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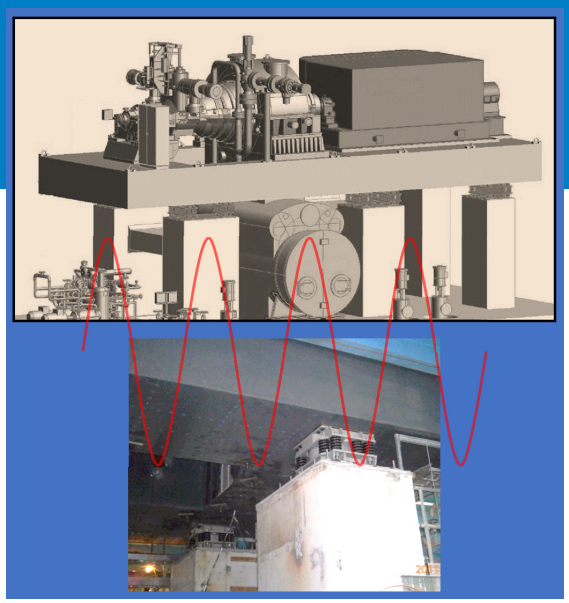

Foundations for Dynamic Equipment

SP-348

Editor:
Carl A. Nelson

American Concrete Institute
Always advancing

Foundations for Dynamic Equipment

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PREFACE

Foundations for Dynamic Equipment

This special publication grew out of the Technical Session entitled “Application of ACI 351-C Report on Dynamic Foundations,” held at the ACI Spring 2019 Convention in Québec City, Québec. Following this event, Committee 351 decided to undertake a special publication with contributions from those session participants willing to develop their presentations into full-length papers. Three papers included in the current publication were contributed by these presenters and their coauthors, with six additional papers provided by others. All but one of the papers deal with the subject matter of ACI 351.3—Foundations for Dynamic Equipment—updated in 2018. The one exception (the paper of Wang and Fang on wind turbine foundations) provides valuable information to engineers dealing with a lack of consistent design criteria among various codes for reinforced concrete foundations subjected to high-cycle fatigue loads.

I would like to thank the members of ACI Committee 351 for their support, in particular the current main Committee and Subcommittee C Chairpersons Susan Isble and Dr. Mukti L. Das, respectively. I also wish to express my gratitude to the authors for their perseverance through the difficult circumstances of 2020, and to the reviewers who generously contributed their time and expertise to this publication.

Last, but not least, I want to thank my wife Cindy for tolerating me (and the growing piles of paper) over the past several months as the deadline approached.

Carl A. Nelson
On behalf of ACI Committee 351

Minneapolis, December 2020

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Predicting Near and Far Field Ground Vibration for Equipment Foundations

David L. Pederson, Anthony J. Baxter and Carl A. Nelson

Synopsis: This paper discusses steps for both computing vibration from equipment foundations using the elastic half-space theory and then computing the decrease in vibration amplitude from the foundation to receivers. The steps are demonstrated on an existing foundation at a project site in Ohio that was subjected to dynamic loading from a hydraulic vehicle test rig. Several approaches are discussed to estimate the dynamic shear modulus of different soils, along with a methodology to establish an equivalent dynamic shear modulus for soils with varying shear wave velocities. Vibration transmission through the soil can affect people and sensitive equipment both near and far from the source. This paper shows a hybrid method and an SRSS method to compute the vibration attenuation through the near field and far field. The calculated results for this site were found to be very close to the measured values. Finally, vibration levels are compared for variations in stiffness, damping and attenuation to evaluate the sensitivity to calculations and/or field measurements. Variations in stiffness result in a nearly proportional change in vibration level while variations in damping and attenuation produce relatively small changes in the results.

Keywords: attenuation, damping, dynamic, elastic half-space, equipment, far field, foundations, frequency, material damping, near field, response, shear modulus, shear wave, stiffness, vibration

Innovative Retrofit of a Steam Turbine Generator Foundation to Mitigate Settlement

Hongchun Liu, Jaspal S. Saini, Gang Zhao, Sushil Chauhan, Namgyu Park, Mahi Galagoda, Steven Wu

Synopsis: This paper discusses an innovative retrofit that stabilized a Steam Turbine Generator (STG) pedestal foundation undergoing unexpected differential settlements during construction. The innovative solution involved driving steel H-piles around the STG foundation perimeter. A new concrete bracket (a.k.a. corbel) was added around the STG foundation perimeter to fully engage and integrate the H-piles with the existing pedestal foundation. The pile layout was established and optimized based on dynamic and static performance analyses of the modified foundation geometry using finite element (FE) software ANSYS, considering bounding pile and soil dynamic impedances. The frequency-dependent dynamic pile impedances were calculated using DYNA6. The continuous settlement monitoring of the STG foundation demonstrated that the retrofit effectively seized the ongoing settlements and stabilized the foundation enabling the subsequent machine installation.

