INTERNATIONAL JOURNAL OF CIVIL AND STRUCTURAL ENGINEERING
Volume 3, No 2, 2012

Research article ISSN 0976 – 4399

Probabilistic analysis of Malaysian bored piles

Sadaf Qasim[1], Indra Harahap[2]
1- PhD Candidate, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, 31750 Tronoh, Perak, Darul Ridwan, Malaysia
2- Associate Professor, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, 31750 Tronoh, Perak, Darul Ridwan, Malaysia
nuzhaterum@gmail.com
doi:10.6088/ijcser.201203013036

ABSTRACT

Initiating to introduce Load Resistance Factor Design in Malaysian Geotechnical industry is also one of the leading motives as LRFD is reliability based method, can work out the probability of failures of the structure and estimate the reliability through statistical knowledge. To overcome the coming risks and the uncertainties in a best possible manner, demands of incorporating LRFD in practice is a dire need of this century. In terms of providing solution of how to strengthen the sub-structures, reliability based LRFD method is proposed and emphasized by calculating resistance factors of bored pile through First Order Second Moment also known as First Order Reliability Method (FORM(and Mean Value First Order Second Moment (MVFOSM) rather the application of fitting strategy. Statistical methods FOSM, AFOSM used to compute the beta values and resistance factors. Comparison of both methods has also been performed. As the most dominant is bore pile so in this document this structure is used for the reliability analysis. Cases of four Kuala Lumpur sites have been taken as a sample to get statistical data. Although the resistance factors developed is not so refined but at least conservative values of resistance factors are in hand to carry out LRFD.

Keywords: Reliability theory, load resistance factor design, working stress design, reliability index.

1. Introduction

Subject of foundation failures is not new as (Sowers 1993) stated about 500 cases of foundation failures, out of which around 450 are accredited to design/construction errors. Design or construction errors can be overcome if of conventional design methods have to be replaced or modified by using reliability principles through Load Resistance Factor Design approach. RBD is a route of designing a system, or a built facility, that proficient to execute a requisite task within a certain level of assertion or reliability, given uncertainty of the design or input parameters. The RBD process heavily uses statistics, probability theory and reliability theory to come out with a reliable design (Siddall 1983). Therefore it requires highly qualified human resources to accomplish such process. On the other hand, if following Load Resistance Factor Design (LRFD) the load and resistance need to multiply by factors, greater than one for load and less than one for resistance, to count for uncertainty. As mentioned earlier if the factors are determined through reliability theory then, the results should conquer a firm level of confidence or reliability (Schneider 1997). Once the load and resistance factors have been established it can be applied easily even by marginally taught personnel. It should be clear that the factors should cover the wide range of possible loads and geometry of structure, and applicable for all possible analysis and design methods.

Received on September 2012 Published on November 2012

Relying on conventional safety factor practices is also one of the major drawbacks. There is no opportunity of estimating the type and intensity of the prevalent uncertainties in conventional practices (Whitman 2000). The contribution of the uncertainties whether its model based (Ronold and Bjerager 1992; Phoon 2005), parametric (Cho 2010) or human can only be tackled through probabilistic means. Probabilistic assessment of geotechnical structures at least gives clear indication about the possibility of its failure (Phoon 2004). One current movement in the geotechnical community is the changeover from the allowable stress design to the limit state design or Load Resistance Factor Design (Kulhawy and Phoon 2002) . According to (FHWA 2001) reported definition of limit state is: *"A limit state is a condition beyond which a structural component, such as a foundation or other bridge component, ceases to fulfil the function for which it is designed".*

The limit state design emerge based on reliability principles is broadly received. Limit state design considers the needs on ultimate limit state (ULS) and serviceability limit states (SLS) separately; whereas reliability principles can be functioned to enumerate uncertainties in an unfailing manner. Limit state design codes have also been put into practice in many places such as Europe, North America, Japan, and Mainland China. The execution of the limit state design codes not only certifies the fulfillment of different limit states and counters uncertainties, but also provides a well-suited design approach for geotechnical works and structural engineering works, which have been based on limit state design for a time. One vital task to apply limit state design code is the calibration of design methods. It is a route to establish partial factors on the load and resistance (Becker 1996). By the employ of these factors, the uncertainties can be taken into explanation and the design can arrive at convinced target reliability.

2. Scope and area of the study

The main purpose here is to provide framework for determination of resistance factors for one of the common geotechnical structure of Malaysian region. Calibration of resistance factors or code calibration is another major issue. Code calibration is a process to optimize predefine sign goal (i.e. cost, safety, risk, reliability etc.) with respect to design variables such as loads and resistances. To achieve this load is capitalized on, by applying load factors greater than one, and the resistance is lowered down, by applying resistance factors smaller than one. In the relevance, the code arrangement is defined such that abuse of the thought design objective, through the application of load and resistance factors, is a rare event. The intention of code calibration is to determine the most appropriate set of load and resistance factors. (FHWA 2001) published some available methods of code calibration which are

1. fitting to different codes,
2. judgment,
3. reliability theory, and
4. Combination.

Talking about fitting, it does not reflects uniform safety ranges so in this case fitting with WSD is to be used. Calibration through combination is basically the product of the above mentioned methods. Combination includes fitting with ASD, reliability theory and off course the judgment or the past experiences. For example determination of resistance factors is carried out by using both fitting with ASD and reliability theory and to check the compatibility in both the methods. Use of LRFD will only be successful if reliability theory has to be involved in the calibration of resistance factors, rather than fitting methods.

Tropical countries like Malaysia is carrying different soil strata, changing with locations and classification is dependent on age. As Kuala Lumpur existing capital of Malaysia located at western part has two prominent soil types based on limestone and Kenny Hill formation. Approximately one third reflects limestone formation. Granite formation is also noted in some areas. Factors like ground conditions, site conditions, its restrictions or constraints give rise to adequate selection of foundation/stabilization measures (Tan Boon and Komoo 1990; Taha, Hossain et al. 1999).

