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PROBABILISTIC FAILURE ANALYSIS OF DYNAMIC PILE CAPACITY USING HILEY AND JANBU FORMULAE

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ABSTRACT

The reliability assessment of the load carrying capacities of piles based on dynamic approach using Hiley and Janbu formulae is reported in this paper. Uncertainties are common phenomena in engineering, therefore all the interrelated variables in the load carrying capacities are treated as random variables with assumed practical probability density functions. The concept of the First-Order Reliability Method (FORM) is a powerful tool for estimating nominal probability level of failure associated with uncertainties and it is the method invoked for the reliability estimations. From the results, there is a correlation between the implied safety levels in Hiley and Janbu formulae. The safety level is clearly different with weight of pile and length of pile. Janbu formula leads to higher safety level than Hiley's for increasing pile length.

Key words: Probabilistic failure analysis, dynamic pile capacity, dynamic pile formulae.

INTRODUCTION

Piles may be structural members of timber, concrete, and/or steel, used to transmit surface loads to lower levels in the soil mass. This may be by vertical distribution of the load along the pile shaft or a direct application of load to a lower stratum through the pile point. A vertical distribution of the load is made using a friction, or "floating", pile, or "end-bearing", pile. This distinction of piles is purely one of convenience since all piles function as a combination of side resistance and point bearing except when the pile penetrates an extremely soft soil to a solid base (Bowles, 1988).

Pile foundations are widely used in highway construction, buildings and other structures. Accurate determination of pile capacity is very important for proper design, construction and estimation of these foundations. It is common in design practice to predict pile capacity by static analysis in advance of pile driving based on the results of in-situ and/or laboratory soil and rock tests. Traditionally, the static loading test is used to determine ultimate capacity of the pile-soil system or the value of a service load to be supported by a pile. In recent decades, because of advances in data acquisition during pile driving and restrikes, dynamic testing has become an integral part of pile capacity prediction and measurement.

Dynamic methods have certain advantages and some uncertainties in their application. Wave equation analysis of driven piles is a prevalent method of pile driving stress calculations. Besides driveability analysis, the wave equation method is used for determination and prediction of pile capacity during both the design stage and for construction control during pile installation. Unfortunately in most cases, computed pile capacity differs substantially from results of both static and dynamic load tests. Errors in determination of pile capacity will create insufficiencies in pile foundation selection and will decrease foundation reliability.

Dynamic measurements of force and velocity at the upper end of the pile during pile driving, followed by a signal matching procedure, is the most common method for dynamic determination of pile capacity. This method is a convenient tool in the pile driving industry. However, though dynamic methods have been used in practice for years, actual reliability of dynamic methods is vague because their comparison with static loading tests is made incorrectly in most cases (Svinkin, 1997).

The reliability of an engineering system can be defined as its ability to fulfill its design purpose for some time period. The theory of probability provides the fundamental basis to measure this ability. The reliability of a structure can be viewed as the probability of its satisfactory performance according to some performance functions under specific service and extreme conditions within a stated time period. In estimating this probability, system uncertainties are modeled using random variables with mean values, variances, and probability distribution functions. Many methods have been proposed for structural reliability assessment purposes, such as First Order Second Moment (FOSM) method, Advanced Second Moment (ASM) method, and Computer-based Monte Carlo Simulation (MCS) (e.g., Ang and Tang,1990;Ayyub and Haldar,1984; White and Ayyub,1985; Ayyub and McCuen,1997) as reported by Ayyub and Patev (1998).

Reliability-based design methods could be used to address many different aspects of foundation design and construction. However, most of these efforts to date have focused on geotechnical and structural strength requirements, such as the bearing capacity of shallow foundations, the side friction and toe-bearing capacity of deep foundations, and the stresses in deep foundations. All of these are based on the difference between load and capacity, so we can use a more specific definition of reliability as being the probability of the load being less than the capacity for the entire design life of the foundation. According to Coduto (2001), various methods are available to develop reliability-based design of foundations, most notably stochastic methods, the First-Order Second Moment, and the Load and Resistance Factor Design method.

