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Static and seismic bearing capacity of shallow strip footings

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ABSTRACT

In this study, the evaluation of static and seismic bearing capacity factors for a shallow strip footing was carried out by using the method of characteristics, which was extended to the seismic condition by means of the pseudo-static approach. The results, for both smooth and rough foundations, were checked against those obtained through finite element analyses.

Under seismic conditions the three bearing capacity problems for N_c, N_q and N_γ were solved independently and the seismic bearing capacity factors were evaluated accounting separately for the effect of horizontal and vertical inertia forces arising in the soil, in the lateral surcharge and in the superstructure.

Empirical formulae approximating the extensive numerical results are proposed to compute the static values of N_γ and the corrective coefficients that can be introduced in the well-known Terzaghi's formula of the bearing capacity to extend its applicability to seismic design of foundations.

1. Introduction

Past earthquakes provided evidence of the susceptibility of shallow foundations to undergo large deformations and failure also in situations where soil liquefaction was not triggered by the ground motion (e.g. [1–5]). In fact, due to rapid changes in shaking direction and amplitude during earthquake loading, the available soil shear strength under a foundation may be repeatedly and momentarily attained inducing several instantaneous failures resulting in the accumulation of permanent settlements rather than in a gross spectacular bearing capacity failure; this makes harder the identification of the actual phenomenon. Moreover, the recognition of foundation failures is sometimes hindered by the failure of the superstructure.

Also experimental evidence of foundation behaviour and bearing capacity failures under seismic loading has been provided by a number of studies reporting the results of shaking table [6–11] and dynamic centrifuge tests [12–14]. Table 1 lists some of these studies along with some details concerning the features and the results of the tests. The results of cyclic and dynamic tests pointed out the crucial influence of the accumulated permanent rotation of the foundation on the degradation of bearing capacity due to the reduction of footing-soil contact area. Rocking is the prevailing mode of deformation, the ratio of the maximum settlement s_{max} to the width B of the foundation being usually in the range 15–30%. However, it is worth noting that in many cases the models were either too high or the cyclic horizontal force was applied well above the foundation and thus they did not represent a simple foundation but rather reproduced small structures. Accordingly, the tests included in the overall behaviour of the model the inertial effects arising both in the soil mass, due to the propagation of seismic waves, and in the superstructure, due to its dynamic response and, in some cases, severe tilting or even toppling of slender models ($H/B > 1.75$, where H is the height of the model) was observed, consistently with field evidence after strong earthquakes [15].

Seismic design of foundations requires, in principle, rigorous modelling of the seismic soil-structure interaction, capable to reproduce non-linear soil behaviour under dynamic loading. Such a general approach is, however, costly and time-consuming and is suitable only for important projects. Also the macro-element approach, though appears as a promising tool for performance-based design of foundations (e.g. [16]), still is far from being an established method of analysis.

In routine analyses the evaluation of bearing capacity and the seismic response of the superstructure are decoupled. The seismic bearing capacity of a foundation can be represented by means of a bounding surface in the space of loading parameters as proposed by Pecker [17] or, alternatively, it can be evaluated using the formula introduced by Terzaghi [18] for a strip footing resting on a homogeneous dry soil subjected to a vertical and uniformly distributed load:

$$q_{ult} = cN_c + qN_q + \frac{1}{2}\gamma B\ N_\gamma \quad (1)$$

In Eq. (1) q_{ult} represents the ultimate load that the soil can sustain under the assumption of rigid plastic behaviour; N_c, N_q and

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Table 1
Experimental studies on seismic bearing capacity.

