International Journal of Engineering and Advanced Research Technology (IJEART)
ISSN: 2454-9290, Volume-3, Issue-5, May 2017

Seismic Bearing Capacity of Strip Footing

Srijita Dey, Bikash Chandra Chattopadhyay, Joyanta Maity

***Abstract*— At present there are quite a number of available methods, to predict the bearing capacity of a strip footing under dynamic loads, but it is not evident which one of these methods predicts more accurately under a given situation. From the viewpoint of possible earthquake effects, India is divided into four zones, for computing seismic forces, either seismic coefficient method (used for pseudo static design of foundations of buildings & bridges) or response spectrum method (used for the case of earth dam) is used [5]. These forces along with the static forces make the foundation subjected to eccentric inclined load. If the resultant load on the foundation has an eccentricity 'e' only in one direction then the dimension of the foundation in that direction is allowed to be reduced by '2e'.**

In this condition it is proposed to study changes of allowable bearing capacity during earthquake for strip footing on sandy soil for various ranges of width of foundation (B), angle of shearing resistance (Φ) of supporting soil and intensity of earthquake from different available theories to check the relativities of such theories. The majority of available solutions in the literature are analytical. Solutions for dynamic bearing capacity for identical foundation were obtained and comparison were made to seek relative differences between the results from such different theories for varying seismic condition.

***Index Terms*— Comparative Study; Purely dry Cohesionless Soil; Shallow Strip Footing; Ultimate dynamic Bearing Capacity.**

I. Introduction

Foundation may be subjected to dynamic forces of variable magnitude and direction due to earthquakes during its life span. As a result a foundation safe enough under static condition need not be so during earthquake. A survey was made to study the reasons for failure of structures during earthquakes in this sub-continent in last few decades. In most of the cases structural failure or liquefaction were identified as major cause of failure. But reduction of bearing capacity during earthquake is also reported as the cause of failure in some cases[5]. Thus reduction in bearing capacity during earthquake should also be considered for safety. Several methods for determining dynamic bearing capacity of soil had been suggested over last few decades with different simplifying assumptions. Validity of such methods are difficult to assess and can only be estimated on the basis of simulated experimental results which are not yet practical to conduct. Some pseudo-static and pseudo-dynamic methods for estimating bearing capacity of footings under earthquake condition are available at present.

From the viewpoint of possible earthquake effects, India is divided into four zones, for computing seismic forces, either seismic coefficient method (used for pseudo static design of foundations of buildings & bridges) or response spectrum method (used for the case of earth dam) is used [5]. These forces along with the static forces make the foundation subjected to eccentric inclined load. If the resultant load on the foundation has an eccentricity 'e' only in one direction then the dimension of the foundation in that direction is allowed to be reduced by '2e'. For reduced dimension of footing, ultimate bearing capacity is estimated by using general bearing capacity equation as per IS 6403:1981 [6]. Saran & Agarwal (1991**)** proposed a theory to determine the bearing capacity of an eccentrically obliquely loaded footing by using limit equilibrium analysis [10]. Richard et. Al. (1993) presented limit analysis including inertial forces due to earthquake and gave the expression for seismic bearing capacity factors [9]. However pseudo-dynamic methods were subsequently introduced to consider the effect of seismic wave velocities in the failure zones on the foundation and several such solutions are available (Choudhury & Nimbalker (2005) [3], Ghosh (2008) [8], Saha & Ghosh (2016)[11]). However purely dynamic analysis for bearing capacity of footing for transient vertical loading (Wallace, 1961 & Triandafilidis, 1965) and for horizontal transient loading (Chummar, 1965) are available. But these methods cannot be used in practice [1].

As a result a theoretical study was undertaken to estimate ultimate bearing capacity under seismic condition for strip footing on cohesionless soil from available methods, for testing the relative differences in the predicted values depending on dimensions of footings, seismic conditions and existing properties of foundation material.

II. Procedure

A theoretical study was undertaken to evaluate dynamic bearing capacity under pseudo-static and pseudo-dynamic condition for strip footing of varying width, different angles of shearing resistance of supporting cohesionless soils and different seismic coefficients. For analysis methods suggested by Richard et. Al.(1993) [9], Abdul-Hamid Soubra (1999)[13], Choudhury and Subba Rao(2005)[2], Shafiee & Jahanandish (2010)[12], for pseudo-static and Ghosh (2008)[8], Ghosh & Saha (2016)[11] for pseudo-dynamic conditions have been used.