Bored piles usually maintain a range of size between 450mm to 2m but in the project of Berjaya central park in Kuala Lumpur bored piles of 3000mm also used. When doing piling in firm clay or sandstone, bored piles finds economical. Cases of Kuala Lumpur sites have been taken as a sample to get statistical data. Although the resistance factors developed may be not completely valid for every situation but at least conservative concept is developed in connection with bore piles structure.

3. Resistance/Load statistics

Information relating to load statistics resistance statistics and reliability analysis are compulsory for the calibration of resistance factors. In this study calibration of load factors are not going to be focused. No doubt valuations of load persuade foremost uncertainty in the design. As there are dissimilar types of load components performing on structures such as dead load, live load, wind load, snow load and earthquake load. Though, the meaning of load works may differ from one type of structures to another. For example, the live loads on bridges symbolize the forces formed by the vehicles (Nowak 1993) while the live load on buildings stand for the force from the influence of people, furniture, partition or other items insides the buildings Statistical (Szerszen and Nowak 2003)analysis on the load components of buildings is carry out in America and China (Ellingwood, Galambos et al. 1980; MOC 2002). Already in hand load statistics (Table 1, Table 2 and Table 3) of (Ellingwood, Galambos et al. 1980) for load components in building structures. (Nowak 1993) recommended a set of statistical parameters for bridge components. Here taking load statistics of Nowak (1993) given in (FHWA 2001) into research as it is considered standard for substructures . Resistance statistics used is generated through pile cases of different sites of Kuala Lumpur. Results of Meyerhof method and static test method has been used to generate bias factor statistics like mean and coefficient of variance. Here in this study variables are assuming uncorrelated, keeping normally distributed probability density function into consideration.

Table 1: Load component statistics (Ellingwood, Galambos et al. 1980)

Load Component	Arbitrary point in time		Maximum 50 year load	
	Bias Factor	COV	Bias Factor	COV
Dead Load	1.05	0.10	1.05	0.10
Dead Load	1.03	0.08	1.03	0.08
Live Load	0.24	0.65	1.00	0.18
Wind	0	0	0.78	0.37
Snow	0.20	0.87	0.82	0.26

Earthquake	0	0	0.66	0.56

Table 2: Load component statistics (MOC 2002)

Load Component		Bias Factor	COV	Distribution
Dead Load	Unfavorable effects	1.06	0.07	Normal
	Favorable effects	1.06	0.07	Normal
Floor Live Load	General cases	0.7	0.29	Extreme Type I
	>4KPa	0.7	0.29	Extreme Type I

Table 3: Load component Statistics (Nowak 1993; FHWA 2001)

Load Component	Bias Factor	COV
Dead Load		
Factory made	1.03	0.08
Cast in Place	1.05	0.10
Asphalt Wearing Surface	1.00	0.25
Live Load	1.10-1.20	0.18

4. Method and tools of the study

Christian (2004) shared three broad categories of reliability analysis. It includes direct reliability analysis, event / fault trees methodologies and other statistical techniques. According to (Ayyub and Assakkaf) direct reliability analysis probabilistically belongs to level II and level III. Level II. Level II needs simple statistical parameters of random variables, sometimes taking linear approximation of non linear limit state Advanced first order second moment (AFOSM) is the example of level 11 also known as first order reliability method (FORM) (Zhao and Ono 1999). Level III is complex as it requires full probabilistic information of each random variable. Level I includes mean value first order second moment (MVFOSM), it is less accurate as it does not the distribution of variables into consideration.

4.1 Mean value first order second moment

First order second moment method lies in Level II. First order second moment is used for the computation of reliability index. Uncertainty relates to the involved variables has been recognized only by mean and variance. Variance can be replaced by covariance in case of correlativity between the variables. Usually bias factor statistics are used to generate mean values of load and resistance. Reliability index needs information of various variables like dead load statistics (COVQD) live load statistics (COVQL) and dead load to live load ratio (QD/QL).The limit state function, ‘G” is linear zed at average values of random variables. Taylor’s series expansion taking only first order term into calculations worked to determine the mean and standard deviation of G. (Baecher and Christian 2003) The general limit state function can be described as

$G = R - Q$

b (1)

4.2 First order second moment

Advanced methods are not in favour to simplify the mathematical rules done in MVFOSM. Advance methods not only pursue mean and the standard deviation but also the normal and lognormal distribution. Process of FOSM is as follows:

1. Rosenblatt transformation is used to change variables from X space to U space
2. Locate the most probable point in U space
3. Determine reliability index
4. Find probability of failure/reliability

(Low and Tang 2007) did modifications in his approach, as put forwarded in 2004. Considering correlation between variables not distributed normally. No use of calculating equivalent normal mean (μ^N) and equivalent normal standard deviation (σ^N) in 2007 approach. Getting '**β**' minimum by changing values of X_i is the main aim. Iteration needs Rackwitz and Fiessler equivalent normal transformation. In the following equations 'C' refers to covariance matrix and 'R' shows matrix of correlation (Rackwitz 2001).

$$\boldsymbol{\beta} = \sqrt{\left[\frac{X_i-\mu_i^N}{\sigma_i^N}\right]^T (\mathbf{R})^{-1} \left[\frac{X_i-\mu_i^N}{\sigma_i^N}\right]} \qquad (2)$$

Alternatively

$$\beta = \sqrt{(\boldsymbol{x}-\boldsymbol{m})^T \boldsymbol{C}^{-1} (\boldsymbol{x}-\boldsymbol{m})} \qquad (3)$$

Where

$$\boldsymbol{\sigma}^N = \frac{\phi\{\Phi^{-1}[F(x)]\}}{f(x)} \qquad (4)$$

$$\boldsymbol{\mu}^N = X - \boldsymbol{\sigma}_i^N * \Phi^{-1}[F(x)] \qquad (5)$$

