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Dynamic Characteristics of Vibration Sources Other Than Earthquakes

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CLASSIFICATION OF PAPERS

Typical sources of man-induced vibrations are operation of machines, pile driving, moving traffic and blasting. Upon transmission of those vibrations into subgrade, the soil serves as a part of the structure system governing the response of the loaded structure sitting on or in the ground and as a medium transmitting the motions to the surrounding area. Various soil and foundation dynamics problems arise in this regard. The session on "Dynamic Characteristics of Vibration Sources Other than Earthquakes" considers those problems. The papers in this session are classified by the loading source, distance from source and type of problem as follows:

Loading Source

Machine operation	11.1, 11.7, 11.11*, 11.13, 11.16, 11.18, 11.20, 11.21, 11.23, 11.24, 11.30
Pile driving	11.8, 11.4
Blasting	11.31, 11.33, 11.35
Moving traffic	11.11*
General	11.5, 11.6, 11.12,11.32

Distance From Source

Loading location including immediate vicinity	11.4, 11.7, 11.13, 11.16, 11.18, 11.20, 11.21, 11.23, 11.24, 11.31, 11.33
Some distance away from loading location	11.1, 11.5, 11.6, 11.8, 11.11, 11.12, 11.31, 11.32, 11,35

Type of Problem

Prediction (and observation) of response	11.1, 11.4, 11.7, 11.11, 11.16, 11.18, 11.20, 11.21, 11.23, 11.24, 11.30, 11.31, 11.33, 11.35
Damage criteria	11.5
Vibration control	11.6, 11.12, 11.13, 11.32

VIBRATION OF MACHINE FOUNDATIONS DUE TO OPERATION

Paper 11.21 deals with crusher foundations and Papers 11.18 and 11.20 deal with paper machine foundations. Those foundations are made of framed structure supporting machines with low speed for the former type and high speed for the latter type. Papers 11.23, 11.24 and 11.30 deal with framed machine foundations in general. In the third paper (Paper 11.30), particular attention is focused on the dynamic response of slabs of framed foundations. Papers 11.7 and 11.16 are concerned with block foundations. Paper 11.13 proposes the method to control the vibration of foundations.

Crusher Foundations

Ring granulators of crushers used in coal mills are generally installed over framed structures in steel or reinforced concrete. The dynamic loads induced by the operation of crushers are due to unbalanced forces caused by rotor-eccentricity and loss of hammers and are due to the impact action of hammers. Their operation speeds are relatively low (i.e. 12.5 Hz for a specific ring granulator described in the paper). **Srinivasulu, Lakshamanan and Sarma** (Paper 11.21) present two case histories of excessive vibration of ring granulator foundations. Crusher foundations are designed for large vibrations caused by expected breakages of hammers. In one of the case histories, however, breakages of hammers led to progressive damage of steel structures supporting a reinforced concrete deck slab on which the crusher sat. The resonant frequency of the framed structure was below the operation speed. It took a considerable time to stop fully the crushed when the machine was shut down twice or three times a day. The resonant frequency and slow stopping process, together with low damping of the steel structure and the large load due to breakages of hammers, were found to have caused excessive vibration during the deceleration process, resulting in structural damages. A vibration isolation system and mechanical brakes to speed up the rate of deceleration were installed for the improvement. The second case history was concerned with excessive vibration damages of a reinforced concrete supporting framed structure on which six crushers were mounted. Excessive vibration occurred when some of those crushers ceased functioning. It was suspected that the crushers which continued working created an adverse loading combination. Locations of some crushers were changed for the improvement.

Paper Machine Foundations

Operation speeds of machines producing papers are fast enough to produce 1,200 to 2,000 m paper per minute. A paper machine foundation consists of a framed structure resting on a concrete slab which may or may not be supported by pile foundations. Formerly framed foundations were fairly rigid because of conservative designs. However, modern framed foundations are much more flexible. This and current trends of machines, bigger in size and faster in speed, require tighter machine alignment tolerance and stricter vibration criteria to ensure a smooth operation of machines. Papers 11.18 and 11.20

present methods for the evaluation of the dynamic response of paper machine foundations and case histories.

