A Numerical Study of Bearing Capacity Coefficients of Soil beneath Foundation under Earthquake Load

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ABSTRACT

Evaluation of soil bearing capacity coefficients of has been the focus of a significant amount of studies by various researchers. In all conducted studies and analyses, by considering different forms of earthquake load with pseudo-static performance, different results have been obtained. In this research, evaluation of soil bearing capacity coefficients under earthquake load has been carried out using finite elements software Plaxis and the obtained results have been compared with those from other published studies. Moreover, the effect of the inertia of the underpinning soil on the soil bearing capacity coefficients was modeled in the pseudo- static mode and the results indicated that bearing capacity coefficients obtained from pseudo-static gave good agreement with other methods. However, comparison of these two results revealed that the results obtained from numerical modeling are more conservative and are on the safety side. Finally, since the pseudo –static load is not characterized as an appropriate alternative for the earthquake load; the effect of underpinning soil on the manner of transferring the earthquake waves until reaching the foundation bed has been also investigated. Evaluation of soil bearing capacity coefficients of has been the focus of a significant amount of studies by various researchers. In all conducted studies and analyses, by considering different forms of earthquake load with pseudo-static performance, different results have been obtained. In this research, evaluation of soil bearing capacity coefficients under earthquake load has been carried out using finite elements software Plaxis and the obtained results have been compared with those from other published studies.

KEYWORDS: Numerical modeling, Bearing capacity, Earthquake load, Plaxis, Pseudo– static load

INTRODUCTION

Investigation on bearing capacity of soil beneath foundation under static conditions and without presence of earthquake load may back to Terzaghi's time and has been extensively studied and developed since then. Although there are many studies on soil bearing capacity without considering earthquake effect, only a few studies have been conducted on soil bearing capacity under earthquake load. Some reasons for that are as follows:

a) In order to consider the effect of cyclic loads on the soil bearing capacity, a proper behavior model is needed and, this in turn requires conducting tests on different soils [6].

b) According to experience and observations, it was found that structural failure is rarely due to the failure of soil beneath foundation. This implies high safety factor for design of foundations considering earthquake load [4].

c) Contrary to structural engineering, applying pseudo static conditions for earthquake load in geotechnical engineering requires using different types of hypothesis which are not consistence with the real behavior of soil.

The bearing capacity coefficients with and without earthquake effect are defined by Nc, Nq, N and Nce, Nqe, N e respectively. It should be noted that by way of comparison, the reduction in each coffecient can be found with and without presence of earthquake load [4, 7]. Although analysis of soil bearing capacity through considering earthquake effect is not fully understood, a large number of studies have been performed to consider different approximation of static conditions of bearing capacity analysis. In what follows, some of the best-known studies are presented.

Meyerhof (1953), Sokolovski (1960) Shinohara et al., (1960) studied the soil bearing capacity against oblique load which its horizontal component was considered as the substitute of earthquake load, Furthermore, Prakash and Chummar (1967) and Shikhiev and Jakovlev (1977) performed more detailed studies on this topic. Okamoto (1973) modeled the reduction of bearing capacity due to the earthquake effect through reduction of internal friction angle equal to $i = \tan^{-1} k_h$ [4]. In other further studies, in addition to the effect of horizontal earthquake load on foundation, upper surcharge and ($q = \gamma D_f$), the effect of this load on different parts of soil beneath foundation have been investigated. As such, Sarma and Isossifelis (1990) and Budehu and AL-Karni (1993) studied the effects of horizontal and vertical components of earthquake load, respectively. As recent studies, it should be mentioned to studies of Chummar and muhan (2002) [7]. According to literature review, it was concluded that the conducted studies can be categorized in three different groups. In the first group, like studies of Meyerhof and Sokolovski, the effect of earthquake has been considered as a horizontal load imposed to structure, foundation and upper surcharge and produced inertia from earthquake has been ignored in soil beneath foundation. In the second group, such as studies of Sarma and Isossifelis (1990), in addition to structure, foundation and upper surcharge, the effect of oblique earthquake load has been considered on the failure region of soil beneath foundation. Finally in the third group, like studies of Budehu and AL-Karni (1993), the vertical component of earthquake has been also considered.