One of the most popular and earliest methods for finding dynamic bearing capacity is due to Richard et. al. (1993) in which ultimate bearing capacity under dynamic condition was found by using only two wedges below foundation instead of three conventional wedges below foundation used in Terzaghi's general bearing capacity solution [9,14]. Hence it will be interesting to compare the bearing capacity value from Richard's method assuming seismic coefficient of nil value with that of Terzaghi's general bearing capacity values. Hence the method of analysis for static condition is described first and the method used for dynamic analysis used in this work are described in subsequent section.

A. Static Condition

According to Terzaghi's General Bearing Capacity equation for strip foundation, $(q_u) = CN_C + \gamma D_f N_q + 0.5\gamma B N_\gamma$.

Where N_c,N_q,N_y are the bearing capacity factors and are dependent on φ-values [14].

B. Pseudo-Static Condition

Ultimate Bearing Capacity for strip footing under dynamic condition as proposed by Richard et. Al. (1993), $q_{ud} = CN_{CE}+qN_{qE}+.5\gamma BN_{\gamma E}$. Where N_{cE}, N_{qE} & $N_{\gamma E}$ are the seismic bearing capacity factors dependent on k_h, k_v, φ and q = γ*D [9]. Soubra (1991) estimated seismic bearing capacity of a footing by upper-bound limit analysis for a wide range of friction angle and seismic coefficient. The ultimate seismic bearing capacity expression, given by them, is – $q_{ud}=CN_c(\alpha_i,\beta_i) +qN_q(\alpha_i,\beta_i) +0.5\gamma BN_\gamma(\alpha_i,\beta_i)$. Where, $N_c(\alpha_i,\beta_i)$, $N_q(\alpha_i,\beta_i)$, $N_\gamma(\alpha_i,\beta_i)$ are the seismic bearing capacity factors obtained by them and seem to be dependent on on φ and kh [13]. Choudhury & Rao (2005) considered a horizontal strip footing of width B and embedment depth D_f with D_f/B<-1 and of length L>>B. The ultimate seismic bearing capacity expression, given by them, is – $q_{ud}=CN_{cd}+qN_{qd}+0.5\gamma BN_{\gamma d}$. Where, Ncd, Nqd, Nyd are the seismic bearing capacity factors obtained by them and seem to be dependents on φ, k_h & k_v [2]. Shafiee & Jahanandish (2010) estimated seismic bearing capacity of strip footing for a wide range of friction angle and seismic coefficient. The ultimate seismic bearing capacity expression, given by them, is – $q_{ud}=CN_c+qN_q+0.5\gamma BN_\gamma$. Where, N_c, N_q, N_γ are the seismic bearing capacity factors obtained by them and seem to be dependent on φ, k_h & k_v [12].

C. Pseudo-Dynamic Condition

Ghosh (2008) estimated seismic bearing capacity of strip footing by using pseudo-dynamic approach. Under the seismic conditions, the values of the unit weight component of bearing capacity factor $N_{\gamma E}$ were determined for different magnitudes of soil friction angle, soil amplification and seismic accelerations both in the horizontal and vertical directions [8]. Ghosh & Saha (2016) estimated seismic bearing capacity of strip footing by using log spiral failure mechanism. Under the seismic conditions, the values of the unit weight component of bearing capacity factor $N_{\gamma E}$ were determined for different magnitudes of soil friction angle, and seismic accelerations both in the horizontal and vertical directions [11]. Unlike in pseudo-static approach, Ghosh (2008), Ghosh & Saha (2016) didn't propose any bearing capacity equation. They only considered $N_{\gamma E}$ factor. However to make the comparisons between the pseudo-static and pseudo-dynamic approaches, the considered ultimate dynamic bearing capacity equation is, $q_{ud}=0.5\gamma BN_\gamma$.