Sy and McKevitt (Paper 11.18) adopt the finite element method for the analysis of a structure and machine system. Springs are attached at nodal points along the base of footing to represent the soil and, if the footing is piled, the pile foundation. Some of formulations and/or charts previously developed by other people are suggested for use in determining the spring stiffnesses of soil and pile foundation. The modal analysis is used in calculating the natural frequencies and the responses for the computational efficiency. Equivalent viscous damping needs to be assigned in each mode to account for the damping in this approach. Two case histories are presented. In both cases, existing piled paper machine foundations were excited by shakers and the soil and pile spring constants were back calculated using the finite element method presented and information obtained in the vibration test. The back calculated soil-pile spring stiffnesses in the first case history were within 20% of the values computed by the simple formulation previously developed. The back calculation in the second case history was necessary for evaluating the foundation-machine responses after the machine was replaced with the new machine, since not enough information of soil and pile was available for this evaluation.

Lee (Paper 11.20) places emphasis on the soil-structure interaction of framed foundations, treating the soil-foundation system as a rigid block supported by a set of a frequency independent spring and dashpot for each displacement mode of the block. Spring and dashpot constants are determined from charts and simple formulations previously developed for rectangular and circular footings in homogeneous soil with or without embedment.

Framed Foundations in General

Madhav, Kathiroli and Iyengar (Paper 11.23) presented an efficient method to calculate the dynamic response of three-dimensional framed foundations by the frequency-domain finite element method. Soil, foundation mat and frames are represented respectively by the Zienkiewicz-Irons Brick 8-noded elements, 8-noded plate elements and frame elements. The axi-symmetric conditions are assumed with respect to each of the horizontal two orthogonal axes and thus the analysis can be made only for one quarter section of the entire domain. Infinite soil domain is represented by the limited number of elements with viscous dampers attached at the outer ends of the nodes. The dynamic stiffness matrix of the entire soil domain is condensed at the soil-mat interface. The mat element stiffness and condensed soil stiffness matrices are added to each other and further condensed at the mat-column connections. This condensed matrix is added to the finite element models of supporting structure and machine at the mat-column connections. Dynamic responses of a specific three-dimensional turbomachinery framed foundation are analyzed by using the afore-explained approach for various conditions. The soil-structure interaction is found to have marked effects on the response of a rotor at low operating frequencies.

Moore and Tan (Paper 11.23) carried out a series of vertical vibration tests on small framed foundations. The models are 1-m span steel portable frames of stiffnesses and supported on two isolated circular footings on a compacted sand deposit. The dynamic load was applied to the center of the cross beam. The test results confirmed that, as the stiffness of the frame increased, the resonant frequency increased and the maximum vibration amplitude decreased. Some of the available methods to estimate the natural frequencies and the vibration response amplitudes of framed foundations were calibrated using the test results. Those methods included "combined method" proposed by Major, "amplitude method" by Barkan and "dynamic deformation method" by Kohoutek: the first method and the second and third methods estimate respectively the natural frequencies and the vibration response amplitudes of framed foundations. The combined method yields that the calculated resonant frequencies are too low compared with the experimental results. The maximum vibration amplitudes estimated by the amplitude method and deformation method are found to yield the computed results reasonably close to the test results except for the most flexible framed foundation.

Vertical walls on foundation slabs stiffen the slab and thus this effect must be taken into account in the dynamic response analysis of foundation slabs. **Andrianov** (Paper 11.30) presents analytical solutions of the vertical vibration of foundation slabs with consideration of stiffening effect of vertical walls. The slab-soil system is treated as a ribbed plate on the Winkler subgrade. Dividing the frequency into three ranges, the solution is obtained for each range of the frequency. In the low frequency range, the "homogenization method" is used together with the Vishik-Lusternik first approximate approach. The "perturbation method" is used in the high frequency range. In the intermediate frequency range, the "two-point Pade-approximation method" is used for matching the solutions obtained by the homogeneous and perturbation methods. Natural frequencies of a ribbed plate on the Winkler subgrade computed by the solutions agree well with those computed by the numerical method.

Rigid Block Foundations

Yu, Richart and Wylie (Paper 11.7) present interesting features of nonlinear torsional response of circular rigid embedded foundations. The authors modified a computer program previously developed for the computation of torsional response of circular rigid foundations resting on a ground surface. Improvements were made for the consideration of embedment and in the approximate integration scheme. The modified program is capable of taking into account the nonlinear soil behavior, slip at the soil-foundation interface and inhomogeneity of ground profile. The program adopts a characteristic-like method for solving a multi-dimensional axisymmetric torsional wave equation and a Ramberg-Osgood shear stress-strain equation for the nonlinear soil behavior. The program was verified with other available analytical results for linear elastic conditions. Effects of nonlinear conditions on the foundation response are presented for specific conditions identical to those of the previously reported field dynamic load tests on an embedded footing. The qualitative comparison of the computed results with the experimental results indicates that the modified computer program can reasonably well predict the torsional footing response when both the inelastic soil behavior and slip at the soil-footing interface are considered.

