Technical note

Design of capping beams

Jeremy Wells, Structures Technical Coordinator, WSP Buildings discusses commonly encountered design situations using capping beams

A capping beam is a member, usually of reinforced concrete construction, that connects the heads of piles forming an embedded retaining wall. It can serve a number of structural purposes and can therefore be subject to a number of different loading conditions. This technical note describes some of the design situations that are encountered. General design guidance is given and some of the methods commonly used to design for concentrated vertical loads from columns are reviewed.

Typical design situations

Two common situations where capping beams are used are in basements of multi-storey buildings and in open basements in industrial process buildings.

Basements of multi-storey buildings

In a multi-storey building, the most important function of the capping beam is usually to distribute substantial vertical column loads to the piles that form the embedded retaining wall.

Generally, a ground floor slab will provide horizontal support to the retaining wall and the capping beam will not be subject to horizontal loading in the permanent condition. However, it may be required to form part of a temporary propping system while the basement is excavated and before the floor slabs are constructed. This results in a requirement to design for horizontal bending. Alternatively the propping system can be designed using temporary walings and not relying on the capping beam. The temporary works scheme should be clarified before the beam is designed (Fig 1).

Open basements

There are some situations in which there is no suspended floor slab to provide propping in the permanent case. In some cases it is viable to design the wall to cantilever from the base but if the basement is deep the capping beam may be required to transfer horizontal loads between anchors or abutting walls. An example is shown in Fig 2. It should be noted that the use of anchors as permanent support should be avoided where possible, due to potential for damage to anchors and corrosion protection requirements.

Initial sizing of capping beams

The size of a capping beam will ultimately be determined by the loading to which it is subjected as well as dimensional constraints. A good starting point is to try a width 300mm greater than the diameter of the pile, or the profile depth of sheet piling, and to assume a square section (Fig 3).

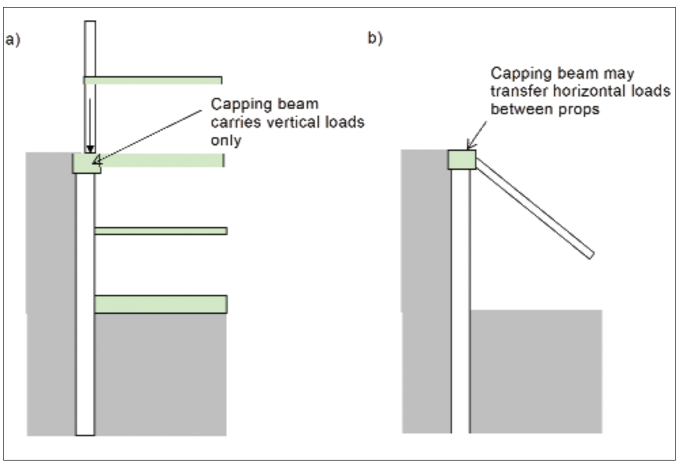
Account will also need to be taken of the dimensional requirements of any lining wall.

The depth will often need to be increased if the beam is required to distribute significant column loads. The limiting factor will often be either the maximum shear stress of 5MPa or $0.8\sqrt{f_{cu}}$ or the need to reduce congestion of tension reinforcement.

It is generally advisable to aim to spread the column loads to no more than three piles. If the column load needs to be spread to more than three piles, the capping beam can become so deep that the original benefit of the embedded retaining wall starts to be eroded.

Types of embedded retaining walls

Embedded concrete pile retaining walls on which capping beams are constructed fall into two main categories, namely contiguous and secant pile walls. Although the name may suggest otherwise, there is a small gap, usually 150mm, between the piles in a contiguous wall. In a secant pile wall the piles overlap. Alternate 'female piles' are constructed first. These are un-reinforced and usually made of a relatively weak concrete, classed as 'firm' or 'soft'. The 'male piles' which are bored through the female piles, are made of full strength concrete. Thus, the classification of a