In all above-mentioned studies, the objective is to determine bearing capacity coefficients Nc, Nq and N_γ. Due to the dependency of these coefficients on internal friction angle ϕ, the obtained results are presented in terms of this parameter. Since Nc and Nq are not dependent to the soil weight, the difference between these two coefficients is less marked. Even if on the basis of analysis method, the status of pseudo failure surface is different, the difference between Nc and Nq is not notable. However, in the case of N , different status of pseudo failure surface will lead to different results for this parameter [5]. In this study, two types of theoretical sections have been used as comparison criteria for failure mechanism. Figure 1 shows the transverse section of a strip foundation with the width of B and status of different layers of soil beneath foundation in the failure region under static and seismic conditions. As it can be seen, the horizontal forces resulting from earthquake and internal angels of failure regions assumed in the theory of Budehu and AL-Karni (1993) are shown. Furthermore, the analysis results are illustrated in Figure 2.

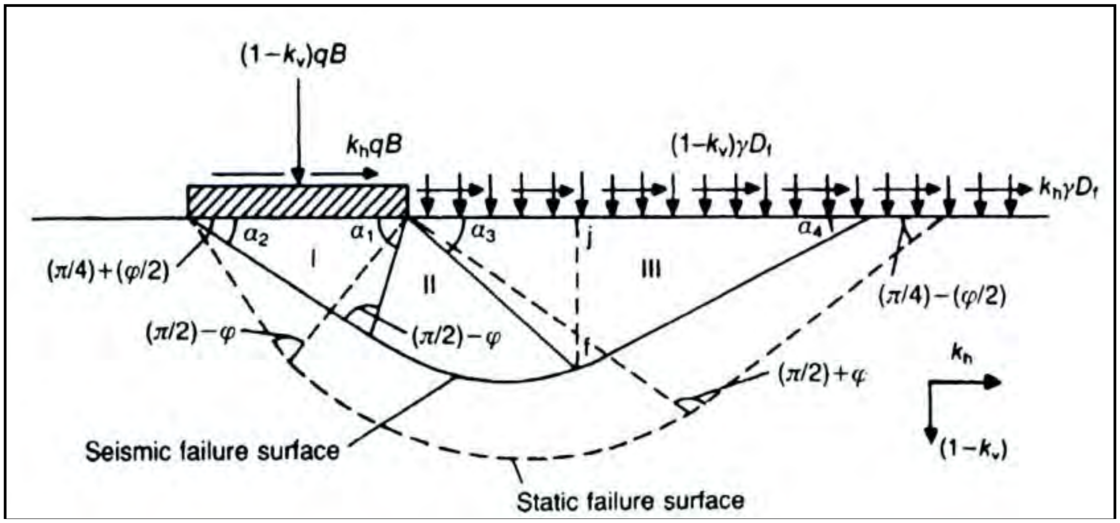

Figure 1: Soil failure mechanism under static and seismic conditions assumed in the theory of Budehu and AL-Karni (1993) [9]

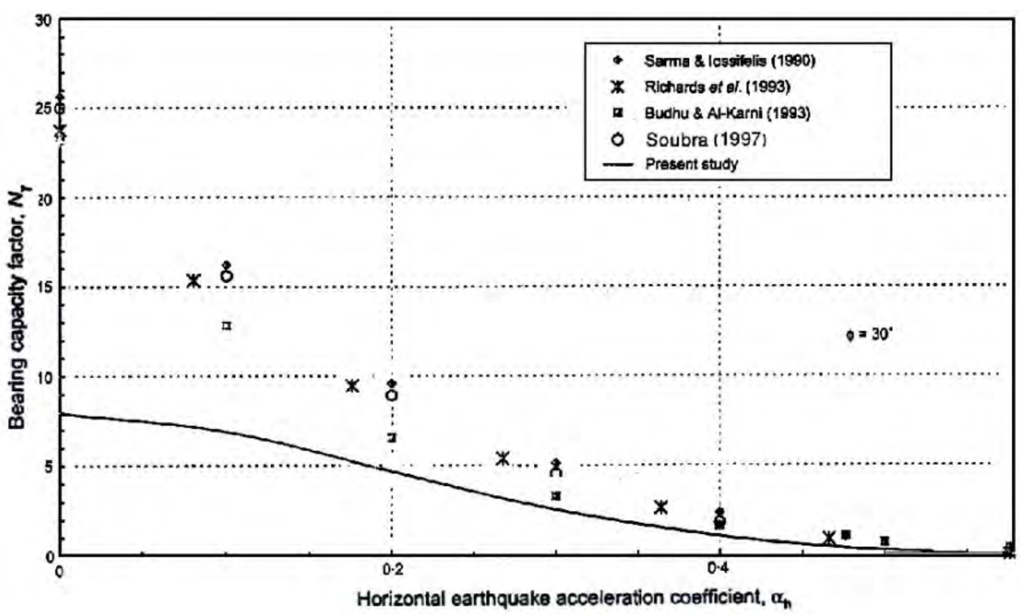

Figure 2: Bearing capacity factor N_γ based on the variations of lateral pressure coefficient for only frictional soil ϕ=30° [10]