Keywords: steam turbine generator foundation, foundation retrofit, foundation settlement, piles, dynamic analysis, frequency-dependent dynamic impedances, soil impedances, pile impedances.

Comparison of Several Methodologies Used for Designing Tabletop Foundations

Mukti Lal Das

Synopsis: The availability of high-speed computers at a reasonable price resulted in various sophisticated analysis and design methodologies for the elevated flexible pedestal (Tabletop) foundations replacing the rule-of-thumb processes based on static equivalent principle which used to produce either unsafe or overly conservative structures. A thorough study is undertaken with four typical models usually selected for static and dynamic analyses in the structural/mechanical engineering practice. It is found that all the models provide comparable results. However, each one has its own advantages and disadvantages. These will be highlighted in the Summary and Concluding Remarks of this paper.

Keywords: Rule-of-thumb, Eigenvalues, Rayleigh frequencies, Turbine force amplitude

Analysis of an Existing Compressor Foundation with Excessive Local Vibration

O. S. Ali Ahmed and Damon G. Reigles

Synopsis: This paper discusses the factors that affect the dynamic response of machine foundation systems, which include (1) the soil dynamic properties, (2) the geometric properties of the foundation, (3) mass of the machine and foundation, and (4) the amplitude and frequency of the applied dynamic loads. The primary objective in any machine foundation design is to limit the foundation response below a specific amplitude threshold. A foundation response exceeding this limit may adversely affect the performance of the machine and damage the machine internals, resulting in costly repairs and lost revenue. Also, the excessive vibrations may result in structural degradation of the foundation, additional excitation stresses on the machine, and increase the compressor unbalance loading. This paper presents dynamic analysis results of a four-cylinder compressor foundation originally designed without consideration for soil-foundation interaction and suffering from excessive vibration. The foundation block supports a 4-cylinder Dresser-Rand compressor, suction and discharge bottles, a crank, and a driving motor with a total weight of approximately 300 kip (1334 kN). A three-dimensional, finite element model representing the soil–foundation system was developed to determine the dynamic characteristics and assess the foundation response under applied dynamic loading from the compressor crank. Results showed that the response of the soil-foundation system is governed by the response of the individual support piers (blocks) and not the global foundation response. This paper also provides a recommended modification to the foundation geometry to reduce the effect of the individual piers' local modes and enhance the foundation dynamic performance.

Keywords: Compressor foundation, soil-structure interaction, finite-element method, dynamic loading, machine foundation, stiffness, damping.

Efficiency of Pile Groups Under Dynamic Loads

O.S. Ali Ahmed

Synopsis: Dynamic pile group effect can either increase or decrease the response of pile-supported structures. This paper presents the results of a three-dimensional finite element model of the pile-to-pile interaction that considers the effect of the surrounding soil to determine the dynamic stiffness and damping for vertical end bearing pile groups subjected to vertical harmonic loading. The results were generated for a wide range of the dimensionless frequency parameter (a_o) for a 9x9-pile group with three different spacings: 2-, 4-, and 6-pile diameter. Both the stiffness and the damping showed an oscillatory behavior with the dimensionless frequency parameter a_o, as well as with the soil shear modulus. Also, the group efficiency was determined as a function of the pile spacing and the soil shear modulus. The efficiency factor for the stiffness can be as high as 1.15 and as low as 0.7 and for the damping as high as 3.75 and as low as 0.4 as a function of the dimensionless frequency parameter a_o.

Keywords: Pile group, soil pile interaction, machine foundation, pile group dynamic stiffness, pile group damping, efficiency factors.