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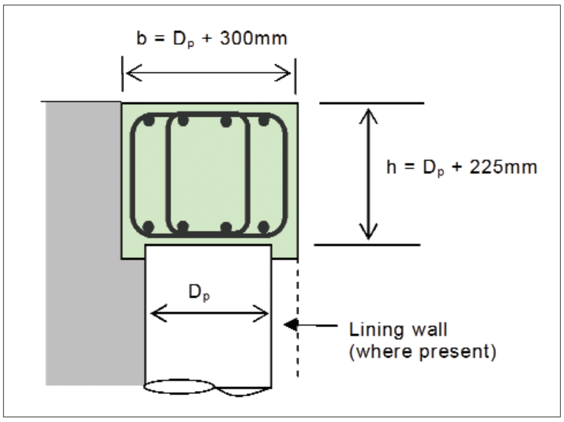
1 Capping beams in multi-storey construction a) permanent b) temporary case

2 An example of a capping beam with anchors and return walls resisting horizontal loads in the permanent condition



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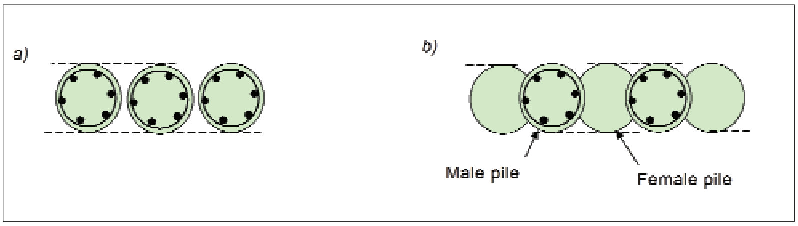

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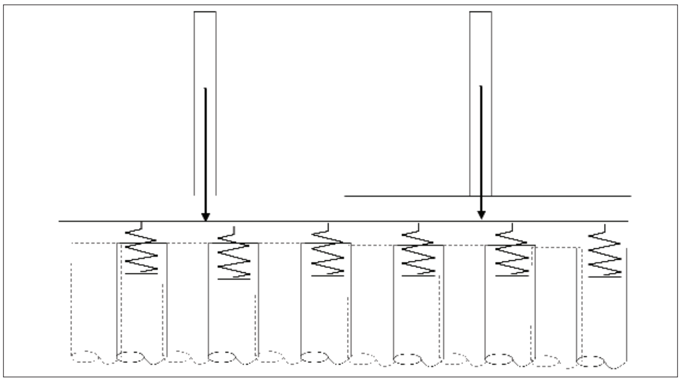
3 Typical section for capping beam
4 Plan of embedded retaining walls a) contiguous and b) secant
5 Elastic design with load-bearing piles modelled as springs
6 Elastic design with spring support distributed between all piles



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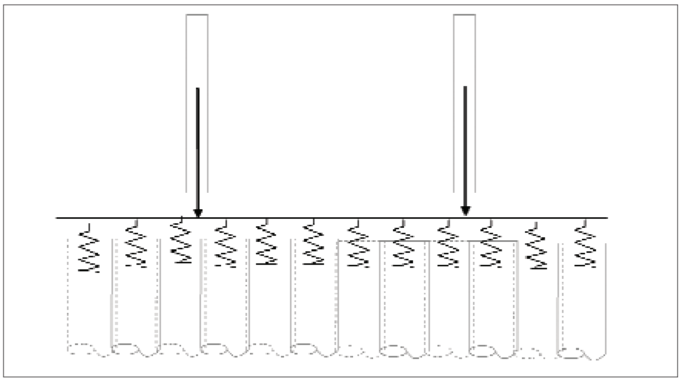

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secant wall can be: 'hard-soft', 'hard-firm' or less commonly 'hard-hard'.

Capping beams are also used at the head of sheet pile walls and sometimes on diaphragm walls.

The type of wall can be significant in the design of the capping beam.

Review of common methods of design for vertical loads

The behaviour of a capping beam under axial load is closely interrelated with the geotechnics of the piles and the soil. Little design guidance seems to have been published for capping beams. The 2004 IStructE report *Design and construction of deep basements including cut-and-cover structures* contains a short paragraph on vertical bearing capacity of piled walls. However, this relates primarily to the geotechnical design providing no direct guidance on the design of the capping beam.

There are a number of methods of design in common use. The four that are considered here are:

– Elastic design with load-bearing piles modelled as springs
– Elastic design with spring support distributed between all piles
– Effective pile group approach
– Strip footing approach.