METHODOLOGY

In this paper, in order to determine bearing capacity parameters under pseudo static and seismic conditions and through using finite element method, seismic load has been imposed to the foundation and soil in the form of dynamic and pseudo static loads. The numerical studies were performed by PLAXIS Software for three following cases:

a) Investigation on the horizontal component of earthquake force in the form of pseudo-static load and its effect on the reduction of bearing capacity of soil beneath foundation.

b) Investigation on the effect of layers of soil beneath foundation on the movement and magnification of earthquake waves from depth to surface.

c) Investigation on the effect of earthquake waves on the soil bearing capacity using accelerographs. Figure 3 shows the position of points where earthquake waves are studied and also variation of waves intensity passing through depth to surface are illustrated in Figures 4 and 5.

The obtained results showed the effect of soil layers, intensity of earthquake waves, duration of earthquake and damping on the passage of earthquake waves from depth to surface of earth. As it can be seen, the effect of wave on the bearing capacity of soil beneath foundation is different and magnification of earthquake waves varies with changes in the conditions.

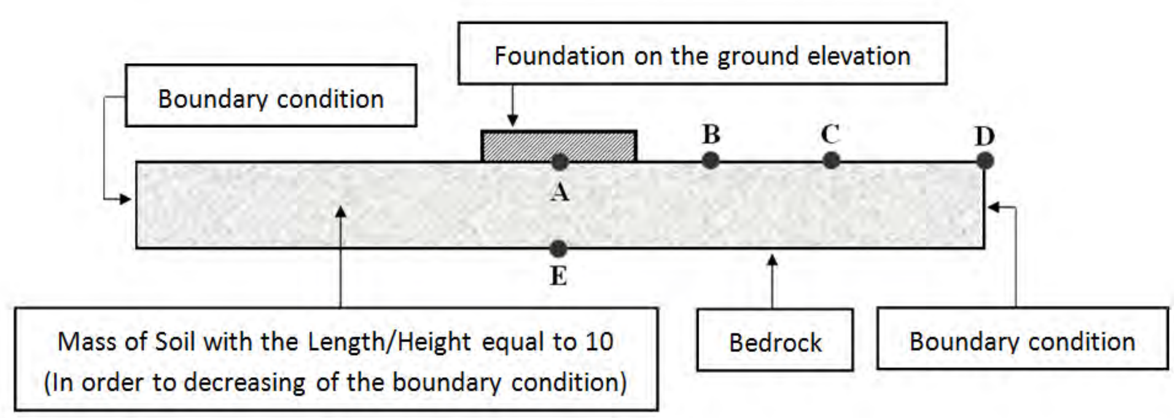

Figure 3: Position of points where earthquake wave has been examined

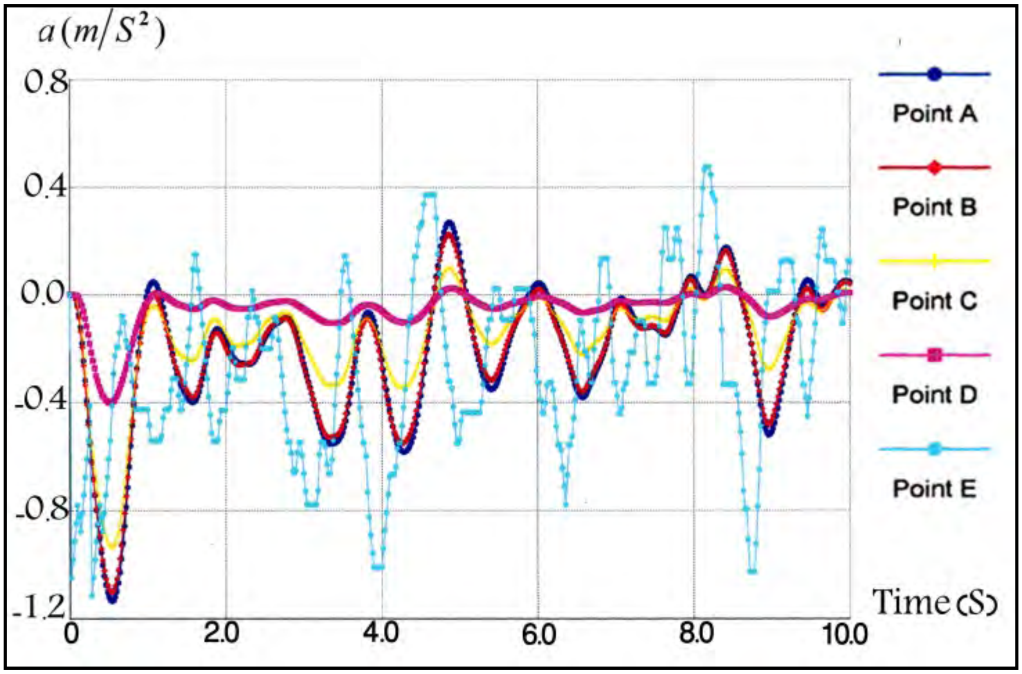

Figure 4: Illustration of earthquake waves variations from depth to surface (through considering earthquake effect $\phi = 30^o$, E = 100 MPa, a = 0.1g)

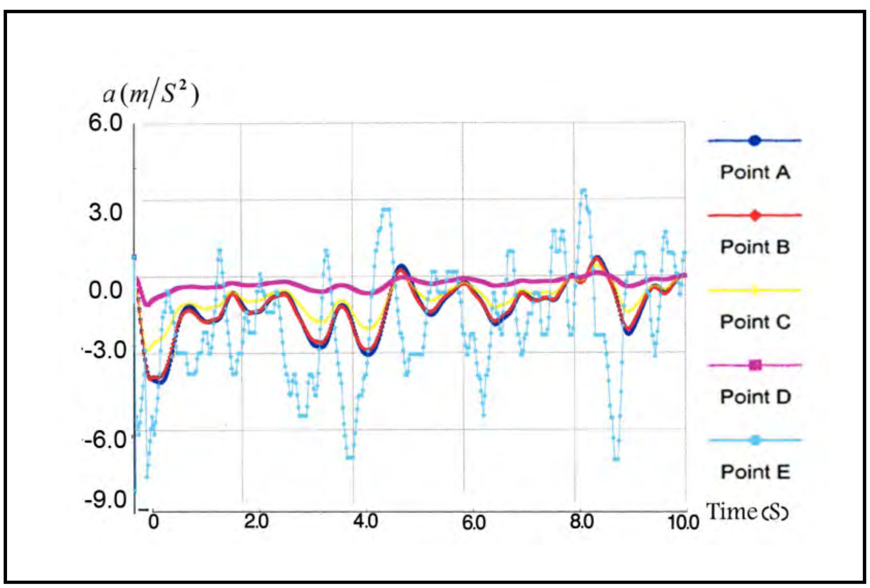

Figure 5: Illustration of earthquake waves variations from depth to surface (through considering damping effect $\phi = 30^o$, E = 100 MPa, a = 0.7g)