In Excel Add in built in Solver tool is used for optimization. In comparison with above mentioned 2004 approach, (Low and Tang 2007) approach is reported more efficient as it skips some tedious steps without showing any changes on conclusion.

$$\beta = \sqrt{(\boldsymbol{n})^T \boldsymbol{R}^{1} (\boldsymbol{n})} \qquad (6)$$

For every trial, original basic random variable X_i is determined by design. Where

$$\mathbf{X_i} = \boldsymbol{F}^{-1}\,[\boldsymbol{\Phi}(\boldsymbol{n}_i)] \qquad (7)$$

and $[\Phi(n_i)]$ = standard normal cumulative distribution The *normal* or *Gaussian* distribution is generally common type of probability distribution function and the distributions of many random variables kowtow to this distribution. It is by and large used for probabilistic studies in geotechnical engineering except there are valid reasons for picking a different distribution. Typically, variables which crop up as a sum of several random effects, none of which dictate the total, are normally distributed. In (FHWA 2001) reported that exact knowledge of distributions is very difficult, that's why best fit approximation is reflected by log normal distribution. Here for simplicity variables are assumed in normal distribution as these are the only two governing distribution in geotechnical engineering. Specifically limit state equation in this scenario becomes:

$$g = \varphi_R(R_b + R_S) - \varphi_Q(Q_D + Q_L) \tag{8}$$

Here in case of distinguishing resistance from load symbol '*R*' is using for both shaft and base resistances carrying suffix of '*b*' and '*s*' mentioned in Equation (8).

φ is basically a factor used to reduce resistance R and load Q. Configuration of piles along with the result of static load tests with results of the same pile cases are also incorporated to mark the difference or for the sake of bias factors. Bias factor is defined as the ratio of measured capacity and predicted capacity. Shaft capacity and base capacity bias factors are concluded separately to make the calculations independent.

In the ongoing research approach of (Low and Tang 1997) has been directed for the computation of reliability index β. Initially values of '*x*' equal to '*m*' values the coefficient of variance is converted into simple variance if the random variables are uncorrelated. For simplicity random variables are considered uncorrelated here. Before the process of optimization 'a' and 'b' can be taken any assumed value, but in general practice it is noted that initially its equal to mean values. As variables are supposed to be uncorrelated so cell E2 and D3 becomes zero. MS Excel has an inbuilt tool of optimization named solver, providing constraints and the target makes it workable without bothering any loops and programming

First order reliability method (FORM) method and Mean value first order second moment (MVFOSM) are used to compare the resistance factor values. In other words its also one way to weigh the accuracy of the methods. Resistance factors are derived on the basis of the computed beta values through MVFOSM. In MVFOSM following expressions (Equation 9 and Equation 10) are used to compute the reliability index (β) and resistance factor (φ) values.

$$\boldsymbol{\beta} = \frac{ln\left[\frac{\lambda_R\left(\frac{Q_D}{Q_L}+1\right)FS}{\lambda_{QD}\frac{QD}{QL}+\lambda_{QL}}\sqrt{\left(1+COV_R^2\right)/\left(1+COV_{QD}^2+COV_{QL}^2\right)}\right]}{\sqrt{\ln\left(1+COV_R^2\right)\left(1+COV_{QD}^2+COV_{QL}^2\right)}} \tag{9}$$

$$\boldsymbol{\varphi} = \frac{\lambda_R\left(\gamma_{QD}\frac{QD}{QL}+\gamma_{QL}\right)\sqrt{\frac{1+COV_{QD}^2+COV_{QL}^2}{1+COV_R^2}}}{\left(\lambda_{QD}\frac{QD}{QL}+\lambda_{QL}\right)exp\left\{\beta_T\sqrt{\ln\left[\left(1+COV_R^2\right)\left(1+COV_{QD}^2+COV_{QL}^2\right)\right]}\right\}} \tag{10}$$

In the above equation load factor statistics (Refer Table 3) like mean (γ), coefficient of variance (COV) and bias factors (λ) of dead load (QD) and live load (QL) are used. In case of resistance factor statistics (γ_R, λ_R and COV_R) it has to be generated through collected data. In FORM already calculated reliability indices through FOSM are used to compute resistance factor values. In FORM provision of taking related distribution with the variables also exists**.**

5. Reliability index and resistance factors determination

The use of LRFD entails the choice of a set of target reliability levels, which decides the probability of failure and, hence, the enormity of the load and resistance factors. The probability of failure exemplify the probability for the condition at which the resistance multiplied by the resistance factors will be less than the load multiplied by the load factors. A fairly accurate liaison between probability of failure and target reliability for a lognormal distribution is offered by (Rosenblueth and Esteva 1972) and is normally in use as reported in (FHWA 2001)**.** In the determination of load and resistance factors, the reliability index should be fixed equal to a certain value in instruct to achieve uniform reliability throughout a structural and geotechnical system. (Ellingwood, Galambos et al. 1980) squabble that target reliability index should be 3.0 for gravity loadings. Some structural elements, like steel connections, have target reliability indices bigger than 3.0 (Fisher, Theodore V. Galambos et al. 1978). In these cases, a main concern is to afford a plastic, gradual failure of the overall structure rather than at random or sudden one without any warning. (Vesic 1973) spotted that foundations are come up with a load-controlled approach and that, only in a number of situations, abrupt bearing capacity failures could transpire. Conversely, most footings are constituents through a larger system of redundant footings, with the likelihood of settlements and load transmits between footings proceeding to any structural disintegration. Hence, bearing in mind each footing as a module of a structural system, a reliability index of 3.0 is dependable with living structural practices, even in the comparatively atypical cases where “brittle” foundation failure would be probable. Values of target reliability index, appropriate for geotechnical design of foundation elements have been resolute by (Barker, Duncan et al. 1991) through analysis of conformist design exercises. These values are listed in Table 4. The values of β_T for piles are lesser than those used for other types of foundations because piles are used in clusters, and there is extensive redundancy in the capacity of pile groups that restrain several piles. The probability of failure of a group of piles, is that all of the piles in the group will fail is minor than the probability of failure of one pile in the group. As a result, adequate values of β_T for capacity of a single pile are less important than other foundation types, because it is apparent here that a single pile would not be used to hold up structural loads. If a single pile is to be used to shore up a structure load, the target value of β must be higher, in the array of 2.5 to 3.5, such as for drilled shafts and spread footings which are often used as a single.

