

This paper is the result of deliberations of the Society's discussion group on
SEISMIC DESIGN OF DUCTILE MOMENT RESISTING REINFORCED CONCRETE FRAMES

SECTION D

FOUNDATIONS FOR DUCTILE FRAMES

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D1.0 SCOPE

D1.1 NZS 4203 sets out general requirements for foundations in sections 3.3.2, 3.3.3 and 3.3.6, and in section 3.3.6.2, and 3.3.6.3, it sets out requirements for capacity design of foundations for ductile reinforced concrete frames.

This article sets out recommendations for determining design loads for foundation systems to support and stabilize ductile frame structures and to couple such structures to the foundation material. Only simple cases are described. The more complex cases met in practice must be considered on their own merits bearing in mind the general principles described below.

D2.0 DEFINITIONS

D2.1 Foundation System - The foundation system comprises all parts of the foundation below the superstructure and includes the soil which provides both vertical, and horizontal support.

D2.2 Soil - The foundation material around and beneath the foundation structure.

D2.3 Foundation Structure - The foundation structure comprises all structural elements, other than soil, which form part of the foundation system.

This includes all structural elements of a ductile frame below the base column hinge, if any, or otherwise below ground level.

D2.4 Foundation Elements - The foundation elements are the individual parts of the foundation structure.

D2.5 Foundation Failure - The inability of the foundation system to continue to support and stabilise the complete structure under the conditions imposed by lateral and vertical loads which are induced by gravity, wind, seismic, or other load effects.

D2.6 Ground Coupling - This is defined as the mechanism by which the ground motion of the earthquake is transmitted to the structure by interaction between the foundation materials and foundation elements by vertical and horizontal friction and bearing.

D2.7 Elastic - Elements remaining elastic are those that have not been loaded to their yield point. The soil is considered to be elastic up to the point where there is a marked increase in strain for little increase in load. (Refer D.10.)

D3.0 BASIC PHILOSOPHY OF DESIGN OF FOUNDATION SYSTEM

The foundation system should maintain its ability to support vertical loads (both designed and induced) while maintaining the designed earthquake energy dissipating mechanism in the superstructure. Damage should be minimised and should be repairable.

This should be achieved by ensuring that :-

either

- (i) foundation elements, and particularly primary elements resisting gravity loads, are designed to remain elastic while maintaining the chosen energy dissipating mechanism, or
- (ii) foundation elements, which at dependable strength are capable of resisting loading conditions corresponding to those induced with SM=2, may be permitted to undergo post-elastic deformations provided they are detailed for ductility.

(Refer NZS 4203 1976 for definitions of S and M)

D4.0 GROUND COUPLING FORCES

D4.1 All elements coupling the structure to the soil should be designed with adequate capacity to ensure that the chosen earthquake energy dissipating mechanism is maintained. To satisfy this condition, loadings on all elements should be considered at a load level where the superstructure reaches its capacity condition.

Where Section G, Columns-Evaluation of Actions, by T. Paulay, is used to estimate the order of inertia forces induced at the over strength capacity of the seismic frame, then the foundation system should be designed for the corresponding horizontal and vertical loads. The horizontal load F_{CS} given below is considered to be a conservative guide and could be modified by a more detailed study.

$$F_{CS} = \sum_{x=1}^{x=n+1} \psi_{avg_x} \cdot F_x$$

Where

F_{CS} = Horizontal seismic ground coupling force on the structure

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n = number of floors

$n + 1$ = roof level

F_x = Code inertia force at x .

ψ_{avg_x} = beam over strength factor at x (from section G) and where $\psi_{avg_x} \leq \psi_{avg_{max_x}}$

$$= \frac{4}{1.15w_l}$$

Where D.3(ii) is complied with, F_{cs} need not be taken as greater than that induced when $SM=2$. However, when this limit applies, the validity of the assumed energy dissipating mechanism may need careful reconsideration.