Assuming that bearing capacity of foundation under static conditions is given and also the imposed load to foundation is less than the ultimate load, in the event of an earthquake, it is probable that foundation reaches to failure stage because of reduction in bearing capacity. Therefore, through first applying a vertical load lower than ultimate bearing capacity of foundation, i.e., around 80% to 95 % of ultimate bearing capacity, and then applying earthquake effect, it is possible to determine combination of static load and maximum acceleration of earthquake which lead to failure. As such, several studies have been performed to determine soil bearing capacity under dynamic conditions for different loading and soil conditions which did not lead to results. In order to compute the coefficients of soil bearing capacity, the effect of earthquake load was considered as horizontal pseudo-static load K_h.q and vertical component of earthquake load (1-Kv.q) [8]. In other words, the propagation of earthquake waves from depth to surface has priority to the earthquake effect as an external force imposed from foundation to soil and can independently affect the behavior of soil beneath foundation. In this paper, in order to investigate the effect of horizontal load Kh.q on the soil failure, the inertia effect of soil beneath the foundation has been considered as Kh.w in the calculations. Moreover, through conducting several calculations, different combinations of vertical and horizontal of earthquake load have been obtained for soil failure conditions. It should be noted that critical conditions have been studied for selective accelerations and the results for Nc and N are shown in Figures 6 and 7.