Table 4: Target reliability indices Values (Barker, Duncan et al. 1991)

Foundation Types	Target Reliability Index
Spread Foundations	3.0-3.5
Drilled Shafts	2.5-3
Grouped Driven Piles	2-2.5

Table 5: For skin resistance only

Safety factor	QD/QL=1	QD/QL=2	QD/QL=3	QD/QL=4
	Reliability index	Reliability index	Reliability index	Reliability index
1.5	1.08	1.13	1.15	1.17
2	1.94	1.99	2.01	2.03
2.5	2.61	2.66	2.68	2.69
3	3.15	3.2	3.22	3.24
3.5	3.62	3.66	3.68	3.7
4	4.01	4.09	4.08	4.1

Table 6: For Toe resistance only

Safety factor	QD/QL=1	QD/QL=2	QD/QL=3	QD/QL=4
	Reliability index	Reliability index	Reliability index	Reliability index
1.5	0.89	0.92	0.93	0.94
2	1.34	1.36	1.37	1.38
2.5	1.68	1.7	1.71	1.72
3	1.96	1.99	2	2.02
3.5	2.2	2.22	2.23	2.24
4	2.4	2.43	2.44	2.45

Table 7: For total resistance

Safety factor	QD/QL=1	QD/QL=2	QD/QL=3	QD/QL=4
	Reliability index	Reliability index	Reliability index	Reliability index
1.5	1.07	1.1	1.12	1.13
2	1.73	1.76	1.78	1.79
2.5	2.24	2.28	2.29	2.3
3	2.66	2.69	2.71	2.72
3.5	3.01	3.05	3.07	3.08
4	3.32	3.35	3.37	3.38

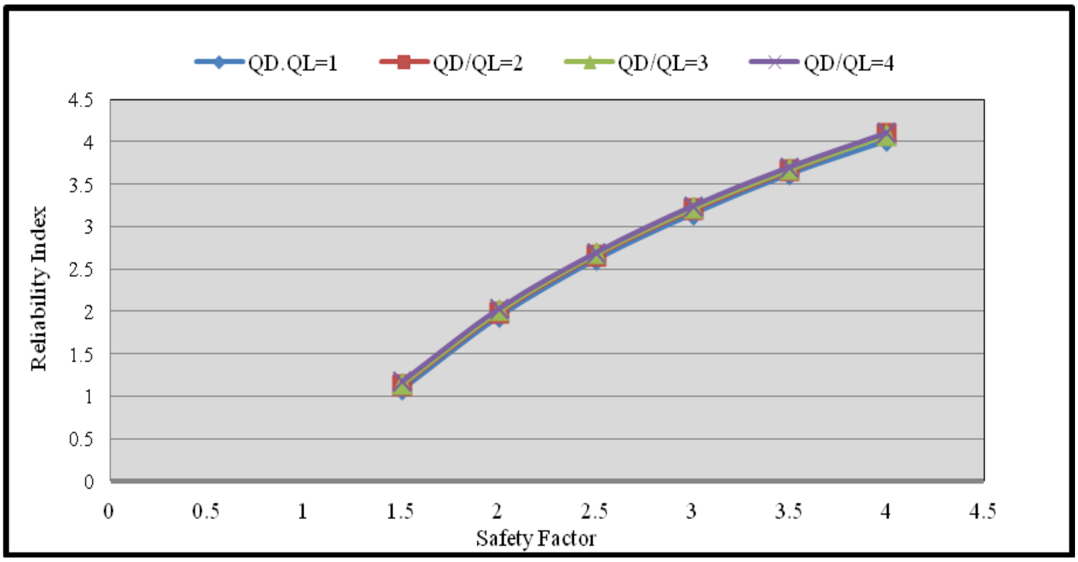

Figure 1: Safety factor influence on reliability indices with different dead load to live load ratios (taking skin resistance only)

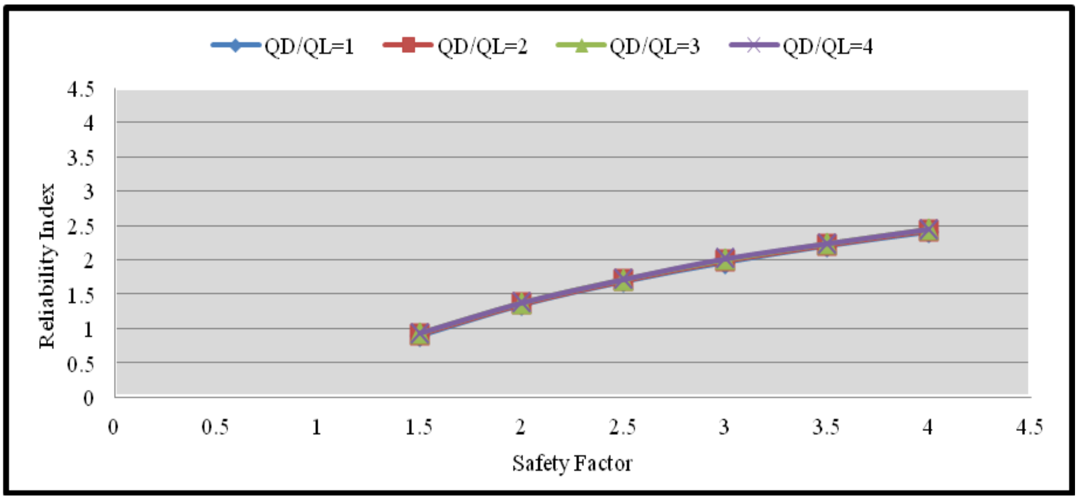

Figure 2: Safety factor influence on Reliability indices with different dead load to live load ratios (taking toe resistance only)