Reference	Experimental device	Model dimensions	Soil	Static load	Dynamic loading	Results and notes
Taylor and Crewe [6]	Shaking table EERC Laboratory Bristol University	$B = 0.4$ m $L = 0.95$ m $H = 0.4$ m $D = 0$ m	Leighton Buzzard sand $D_r = 58\%$	$W = 3.65$ kN $V = 30$ kN	1976 Friuli earthquake scaled Gemona record compressed in time $a_{max} = 0.44–1.5\ g$	$s_{max} = 97$ mm $\vartheta_{\mu\alpha\xi} = 5°$
Maugeri et al. [7, 8]	Shaking table EERC Laboratory Bristol University	$B = 0.4$ m $L = 0.95$ m $H = 0.4$ m $D = 0.1$ m	Leighton Buzzard sand $\gamma_d = 15.4$ kN/m^3 $e_{max} = 0.79$ $e_{min} = 0.49$ $D_r = 48.5\%$ [7] $D_r = 53.34\%$ [8]	$W = 3.65$ kN $V = 30$ kN [7] $V = 20$ kN; $e = 0.05$ m [8]	Sine dwell, $f = 5$ Hz $a_{max} = 0.15–0.665\ g$ [7] $a_{max} = 0.10–0.35\ g$ [8]	$s_{min} = 55$ mm; $s_{max} = 73$ mm [7] $d_{max} = 4.7$ mm; $\vartheta_{max} = 2.6°$[7] $s_{min} = -128$ mm; $s_{max} = 66$ mm; $\vartheta_{max} = 25.8°$ [8] Detection of the slip surface
Al Karni and Budhu [9]	Shaking table	$B = 0.102$ m $L = 0.102$ m $H = 0.178$ m $D = 0$ m	Silica sand $D_{50} = 0.55$ mm $C_u = 2.5$ $e_{max} = 0.95$ $e_{min} = 0.58$ $D_r = 67 \pm 5\%$	$W = 0.205$ kN	Irregular shaking $a_{max} = 0–1.05\ g$ $f = 3$ Hz	$s_{max} = 50$ mm; $d_{max} = 60$ mm; $\vartheta_{max} = 55°$ Detection of the slip surface
Knappet et al. [10]	Shaking table Cambridge University	$B = 0.05$ m $L = 0.3$ m $H = 0.1$ m $D/B = 0–0.5$	Silica sand $D_{50} = 0.9$ mm $e_{max} = 0.82$ $e_{min} = 0.495$ $D_r = 67\%$	$q = 8.42$ kPa	Sinusoidal shaking $a_{max} = 0.16-0.31\ g$ $f = 2.28-3.6$ Hz	$s_{ave} = 1.35–13.41$ mm Model toppling Detection of the deformation pattern
Shirato et al. [11]	Shaking table PWRI Tsukuba	$B = 0.5$ m $L = 0.5$ m $H = 0.25$ m $D = 0–0.05$ m	Toyoura sand $\gamma_d = 15.7$ kN/m^3 $D_r = 80\%$	$W = 8.39$ kN	1993 Hokkaido Nansei Oki earthq. Schichiho Bridge record 1995 Kobe earthquake NS JMA record	$s_{max} = 6–17.6$ mm $d_{max} = 3.5–101.6$ mm $\vartheta_{\mu\alpha\xi} = 0.57° - 9.22° -$ toppling Pressure beneath the foundation recorded Reduction of footing–soil contact area
Zeng and Steedman [12]	Centrifuge test (50g) Cambridge Geotechnical Centrifuge Centre	prototype $B = 1.67$ m $H = 5$ m $D = 0.5$ m	Hostun sand dry or saturated $D_{50} = 0.35$ mm $e_{max} = 0.967$ $e_{min} = 0.607$ $D_r = 55–63\%$	prototype $q = 383$ kPa	Irregular shaking $a_{max} = 0.19–0.45\ g$	Dry model (prototype): $s_{max} = 0.3$ m; $\vartheta_{max} = 6.3°$ soil heave 0.15 m Saturated model (prototype): $s_{max} = 0.5$ m; $\vartheta_{max} = 12°$ soil heave 0.10 m Sudden failure was observed
Garnier and Pecker [13]	Centrifuge test (100g) LCPC Nantes Centre	prototype $R = 30$ m	Antirion clay with vertical inclusions	$W = 8.9–9.3$ kN	$T = \pm 5$ to ± 35 MN (applied at 11.8 m from foundation) $M = \pm 70$ to ± 170 MNm 5–10 loading cycles	$s_{max} = 0.6$ m $d_{max} = 1.8$ m
Gajan et al. [14]	Centrifuge test (20g) Center of Geotechnical Modeling University of California, Davis	prototype $B = 0.4–1$ m $L = 2.5–4$ m $D = 0–0.7$ m	Nevada sand $D_{50} = 0.17$ mm $C_u = 1.6$ $e_{max} = 0.881$ $e_{min} = 0.536$ $D_r = 60\%$ and 80% San Francisco Bay mud $LL = 90\%$ $PL = 38\%$ $S_u = 100$ kPa	various models with different weight	Vertical slow cyclic tests Horizontal slow cyclic tests Dynamic irregular shaking	The settlement in dynamic tests is larger than the settlement in horizontal slow cyclic tests Reduction of footing–soil contact area and rounding of soil surface beneath the footing observed in slow cyclic horizontal loading No significant uplift observed in dynamic tests

Key: B,L,R,H,D: width, length, radius and height of the foundation, and depth of embedment; γ_d, e_{max}, e_{min}, D_r, D_{50}, C_u: soil dry density, maximum and minimum void ratio, relative density, average soil particle diameter, uniformity coefficient; LL, PL, S_u: soil liquid and plastic limit, undrained shear strength; W, V, e, q: weight, vertical force, eccentricity, applied pressure; T, M: applied cyclic horizontal force and moment; a_{max}, f: maximum acceleration and frequency of dynamic horizontal loading; g: gravity acceleration; s_{min}, s_{max}, s_{ave}, d_{max}, ϑ_{max}: minimum, maximum and average permanent settlement (positive downwards), maximum horizontal permanent displacement, maximum permanent rotation.