Important parameters required for the calculation of responses of machine foundations are often back-calculated from a model block resonance test at the site. **Basavanna and Nagakumar** (Paper 11.16) proposes a method to back-calculate those from the ascending part of a resonance curve obtained from a field test. The authors first examined the method previously proposed using available experimental results. The previously proposed method is based on the frequency independent radiation damping ratio. The available experimental results include response curves covering from the ascending part through the descending part. The parameters back-calculated by the previously proposed method failed to yield the computed response curves not only reasonably close to those obtained in the field tests but also physically consistent. The authors reviewed the compliance function of a massless footing based on wave propagation theory and found that the radiation damping ratio was linearly proportional to the frequency. The previous proposed method was modified by implementing the frequency dependence of the radiation damping ratio. The back-calculated parameters by the modified method were found to be capable of producing the computed response curves close to those obtained by experiments at the frequencies around the resonance.

Control of Foundation Response

"Active control" is a method to control the dynamic response of structures by providing the external energy controlled by computer and has recently drawn a significant attention in earthquake engineering. **Pantelides** (Paper 11.13) describes briefly active control systems and their algorithms. Effectiveness of active control is demonstrated for a specific reinforced concrete framed foundation subjected to ground excitation. An active tendon system was used for active control and the continuous Ricatti optimal control algorithms were used for determining the control force. The author indicates that active control can be designed to control excessive vibration of machine foundations during normal operation and, as a result, also to reduce the vibration transmitted to nearby structures.

METHODS FOR PREDICTION OF TRANSMITTED GROUND VIBRATION LEVEL

Ground vibration transmitted from the loading source is often estimated for the safety of the nearby structures, particularly vibration sensitive structures or facilities. Papers 11.3 and 11.11 deal primarily with ground vibrations generated by machine foundations. In addition, Paper 11.11 also considers the moving traffic load. Ground vibration induced by pile driving is considered in Paper 11.8. Papers 11.31 and 11.35 deal respectively with ground vibration and water pressure generated by blasting.

Svinkin (Paper 11.1) presents a method to predict the motions transmitted from a proposed machine foundation to existing soil, buildings and equipment located some distance away. The presented method is based on the Duhemel integration with an impulse response function which relates the responses at the locations of interest due to an impulse load at the location of expected loading source. Thus impulse response functions must be determined beforehand. Those can be determined directly at the site where the transmitted motions are predicted. The locations to determine the impulse response functions can be the surface or below ground or any point at the building and equipment. He measured the soil motions around existing machine foundations and also predicted those motions by the method presented. It is found that key assumptions used are generally valid and the method can predict the motions reasonably well. The author states that the method is best used at a distance more than 5~10 equivalent radius of the foundation base for machine foundations with areas bigger than 10 m^2, and at distances 20~30m for foundations with smaller areas.

Palloks (Paper 11.11) presents a procedure, to estimate the magnitudes of transmitted vibrations at a planned location for sensitive devices, and examples of application of this procedure. The method is based on the transfer function analytically derived. Magnitudes of vibrations are evaluated either deterministically or probabilistically using the transfer function. The latter are used conveniently for predicting the vibration induced by moving traffics. The input soil information is obtained by vibration tests on rigid footing and refraction surveys at the site. The procedure was applied to find the minimum admissible distance from the existing traffic routes as well as from a future compressor station for the location of the planned vibration sensitive devices.

Jedel (Paper 11.8) presents a case history in which transmitted vibrations due to pile driving were predicted. This paper is summarized in PILE DRIVING. **Borisov** (Paper 11.31) and **Thandavamoorthy** (Paper 11.35) present the materials concerned with transmitted motions due to blast loading. This paper is summarized in BLAST LOADING.

PILE DRIVING

There are basically three major engineering problems associated with pile driving: pile drivability, evaluation of the static pile capacity and ground vibrations induced by pile driving. Papers 11.4 and 11.8 are concerned respectively with the last problem and the first two problems.