D4.2 Particular attention should be given to forces developed on retaining walls, especially on sloping sites, and also in or on piles, particularly raker piles which may be required to take the full ground coupling force.

D4.3 In addition to the coupling forces, the structural foundation elements should be designed for lateral soil pressures on the foundation system resulting from earthquake forces in any direction including effects due to variation in ground level or in retained material. The seismic magnification of such forces should also be considered (refer MWD Retaining Wall Design Notes July 1973).

D5.0 FOUNDATION ELEMENTS- DESIGN REQUIREMENTS

D5.1 General

Primary gravity load resistant foundation elements should preferably remain elastic under design loads. Damage below ground level should be avoided as such damage could go undetected and could be subject to deterioration with time, e.g. corrosion or reinforcement. It is desirable that at least one face of the foundation beams can be made accessible for inspection. It is considered that where signs of distress are visible on one face the whole beam should then be inspected.

D5.1.1 Column Stub - The column stub is the extension of the column to the foundation pad if the pad is below the foundation beam. It is a primary gravity resisting element and should preferably be designed to remain elastic. It should be detailed as for the columns. Reinforcement size and spacing generally should not be less than that in lowest storey columns. For design moment and shear refer text (in some cases these shears can be very high). It may be possible to allow a column base hinge in the column stub in lieu of the lowest storey column base hinge provided the hinge area is permanently accessible for inspection.

D5.1.2 Column Stub-beam Joint - The column stub-beam joint is a primary gravity resisting member and should be designed to remain elastic. Detail as for joints in superstructure.

D5.1.3 Pad - A pad is a primary gravity load resisting member. It is usually sized for gravity load but is detailed to resist seismic gravity load plus the applied moment (see diagrams) and remain elastic.

Where rocking occurs, design for moments and shears developed by the soil, allowing for the strength gained due to consolidation etc. Where uplift forces can occur on all or part of the pad, the top of the pad shall be reinforced with steel to take the applied forces with not less than .001 times the gross cross section area of the pad in each direction.

D5.1.4 Foundation Beams - The foundation beam is not a primary gravity resisting member. It should remain elastic where practical. It may be allowed to yield once the column base moment exceeds that corresponding to the moment induced when $SM=2$ in type 2 foundations. (Refer D.12.)

Ductile detailing should be provided if yielding is possible, otherwise use normal detailing to the current design code.

D5.1.5 Tie Beams - Tie beams are not required to remain elastic in flexure. Use normal detailing to the current design code.

D5.1.6 Pile Cap - Pile caps are primary gravity load resisting elements and should preferably be designed to remain elastic under all conditions. Use normal detailing to the current design code.

D5.1.7 Pile - The piles are primary gravity loads resisting elements. They should remain elastic wherever possible. Normal detailing except for the upper section. Piles should be anchored to the superstructure, directly or through a pile cap. The upper end of every pile should be reinforced as a potential plastic hinge region, unless it can be established that there is no possibility of significant lateral deflection in the pile resulting from either movement of the building relative to the ground or ground deformation. The potential plastic hinge region shall be considered to extend from the underside of the pile cap over a length of not less than the longest cross sectional dimension of the pile. The transverse reinforcement should be proportioned with due regard to the shear that can be generated with the mechanisms that are intended, or are likely to form, in accordance with the structural layout, the soil conditions and the construction details adopted.

D5.1.8 Soil - Soil is a primary gravity load resisting element. It is generally desirable that the soil remain elastic (refer D2.7). Where the soil is of low sensitivity and not prone to liquefaction it may be acceptable to allow rocking or rotation of the footing in the soil at loads corresponding to those induced when $SM=2$, and provided the vertical load carrying capacity is preserved.

D5.1.9 Raft - A raft is a primary gravity load resisting element. It should not yield if this affects its gravity load carrying ability, i.e. use type 1 foundation.