Elastic design with load-bearing piles modelled as springs

The behaviour of a capping beam under vertical load from a column can be considered as a flexible continuous foundation on discrete flexible supports.

A conservative approach that can be used in any situation is to model the capping beam as a continuous beam on spring supports (Fig 5). This requires input from a geotechnical engineer on suitable spring stiffnesses to be used for design. Use of transformed or cracked sections for analysis, as allowed in BS 8110-1 2.5.2 c) and BS EN 1992-1-1 5.4[3] will more accurately reflect the stiffness of the beam relative to the piles. This approach will lead to a more economical design for the capping beam and avoid underestimation of pile loads. The appropriate reduction in stiffness varies with load and reinforcement percentage but will generally be of the order of 50%.

Using this method it is appropriate to allow redistribution of sagging moments from under the column to the top of the beam, in accordance with BS 8110 clause 3.2.2 and BS EN 1992-1-1 5.5. It is suggested that this is limited to 20% where the column carries gravity loads only and 10% where it forms part of the lateral stability system.

Elastic design with spring support distributed between all piles

For a secant wall, it seems reasonable to make some allowance for the continuous nature of the support by either demonstrating, or assuming, that a female pile can transfer any load applied to it to the adjacent male piles by shear across the cast *in situ* surface between. If a reinforced concrete lining wall is present this will also contribute to the transfer of loads along the wall. On this basis, the spring stiffness of male and female piles can be taken as half the stiffness of the male piles (Fig 6). If support is modelled in this way, and the width of the column is also modelled, economies can be achieved in the design.

A similar model can be adopted for sheet pile and diaphragm walls. Redistribution of moment as described for the previous design method can be applied to the results of the analysis.

Effective pile group approach

One common practice is to design the capping beam local to a column as a rigid pile cap. The number of piles supporting the effective pile cap is determined by dividing the column load by the working load of one pile. If the set-out of the piles relative to the column is not known it would seem a logical precaution to make an allowance for eccentricity between the centreline of the column and the centre of the effective pile group. This could be done by increasing the number of piles in the effective pile group by one, but this approach will generally give more conservative answers than a full elastic analysis. As there is conservatism in the assumption that the wall makes no contribution to load distribution, the aim is generally to produce a less conservative design. On this basis, it is recommended that no adjustment be made for eccentricity.

In the case where a single pile has adequate capacity to carry the full column load, this design method suggests that there is no load on the capping beam. In fact, elastic shortening of the pile and pile settlement will result in load being distributed to adjacent piles, applying significant loading to the capping beam. To take

Pile wall type	F_{column}	P	l	c	capping beam depth	capping beam width	Elastic analysis support at male piles only			Elastic analysis support distributed to male and female piles			Effective pile cap method					Strip footing method			
							V_{max} (ult)	d_{min}	M_{max} (ult)	V_{max} (ult)	d_{min}	M_{max} (ult)	N	V_{max} (ult)	d_{min}	M_{max} (ult)	redist from elastic	V_{max} (ult)	d_{min}	M_{max} (ult)	redist from elastic
	kN	kN	m	m	mm	mm	kN	mm	kNm	kN	mm	kNm	no.	kN	mm	kNm		kN	mm	kNm	
Secant	6360	6360	1.4	0.875	1300	1300	2967	456.5	4581	2967	497	4581	3	3180	489	4452	3%	1789	275	234.77	95%
Secant	19200	6360	1.4	0.875	2000	1300	10421	1750	19106	9730	1497	14240	3	9600	1477	13440	6%	11419	1757	9567.2	33%
Secant	25440	6360	1.4	0.875	2600	1300	14677	2258	32982	14654	2254	26358	4	14310	2202	26712	-1%	16099	2477	19017	28%
Secant	31800	6360	1.4	0.875	3300	1300	19149	2946	47835	19024	2927	38733	5	19080	2935	40068	-3%	20869	3211	31955	17%
Secant	25800	8650	1.92	1	1800	1800	12542	1394	25533	12542	1394	25533	3	12900	1433	24768	3%	15971	1775	18873	26%
Contiguous	6360	6360	1.05	0.875	1300	1300	3345	515	4238	-	-	-	3	3180	489	3339	21%	795	122	34.781	99%
Contiguous	19200	6360	1.05	0.875	1750	1300	10867	1672	16400	-	-	-	3	9600	1477	10080	39%	10425	1604	5980.9	64%
Contiguous	25400	6360	1.05	0.875	2450	1300	15050	2315	28451	-	-	-	4	14288	2198	20034	30%	15075	2319	12506	56%