The purpose of design is the achievement of acceptable probabilities that the structure being designed will not become unfit in any way for the use for which it is intended. Engineering problems of this structure, however, often involved multiple failure modes; that is, there may be several potential modes of failure, in which the occurrence of any one of the potential failure modes will constitute non- performance of the system or component. Recent researches in the area of structural reliability and probabilistic analysis have centered around the development of probabilistic-based design procedures. These include load modeling, ultimate and service load performance and evaluation of current levels of safety/reliability in design (e.g., Farid Uddim, 2000; Afolayan, 1999; Afolayan, 2003; Afolayan and Opeyemi, 2008; Opeyemi, 2009).

In this paper, a First-order reliability assessment of dynamic pile capacity using Hiley and Janbu formulae is reported.

DYNAMIC PILE CAPACITY

Estimating the ultimate capacity of a pile while it is being driven in the ground at the site has resulted in numerous equations being presented to the engineering profession. Unfortunately, none of the equations is consistently reliable or reliable over an extended range of pile capacity. Because of this, the best means for predicting pile capacity by dynamic means consists in driving a pile, recording the driving history, and load testing the pile. It would be reasonable to assume that other piles with a similar driving history at that site would develop approximately the same load capacity.

Dynamic formulae have been widely used to predict pile capacity. Some means is needed in the field to determine when a pile has reached a satisfactory bearing value other than by simply driving it to some predetermined depth. Driving the pile to a predetermined depth may or may not obtain the required bearing value because of normal soil variations both laterally and vertically.

The basic dynamic pile-capacity formula termed the *rational pile formula* depends upon impulse – momentum principles.

Dynamic Pile Formulae

The available dynamic pile formulae include:

(a) Canadian National Building Code (use SF = 3)

$$P_u = \frac{e_h E_h C_1}{s + C_2 C_3} \quad (1)$$

in which

$$C_1 = \frac{W_r + n^2 (0.5W_p)}{W_r + W_p},$$

$$C_2 = \frac{3P_u}{2A}, \text{ and}$$

$$C_3 = \frac{L}{E} + 0.0001$$

(b) Danish formula (use SF = 6)

$$P_u = \frac{e_h E_h}{s + C_1} \quad (2)$$

where

$$C_1 = \sqrt{\frac{e_h E_h L}{2AE}}$$

(c) Gates formula (use SF = 3)

$$P_u = a\sqrt{e_h} E_h (b - \log s) \quad (3)$$

(d) Janbu (use SF = 3 to 6)

$$P_u = \frac{e_h E_h}{k_u s} \quad (4)$$

where

$$k_u = C_d (1 + \sqrt{1 + \frac{\lambda}{C_d}})$$

and

$$C_d = 0.75 + 0.15 \frac{W_p}{W_r}$$

$$\lambda = \frac{e_h E_h L}{AEs^2}$$

(e) Modified ENR formula (use SF = 6)

$$P_u = \frac{1.25 e_h E_h}{s + 0.1} \frac{W_r + n^2 W_p}{W_r + W_p} \quad (5)$$

(f) AASHTO (use SF = 6); primarily for timber piles.

$$P_u = \frac{2h(W_r + A_r p)}{s + 0.1} \quad (6)$$

(g) Navy-McKay (use SF = 6)

$$P_u = \frac{e_h E_h}{s(1 + 0.3C_1)} \quad (7)$$

where

$$C_1 = \frac{W_p}{W_r}$$

(h) Pacific Coast Uniform Building Code (PCUBC) (use SF = 4)

$$P_u = \frac{e_h E_h C_1}{s + C_2} \quad (8)$$

$$C_1 = \frac{W_r + kW_P}{W_r + W_p}$$

k = 0.25 for steel piles
= 0.10 for all others

$$C_2 = \frac{P_u L}{AE}$$

(i) Hiley

$$P_u = \frac{e_h E_h}{s + \frac{1}{2}(k_1 + k_2 + k_3)} \frac{W + n^2 W_p}{W + W_p} \qquad (9)$$

List of symbols

A	=	Pile cross-sectional area
E	=	Modulus of Elasticity
e_h	=	Hammer efficiency
E_h	=	Manufacturers' hammer-energy rating
H	=	height of all of ram
K_1	=	elastic compression of capblock and pile cap and is a form of PuL/AE
K_2	=	elastic compression of pile and is of a form of PuL/AE
K_3	=	elastic compression of soil, also termed quake for wave-equation.
L	=	Pile length
N	=	Co-efficient of restitution
P_u	=	Ultimate pile capacity
S	=	amount of point penetration per blow.
W_p	=	Weight of pile including weight of pile, cap, driving shoe, and capblock (also includes anvil for double-acting steam hammers)
W_r	=	Weight of ram (for double-acting hammers include weight of casing).