D5.1.10 Strip Footing - The strip footing is usually an extension of the foundation beam, but is also a primary gravity load resisting element member. It should not yield if this affects its gravity load carrying ability, i.e. use type 1 foundation.

D6.0 ANALYSIS

D6.1 In general, design may be based on an independent evaluation for each principal direction, but with consideration of critical aspects of concurrent action such as column axial loads and soil pressures.

D7.0 LOADING

D7.1 The column axial loads on the foundation should be taken as those used in the final design of the column (refer section G - Columns - Evaluation of Actions) and shall include concurrency effects (see D6.0). For type 1 foundations (D12.1) where the foundation is proportioned to maintain the hinge in the column, the column moments on the foundation shall be taken as the overstrength moment at the corresponding design axial load, as above, based on the column interaction diagram for the above axial loads. For type 2 foundations (D12.2) the moment should be that corresponding to the elastic analysis of the superstructure scaled to the level corresponding to that induced when $SM=2$.

D8.0 UPLIFT

D8.1 In accordance with Cl. 3.3.6.2.2 NZSS 4203. 1976.

"Uplift of the entire foundation element may be permitted for not more than one-quarter of the total number of such elements for building deformations in any direction."

If uplift is possible the foundation beams connected to the element must be detailed for ductility. Column stub, foundation pads, pile caps etc. shall be designed to withstand all vertical forces resulting from uplift including self weight, weight of soil frustum and slab uplifted, friction with the soil etc. These forces should be resisted at dependable strength. Details that are non ductile shall have a dependable strength greater than the overstrength of those that are ductile.

The footing itself and the elements restraining such a footing which is expected to uplift, need not be designed to resist the column base design moment in the uplift condition, provided the column base design moment can be accommodated by the combined action of the footing and other restraining elements under all other conditions of design loading.

D9.0 SETTLEMENT

D9.1 Settlement induced forces in foundation beams need not be combined with seismic induced forces, provided such beams are not intended to stiffen the foundation and re-distribute loads to control differential settlements.

Where ductile behaviour under seismic conditions is the design basis for foundation beams, the effect of differential settlement may require special consideration.

D10.0 SOIL STRESSES

D10.1 Where foundation elements are designed to withstand capacity design loadings, the overall factor of safety should be not less than 1.1 in satisfying that loading.

D10.2 Foundations must also comply with the strength method of design (for loadings specified in NZS 4203 Cl.1.3.2). Over and above the factor of safety implied by the factored loads, an additional factor of safety of 1.8 should be applied.

D11.0 MATERIALS - Refer Bulletin of NZNSEE Vol. 10, No. 2 June 1977, Page 75, clauses E.4.2 and C.E.4.2.

D12.0 BASIC STRUCTURAL TYPES (see diagrams)

D12.1 Type 1 - Base Column Hinge Type

A type 1 foundation structure is defined as one in which a column base hinge is designed to form at the base of the lowest storey columns and the foundation elements remain elastic.

D12.2 Type 2 - Yielding Foundation Type

A type 2 foundation structure is defined as one in which yielding in rotation is permitted if the lateral load exceeds that corresponding to the load level induced when $SM=2$. A column base hinge may or may not form at the base of the first storey columns some foundation elements may yield and the soil may also yield due to a footing rotation.

D13.0 STRUCTURAL DESIGN

D13.1 Type 1 (see Figs. 1 and 2)

When a column base hinge is chosen to form in the lowest storey columns, the ideal moment resistance of the foundation system at this point should not be less than the overstrength flexural capacity of the column under the imposed range of axial loads. The axial loads shall be those used in the column design (refer section D7.0). This type of foundation structure is usually designed to remain elastic and in such cases normal detailing to the current design code is satisfactory.

