Literature Review on Effects of Lateral Forces on Shallow Foundations

Pallavi R. Kulkarni, Tejashri R. Sambre

Abstract—Foundations of any building or structure shall be designed and constructed to withstand safely all the dead, imposed and wind loads without impairing the stability or inducing excessive movement to the building or of any other building, street, land, slope or services. Shallow footings are subjected to lateral forces induced by earthquake movements, wind loads, water wave pressure, lateral earth pressure, and transmitting power cables. In some structures such as water front structure, earth retaining structure and transmitting power structures, the lateral forces acting on the footings may be dominant. Building only with shallow foundation may overturns under earthquake load. The seismic risk mitigation is one of the greatest challenges of the Civil Engineering and an important contribution toward this challenge can be given by the Geotechnical Earthquake Engineering. Design of foundations in seismic areas needs special considerations compared to the static case.

Index Terms—Shallow foundation, earthquake, symmetry of footings, lateral forces.

I. INTRODUCTION

A shallow foundation should be structurally adequate to sustain all the applied loads and transmit them safely to the ground without undue settlement. It should generally be constructed of reinforced concrete, and rest on a rock or soil stratum with adequate bearing capacity at a shallow depth from ground level. A shallow foundation should neither overload the foundations or structures of adjacent buildings or the ground supporting such foundations or structures, nor render any instability to any hillside or slope, nor interfere with any drain, nullah, sewer or other services in its vicinity.

II. LITERATURE REVIEW

Various authors have contributed to several aspects in the form of research papers and text books, which are unique and are based on research. Latest selected publications and the state of art related to effects of lateral forces on shallow foundation is presented here. In the last years the seismic action has increased in many National Codes according to recent records which show values up to 0.8 g for very destructive earthquakes. Literature survey can be classified under two heads as:-

- Experimental Work
- Analytical Work using Finite Element Methods

Experimental Work

The experimental work done by authors and literatures have been discussed here -

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Debasis Roy[1] carried out research on strength considerations which essentially involves ensuring that the foundation loads remain well below that dictated by the allowable bearing capacity under seismic conditions and serviceability is ensured by designing the substructure for the estimated permanent ground deformation. Simple procedures for estimating bearing capacity and permanent ground deformation under earthquake conditions are presented.

Mahmoud Ghazavi and Armin Salmani Mahali [6] focused views on the seismic force considered as pseudo-static forces acting on both footing and soil is determined. To obtain the ultimate bearing capacity, an imaginary retaining wall is assumed to pass the footing wedge and the lateral earth pressure exerted on the wall in active and passive conditions are determined. The bearing capacity factors are computed for various values of soil friction angle, seismic acceleration coefficients in horizontal and vertical directions, ground inclination, and distance of the foundation from the slope edge. The effects of various parameters on seismic bearing capacity factors have been studied.

Dhiraj Raj and Bharathi M [2] gave idea about the small to medium rise buildings, shallows foundations are frequently used in hilly regions. In such situation, obtaining the minimum value for bearing capacity of the foundation is either from: (i) foundation failure; or (ii) overall stability of the slope. Various methods proposed by the researchers are available to find the ultimate bearing capacity of shallow foundation on the face of the slope or near edge of the slope, based on: (i) Limit equilibrium analysis; (ii) Slip line analysis; (iii) Limit analysis; and (iv) Finite element analysis. The method for bearing capacity estimation on sloping ground was first proposed by Meyerhof (1957) and later on many researchers had contributed in this area.