RELIABILITY ESTIMATES

First Order Reliability Method (FORM)

The general problem to which FORM provides an approximate solution is as follows. The state of a system is a function of many variables some of which are uncertain. These uncertain variables are random with joint distribution function $F_x(x) = P(\bigcap_{i=1}^{n}\{X_i \le x_i\})$ defining the stochastic model. For FORM, it is required that F_X (***x***), is at least locally continuously differentiable, i. e., that probability densities exist. The random variables ***X***$= (X_1, ...X_n)^T$ are called basic variables. The locally sufficiently smooth (at least once differentiable) state function is denoted by g(***X***). It is defined such that g(***X***)>0 corresponds to favourable (safe, intact, acceptable) state. g(***X***)=0 denotes the so-called limit state or the failure boundary. Therefore, g(***X***)<0 (sometimes also g(***X***)$\le$0) defines the failure (unacceptable, adverse) domain, F. The function g(***X***) can be defined as an analytic function or an algorithm (e.g., a finite element code). In the context of FORM it is convenient but necessary only locally that g(***X***) is a monotonic function in each component of ***X***. Among other useful information FORM produces an approximation to $P_f = P(X \in F) = P(g(X) \le 0) = \int_{g(x)\le 0} dF_X(x) \quad = \quad \phi(-\beta_R)$

(10)

in which β_R = the reliability or safety index. (Melchers, 2002).

NUMERICAL ILLUSTRATION

Dynamic pile capacity using Hiley formula

The functional relationship between allowable design load and the allowable dynamic pile capacity using Hiley formula is expressed as:

G(x) = Allowable Design Load – Allowable Pile Capacity

So that,

$$G(x) = 0.35 f_y A_p - \left\{ \frac{eh\ Eh}{S + \frac{1}{2}(K_1 + K_2 + K_3)} * \frac{W + n^2 W_p}{W + W_p} \right\} \Big/ SF$$

$$= 0.35 f_y A_p - \left\{ \frac{eh\ Eh}{S + 0.5\left(K_1 + \frac{P_u L}{AE} + K_3\right)} * \frac{W + n^2 W_p}{W + W_p} \right\} \Big/ SF \qquad (11)$$

Where:

A = Pile cross-sectional area, E = Modulus of Elasticity, e_h= Hammer efficiency, E_h = Manufacturers' hammer-energy rating, K_1 = elastic compression of capblock and pile cap and is a form of PuL/AE, K_3 = elastic compression of soil, also termed quake for wave-equation, L= Pile length, n = Co-efficient of restitution, P_u = Ultimate pile capacity, s = amount of point penetration per blow., W_p =Weight of pile including weight of pile, cap, driving shoe, and capblock (also includes anvil for double-acting steam hammers), W_r = Weight of ram (for double-acting hammers include weight of casing).

Table 1 shows the assumed statistical values and their corresponding probability distributions.

Table 1- Stochastic model for dynamic pile capacity using Hiley formula

Variables	Probability density function	Mean values	Coefficients of variations
F_y	Lognormal	460×10^3kN/m^2	0.15
A_p	Normal	1.60×10^{-2} m^2	0.06
e_h	Normal	0.84	0.06
E_h	Lognormal	33.12 kN/m	0.15
S	Lognormal	1.79×10^{-2} m	0.15
K_1	Lognormal	4.06×10^{-3} m	0.15
P_u	Lognormal	950kN	0.15
L	Normal	12.18m	0.06
E	Lognormal	209×10^6 kN/m^2	0.15
K_3	Lognormal	2.54×10^{-3} m	0.15
W	Gumbel	80 kN	0.30
N	Lognormal	0.5	0.15
W_p	Lognormal	18.5 kN	0.15
SF	Lognormal	4.0	0.15

Dynamic pile capacity using Janbu Formula

The functional relationship between the allowable design load and the allowable dynamic pile capacity using Janbu formula is expressed as follows:

G(x) = Allowable Design Load – Allowable Pile Capacity

So that,

$$G(x) = 0.35 f_y A_p - \left\{ \frac{eh\, Eh}{K_u S} \right\} \Big/ SF$$

$$= 0.35 f_y A_p - \left\{ eh\, Eh \Big/ \left(0.75 + 0.15\frac{W_P}{W_r}\right) \left(1 + \sqrt{1 + \frac{eh\, EhL / AES^2}{0.75 + 0.15\frac{W_P}{W_r}}} \right) S \right\} \Big/ SF \quad (12)$$

All the variables in Equation (12) are as defined in Equation (11)

In Table 2, the statistical and probabilistic descriptions of the variables in the functional relations are presented

Table 2- Stochastic model for dynamic using Janbu formula

Variables	Probabiity density function	Mean values	Coefficient of variations
F_y	Lognormal	460 x 10^3KN/m^2	0.15
A_p	Normal	1.60 x 10^{-2} m^2	0.06
e_h	Normal	0.84	0.06
E_h	Lognormal	33.12 KN/m	0.15
W_p	Lognormal	18.5 KN	0.15
W_r	Gumbel	35.58 KN	0.30
L	Normal	12.18m	0.15
E	Lognormal	209 x 10^6 KN/m^2	0.06
S	Lognormal	1.79 x 10^{-2} m	0.15
SF	Lognormal	6.0	0.15

DISCUSSION OF RESULTS

Starting with the assumed statistical values and the probability distributions given in Tables 1 and 2, the formulae for dynamic pile capacity by Hiley and Janbu are rated. As is common in practice, the length of piles and weight of piles are subjected to variations and the results of the assessment are as displayed in Figures 1 and 2.

Hiley formula generally and grossly provides a very conservative pile capacity; the safety level grows with increasing weight of pile (Fig.1) and length of pile (Fig.2). Just like the Hiley formula, Janbu formula shows generally and grossly conservative pile capacity, the safety level increases as weight of pile and length of pile increases, but; Janbu's results provides lesser piling conservation compared to Hiley's with respect to weight of pile (Fig.1), and higher in the case of the length of pile (Fig 2).