D13.1.1 Case 1A - Strong Foundation Case (Fig. 1)

Where the column moment is resisted by a pad and foundation beams the overstrength moment of the column may be distributed elastically to the foundation beam and the pad and resisted at ideal strength. Special consideration should be given to the possibility of elements yielding caused by the uncertainties of the load distribution. Normal detailing to the current design code may be used provided all elements remain elastic. Note. As the distribution of moments may only be approximate, it may be decided to design the foundation beams to resist the whole moment in which case the pads need only be sized for axial loads provided such pads and any column stubs are detailed to avoid yielding.

D13.1.2 Case 1B - Shear Box Case (Fig. 2)

Where the column moment is resisted principally by a couple formed between the floor slab and the pad, the design moment at ideal strength at the top of the column stub will be the column overstrength moment less the moment distributed to the beam at that level. The moment at the bottom of the column stub will be the carry over moment of

approximately half that at the top of the column stub. Continuation of the column steel down to the level of the pad will normally provide ample moment resistance except in cases of a high axial load increment at that level. The design shear, at ideal strength, on the column stub will be the change in the moments in the stub divided by the height. In a type 1 structure the stub should remain elastic so that the concrete may contribute to shear resistance. Normal detailing to the current design code may be used. The soil pressures should be designed for the axial load. The pad or footing in contact with the soil should be designed to sustain the design axial load plus the moment at the base of the column stub. The resisting couple between the floor slab and the soil at the pad level, would have to resist at ideal strength, the overstrength moments of the column base hinges, by direct thrusts or by diaphragm action to foundation walls acting as a shear box, plus coupling forces.

D13.2 Type 2 (Figs 3, 4 and 5)

Where the overstrength moment of the column base exceeds that induced when $SM=2$, it is permissible to consider a column moment applied to the foundation system corresponding to the column moment based on $SM=2$. With this type of foundation yielding will occur in the foundation beams and possibly rotation of the pad due to localised deformation of the soil.

D13.2.1 Case 2(a) - Yielding Beam Case (Fig. 3)

Where the foundation beams are designed to resist the whole applied moments as in D13.2, the foundation pad may be sized for axial loads only, at dependable strength levels (refer F7 and F10). The effect of rotation of the foundation pad may usually be neglected.

D13.2.2 Case 2(b) - Yielding Soil Case (Fig. 4)

Where the foundation pad is designed to resist the whole applied moment and the interconnecting beams are essential ties, the foundation should be designed for the applied moments induced when $SM=2$ plus the design axial loads. The pad should be designed for the maximum moment that can be developed in the pad at its ideal strength. This occurs when the maximum axial load is resisted near the edge of the footing by the soil at its maximum strength with allowance for the effects of consolidation, etc.

D13.2.3 Case 2(c) - Yielding Beam and Yielding Soil Type (Fig. 5)

Some cases intermediate between Cases 2a and 2b may occur. In such cases special consideration should be given to avoid premature yielding of any element caused by the uncertainties of the load distribution.

D13.2.4 Column Stubs for type 2 foundations should be detailed for ductility. The moments and shears will depend on coupling to the ground and the levels at which it is applied (see diagrams). In some cases

stub columns can develop very high shears. In such cases the shear resistance of the stub column can be increased by increasing the cross sectional area. In any case, as the level and degree of coupling achieved in practice are not accurately predictable, it is recommended that in all cases the size, spacing and detailing of flexural reinforcement and ties in the column stub should not be less than the standard used in the columns immediately above.

D13.2.5 Foundation Beams for type 2 foundations should be designed to resist the design applied moments at dependable strengths. The beams should be detailed to the same standards of ductility as for beams in the superstructure. Ground restraint on foundations can shorten the lever arm of the forces applied to the foundation beam and thus increase the applied shear.

To ensure a measure of ductility in shear, the shear reinforcement should be designed for a minimum of 1.25 times that corresponding to the shear developed by the overstrength flexural capacity of the beams neglecting ground restraint.

REFERENCE

T. Paulay, "An Application of Capacity Design Philosophy to Gravity Load Dominated Ductile Reinforced Concrete Frames", Bulletin NZNSFE, Vol. 11, No. 1 March, 1978.