[1] VALUES OF BEARING CAPACITY FACTORS OBTAINED FROM DIFFERENT THEORIES FOR DIFFERENT CONDITIONS

Table 1: Nc, Nq, Nγ values corresponding to different φ-values after Terzaghi (1929)

φ – value	N_c	N_q	N_γ
30°	37.2	22.5	19.7
35°	57.8	41.4	42.4
40°	95.7	81.3	100.4

Table 2: NcE ,NqE, NγE values corresponding to different φ-values after Richard et. al. (1993)

φ-Value	k_h	k_v	N_{cE}	N_{qE}	$N_{\gamma E}$
30°	0	0	26.89	16.53	43.46
35°	0	0	69.29	29.907	117.352
40°	0	0	41.28	59.146	453.02

Table 3: N_{cE},N_{qE}, $N_{\gamma E}$ values corresponding different φ-values& k_h, k_v after Richard et. al. (1993)

φ-Value	k_h	k_v	N_{cE}	N_{qE}	$N_{\gamma E}$
30°	0.1	0* k_h	19.74	12.397	25.044
	0.2		14.09	9.133	14.76
	0.3		9.56	6.517	8.461
	0.4		5.09	4.408	4.461
	0.1	0.5*k_h	22.31	13.88	28.04
	0.2		13.11	8.57	12.78
	0.3		6.77	4.91	5.26
	0.4		2.84	2.64	1.79
35°	0.1	0* k_h	30.23	22.169	59.936
	0.2		21.92	16.351	34.029
	0.3		15.41	11.791	19.71
	0.4		10.37	8.264	11.216
	0.1	0.5* k_h	29.66	21.77	59.34
	0.2		20.77	15.54	29.9
	0.3		12.48	9.74	13.79
	0.4		6.47	5.53	5.71
40°	0.1	0* k_h	50.2	43.123	169.779
	0.2		36.33	31.483	86.725
	0.3		25.95	22.776	48.685
	0.4		18.15	16.228	28.127
	0.1	0.5* k_h	48.64	41.81	166.78
	0.2		33.33	28.97	73.36
	0.3		21.79	19.28	34.76
	0.4		12.19	11.23	15.04

Table 4: N_c,N_q, N_γ values corresponding to different φ-values& k_h after Soubra (1999)

φ-Value	k_h	k_v	N_c	N_q	N_γ
30°	0.1	0* k_h	25.09	14.34	13.59
	0.2		20.32	10.67	7.67
	0.3		16.12	7.54	3.8
	0.4		12.58	4.97	1.51
35°	0.1	0* k_h	37.74	25.7	31.23
	0.2		30.06	19.08	18.32
	0.3		23.5	13.65	9.89
	0.4		18.12	9.36	4.77
40°	0.1	0* k_h	60.38	48.89	75.92
	0.2		47.12	35.96	45.12
	0.3		36.18	25.73	25.31
	0.4		27.47	17.89	13.29

Table 5: N_{cd},N_{qd}, $N_{\gamma d}$ values corresponding to different φ-values& k_h, k_v after Choudhury & Rao (2005)

φ-Value	k_h	k_v	N_{cd}	N_{qd}	$N_{\gamma d}$
30°	0.1	0* k_h	28	14	9.2
	0.2		10	7	4
	0.3		6	3.6	1.9
	0.4		3	1.9	0.78
	0.1	0.5* k_h	27	11	9
	0.2		8.5	5.9	2.8
	0.3		5	2.7	1.1
	0.4		2	0.9	0.2
40°	0.1	0* k_h	40	41	55
	0.2		22	25	21
	0.3		18	15	9
	0.4		8.9	8	4
	0.1	0.5* k_h	38	40	50
	0.2		29	21	16
	0.3		14	11	5
	0.4		7	4	0.9

Table 6: N_c,N_q, N_γ values corresponding to different φ-values& k_h after Shafiee & Jahanandish (2010)

φ-Value	k_h	k_v	N_c	N_q	N_γ
30°	0.1	0* k_h	29	18	9
	0.2		25	12	5
	0.3		18	9	3
	0.4		15	7	2.2
35°	0.1	0* k_h	50	29	30
	0.2		23	24	17
	0.3		30	19	9.8
	0.4		28	10	6
40°	0.1	0* k_h	70	54	60
	0.2		60	43	40
	0.3		50	33	28
	0.4		37	27	17