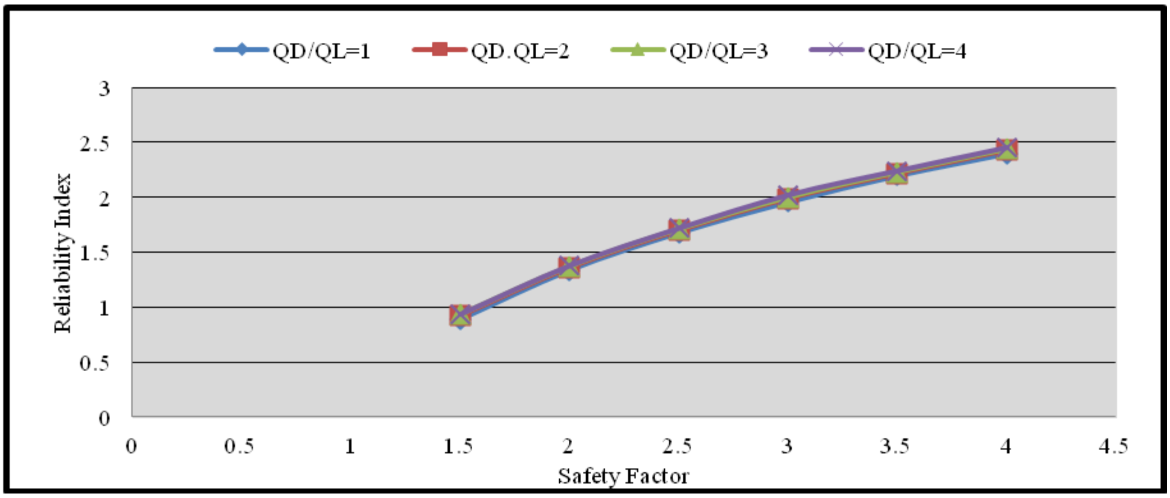

Figure 3: Safety factor influence on Reliability indices with different dead load to live load ratios (taking total resistance only)

Table 8: For skin resistance only

Reliability index	QD/QL=1	QD/QL=2.5	QD/QL=4
	Resistance factor	Resistance factor	Resistance factor
1	0.99	0.95	0.92
1.5	0.84	0.8	0.78
2	0.69	0.67	0.66
2.5	0.6	0.54	0.56
3	0.51	0.49	0.47
3.5	0.43	0.4	0.41
4	0.36	0.34	0.33

Table 9: For toe resistance only

Reliability index	QD/QL=1	QD/QL=2.5	QD/QL=4
	Resistance factor	Resistance factor	Resistance factor
1	0.65	0.63	0.62
1.5	0.38	0.36	0.34
2	0.22	0.2	0.2
2.5	0.12	0.12	0.11
3	0.07	0.06	0.05
3.5	0.04	0.03	0.028
4	0.02	0.019	0.012

Table 10: For total resistance only

Reliability index	QD/QL=1	QD/QL=2.5	QD/QL=4
	Resistance factor	Resistance factor	Resistance factor
1	0.9	0.84	0.82
1.5	0.72	0.67	0.66
2	0.58	0.54	0.53
2.5	0.46	0.43	0.42
3	0.37	0.35	0.34
3.5	0.3	0.28	0.27
4	0.24	0.22	0.22

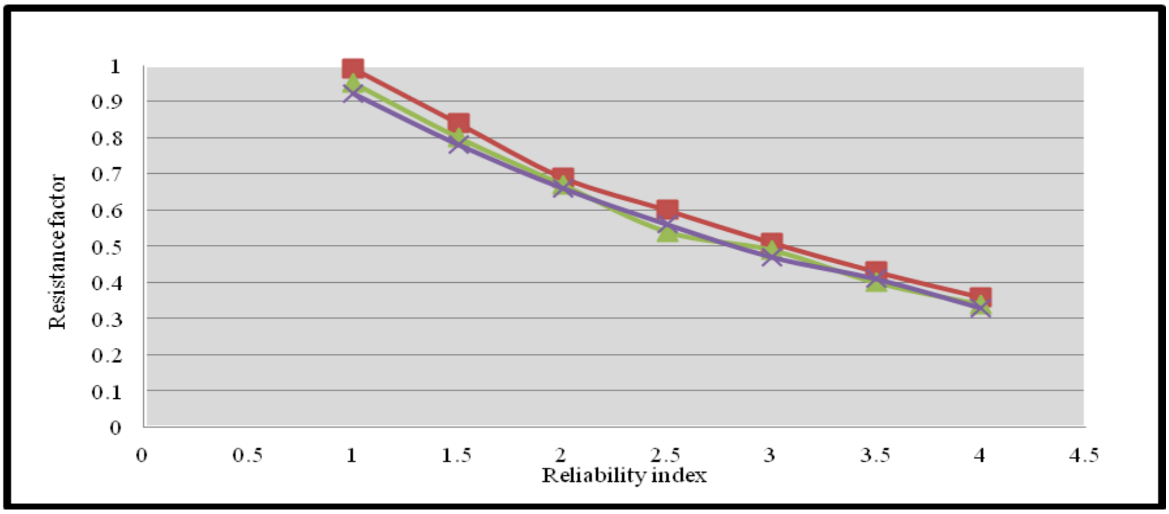

Figure 4: Resistance factors determination for skin resistance on various reliability indices (By taking different dead load to live load ratios)