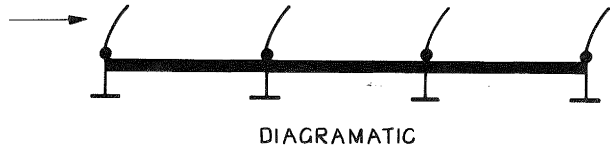
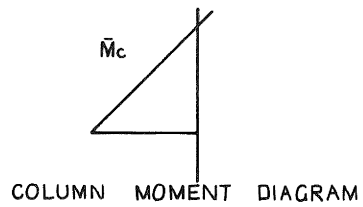
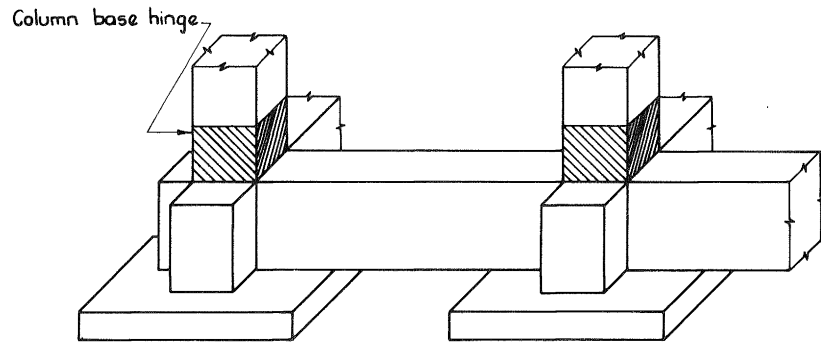


FIGURE 1
CASE 1A: BASE COLUMN HINGE TYPE - STRONG BEAM CASE

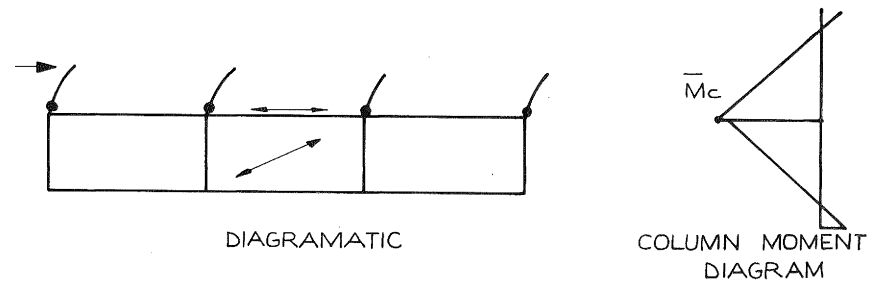
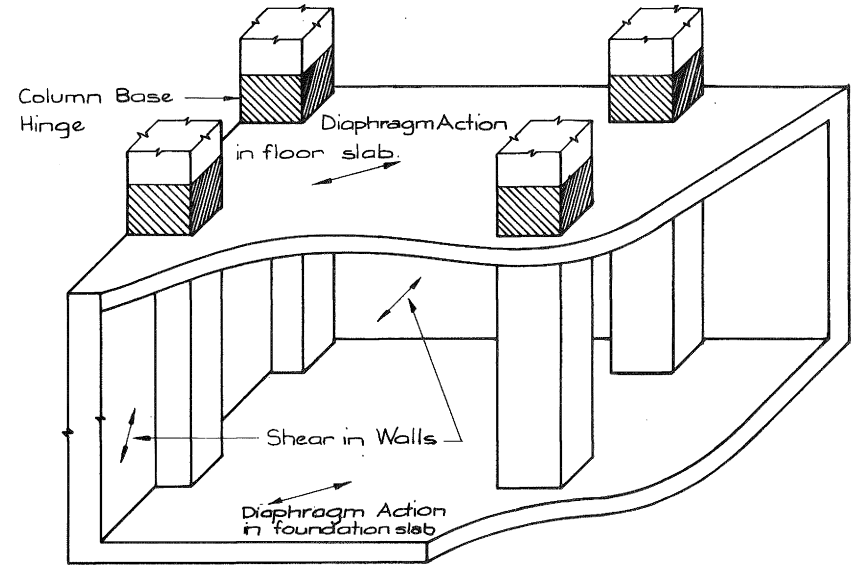
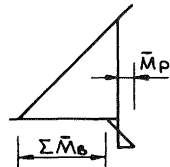
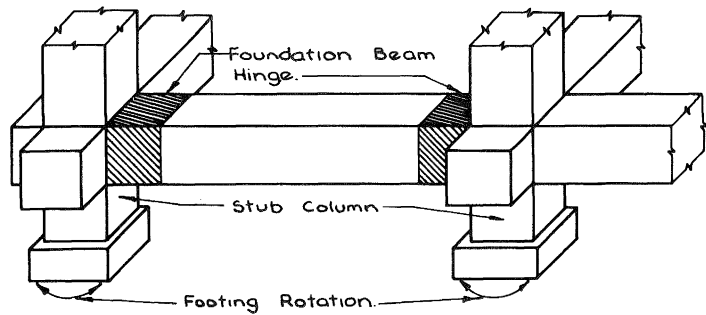


