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Collapse mechanisms and strength prediction of reinforced concrete pile caps

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ABSTRACT

This paper describes an upper bound plasticity approach for strength prediction of reinforced concrete pile caps. A number of collapse mechanisms are identified and analysed. The procedure leads to an estimate of the load-carrying capacity and an identification of the critical collapse mechanism. Calculations have been compared with nearly 200 test results found in the literature. Satisfactory agreement has been found. The analyses are conducted on concentrically loaded caps supported by four piles. The paper briefly outlines how the approach may be extended to more complicated loadings and geometries. It is argued that the upper bound approach may be a useful complement to the widely used lower bound strut-and-tie method. Especially when dealing with strength assessment of existing structures.

1. Introduction

This paper deals with strength prediction of reinforced concrete pile caps and has been prepared on the basis of a Ph.D. project conducted by the first author, [1]. A pile cap is basically a foundation block supported by piles. In high rise buildings, pile caps are for example used to support columns while in bridge engineering, pile caps are typically used to transfer vertical and transverse loads from the bridge pier to the piles, see illustration in Fig. 1. Depending on the applied loads and the number of piles, pile caps can be rather massive structures. Typically, the centre to centre distance between adjacent piles is about three times the pile diameter and the cap thickness is larger than the pile diameter.

Strength prediction of pile caps has traditionally been based on a sectional approach where the sectional forces are calculated based on beam theory [2,3]. Pile caps, however, are normally characterised by a small span to depth ratio where it is easier for the shear action to be transmitted directly to the supports. For that reason the more recent design codes, e.g. Eurocode [4] and AASTHO LRFD [5], recommend that strength verification of pile caps may be based on strut-and-tie models.

Strut-and-tie modelling has in recent years dominated the research into limit analysis of pile caps [6–11]. The method is based on the lower bound theorem of plastic theory and therefore provides lower bound solutions for the load-carrying capacity. A major challenge in strut-and-tie modelling is to develop suitable 3-dimensional models which may be used in practice. Even though the approach is conceptually simple, 3-dimensional models may become quite complex, especially in the nodal zones. It is therefore not unusual to see pile caps designed by use of plane strut-and-tie models in practice. This is a very simplified and conservative approach, which may be acceptable in design situations but is less suitable when dealing with strength assessment of existing structures.

When assessing the strength of existing structures, engineers often strive to determine both lower bounds as well as upper bounds for the load-carrying capacity. This is an efficient way to narrow down the interval within which the actual load-carrying capacity can be expected and thus a way to decide whether the structure needs strengthening or not. For pile caps, lower bound solutions may – as mentioned – be obtained from strut-and-tie models. Investigations of upper bound methods for pile caps have not been reported in the literature.

The objective of this paper is to demonstrate how an upper bound plasticity approach may be used to predict the critical failure mode and the load-carrying capacity of pile caps. The basic idea is to identify and analyse a number of collapse mechanisms and take the lowest calculated capacity as an estimate for the actual load-carrying capacity. Failure in pile caps is normally divided into three main categories, namely punching shear failure, shear failure and flexural failure. These distinct failure modes are investigated in this paper. Local anchorage failure is not considered as such failure should in practice be prevented by adequate detailing of the reinforcement. The investigations reveal that punching failure is not likely to occur for typical pile cap geometries. The calculations have been compared with nearly 200 test results and satisfactory agreement has been found.

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Notation

Roman letters

a	vector
a_1	shear span
b	vector
b_a	distance from centre of pile to centre of column
b_c	width of column
c	vector
c	$=½l - b_a - ½D$
d	depth of pile cap
d_e	effective depth
f_c	uniaxial cylinder compressive strength of concrete
f_t	tensile strength of concrete
f_y	yield stress of reinforcement
k	H/P
l	side length of pile cap
$\mathbf{n}_1$, $\mathbf{n}_2$	normal vectors
u	(u_x, u_y, u_z) vector describing relative displacement in failure surface
u	displacement
w	crack opening
A_i	area of surface S_i ($i = 1, 2, \ldots, 6$)
A_s	reinforcement area per unit length
D	diameter of pile
H	transverse sectional shear force
M	sectional moment
M_{pile}	sectional moment in pile
P	load on pile cap
P_{exp}	experimental ultimate load
$P_{k=0}$	P_u for $k = 0$
P_u	calculated load-carrying capacity
$P_{u,f}$	flexural capacity
$P_{u,p}$	punching shear capacity
$P_{u,s}$	sectional shear capacity
T	sectional shear force in pile
W_E	external work
W_I	internal work
$W_{I,c}$	internal work (dissipation) in concrete
$W_{I,s}$	internal work (dissipation) in reinforcement