Table 1 Comparison of results for different design methods

Notes
1 A typical cracked section factor of 0.5 has been used for elastic analysis in all cases.
2 The depth of the capping beam has been based on typical actual cases for projects.
3 Pile stiffness has been based on a pile settlement of 10mm at working load.

account of this situation, the beam needs to be designed to spread the column load to at least three piles.

$$N \geq \frac{F_{column}}{P} \geq 3$$

where P is the working load capacity of one pile and N must clearly be an integer value.

Note that using this method for secant pile walls, the column load is spread to male piles, ignoring the contribution from the female piles.

This simplified approach relies on pile settlement to redistribute the load between the piles to overcome any theoretical overload of the pile directly under the column. This is not an unusual assumption, being common to all conventional rigid pile cap design; however the capping beam is not generally as deep, or hence as stiff, as a pile cap and significant pile settlement and plastic redistribution of moments in the reinforced concrete section is required. For piles with diameters in the typical range of 600mm to 1200mm and working loads between 1500kN and 10 000kN, pile capacity will generally be governed by soil capacity rather than concrete strength and the necessary pile settlements should be achievable. Redistribution of moments is addressed later.

By modelling a length of the beam as a pile cap, the hogging moments arising due to continuity are lost from the design model. Top reinforcement equal to at least 40% of the bottom reinforcement should be provided.

When checking the shear it seems a reasonable assumption, given the close spacing of the piles, that a load of F_{column}/N is transferred into the wall below in direct bearing and does not contribute to shear.

The reinforcement requirement calculated between the outer piles of the effective pile group should be applied over the remainder of the capping beam.

The maximum pile settlement under working load should be specified as 10mm.

Strip footing approach

Using the assumption that a female pile can transfer any load applied to it to the adjacent male piles, capping beams are sometimes designed as a continuous strip footing subject to a concentrated load from the column.

Bearing capacity $p = \frac{P}{l}$

Where P is the working load capacity of one pile and l is the spacing of load bearing piles

Length of bearing $L = \frac{F_{column}}{p} = \frac{lF_{column}}{P}$

If the width of the column is taken into account, with the maximum moment calculated at the face of the concrete column or stiff baseplate, the moment and shear in the capping beam become:

$$M = \frac{\gamma_f F_{column}}{8l}\left(\frac{F_{column}\,l}{P} - c\right)^2$$

$$V = \frac{\gamma_f F_{column}}{2l}\left(\frac{F_{column}\,l}{P} - c\right)$$

Comparison of design methods

A comparison of results for various examples of pile load, diameter and capping beam depth are given in Table 1.

For secant pile walls, the results suggest that the percentage redistribution of peak moments required to achieve the effective pile cap assumption is less than 10%. Using the strip footing approach and calculating moments at the face of the support, up to 33% redistribution is required. This suggests that for a beam designed using the strip footing approach with a partial safety factor for load of 1.5 a plastic hinge will be on the point of forming under the column at working loads. Any increase in load could lead to serviceability problems in the form of increased settlement of the column and cracking of the capping beam.

For contiguous piled walls, the increase in redistribution required for both the effective pile cap and strip footing methods is greater than 33%, suggesting that neither provides a satisfactory method of design.

In many cases, due to programme constraints the capping beam has to be detailed early in the design process, sometimes before all issues affecting the superstructure have been addressed. This should be taken into account in deciding to what extent the design solution should be driven by economy.

If the strip footing approach is used, care must be taken that the capping beam cross-section and minimum reinforcement requirement are sufficient to distribute loads when the capacity of a single pile is greater than the service load of the column.