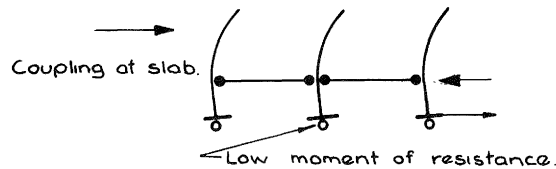
FIGURE 2
CASE 1B: BASE COLUMN HINGE TYPE, SHEAR BOX CASE



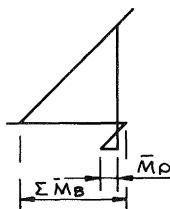
Comments on Moments & Shear in column stubs

Moments low - limited by pad.
Shear moderate.

MOMENT DIAGRAM



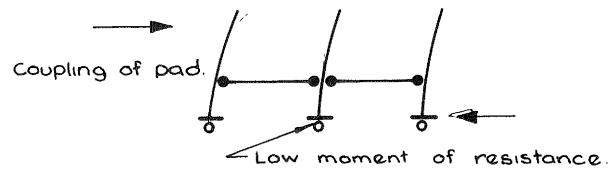
DIAGRAMATIC



Comments on Moments & Shear in column stubs

Moments increase with increasing stub height.
Shear slightly greater than in lower storey columns.

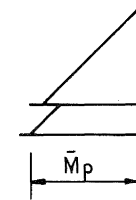
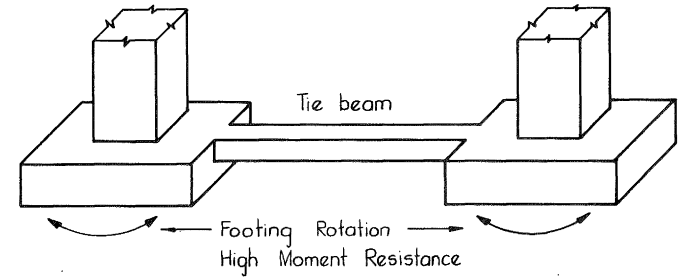
MOMENT DIAGRAM