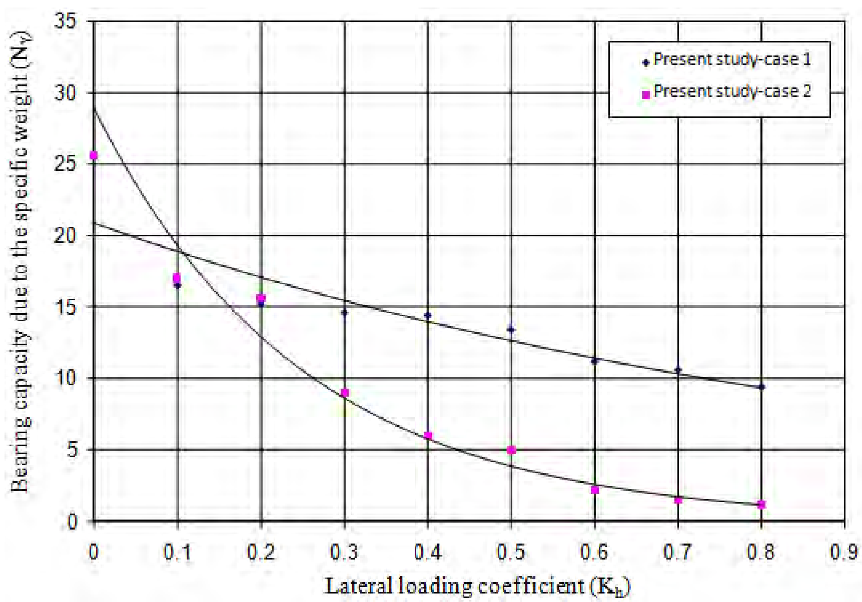

Figure 6: Variations of bearing capacity due to the specific weight (N_γ) versus lateral loading coefficient (K_h) for soil with c=0 and ϕ = 30^o (first case: with considering inertia of soil mass and second case: without considering the inertia of soil mass)

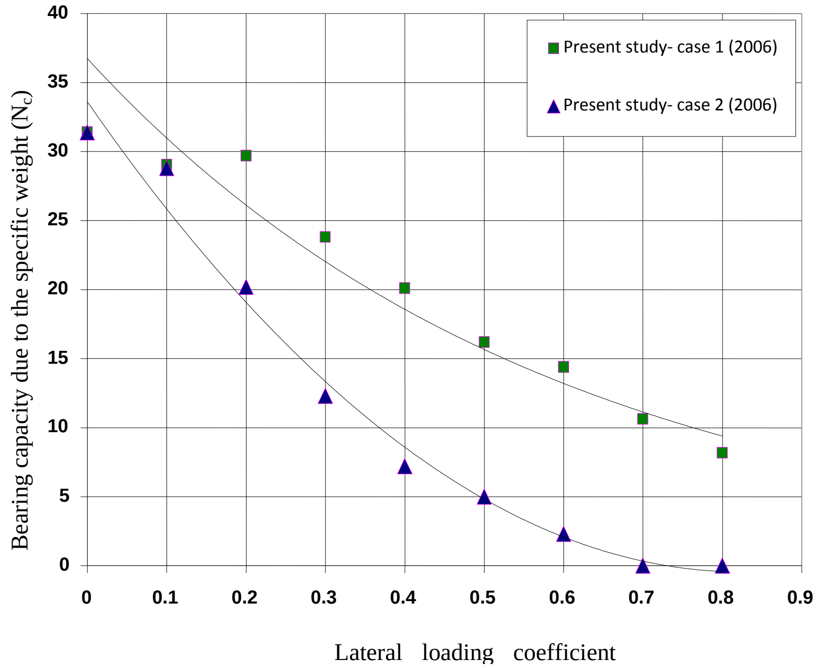

Figure 7: Variations of bearing capacity due to the cohesion (N_c) versus lateral loading coefficient (K_h) for soil with c=50 KPa and $\phi = 30^o$ (first case: with considering inertia of soil mass and second case: without considering the inertia of soil mass)

As shown in Figures 6 and 7, the reducing rate of bearing capacity is more sensible when the inertia effect of soil is considered. It should be mentioned that similar studies have been performed for other coefficients of soil bearing capacity which is not in the scope of this paper. For the sake of comparison of obtained results with other studies, Figures 8 and 9 are presented. In these figures, bearing capacity coefficients Nc, N_γ have been compared with the results of other studies with and without considering the inertia effect of soil mass beneath foundation [1, 2 and 3].