Rupashree Ragini Sahoo [9] discussed about the bearing capacity and settlement study of shallow footings is a subject which needs consideration for design of a foundation. Most of the studies relate to the case of a vertical load applied centrally to the foundation. However, when loads are applied eccentrically to the foundation, the bearing capacity is different from centrally loaded footings. Meyerhof (1953) developed empirical procedures for estimating the ultimate bearing capacity of foundations subjected to eccentric loads. All the bearing capacity estimation methods may be classified into the following four categories: (i) the limit equilibrium method; (ii) the method of characteristics; (iii) the upper-bound plastic limit analysis; (iv) slip line method and (v) the numerical methods based on either the finite- element method or finite-difference method. Footings are very often subjected to eccentric loads. This problem has been studied in detail by few investigators. The effective width method by Meyerhof (1953) is widely used for calculating the bearing capacity of eccentrically loaded footings. Footings are often

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subjected to eccentric loading due to (i) Moments with or without axial forces; (ii) The oblique loading; and (iii) Their location near the property line. Due to load eccentricity, the overall stability of foundation decreases along with settlement and tilting of the foundation which reduces the bearing capacity. The increase of stress in soil layers due to the load imposed by various structures at the foundation level will always be accompanied by some strain, which will result in the settlement of the structures.

K. J. McManus and N. R. R. Burdon [5] studied three possible failure mechanisms are commonly identified for shallow foundation systems (e.g. Clough and Duncan, 1991).

Osamu KANEKO, et al., (04) [8] presented a case study on the developed a systematic approach for the seismic evaluation of building foundations. The proposed approach allows structural engineers to choose between an empirical based, relatively simple method, and a theoretical, more rigorous method involving numerical seismic response analysis, as may be appropriate for the seismic evaluation of foundations. Applicability of this approach is verified in the case study of some buildings in Sendai city, which suffered damage to their foundations during the 1978 Miyagiken-oki Earthquake and the 2011 Great East Japan Earthquake.

Analytical Work using Finite Element Methods

Studies done by authors and research work done by analytical methods and software applications studied are discussed here-

Suman M. Sharma, et al., (03) [10] presented the common practice to design the foundation is to provide, first the shallow foundation such as isolated footing or raft to support structure and if this is not adequate then deep foundation like piled foundation. In this paper the choice between a raft and beam and slab raft foundation depends upon the soil properties and the weight of the building. In this Paper, study is carried out for comparison of “Raft foundation” and “Beam and Slab Raft foundation”. Excel Spread Sheet (manual) is prepared for the analysis and design of Raft foundation. Beam and Slab Raft foundation is analyzed and designed by using Excel Spread Sheet (manual) and STAAD Pro. Software. In this Paper analysis and design of economical foundation for high rise building has been done considering both geotechnical and structural design aspect. Quantitative study has been carried out for different values of Soil Bearing Capacity. Based on this study we conclude that for given bearing capacity like 180 kN/m2, 220 kN/m2, and 250kN/m2) Beam and Slab Raft foundation is found most safe and economical rather than Raft foundation.

G. Srilakshmi and B. Rekha [4] carried out studies on MAT foundation. But there is lacking of theoretical studies on the MAT foundation relatively. In addition to that, analysis of MAT foundation by conventional methods viz., rigid method and flexible method are cumbersome and time consuming. So to overcome these limitations the authors of these papers have tried to do the analysis of MAT foundation by Finite Element Method. FEM is very efficient method for complex boundaries and nonlinear material properties when compared with all other methods. In this work, analysis of MAT foundation has been studied by finite element software Ansys. The content of this paper is limited to 2-D ax symmetric nonlinear analysis in medium sand with respect to the geometric features which include the size and thickness of MAT foundation under compression. On the material side, while the MAT is treated as linear, soil and soil-mat interface are nonlinear, where the Drucker-Prager constitutive model is used for soil. The nonlinear analysis is incremental iterative mixed method which yields to higher accuracy. The results of this analysis will be sustained to interest to designers of MAT foundation.

Nirmal John Joy and Hashifa Hassan [7] studied the combined pile raft foundations provide an economical foundation option for circumstances where the raft foundation can satisfy the bearing capacity requirement but fails to keep differential as well as maximum settlement below the maximum allowable limit. It had been established that augmenting features like thickness of raft, length of piles etc has decreased the settlement of raft and on other hand: decreasing ‘spacing/depth’ of piles has increased settlement of raft. In this paper permuted arrangement of piles were adopted rather than a uniform arrangements; such that an improved performance of CPRF system can be envisioned. In this paper CPRF is analyzed using Finite Element Software Plaxis 3D with permuted arrangement of piles. Three different Pile diameters and its combinations were modelled and analyzed. For the study a 10 storey building founded on Medium Dense Sand was analyzed in STAAD. Pro Software to determine the loads to be transferred, after fixing dimensions of raft and settlement analysis of raft Plaxis 3D work programme was composed. Piled Rafts with various combinations of piles were modelled and analyzed. From the comparison of results, it has been found out that; installing high capacity piles at region with maximum load concentration and reinforcing the rest of the raft with medium capacity piles have the most important effect on significantly reducing maximum settlement and the differential settlement.