DIAGRAMATIC

FIGURE 3

CASE 2A: YIELDING FOUNDATION TYPE, YIELDING BEAM CASE



MOMENT DIAGRAM

Comments on Moments & shear in column stubs

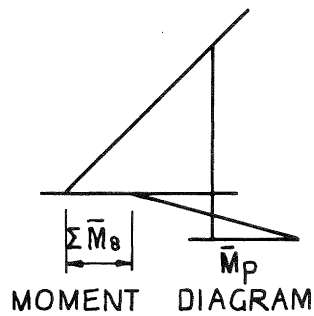
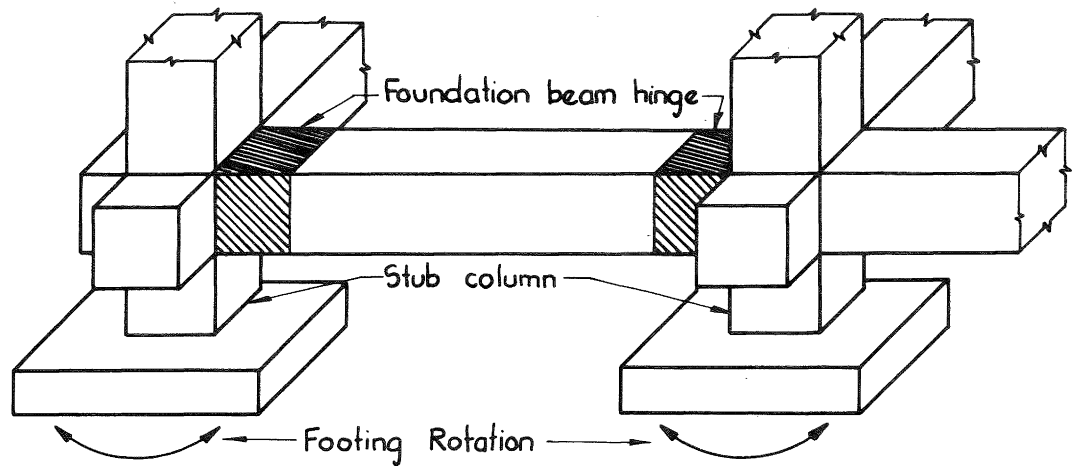
Moments high - increases with increased stub column height.
Shear slightly greater than lower storey columns.



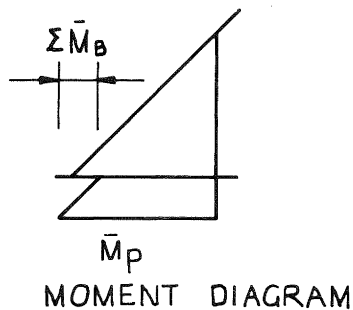
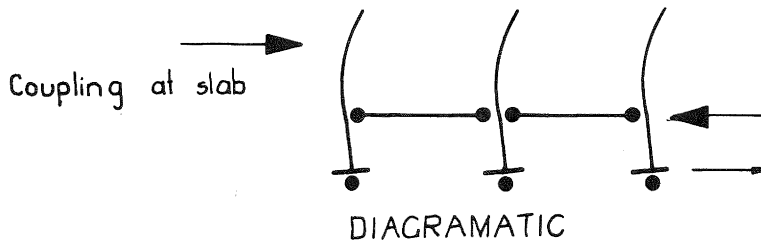
DIAGRAMATIC

FIGURE 4

CASE 2B: YIELDING FOUNDATION TYPE, YIELDING SOIL CASE



Comments on Moments & shear in column stubs.
 Moments moderate.
 Shear may be very high - increases with decreased column height.



Moments moderate - increases with increased stub column height.
 Shear slightly greater than lower storey columns.

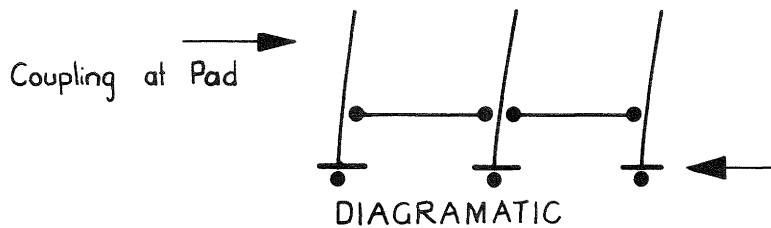


FIGURE 5
 CASE 2C: YIELDING FOUNDATION TYPE, YIELDING BEAMS & SOIL CASE