Table 7: $N_{\gamma E}$ values corresponding to φ=30° & different k_h values after Ghosh (2008)

φ-Value	k_h	k_v	$N_{\gamma E}$
30°	0.1	0.5* k_h	20.39
	0.2		9.98

Table 8: $N_{\gamma E}$ values corresponding to φ=30° & different k_h values after Saha & Ghosh (2016)

φ-Value	k_h	k_v	$N_{\gamma E}$
30°	0.1	0.5* k_h	4.067
	0.2		1.371

III. DATA CONSIDERED FOR CALCULATION

In this work width of strip footing is selected within the range used in practice and four different sizes are considered, which are given below in Table-9. Depth of foundation (D_f) = 1.5m. is considered in this paper.

ultimate bearing capacity of above footings are evaluated by assuming supporting medium to be dry cohesionless soil of φ-values ranging over the wide values of 30°, 35°, 40°. The corresponding unit weight of soil is chosen from available co-relation between angle of shearing resistance and corresponding dry density, which is given in Table-10.

For all the above footing and foundation soil condition Seismic bearing capacity are evaluated in this paper by considering K_h varying from .1 to 0.4 for K_v =0*K_h.

Table 9: Considered B-values in m.

B-value in m.	1.5	2	2.5	3

Table 10: φ-values & its corresponding γ_d in KN/m^3

φ - value	γ_d in KN/m^3
30°	19.5
35°	20.5
40°	21.5

IV. COMPARISON BETWEEN DIFFERENT THEORIES

Detailed results of ultimate dynamic bearing capacity of a strip footing on cohesionless soil, for different B-values, different φ-values, k_h and k_v values seismic co-efficient, have been evaluated for different theories, From these results it has been seen that with increase in k_h values bearing capacity decreases and with increase of B-values bearing capacity increases both in static condition and in dynamic condition though not in same manner in dynamic condition.

Comparison of Ultimate Bearing Capacity in static conditions

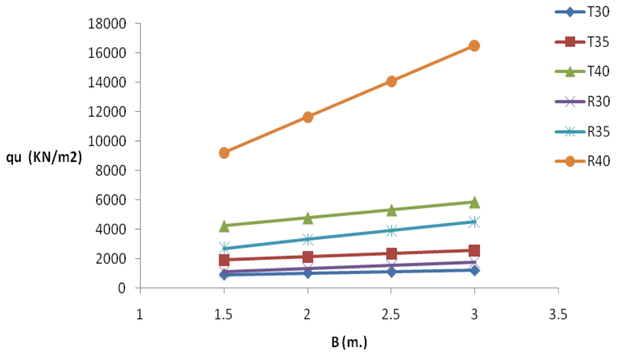

Figure 1: q_u vs. B values obtained from Terzaghi's method & Richard et. al. method in static condition for different φ values

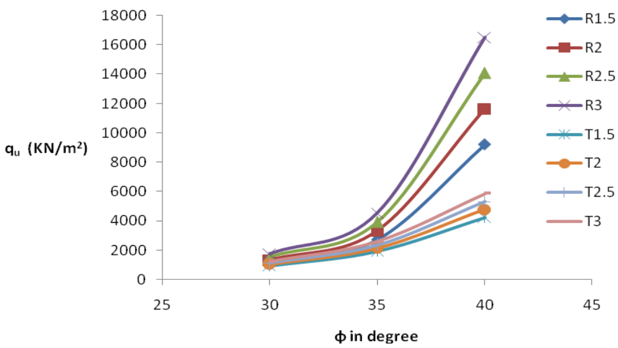

Figure 2: q_u vs. φ Obtained from Terzaghi's method & Richard et. al. method in static condition for different B values.

Fig.1 and 2 shows for higher B values and φ values q_u value increases for both Terzaghi's theory and Richard et.al. theory in static condition. But Richardet.al. overestimate the q_u value to great extent for both varying B and φ values.