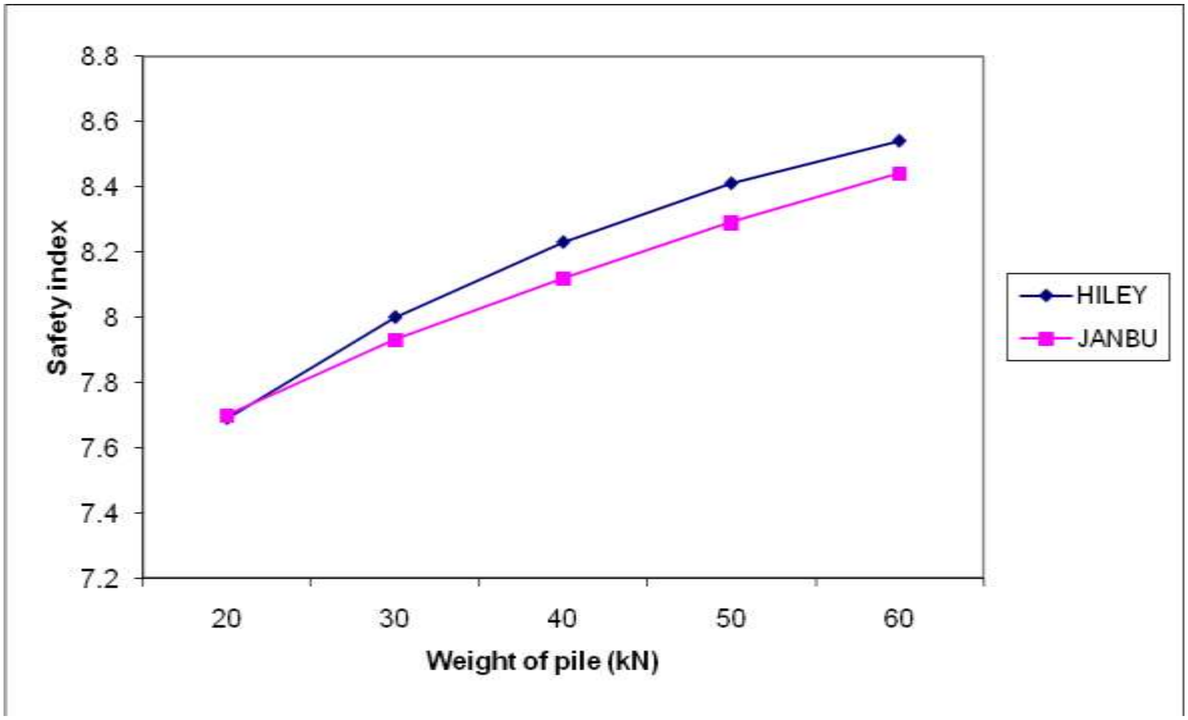

Fig. 5.40 - Safety index (β_R) against Weight of pile using Hiley and Janbu formulae

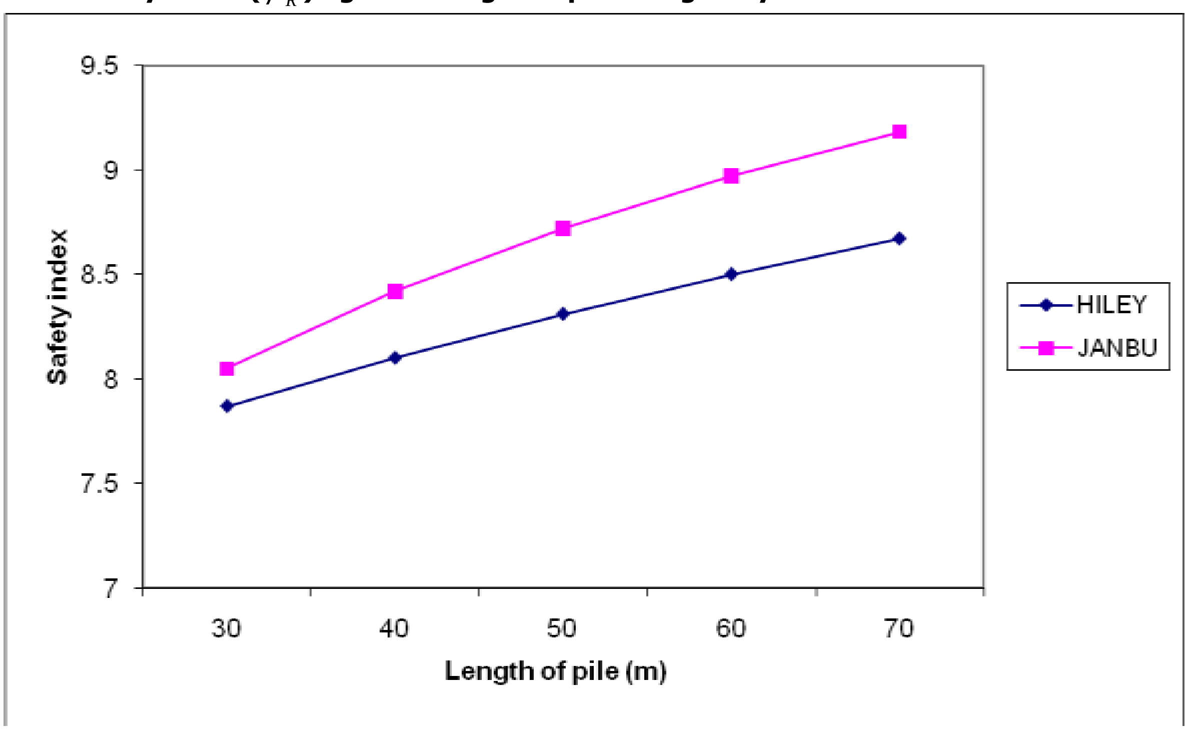

Fig. 5.41 - Safety index (β_R) against Length of pile using Hiley and Janbu formulae

CONCLUSION

The First-Order Reliability Method has been employed to rate dynamic pile capacity using Hiley and Janbu formulae. All relevant variables are considered random with assumed probability density distributions. From the results, it can be concluded that there is a correlation between the implied safety levels in Hiley and Janbu formulae. The safety level is clearly different with weight of pile and length of pile. Janbu formula leads to higher safety level than Hiley's for increasing pile length.

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