Greek letters

α	angle between failure surface and the displacement vector
α_1, α_2	angles between failure surface and the displacement vector
β	angle defining inclination of failure plane
φ	angle of internal friction for concrete ($\tan\varphi = ¾$)
λ_1, λ_2	constant
ν	effectiveness factor
ν_0	factor taking into account microcracking and softening
ν_s	crack sliding reduction factor
θ	angle of rotation
ρ_l	longitudinal reinforcement ratio
τ_{exp}	$P_{exp}/(2dl)$
τ_u	$P_u/(2dl)$
$\tau_{u,f}$	$P_{u,f}/(2dl)$
$\tau_{u,p}$	$P_{u,p}/(2dl)$
$\tau_{u,s}$	$P_{u,s}/(2dl)$
Φ	mechanical degree of reinforcement

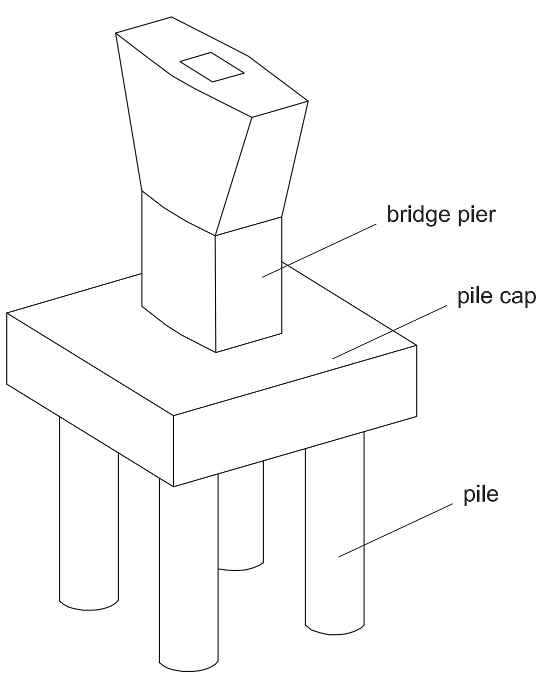

Fig. 1. Illustration of bridge substructure with pier, pile cap and piles.

2. The approach

Most research concerning pile caps has been focused on four-pile caps with concentric loading [6–19]. To enable comparisons, the four piles configuration also forms the basis for the present investigation. However, as discussed in Section 2.4, it is rather straight forward to extend the upper bound approach to pile caps with more than four piles and pile caps with eccentric loadings.

It is assumed that the pile cap is provided with an orthogonal reinforcement mesh at the bottom face. The reinforcement areas per unit length in both directions are assumed to be identical and termed A_s. The reinforcement material is assumed to be rigid, perfectly-plastic with yield stress f_y. Furthermore, it is assumed that the reinforcement is well-anchored, so that local anchorage failure does not take place.

The concrete is treated as a Modified Coulomb material obeying the normality condition of plastic theory and having an angle of internal friction φ given by $\tan\varphi = 3/4$, see Nielsen and Hoang [20]. The tensile strength of concrete is neglected and the plastic compression strength is taken as νf_c where ν is the so-called effectiveness factor (see later) and f_c is the uniaxial cylinder compressive strength.

2.1. Punching shear failure

Punching shear failure in a massive concrete block like a pile cap might be difficult to imagine. In plastic analyses of punching shear in slabs, it is usually assumed that the longitudinal reinforcement does not yield. This implies that the relative displacement **u** in the failure surface (yield line) must be perpendicular to the plan of the slab (see Fig. 2). According to the normality condition of plastic theory, the angle α between **u** and the failure surface cannot be smaller than the angle of friction, i.e. $\alpha \geqslant \varphi$ is required. With this restriction and with the assumption of **u** being perpendicular to the plane of the slab, a geometrically admissible punching