V. Comparison of Ultimate Dynamic Bearing Capacity in Pseudo-Static Conditions

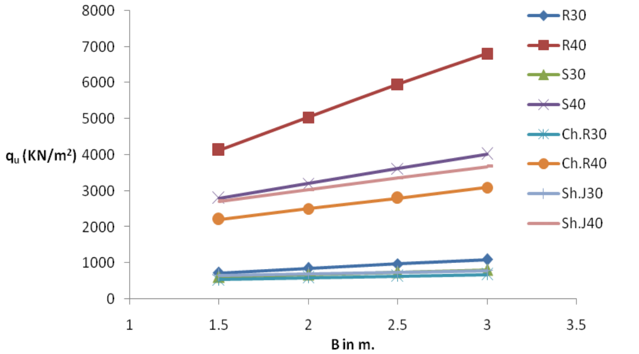

Figure 3: q_u vs. B value for different theory in pseudo-static condition for k_h=0.1 & φ=30°,40°

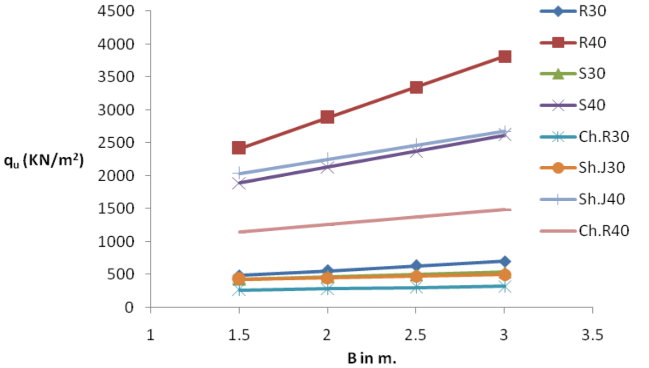

Figure 4: q_u vs. B value for different theory in pseudo-static condition for k_h=0.2 & φ=30°,40°

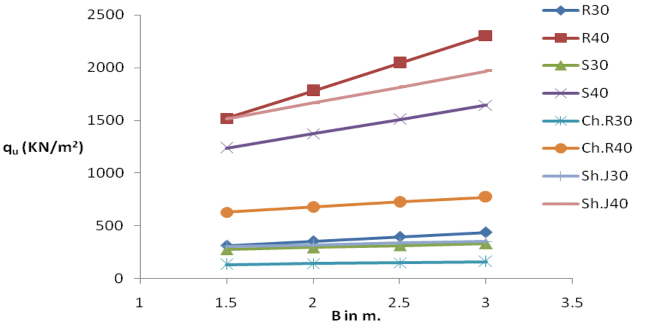

Figure 5: q_u vs. B value for different theory in pseudo-static condition for k_h=0.3 & φ=30°,40°

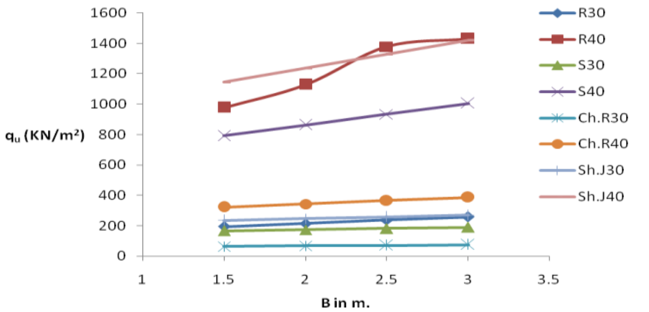

Figure 6: q_u vs. B value for different theory in pseudo-static condition for k_h=0.4 & φ=30°,40°

From Figures. 3 to 6 it is seen that Richard's theory always predict larger q_u values compared to that of obtained from others theory for both high and low values of φ. But in few cases it gives smaller values compared to that of obtained from others theory. For k_h=0.2 & φ=30°, for k_h=0.2, φ=40° the difference of q_u values obtained from Richard's theory, Shafiee's theory and Soubra's theory are quite small for lower B values whereas for k_h=0.3, φ=30°, k_h=0.3, φ=40° it is seen that Richard's theory and Shafiee's theory give quite similar values of q_u for B=1.5m. and for higher B values the difference of q_u values are small. But for all above mentioned figure the values of qu obtained from Choudhury's theory are very much low compared to the others. Also for a fixed width of footing Richard's theory overestimate qu values for lower kh and for higher kh the difference qu values obtained from Richard's theory, Soubra's theory and Shafiee's theory are less. But for all cases (B=1.5m., 2.0m., 2.5m., 3.0m.) qu values obtained from Choudhury's theory gives quite smaller values. q_u vs. k_h value for different B values for φ=30°, 40° for different theory in pseudo-static condition are given in Fig. 7 to 10.

