low cost, low rise building which is otherwise very stiff and is prone to earthquake damage. Presence of soft clay layer at certain depth below the foundation may help to float the building and slide during strong seismic events.

BASE ISOLATION BY SOIL LIQUEFACTION

Soil loses its shear strength and behaves almost like a fluid, because of sudden rise in pore water pressure, during transient pass of high intensity earthquake tremors. This phenomenon of loss of soil shear strength is known as liquefaction. This property of soil could be utilized [2] as a shock protective measure provided the volume change in the soil could be prevented. In contrast with the previous methods, energy dissipation through hysteresis loss helps isolation in this method.

The superstructure directly rests on sand filled isolators each of which transmits the load on the foundation. Thus these sand filed isolators create a barrier for the transmission of shock waves from the foundation to the superstructure The sand is contained within an impermeable elastic wall and a pipe network connects all these chambers with a water reservoir kept at the same level. Because of the undrained condition in each isolator and impermeable side wall, the volume and the height of the isolators remain unchanged even after the liquefaction of sand inside the isolators. This ensures the safety in bearing capacity and stability of the structure. It is desirable that under weak earthquake loading the sand contained within the isolator boxes should not liquefy. But under strong shear loading it should immediately liquefy and bring down the eigenfrequencies of the superstructure by promptly reducing the stiffness at the base. This desirable property is achieved by the fact that the threshold position for liquefaction of a loose, cohesionless, saturated, undrained sandy soil is determined by initial density, loading amplitude, and number of shear loading cycles applied on it.

CONCLUSIONS

In this paper different aspects of Mechanical and Geodynamic Isolation of Foundation have been briefly reviewed. Reduction of transmissibility from machine created noise could be achieved by mounting the source on different combinations of isolators. A single degree mass spring system may be the initial guide for a trial choice but, because of the limited freedom of selection left with the designer, a multi degree mass spring dashpot combination with possible decoupling of modes helps the analysis. In Geodynamic isolation remedial measure in the form of barrier may be taken near the source (Active Isolation) or near the receiver (Passive Isolation). Diffraction of wave creates a shadow zone behind the barrier and the object to be isolated should be within this shadow zone. Length and Depth of the barrier should be selected properly otherwise appreciable reduction may not be achieved. The potentiality of saturated cohesionless soil to liquefy under earthquake shear loading may also be used for isolation of building bases provided the supporting sand is kept in a confined elastic container prevented from any volume change. Because of several constraints present in real life problems designers may try a combination of different methods.

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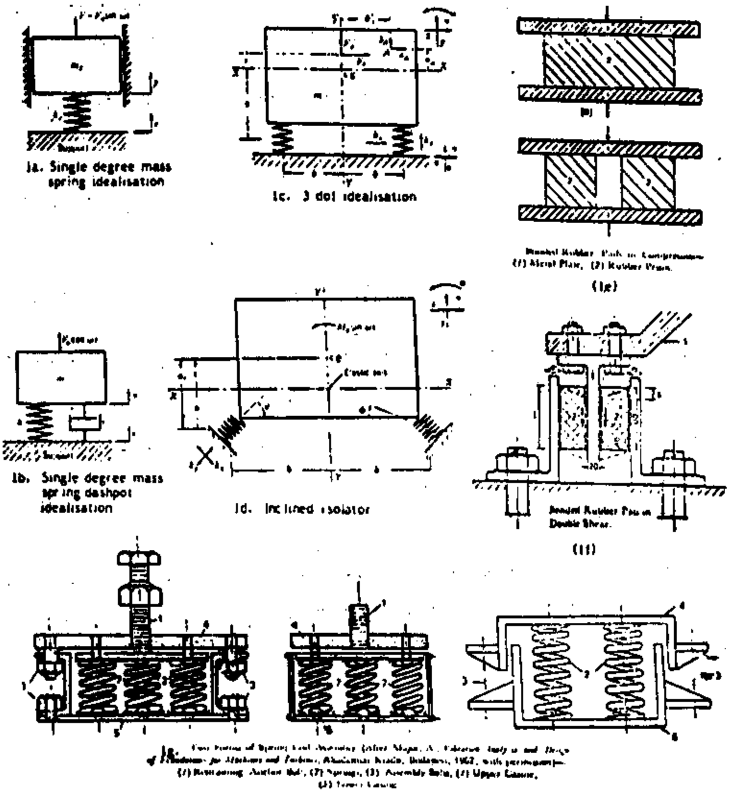


1a. Single degree mass spring idealisation

1b. Single degree mass spring dashpot idealisation

1c. 3 dof idealisation

1d. Inclined isolator

Bonded Rubber Pads in Compression
(1) Metal Plate, (2) Rubber Prism.

(1e)

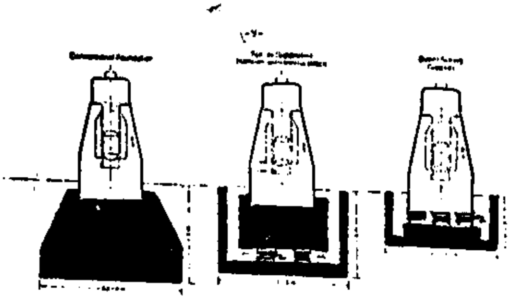
Bonded Rubber Pads in Double Shear.