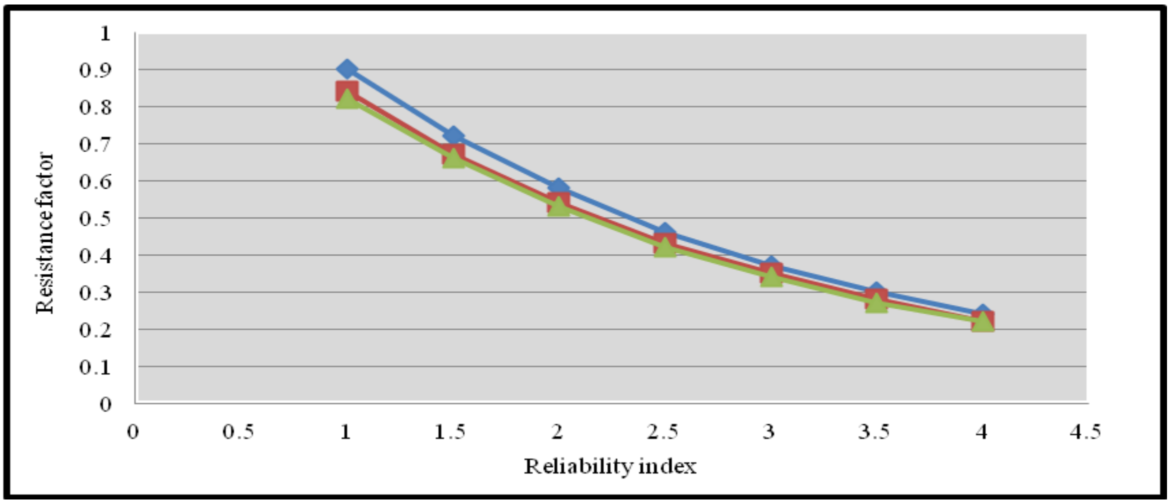

Figure 5: Resistance factors determination for toe resistance on various reliability indices (by taking different dead load to live load ratios)

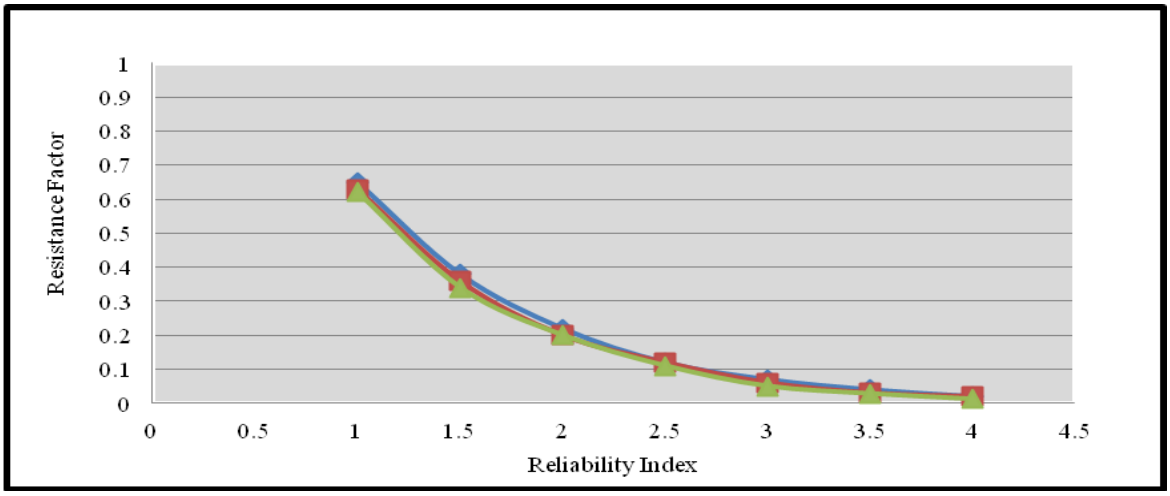

Figure 6: Resistance factors determination for total resistance on various reliability indices (by taking different dead load to live load ratios)

Table 11: For Skin Resistance only

Reliability Index	Resistance Factor (FORM)	Resistance Factor (MVFOSM)
1.5	x	x
2.0	x	x
2.5	0.69	0.60
3.0	0.64	0.51
3.5	0.60	0.43
4.0	0.54	0.36

Table 12: For Toe Resistance only

Reliability Index	Resistance Factor (FORM)	Resistance Factor (MVFOSM)
1.5	0.8	0.38
2.0	0.74	0.22
2.5	0.68	0.12
3.0	0.63	0.07
3.5	0.59	0.04
4.0	0.55	0.02

Table 13: For Total Resistance only

Reliability Index	Resistance Factor (FORM)	Resistance Factor (MVFOSM)
1.5	x	x
2.0	x	0.58
2.5	0.81	0.46
3.0	0.74	0.37
3.5	0.69	0.30
4.0	0.65	0.24

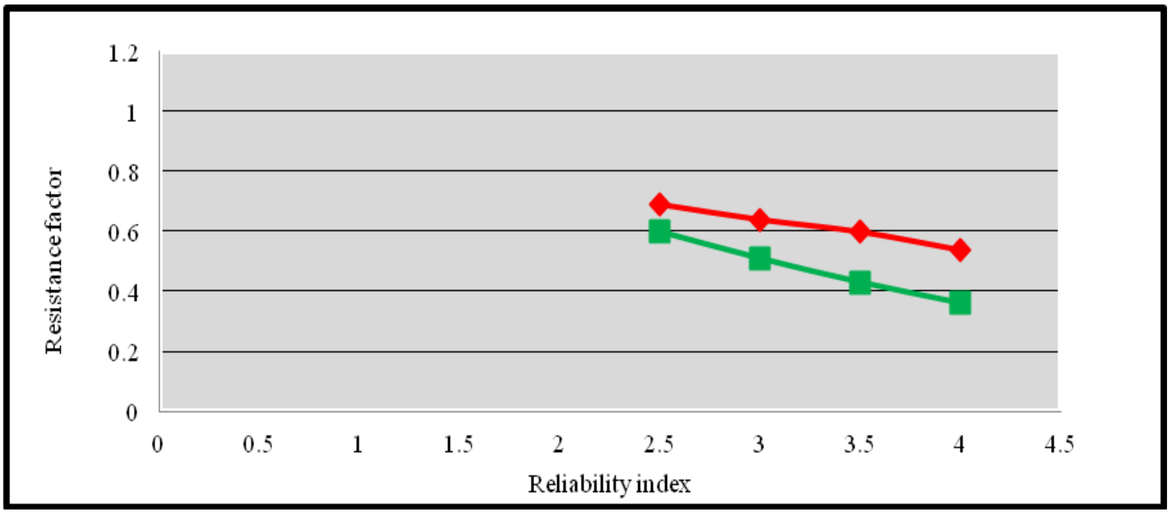

Figure 7: Resistance factors comparison with FORM and MVFOSM (for skin resistance)