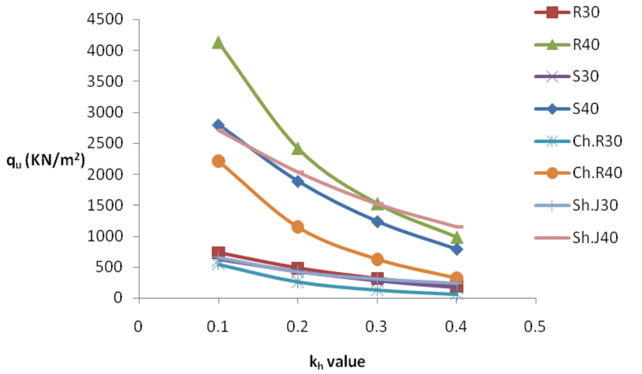

Figure 7: q_u vs. k_h value for different theory in pseudo-static condition for B=1.5m. & φ=30°, 40°

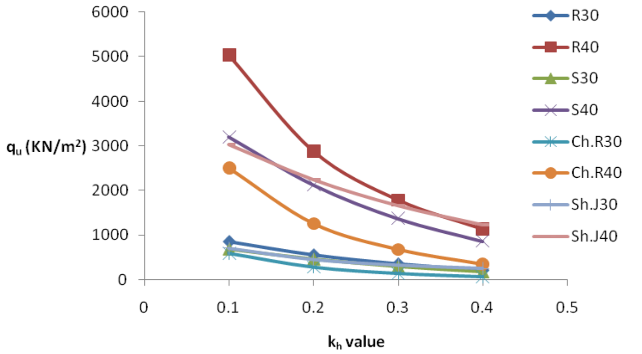

Figure 8: q_u vs. k_h value for different theory in pseudo-static condition for B=2.0m. & φ=30°, 40°

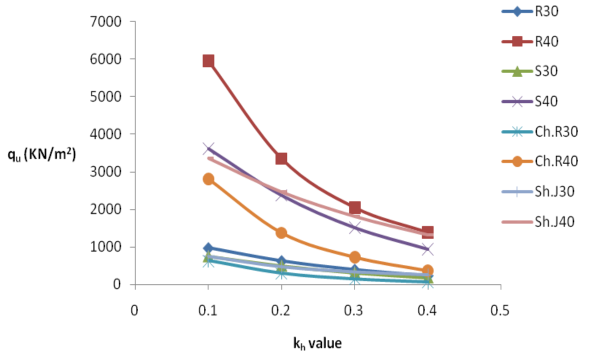

Figure 9: q_u vs. k_h value for different theory in pseudo-static condition for B=2.5m. & φ=30°, 40°

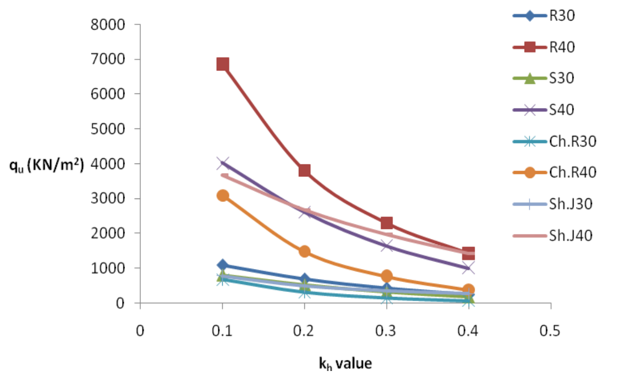

Figure 10: q_u vs. k_h value for different theory in pseudo-static condition for B=3.0m. & φ=30°, 40°

Comparison of Ultimate Dynamic Bearing Capacity between Pseudo-Static & Pseudo-Dynamic Conditions