It is well known that the response of saturated soil to loading are affected by the pore fluid response in a soil mass. However, this effect is generally not taken into account in the estimations of the pile drivability and static pile capacity evaluated from pile driving. **Holsher** (Paper 11.4) studied the fundamental behavior of saturated soil subjected to driving impact, using the axisymmetric finite element program coded for the two-phase mixture soil consisting of soil skeleton and pore fluid. The elasto-plastic behavior with or without dilatancy is considered in the stress-strain constitutive law implemented in the program. Saturated soil along the shaft is found to be idealized by a single phase solid reasonably well, provided that volumetric change does not occur. Major findings on the saturated soil response around the pile toe are: 1) the wave propagation under the pile toe is mainly within a narrow region in the axial direction, 2) this region is even narrower when the skeleton behaves plastically, 3) the shear wave propagates radially from this region, 4) the plastic zone propagates with the speed of the fast wave in the saturated soil, 5) the plastic state is limited to the region of the axial wave propagation, 6) an increase in material strength results in an increase of pore pressure, and 7) plastic dilatancy results in a high toe resistance. Those findings indicate that the saturated soil behavior around the pile toe can not be simulated satisfactorily by using a single phase material.

Jedele (Paper 11.8) presents a case history in which the investigation was conducted to limit the pile driving energy for the safety of the nearby structure. The structure under the consideration was a historic dam located 300 feet upstream from the expected location of pile driving. Vibrations generated during the normal operation of the dam were measured and found to be below the proposed damage threshold criteria for historic and older sensitive buildings. A simulated pile driving test was also conducted with energy up to 3,000 ft-lbs at a distance 110 feet from the dam. The vibrations measured at the dam indicated no significantly different levels of vibrations. The vibration levels measured at various locations during the simulated pile driving showed a linear relationship between the peak particle velocity and scaled distance (= distance divided by square root of impact energy exerted by hammer) in log-log scale. Based on this relationship, a 22,000 ft-lb hammer was judged to produce the vibrations close to those observed in the simulated pile driving test at the dam and was adopted for pile driving. This vibration level anticipated was confirmed during the pile driving in the actual construction.

BLAST LOADING

Strong motions can be generated in the surroundings of a blasting area when explosives are charged. Those motions may cause damages to structures and also compact loose cohesionless soils. Papers 11.31 and 11.35 are concerned with safety of the structures from shock waves. Paper 11.33 is concerned with soil compaction.

The larger the blast is, the more effective a blast operation is in many cases. However, the safety consideration often limits the size of the blast. **Borisov** (Paper 11.31) presents the factors to be considered for optimizing the blast operation with respect to the safety of structures nearby. The author has suggested that the optimization of the blast operation should be based on the stresses induced in the members and damage accumulations of the structure rather than the ground movement in the structure base.

Underwater borehole blasting is often used in hydrotechnical construction practice such as dredging operations with pressure charges, destruction of underwater structures, etc. It generates shock waves and may cause serious vibration hazards to structures in the vicinity. Thus, before the operation, the amplitude of vibration of the structure and safe distance from the blasting location must be evaluated. However, very little information is available regarding the characteristics of shock waves generated by underwater borehole blasting. **Thandavamoothy** (Paper 11.35) presents the results of fundamental experimental study of the characteristics of those waves. Experiments were conducted on 1/10 scaled models in a laboratory environment. Explosives were set either in the water directly or in a concrete block submerged in the water. Boreholes were created in the concrete block in two different sizes. The pressures were measured in the water. Fourier spectra and transfer functions, ratio of the spectra of buried charge over the spectra of free charge, were computed from the measured water pressure. Major findings are: 1) a pressure wave generated by the buried charge is substantially smaller than that generated by the free charge in the water, and 2) transfer functions of buried charge for two different boreholes are similar to each other.

When deep loose deposits of cohesionless soils are compacted by using explosives, charges are commonly set inside deep boreholes. However, they may be set on the ground surface for the compaction of the soil within 1.5 to 2 m depth. This can reduce the cost and time in elaborately making the boreholes. **Agarwal and Ram** (Paper 11.33) propose such a compaction method and present the numerical method to evaluate the depth of effective compaction by explosives on the surface. The method is based on the finite difference approach with iterative algorithm for solving wave equation. Soil is treated as a plane strain elastic medium. The time history of vibration due to traveling pressure pulse is computed first and the compaction is judged to take place when the maximum vertical acceleration in the time history is above unity. The numerical method was verified by comparing computed responses with those computed by an available rigorous analytical solution and the depth of effective compaction was evaluated for the case considered. The computed depth shows the effectiveness of the compaction by explosives on the surface.

WAVE SCREENING BARRIERS

The transmitted vibrations can be controlled by wave barriers or/and by reducing the response of foundations directly subjected to dynamic loading. Paper 11.13 deals with the former and is summarized in VIBRATION OF MACHINE FOUNDATIONS DUE TO OPERATION. Papers 11.6, 11.12 and 11.32 deal with the latter. The types of wave barriers discussed are open trenches (Paper 11.12), trenches with infilled material (Papers 11.6 and 11.12) and and pile and silo barriers (Paper 11.32).