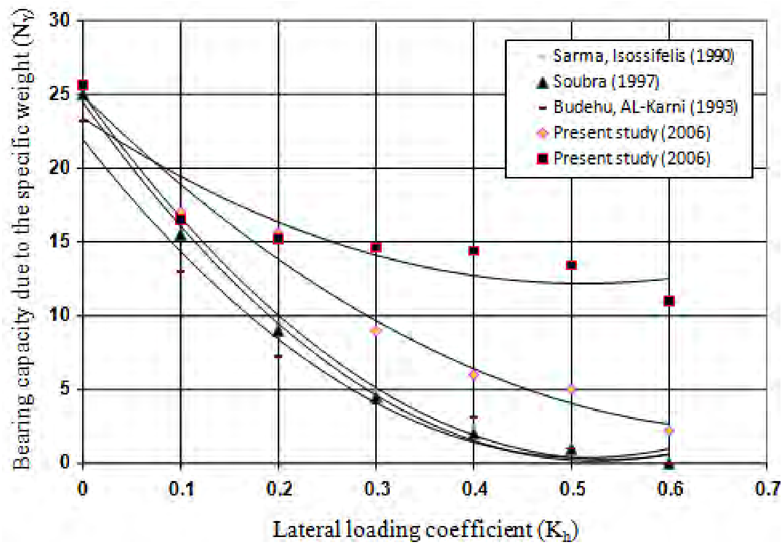

Figure 8: Comparison the variations of bearing capacity due to the specific weight (N_γ) versus lateral loading coefficient (K_h) for soil with c=50 kPa and ϕ = 30^o in this study and other studies

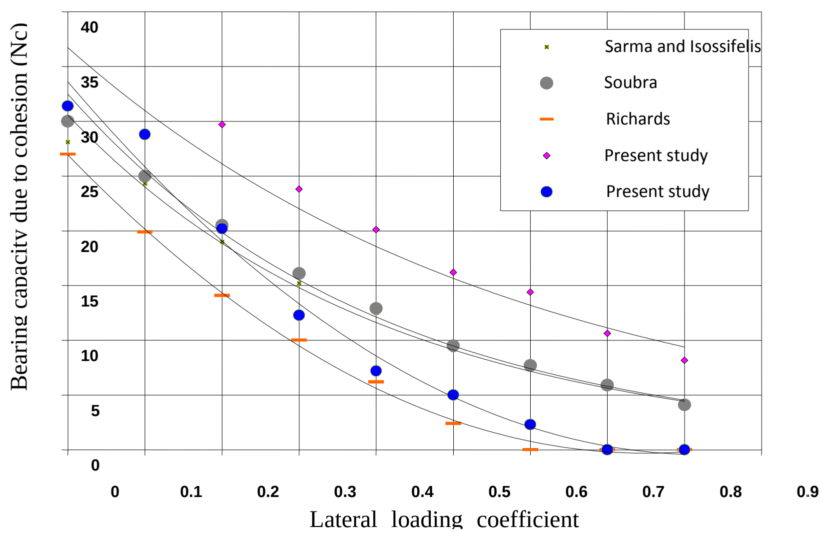

Figure 9: Comparison the variations of bearing capacity due to cohesion (N_c) versus lateral loading coefficient (K_h) for soil with c=50 kPa and ϕ = 30^o in this study and other studies

Furthermore, through considering the inertia of soil mass, the ratio of pseudo static to static condition of N_c and N_γ are depicted in Figures 10 and 11, respectively.