It should be noted that, in ignoring the continuity of the capping beam, both of the simplified methods described here give quite a crude picture of the moment and shear force distribution in the capping beam. The comparison in table 1 is made on the basis of maximum moments and shear forces under the column. Variation in moment at points away from the column will be even more marked. This can be significant in establishing the spacing of links and curtailment of tension reinforcement.

For secant pile walls, the effective pile cap approach to design appears to provide a reasonable balance between economy and conservatism which should be appropriate for preliminary design. An elastic design with redistribution of peak moments will provide the most accurate picture of the moments and shear forces in the beam. This will allow reinforcement to be distributed effectively and, as a result, produce the most economical design.

For contiguous pile walls, elastic design with redistribution of moments is the only method that will provide consistently reliable results.

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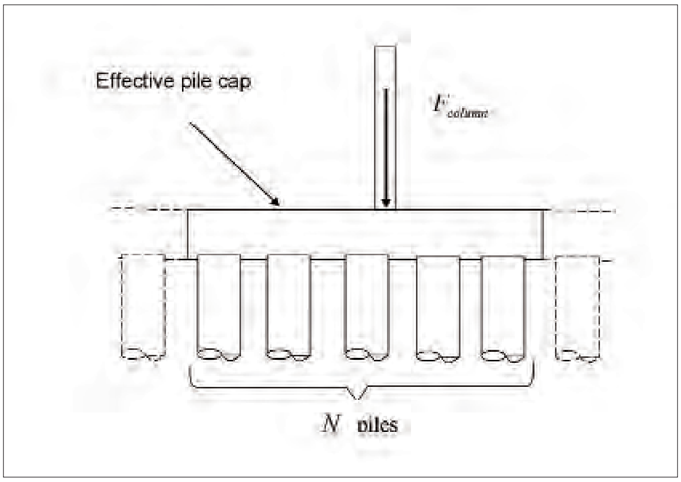

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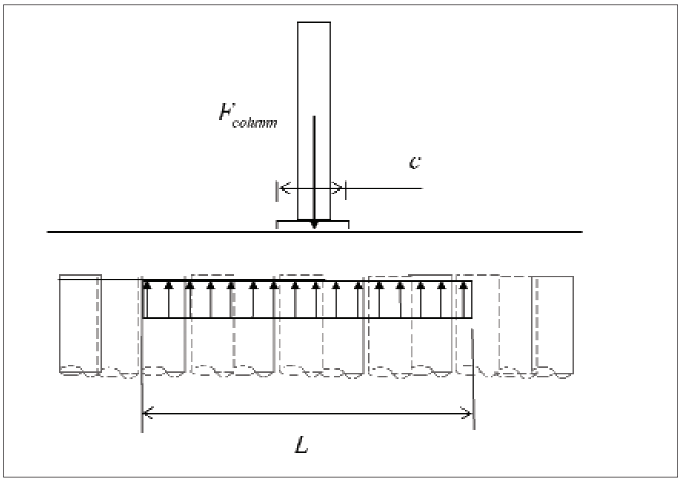

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7 Simplified design model for capping beam – effective pile cap approach
8 Simplified design model for capping beam – strip footing approach

Design for horizontal loads

Where the capping beam is required to distribute horizontal propping loads, the propping forces should be provided by the designer of the propping system. The load from the retained earth can then be calculated by assuming the prop or anchor forces result from uniformly distributed loading on the capping beam. The beam can be designed as a continuous beam with uniform loading and rigid support at the props.

When both can occur at the same time, the horizontal load case should be combined with the vertical load case in the design of the reinforced concrete section.

The effect of column eccentricity

When the capping beam is loaded by a column which is eccentric to the line of the piles, the ground floor slab or the piles need to be designed to resist the resulting eccentric moment. If a number of piles are required to resist the moment it will need to be transferred by torsion in the capping beam. In most cases it is better to design the slab (or a beam at slab level) to carry the moment, thus avoiding the problem of torsion in the capping beam.

References

1. Institution of Structural Engineers, *Design and construction of deep basements including cut-and-cover structures,* 2004
2. BS 8110-1:2005, *Structural use of concrete – Part 1: Code of practice for design and construction,* BSI, London
3. BS EN1992-1-1:2004, *Eurocode 2: Design of concrete structures – Part 1-1: General rules and rules for buildings*, CEN, 2004