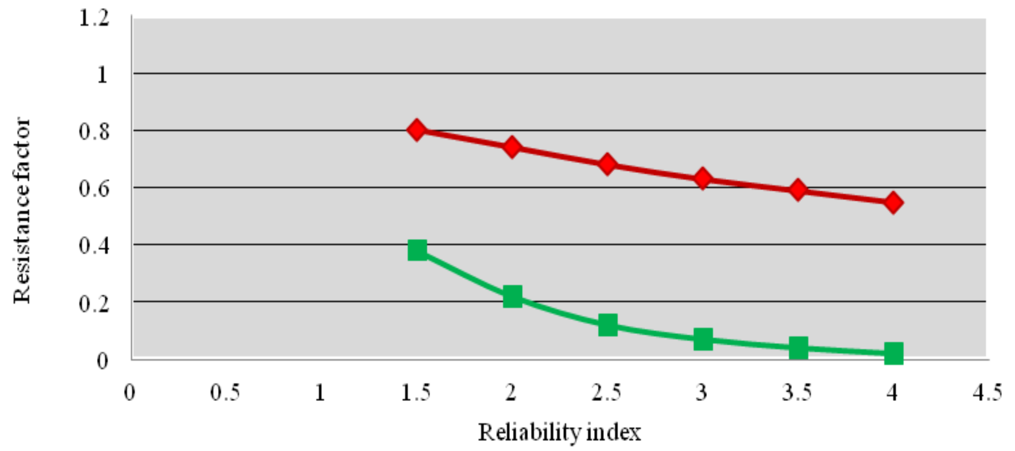

Figure 8: Resistance factors comparison with FORM and MVFOSM (for toe resistance)

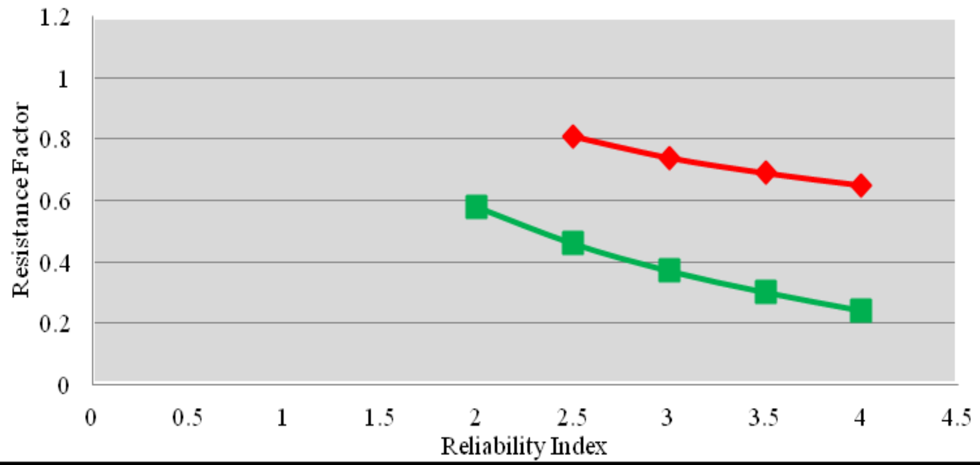

Figure 9: Resistance factors comparison with FORM and MVFOSM (for total resistance

5.1 Summary and conclusion

The resistance factors developed are based on many different sizes of pile load test database with different grades of diversity in pile configurations, test locations and soil types. Development or calibration of resistance factors for bored piles has been carried out through probabilistic methods as it finest serves for the introduction of LRFD in geotechnical engineering in Malaysian region. LRFD is reliability based method, so it's fruitful to have resistance factors with FORM and MVFOSM. No doubt results drawn from MVFOSM is not so refined as compared to FORM (refer Figure 4 to Figure 9) but it's also a fact that for parametric study MVFOSM is best feasible method (Paikowsky 2004). As exercise of FORM needs iterations therefore a parametric study more simply obtained by using the MV FOSM relationships. Through MVFOSM relationships reliability index has been calculated on different safety factor values. The results mentioned in Table 5 to Table 7 along with its graphical representations stating (refer Figure 1, 2 and 3) that increase in the safety factor values increases the reliability of the structure but this is not always the situation. Reliability of the structure can also be checked through another medium of probability of failure.

Sometimes even lesser safety factor imposes minimal chances of failure. Like (Lacasse and Nadim 1996) confirmed, by re-assessing the design of pile inaugurated in 1976.The supplementary information sometimes not only bring changes in the safety factor values but along with it also reduces uncertainties because of having more authentic information regarding soil parameters.

Introduction of LRFD is a burning issue now as (Fenton and Grifths 2007) stated. Recent geotechnical design codes are wandering on route to follow Load and Resistance Factor Design (LRFD) methodologies. The Danish geotechnical code has been based on LRFD for numerous decades, but more freshly the Eurocode and the Australian Standards have warped in this path. Where the geotechnical system chains a structure, the load factors are normally resolute by the structural codes. The geotechnical resistance factors, classically determined by calibration with traditional working stress (or allowable stress) design; have so far to be visibly distinct in geotechnical design codes. Research into the reliability of geotechnical systems is essential in command for resistance factors to be determined.