From the above literature survey, following conclusions can be drawn as

- Like many design processes, foundation design is an iterative process. First, the loads on the elevated structure are determined. Then a preliminary foundation design is considered, flood loads on the preliminary design are determined, and foundation style is chosen and the respective elements are sized to resist those loads.
- With information on foundation size, the design professional can accurately determine flood loads on the foundation and can, through iteration, develop an efficient final design. Because flood loads depend greatly on the foundation design criteria, the discussion of foundation design begins there.
- The appropriate styles of foundation are then discussed and how the styles can be selected to reduce vulnerability to natural hazards and to effects of lateral forces.
- The case study shown in the forthcoming chapter discusses about how the analytical studies and research can allow replacing the deep foundation i.e. the pile foundation with a shallow foundation.
- This shows the workability and feasibility of shallow foundation against the effect of lateral forces, (seismic forces or the forces due natural hazards).
- In this parametric study, different piled raft configurations have been analyzed by

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two-dimensional plane-strain finite element analyses using ANSYS.

- An idea for designers and practitioners about benefits of using different combination of piles in raft.

III. METHODOLOGY

The basic principle of any design is that the product should meet three basic requirements namely, (i) function, (ii) cost, and (iii) reliability. While the terms function and cost are simple in principle, reliability concerns various technical factors relating to serviceability and safety. As the above three criteria are interrelated, and because of the normal constraints on cost, compromise with function and reliability generally have to be made. In considering the means of achieving the above requirements it is necessary to take into account both the limitations and the opportunities arising from the availability of construction materials and components and of construction skills. In seeking the optimum of the proposed construction, designers should choose forms and materials that give the best failure modes in earthquakes with functional and cost requirements. The form or configuration of the construction is the geometrical arrangement of all of the elements, i.e., structure, architecture, equipment, and contents. In order to achieve reliable earthquake resistance the form of construction should be decided from consideration of the following factors: (1) Simplicity and symmetry, (2) Length of plan, (3) Shape in elevation, (4) Uniformity and continuity, (5) Stiffness, (6) Failure mode, and (7) Foundation conditions. Earthquake repeatedly demonstrated that the simplest structures have the greatest chance of survival. There are three main reasons for this. First, our ability to understand the overall behaviour of a simple structure is markedly greater than it is for a complex one, e.g. torsional effects are particularly hard to predict on an irregular structure. Second, our ability to understand simple structural details is considerably greater than it is for complicated ones. Third, simple structures are likely to be more buildable than complex ones. Symmetry is desirable for much the same reasons. It is worth pointing out that symmetry is important in both directions in plan and in elevation as well (Fig. 1). Lack of symmetry produces torsional effects which are sometimes difficult to assess and can be very destructive. As with non-seismic design, the nature of the subsoil will determine the minimum depth of foundations. In earthquake areas this will involve consideration of the following factors: (a) Transmission of horizontal base shears from the structure to the soil, (b) Provision for earthquake overturning moments (e.g. tension piles), (c) Differential settlements, (d) Liquefaction of the subsoil, and (e) The effect of embedment on seismic response. The effects of depth of embedment are not fully understood at present, but some allowance for this effect can be made in soil structure interaction analyses, or when determining at what level to apply the earthquake loading input for the superstructure analysis. Three basic types of foundations may be listed as;

(1) Discrete pad
(2) Continuous rafts
(3) Piled foundations.

