Ocean Engineering 146 (2017) 268–281

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Stresses and pore water pressure induced by machine foundation on saturated sand

Mohammed Y. Fattah [a,*], Mosa J. Al-Mosawi [b], Abbas F.I. Al-Americ [b]

[a] Building and Construction Engineering Department, University of Technology, Baghdad, Iraq
[b] College of Engineering, University of Baghdad, Iraq

ARTICLE INFO

Keywords:
Dynamic response
Machine foundation
Stress
Pore water pressure
Saturated sand

ABSTRACT

In this study, the response and behavior of machine foundations resting on dry and saturated sand was investigated experimentally. In order to investigate the response of soil and footing to steady state dynamic loading, a physical model was manufactured. The manufactured physical model could be used to simulate steady state harmonic load at different operating frequencies. Total of (84) physical models were performed. The parameters that were taken into considerations include loading frequency, size of footing and different soil conditions. The footing parameters were related to the size of the rectangular footing and depth of embedment. Two sizes of rectangular steel model footing were used (100 × 200 × 12.5 mm) and (200 × 400 × 5.0 mm). The footing was tested in all parameters at the surface and at 50 mm depth below model surface. Meanwhile the investigated parameters of the soil condition included dry and saturated sand for two relative densities 30% and 80%. The response of the soil to dynamic loading includes measuring the stresses inside the soil using piezoelectric sensors as well as measuring the excess pore water pressure by using pore water pressure transducers.

It was found that the rate of increase in excess pore water pressure ratio decreased remarkably at a depth of 0.5 B–1.5 B (B is the footing width) for medium and loose dense sand, respectively. Moreover, excess pore water pressure ratio increases with increasing the eccentricity of dynamic load. The generated pore water pressure is always greater under the point of load application. Its value reduces with a certain percentages at any point away from the point of load application. In addition, the rate of variation of pore water pressure with eccentricity for loose sand is less than that for medium dense sand. The dynamic stress increments resulting from the dynamic load on the foundation reduce with depth. In addition, the dynamic stresses under the corner are slightly greater than the stresses at the center by a percentage of about 10.0%. The excess pore water pressure increases with increasing the relative density of the sand, the amplitude of dynamic loading and the operating frequency. In contrast, the rate of dissipation of the excess pore water pressure during dynamic loading is more in the case of loose sand.

1. Introduction

Machine foundations are regarded as the most important elements of industrial structures like power plants, steel plants, petrochemical complexes, and fertilizer plants … etc. It consists of a number of reciprocating and centrifugal machines which play an important part in ensuring efficient performing of the process, and that the output product is of the required quality. If any of these parts starts malfunctioning or breaks down due to disproportionate vibration or large settlement of the foundations, this may lead to catastrophic performance requirements at a certain times(Chowdhury and Dasgupta, 2010).

Different factors have major influence on the behavior of the machine foundations, such as dynamic soil properties that support the foundation, weight of the foundation and vibrating equipment, contact area of foundation with soil, static soil pressure, nature and magnitude of unbalanced force. The complexity of dynamic loading in nature as well as the non-homogeneity of soil makes the analysis and design of foundations subjected to dynamic load to be complex (Ramesh and Kumar, 2011).

The essential target in the design of foundation subjected to dynamic loads is neither to limit the amplitudes that affect the adequate operation of the machine nor will they disturb the people working in the vicinity. Hence, a crucial factor to obtain a successful machine foundation designs the reliable engineering analysis of the response of foundation subjected

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* Corresponding author.
E-mail addresses: myf_1968@yahoo.com (M.Y. Fattah), prof_mosa_2006@yahoo.com (M.J. Al-Mosawi), alameri.abbas@gmail.com (A.F.I. Al-Americ).

https://doi.org/10.1016/j.oceaneng.2017.09.055
Received 21 October 2016; Received in revised form 15 July 2017; Accepted 24 September 2017

to dynamic loads from the anticipated and predictable operation of the machine (Gazetas, 1983).

The type of dynamic loading applied on soil or the foundation of a structure depends on the nature of the source producing it. Dynamic loads vary in their magnitude, direction, or position with time. More than one type of variation of forces may coexist (Das and Ramana, 2011). Dynamic conditions relevant to geotechnical engineering fall into several categories: (1) earthquakes, (2) machinery vibrations, and (3) other human made disturbances such as blasting, pile driving, soil compaction, rail, or truck traffic, water hammer in pipes, etc. In addition, dynamic instrumentation such as a portable seismograph or ground-penetrating radar is used as nondestructive investigative tools (Handy and Spangler, 2007).

Common soil dynamics problems include the response of machine foundations to dynamic loads and the response of soil deposits and earth structures to earthquake loads.

Dynamic loadings may produce a wide range of deformations of soils. In the intermediate range, soil deformations vary from small amplitude, nearly elastic, to plastic following earthquakes, water waves or machine developed forces. Small amplitude deformations of soils are developed adjacent to foundations designed to sustain many stress repetitions without permanent settlements (Richart, 1962).