The resistance factors are calibrated separately for total, skin and toe capacities in an attempt to mark the fluctuations between the three resistance factors. Refinement of the two selected methods of FORM and MVFOSM is also proved through this exercise. Toe capacity resistance factors impose remarkable difference in every situation. It is also shown through results the resistance factor for total capacity is larger than both the skin and toe resistance factors. Thus, the combination of the skin and toe resistance factors does not capitulate, a factored resistance correspondent to that by the total capacity resistance factor. One possible excuse for this is the averaging upshot of the deviation in skin and toe capacities when they are combined to total pile capacity. The piles widen both skin and toe resistances, but the percentage of skin or toe capacity to total capacity is not invariable. For these grounds, the resistance factors for only total capacity are suggested. Conservatism is employed in the assortment of the recommended resistance factors due to the limited number of the data points but at least the ranges of the resistance factors can be easily estimated for this particular structure.

6. References

1. Ayyub, B. M. and I. A. Assakkaf "Reliability-Based Structural Design."

2. Baecher, G. B. and J. T. Christian., (2003), Reliability and statistics in geotechnical engineering, John Wiley & Sons Inc.

3. Barker, R. M., J. M. Duncan, et al. (1991), Manuals for the design of bridge foundations, NCHRP Report 343 transportation research board, National research council, Washington, DC.

4. Cho, S. E. (2010), Probabilistic assessment of slope stability that considers the spatial variability of soil properties. Journal of geotechnical and geoenvironmental engineering, 136(7), pp 975-984.

5. Christian, J. T., (2004), Geotechnical engineering reliability: How well do we know what we are doing? Journal of geotechnical and geoenvironmental engineering, 130, p 985.

6. Ellingwood, B., T. V. Galambos, et al. (1980), Development of a probability based load criterion for American national standard A58 NBS special report 577, U.S. department of commerce, National bureau of standards, 222.

7. Fenton, G. A. and D. V. Grifths., (2007), Reliability based deep foundation design in probabilistic applications in geotechnical engineering. Geotechnical specialty publication No. 170 ASCE.

8. FHWA (2001), Load and Resistance Factor Design (LRFD) for highway bridge substructures HI-98-032, National highway institute, U.S. Department of transportation.

9. Fisher, J. W., Theodore V. Galambos, et al. (1978), Load and resistance factor design criteria for connectors, Journal of the structural division ASCE, 104(9), pp 1427-1441.

10. Kulhawy, F. H. and K. K. Phoon (2002), Observations on geotechnical reliability-based design development in North America, Taylor & Francis.

11. Lacasse, F. and S. Nadim., (1996), Uncertainties in characterizing soil properties, In uncertainty in the geological environment: From theory to practice proceedings of uncertainty 96 NY USA, Geotechnical special publication no 58, ASCE

12. Low, B. K. and W. H. Tang., (1997), Efficient reliability evaluation using spreadsheet. Journal of geotechnical and geoenvironmental engineering, ASCE 123(7), pp 749-752.

13. Low, B. K. and W. H. Tang (2007), Efficient spreadsheet algorithm for first-order reliability method. Journal of engineering mechanics, 133, p 1378.

14. MOC (2002), Load code for the design of building structures. Ministry of construction, Beijing

15. Nowak, A. S., (1993), Load model for highway bridges. Proceedings of the IFIP WG7.5 fifth working conference on reliability and optimization of structural systems VTakamatsu, North-Holland Publishing Co.

16. Paikowsky, S. G., (2004), Load and Resistance Factor Design (LRFD) for Deep Foundations NCHRP 507, National Coperative Highway Research Program.

17. Phoon, K. K., (2004), Towards reliability-based design, for geotechnical engineering. National University of Singapore, Singapore (Special lecture for Korean Geotechnical Society, Seoul).

18. Phoon, K. K., (2005), Reliability- based design incorporating model uncertainties. 3rd International conference on geotechnical engineering combined with 9th yearly meeting of the Indonesian Society for Geotechnical Engineering, Samarang, Indonesia.

19. Rackwitz, R., (2001), Reliability analysis--a review and some perspectives. Structural safety 23(4), pp 365-395.

20. Ronold, K. O. and P. Bjerager., (1992), Model uncertainty representation in geotechnical reliability analyses. Journal of geotechnical engineering, 118(3), pp 363-376.

21. Rosenblueth, E. and L. Esteva., (1972), Reliability basis for some mexican codes. ACI Publication SP-31. . Detroit, MI, American Concrete Institute.

22. Schneider, J., (1997), Introduction to safety and reliability of structures.

23. Structural Engineering Documents 5., International Association for Bridges and Structural Engineering (IABSE).

24. Siddall, J. N., (1983), Probabilistic engineering planning and design principles and applications. M. Dekker New York

25. Sowers, G. F., (1993), Human Factors in civil and geotechnical engineering failures. Journal of geotechnical engineering, 119(2), pp 238-256.

26. Szerszen, M. M. and A. S. Nowak., (2003), Calibration of design code for buildings (ACI 318): Part 2 - reliability analysis and resistance factors. Structural journal 100((3)), pp 383-391.

27. Taha, M. R., M. Hossain, et al. (1999), Geotechnical behaviour of a Malaysian residual granite soil. Pertanika journal of science & technology, 7(2), pp 151-169.

28. Tan Boon, K. and I. Komoo., (1990), Urban geology: Case study of Kuala Lumpur, Malaysia. Engineering geology, 28(1-2), pp 71-94.

29. Vesic, A. S., (1973), Analysis of ultimate loads of shallow foundations. Journal of the soil mechanics and foundations division, ASCE 99(1), pp 45-73.

30. Whitman, R., (2000), Organizing and evaluating uncertainty in geotechnical engineering. Journal of geotechnical and geoenvironmental engineering (July).

31. Zhao, Y. G. and T. Ono., (1999), A general procedure for first/second-order reliabilitymethod (form/sorm). Structural safety, 21(2), pp 95-112.