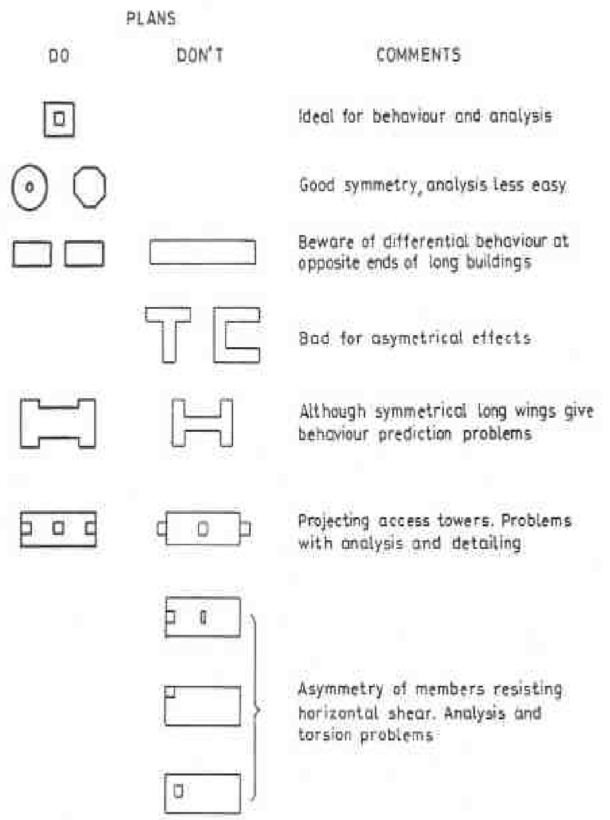

Fig. 1: Simple rules for plan layouts of aseismic buildings.

Aseismic Design of Foundations

Before completing the design of the foundations it is assumed that the dynamic characteristics of the subsoil have been determined and a suitable form for the substructure should also have been chosen. It then remains to design the foundations for appropriate seismic forces which arise (i) directly from the deformation of the adjacent soil and (ii) as a result of the earthquake forces acting in the superstructure. While our ability to estimate the seismic forces from (ii) above is now quite advanced, there remains a great deal of uncertainty about the magnitude and effect of the forces induced directly by the ground. This is true despite the increasing attempts to elucidate the soil-structure interaction problem by sophisticated analytical and experimental techniques. In current design practice it is often found convenient to consider two separate stress systems: (i) the seismic vertical stresses (e.g. due to overturning moments) and (ii) the seismic horizontal stresses (e. g. due to base shear on the structure). Overturning moments are not usually a problem for buildings as a whole, unless it is very slender, but can be difficult for individual footings such as column pads or shear wall strip footings. The foundations should, of course, be proportioned so as to keep the maximum bearing pressures due to overturning moments and gravity loads within the allowable seismic value for the soil concerned. Unfortunately there is little agreement on what constitutes safe seismic bearing pressures on sedimentary soils. Most earthquake codes do not discuss the effect of soil type on bearing pressures. It appears that most soils are capable of sustaining higher short-term loads than long-term loads, with the exception of some sensitive clays which loose strength under dynamic loading.

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Experimental Analysis Method for Lateral Resistance of Shallow Foundation

A simple method of analysis was developed and found to give good predictions for the experimental results while accounting for all of the main parameters. The analysis predicts that lateral load capacity is highly sensitive to the eccentricity (height above ground) of the applied lateral load. Three possible failure mechanisms are commonly identified for shallow foundation systems (e.g. Clough and Duncan, 1991) as shown in Fig 2: "Wedge Failure", "Flow-Under Failure", and "Tip-to-Top Failure". The "Wedge Failure" is based on classical Rankine passive earth pressure theory, and shows that vertical movement of the structure may be necessary to develop full lateral earth pressure against the foundation beams. The "Wedge Failure" figure also shows the inherent incompatibility between the mechanisms of sliding friction and passive earth resistance with development of the failure wedges lifting the structure off its base. The "Flow-Under Failure" would apply only to very soft soils such as soft clays. If the foundation beams are spaced closely then a "Tip-to-Tip" failure may occur with shearing of the soil beneath the foundation beams prior to development of a wedge failure mechanism.