(1f)

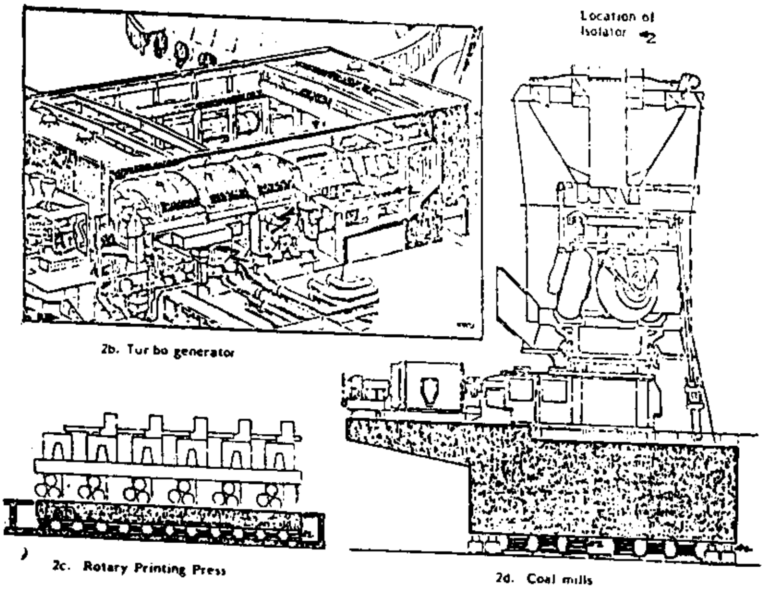
1g. Two Forms of Spring Load Assembly (After Major, A., Vibration Analysis and Design of Foundations for Machines and Turbines, Akademiai Kiado, Budapest, 1962, with permission.
(1) Restraining Anchor Bolt, (2) Springs, (3) Assembly Bolts, (4) Upper Casing,
(5) Lower Casing

Fig. 1. Mathematical models and different forms of isolation system.

Fig. 1. Mathematical models and different forms of isolation system.



2a. Hammer foundation

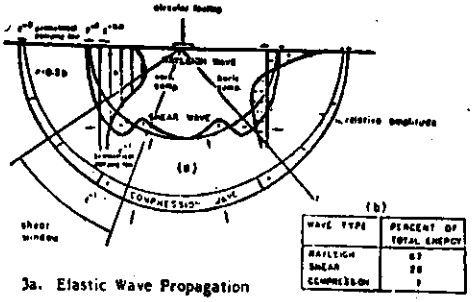


2b. Tur bo generator

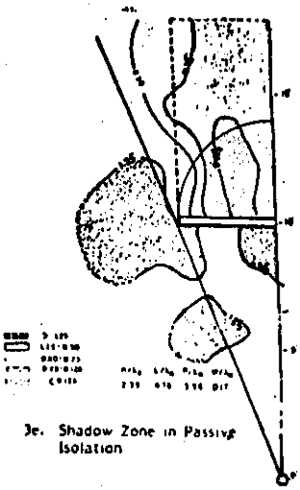
2c. Rotary Printing Press

2d. Coal mills

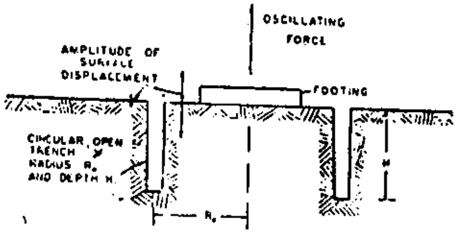
Fig. 2. Application of isolator in industry (courtesy GERB)



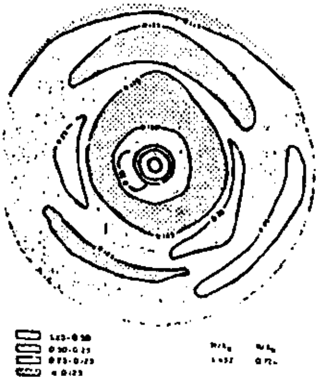
3a. Elastic Wave Propagation



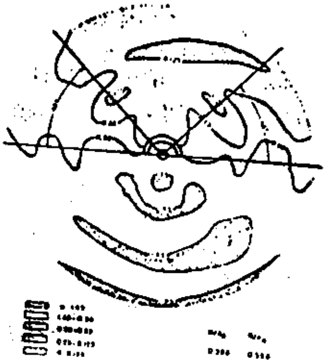
3e. Shadow Zone in Passive Isolation



3b. Active Isolation by Circular Trench



3c. Shadow Zone in full circular Trench.



3d. Shadow Zone in Semicircular Trench

Fig. 3. Geodynamic Isolation

Fig. 3_a Geodynamic Isolation