Design of a Spring Isolated Steam Turbine on an Existing Foundation

Ping (Philip) Jiang, Ron McDonel

Synopsis: A more than 50-year old Steam Turbine/Generator (STG) table-top concrete foundation was retrofitted to support a new STG/Condenser unit. This new machine unit is set on a sub skid with spring/damper assemblies underneath and located on existing concrete table top columns. This paper presents a case study of the seismic design and evaluations of the existing foundation structure that were performed to assess and qualify the structure's service and strength capabilities. Based on these evaluations, modifications to the existing STG foundation were minimized allowing the cost effective reuse of the existing foundation resulting in significant savings for the overall installed cost of the project.

Keywords: dynamic analysis, machine foundation, retrofit, seismic, spring isolator

Elevated Foundations for Rotating Machines for High Speed Balancing Facilities

Pericles C. Stivaros and Pablo A. Bruno

Synopsis: This paper presents a case study involving the structural analysis and design of an elevated foundation plinth to support multiple pieces of rotating machines with different operating weights and speeds. The equipment is used to operate a high-speed balancing testing facility for turbines and rotors that are located within an adjacent testing chamber. This project comprised of several layout and design challenges, including vibration and resonance concerns, effects of multiple operating frequencies, plinth shape, and pile foundation effects. Major concern was to maintain the high precision and strict tolerance limitations required by the high-speed balancing operations. Elevated machine foundations integral with other structures possess many natural frequencies, both locally and globally. The traditional design rules-of-thumb are not adequate for analyzing and designing elevated machine foundations. A computer-based finite element analysis method is required to identify the multiple natural frequencies of a complicated foundation structure. The strength design of a machine foundation can become very challenging when trying to implement code requirements that are mostly applicable to building elements and not to massive concrete foundations. This study recognizes the need for the development of a design standard to include special design requirements for mass concrete machine foundations.

Keywords: machine foundations, dynamic loads, vibration, resonance, pile foundations

Notional Piles for Generalized Foundation Modeling Based on the Novak Procedure

Tim Hogue, David Kerins, and Matthew Brightman

Synopsis: The "Notional Pile" formulation is developed for modeling a group of piles in a foundation. It is a new procedure for foundation modeling for dynamic analysis in conformance with ACI 351.3R. It is an augmentation of the well-known Novak procedure. Foundation stiffness is represented as a set of notional pile elements. This differs from conventional procedures in which the pile group stiffness is represented by a set of springs lumped at one point. With notional piles and finite element modeling of the cap, flexible-cap modes of vibration can be extracted. With conventional procedures, only lower-frequency rigid body modes can be extracted. Notional piles distribute stiffness more realistically and enable cap-pile interaction. A specific case is used to illustrate the new procedure. For that case, the cap did not have a regular distribution of mass or stiffness. Dynamic loads were applied with considerable eccentricity, at multiple locations and with multiple frequencies. Notional piles accommodated these irregularities. The notional pile formulation was validated by comparing measured to computed foundation responses. The comparison was good but not great. The foundation was to be reconfigured for new machinery. The retrofit design was modeled using notional piles. Responses were computed and compared to applicable limits.

Keywords: ACI 351.3R, dynamic analysis, foundation modeling, notional piles, Novak procedure, pile cap flexibility, pile/cap interaction, pile group modeling, model validation.

Comparison of Fatigue Design Code Requirements for Wind Turbine Foundations

Xuan Wang and Shu-jin Fang

Synopsis: One of major challenges for the US wind industry is the lack of consistent fatigue design criteria. ASCE/AWEA RP2011 recommends several design codes for fatigue analysis of land-based wind turbine support structures. However, it does not provide discussions on the differences and limitations of these codes. The purpose of this paper is to present our findings on the application of fatigue design codes including Model Code 2010 (MC10), Eurocode 2 (EC2), Det Norske Veritas (DNV), and ACI 215. Comparison of the design results from using these codes/standards are summarized. Due to lack of consistency in the design standards, evaluation results may vary greatly, which can be confusing and inconclusive at times. In addition, this study shows that there will be significant differences on fatigue design adequacy depending on which analysis method is used: the average sectional method or finite element method, the two principal methods used to analyze fatigue. A number of suggestions and critical comments are also provided in this paper for helping development of more consistent fatigue analysis and design criteria for wind turbine foundations.

Keywords: Average Sectional Method, Cumulative Damage, Fatigue Design, Finite Element Method, Limit State, Partial Safety Factors, Wind Turbine Foundation