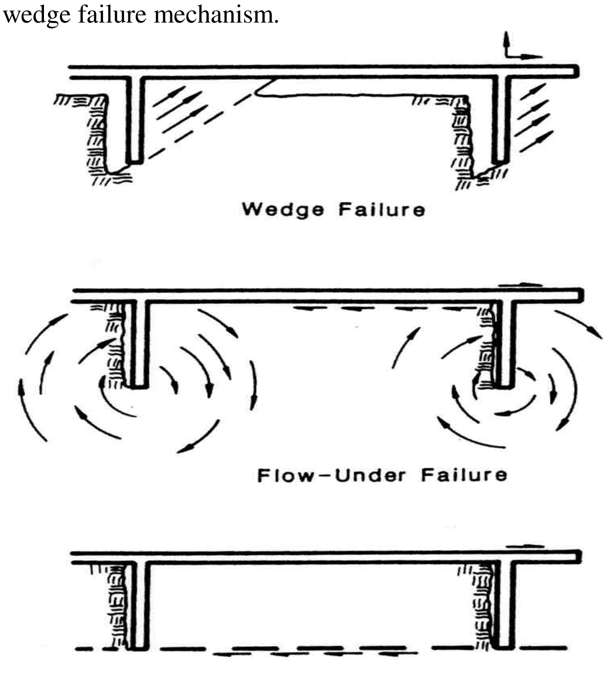

Fig. 2: Failure mechanisms for shallow foundations with lateral loading.

Murff and Miller (1977) developed equations for predicting the critical spacing of foundation beams necessary to generate a "Tip-to-Tip" failure mechanism. For the idealized foundation system shown in Figure 2, the lateral force developed for each foundation beam is given by:

F = 2 Ka (Q h/ Ka + h)1/2

in which Ka = weighted average shear strength of the soil, Q = vertical load, and h = depth of the foundation beams. The critical spacing of the foundation beams to generate a "Tip-to-Tip" failure then is given by:

q / Ka= 0.25 (Kh/ Ka)2 x (S / h) – (h / S)

in which q = vertical load per unit area, Kh = horizontal shear strength of the soil, S = beam spacing.

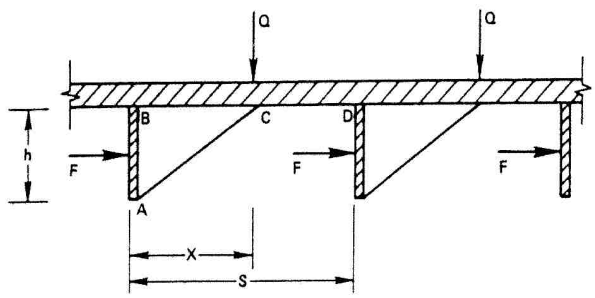

Fig. 3: "Tip-to-Tip" failure mechanism.

The resulting relationship between vertical loading on the foundation and the critical foundation beam spacing is illustrated in Fig 3. The application of these results is limited in practice because the soil shear strengths Ka and Kh are only suitable for modeling the undrained soil condition, i.e. short term loading in silts and clays.

IV. CONCLUDING REMARKS

The concluding remarks extracted from the present study are:

- Building only with shallow foundation may overturns under earthquake load.
- The different methodologies for evaluation of ultimate bearing capacity of the shallow foundation on slope or near the slope have its own assumptions and limitations.
- Each method depends upon several factor involved in estimating the ultimate bearing capacity of the shallow foundation on the top of slope, hence it is difficult to identify a single common factor dominating the ultimate bearing capacity.
- Structural design of foundations involves satisfying two requirements: (a) a factor of safety of 2 or more is available against bearing capacity failure under seismic loading and (b) the permanent ground deformation can be accommodated by the foundation system and superstructure.
- It may be possible to resist some or all of these horizontal forces by passive action of the soil, particularly for light buildings.
- Combined Pile Raft Foundation has a better scope for both research and applications in the field.
- Behavior of piled raft was analyzed for different sizes of raft, pile lengths, pile diameter by finite element method, by assuming foundation system as a 2-D plane strain system using ANSYS.

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