Open or infilled trenches are often used for wave barriers. Open trenches are a most efficient wave barrier since the air can not transmit soil motions. However, it is often difficult to install permanent open trenches in populated areas and stability considerations limit the maximum depth of excavation. In order to overcome those problems associated with open trenches, **Massarsch** (Paper 11.6) proposes a "gas cushion screen". In this barrier, gas cushions are installed in the vertical trench and self-hardening cement-bentonite grout is filled in the trench to create water-tight protection layers around the cushions. Efficiency of the gas cushion barrier for screening waves was examined through numerical simulations and field tests. The boundary element method was used for numerical simulation. Numerical simulation study shows that the amplitude reduction factors for the gas cushion screen are almost identical to those for open trenches in both vertical and horizontal soil motions. Field tests were conducted at two different sites. A gas cushion screen with 12 m depth and 20 m length was installed at a sandy soil site and ground vibrations were generated at the ground surface. The average amplitude reduction factors were 0.25 for 10~14 Hz and 0.20 for 21~29 Hz. A gas cushion screen with 6 m depth and 10 m length was installed at another sandy soil site. Ground vibrations were generated by the explosive charge and vibrator. The reduction factors varied between 0.25 and 0.3 for vibrations by explosive charge and between 0.2 and 0.5 for vibrations by vibrator. Isolation efficiency of the screen cushion barrier was markedly reduced by the water that penetrated into the voids between the cushions and the grout layers.

Al-Hussaini and Ahmad (Paper 11.12) studied the efficiency of passive wave barrier trenches using the frequency-domain boundary element method and proposed simple formulations expressing the efficiency of wave barriers for various conditions as a function of key parameters. Major findings in their study on screening efficiency of open and infilled trenches for vertical motions are: 1) efficiency of an open trench is nearly independent of its width except for a shallow trench, whereas that of an infilled trench is highly dependent on its width, 2) the optimum depth of a trench is 1.2 times of the Rayleigh wave length, 3) efficiency is dependent on the depth-width ratio as well as the cross section area of a trench, and 4) the ratio of the infilled material shear wave velocity over the soil shear wave velocity should be larger than 2.5. Major findings for screening the vertical motions by an open trench in a ground made of a layer underlain by half-space are: 1) if the half-space has a lower stiffness than the upper layer, the layering effects can be ignored, 2) if the surface layer is deeper than six times the Rayleigh wave length, the surface layer can be ignored, and 3) if the ratio of the layer soil shear wave velocity over the underlain soil shear wave velocity is smaller than around 0.7~0.75, trenches need to be built deeper compared with a corresponding homogeneous soil. The barriers are found to be more effective for screening vertical motions than the horizontal motions.

Xian-Jian (Paper 11.32) presents simple formulations for designing wave screening silo and pile barriers. Those formulations are based on the elastic wave propagation. There are three important aspects of wave propagation governing the design of barriers. The transmission effect defines the efficiency of a barrier. The dimensions of length and depth of a barrier are defined by the diffraction effect. When the bending wave length in the barrier is equal to incident wave length, the response of the barrier amplifies the soil motions: it is called "coincident effect" dependent on the dimensions and properties of the barrier and soil properties. The barrier must be designed so as to avoid the coincident effect. It is shown that, even if the diameters of barrier silo and pile are much smaller than 1/6 of the shielded wave length, they can effectively screen the wave.

DAMAGE CRITERIA

European vibration codes and recommendations, published in the literature, are based on simple observation of damaged structures. They vary within a wide range even if conditions are apparently similar. Thus, it is desired to develop a rational vibration criteria which can be applicable uniquely. **Massartsch and Broms** (Paper 11.5) present a rational simple equation to calculate the permissible vibration level. The formulation is based on the wave propagation theory with significant simplification of complex real situations. Ground distortion is found to be the single most important factor controlling the damages of structures caused by vibrations transmitted through the soil. A rational formulation of the vibration-induced ground distortion identifies the frequency and wave propagation velocity of the ground as important factors controlling the degree of distortion. The critical distortion for the structure standing on the ground is found to be the deflection ratio equal to 1.5×10^{-5}. Based on this number and the formulation of ground distortion, a simple equation is developed to calculate the permissible vibration level defined by the particle wave velocity of the ground. A comparison of the computed values with those defined in existing European codes and recommendations shows a good correlation, considering the large difference among existing codes and recommendations.