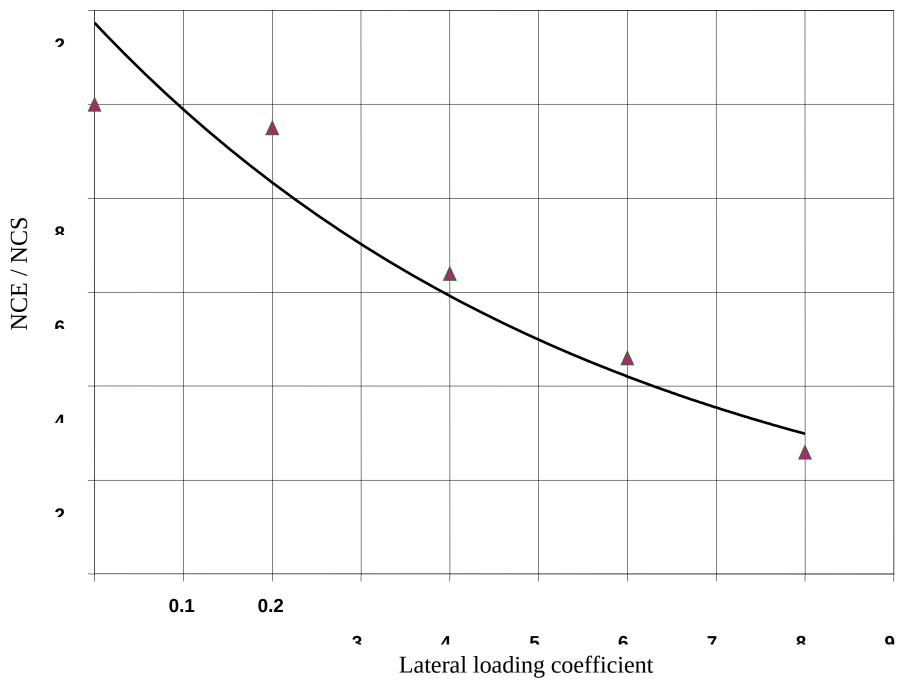

Figure 10: Ratio of pseudo static to static condition of N_c

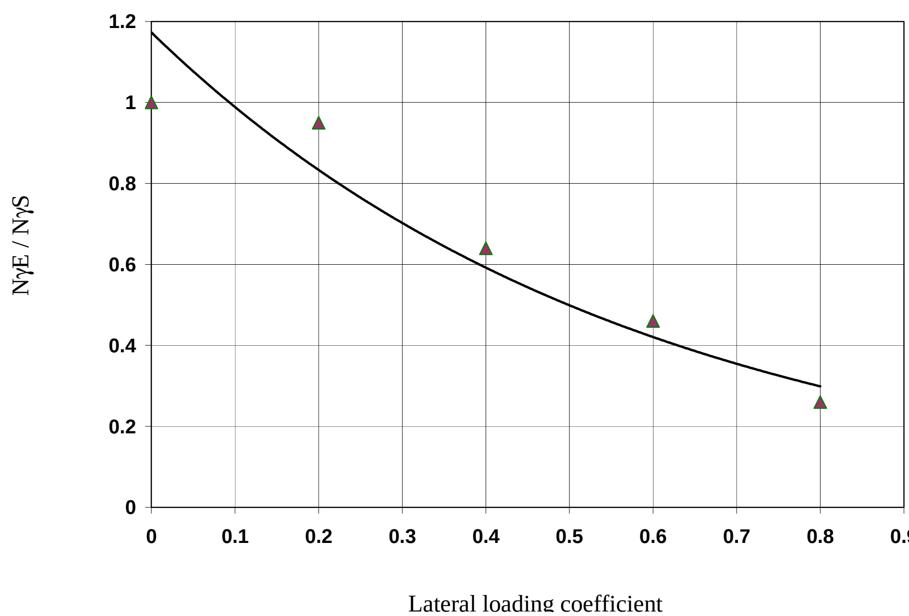

Figure 11: Ratio of pseudo static to static condition of N_γ

CONCLUSIONS

The results of the present study can be summarized as follows:

(1) PLAXIS finite element software models the soil beneath foundation on the basis of layer type, acceleration, damping and magnification of earthquake waves passing from depth to the surface of earth.

(2) This software is capable to consider the inertia effect of soil mass to estimate bearing capacity and its parameters under pseudo static conditions.

(3) The reducing rate of bearing capacity because of the earthquake is more sensible when the inertia effect of soil is considered.

(4) Seismic modeling of soil bearing capacity by pseudo static load fails to consider the effect of parameters such as soil compaction, instantaneous increase in pore water and strength parameters of soil, i.e., cohesion and internal friction angle during earthquake.

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