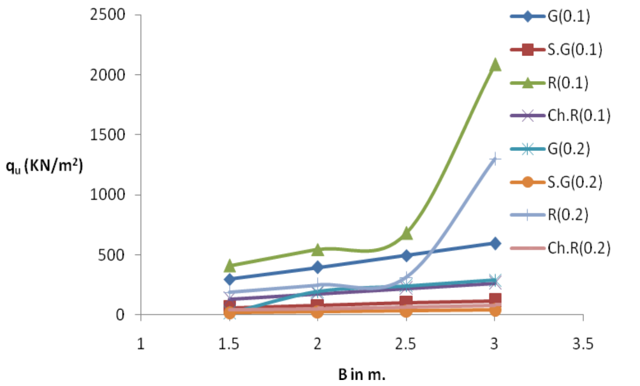

Figure 11: q_u vs. B value for different theory in pseudo-static condition for k_h=0.1, 0.2, k_v=0.5*k_h & φ=30°

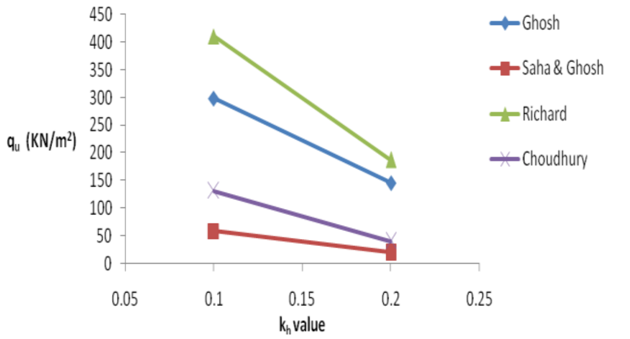

Figure 12: q_u vs. k_h value for different theory in pseudo-static condition for B=1.5m. & φ=30°

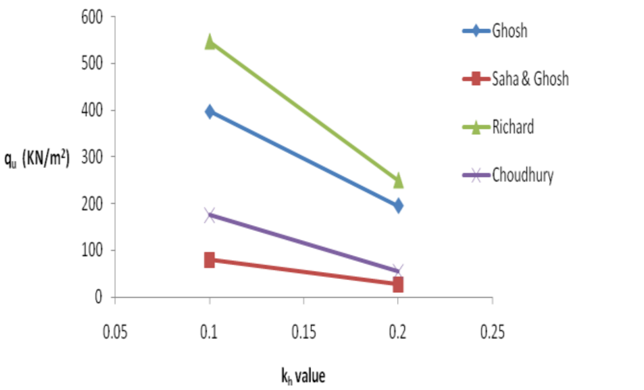

Figure 13: q_u vs. k_h value for different theory in pseudo-static condition for B=2.0m. & φ=30°

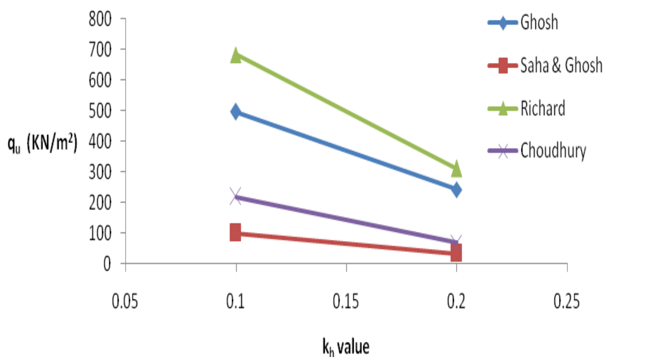

Figure 14: q_u vs. k_h value for different theory in pseudo-static condition for B=2.5m. & φ=30°

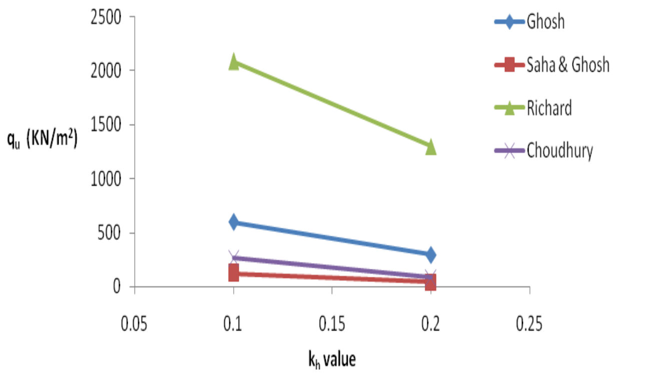

Figure 15: q_u vs. k_h value for different theory in pseudo-static condition for B=3.0m. & φ=30°