The offshore industry requires designing for deep water where breaking wave loads are relatively significant. However, wave breaking will be much more prevalent in the relatively shallow waters being considered for wind energy structures. The waves and current are often assumed to be statistically independent. Hydrodynamic interactions between waves and currents are generally ignored in design, although strongly sheared currents can cause local wave steepening and breaking. In addition, vibrations caused by machinery on offshore platforms have to be taken into consideration.

In the machine foundation analysis and design, the solution of the problem is always performed using simple vibration problem. It is well known that the vibration problem may be solved as free or forced vibration according to the idealization of the problem.

The forced vibration of a foundation is most often investigated by modeling the soil as a single-phase linear elastic medium. However, real soils in general are two-phase materials involving a solid skeleton and pore fluids and thus should be more realistically regarded as poro-elastic materials (Chen et al., 2006).

The criteria for design of machine foundations require that the vibration amplitude should not exceed a given value. Therefore, the machine foundation design requires a systematic use of principles of soil engineering, soil dynamics, and theory of vibration (Mandal and Baidya, 2003).

The amplitudes of displacement or velocity or acceleration of the machine foundation should be within permissible limits. The permissible limits are depending upon the operating frequency of the machine as well as soil type and characteristics. In no case should the permissible amplitude exceed the limiting amplitude prescribed for the machine by the manufacturer.

All machines under normal operation usually induce a periodic dynamic load on the foundation. This induced dynamic load causes some portion of the soil underlying the foundation to be subjected to vibration and it is essential that the natural frequency (ω_n) of this vibration should be far away from the operating frequency of the machine (Chowdhury and Dasgupta, 2010).

1.1. Pore water pressure under dynamic loading

The soil is a multi-phase system. It always consists of soil, gas and fluid phase. When soil is described as saturated soil, this means that the soil falls into two-phase system. The presence of fluid (water) within soil plays important role in soil behavior. This is due to its effect on the resulting effective stress. Generally, the presence of water causes reduction in shear strength of the soil in static analysis. While in the case of dynamic loading, the water pressure not only leads to a decrease in shear strength, but also it causes high reduction in cemented soil skeleton that may lead to soil liquefaction.

There are several approaches to determine the behavior of a two-phase medium. In general, they can be categorized as uncoupled and coupled analysis. In the uncoupled analysis, the response of saturated soil is computed without considering the effect of soil-water interaction, and then the pore water pressure is calculated separately by means of a pore pressure generation model. In the coupled analysis, all unknowns are computed simultaneously at each time step.

Liquefaction phenomenon was recognized during the early developments in soil mechanics (Omarov, 2010). Liquefaction can be defined as a phenomenon in which soil skeleton loses its strength when a dynamic load is applied to them and tend to flow as a liquid. The phenomenon of pore pressure build-up followed by the loss of soil strength is known as liquefaction.

The common customary methods to characterize the liquefaction potential of soils both in laboratory and field are gathered under two main categories: (1) cyclic stress-based and (2) cyclic strain-based approaches. Earthquake loading and the soil liquefaction resistance are characterized in terms of cyclic stresses in the cyclic stress-based approach, while they are characterized by the induced cyclic strains in the cyclic strain-based approach (Omarov, 2010).

Even though cyclic stress-based and cyclic strain based approaches are most widely used in the field of geotechnical earthquake engineering, some other approaches such as energy-based, effective stress-based response analysis and probabilistic approaches have been also developed (Omarov, 2010).

Both cyclic stress-based and strain-based approaches comprise three main steps:

1. Estimation of the cyclic shear stress or strain induced at various depths within the soil by the earthquake loading, together with the number of loading cycles,
2. Estimation of the cyclic shear strength or resistance of the soil in cyclic stress-based approach; or expected pore water pressure ratio, *ru*, corresponding to the determined shear strain in cyclic strain based approach
3. Comparison between the induced cyclic shear stress and soils' resistance in stress-based approach or evaluation of pore water pressure ratio in strain based approach.

Numerous research and studies confirm that sand that has uniform gradation and rounded soil particles, very loose or loose density state, recently deposited with no cementation between soil grains, and any prior preloading or seismic shaking are the most soil type that is susceptible to liquefaction (Day, 2002). Some researchers showed that dry cohesionless soil and dense saturated sand soil might possess a liquefaction behavior.

Alla (2009) mentioned that unsaturated soils are considered safe against cyclic shear because of the high compressibility of the pore air. Liquefaction is generally associated with saturated soils but there have been cases where even unsaturated soils are prone to liquefaction when they are underlain or overlain by seams of saturated soils. As well as when degree of saturation decreases to 90%, the cyclic shear strength is double that of fully saturated soil under ordinary testing conditions in case of fine clean sands. A complete liquefaction state for unsaturated soils is the condition in which both pore air and water pressure are at the same pressure as the initial mean total confining pressure.

As well as many researches are devoted to study the liquefaction behavior of sand subjected to heavy loads such as blast loading and earthquake, lately, efforts have been made by some researches to elaborate the possibility of producing liquefaction due to other types of dynamic loading.

Xiaobing et al. (2004) studied the influence of the vertical vibration loading on the liquefaction of saturated sand. They