From Fig.-11 for k_h=0.1, 0.2, k_v=0.5*k_h & φ=30° it is seen that with increasing B values q_u values are also increasing linearly but values of qu obtained from Richard et.al. theory increasing in non-linear manner. Also from Fig- 12 to 15 for φ=30° and varying B values, with increasing k_h, values of q_u decreases for all theories. But again Richard et.al theory gives much higher q_u values compared to that of obtained from other theories. But qu values obtained from Saha & Ghosh theory gives comparatively low values than other theories.

VI. CONCLISION

Detailed examination regarding available methods to find dynamic bearing capacity of strip footings on cohesionless soils under seismic condition has been made in this paper. General Codal provision prescribes allowable bearing under dynamic condition to take a higher value than that in static condition [IS 1893]. However many researchers indicates just reverse fashion in practice [indra]. With this view attain an examination was made to find the predicted values of dynamic bearing capacity from allowable theories advanced by recent researchers under varying width of strip footing and different soil properties and seismic condition.

For the purpose of comparison bench mark solution for dynamic bearing capacity was taken those from Richard et.al (1993) which was the most important publication within last two decades which indicated large scale research activity in this domain.

However, from all the comparisons it is seen that Richard et.al. theory gives higher values may be due to the model chosen by Richard et.al (two wedge below foundation at failure condition). But in pseudo-dynamic condition Saha & Ghosh theory gives much lower values compared to other theories.

ABBREVIATIONS

B=Width of foundation
φ=Angle of shearing resistance.
k_h=Horizontal seismic co-efficient
k_v=Vertical seismic co-efficient.
q_u=ultimate bearing capacity.
R30= Richard et.al. values at φ=30°
R40= Richard et.al. values at φ=40°
S30= Soubra's value at φ=30°
S40= Soubra's values at φ=40°
Ch.R30= Choudhury & Rao's values at φ=30°
Ch.R40= Choudhury & Rao's values at φ=40°
Sh.J30= Shafiee & Jahanandish's values at φ=30°
Sh.J40= Shafiee & Jahanandish's values at φ=40°
R1.5= Richard et.al. values at B=1.5
R2= Richard et.al. values at B=2.0
R2.5= Richard et.al. values at B=2.5
R3= Richard et.al. values at B=3.0
T1.5 =Terzaghi's values at B=1.5
T2= Terzaghi's values at B=2
T2.5= Terzaghi's values at B=2.5
T3= Terzaghi's values at B=3
G(0.1)= Ghosh's value at k_h=0.1
G(0.2)= Ghosh's value at k_h=0.2
S.G(0.1)= Saha & Ghosh's value at k_h=0.1
S.G(0.2)= Saha & Ghosh's value at k_h=0.2
R(0.1)= Richard et.al.'s value at k_h=0.1
R(0.2)= Richard et.al.'s value at k_h=0.2
Ch.R(0.1) =Choudhury & Rao's value at k_h=0.1
Ch.R(0.2) =Choudhury & Rao's value at k_h=0.2

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Srijita Dey, Post Graduate Student, of Geotech. Dept., Meghnad Saha Institute of Technology, Kolkata.

Bikash Chandra Chattopadhyay, PhD (IIT, Kharagpur) is Professor of C.E. Dept., Meghnad Saha Institute of Technology, Kolkata. He has been Head of C.E. Dept., Dean of Research and Consultancy and Coordinator of Quality Improvement Programme at Bengal Engineering and Science University [BESUS, presently IIEST], Shibpur. He has been engaged in teaching geotechnical engineering, research and consultency over last 46 years and received Leonard's award for the best PhD thesis from IGS in 1987. He has published several books in the areas of his specialisation and more than 140 research papers in different national and international conferences and journals.

Joyanta Maity, PhD (JU) is Assistant Professor of C.E. Dept., Meghnad Saha Institute of Technology, Kolkata. He is actively engaged in teaching both PG and UG Civil Engineering students for more than a decade. His research interests include ground improvement techniques, use of alternative materials and use of natural geofibers in Civil Engineering. He has published more than 35 papers in different national and international conferences and journals.