Chapter 3

GENERAL CONCEPTS OF EARTHQUAKE RESISTANT DESIGN

3.1 INTRODUCTION

Experience in past earthquakes has demonstrated that many common buildings and typical methods of construction lack basic resistance to earthquake forces. In most cases this resistance can be achieved by following simple, inexpensive principles of good building construction practice. Adherence to these simple rules will not prevent all damage in moderate or large earthquakes, but life threatening collapses should be prevented, and damage limited to repairable proportions. These principles fall into several broad categories:

(i) Planning and layout of the building involving consideration of the location of rooms and walls, openings such as doors and windows, the number of storeys, etc. At this stage, site and foundation aspects should also be considered.

(ii) Lay out and general design of the structural framing system with special attention to furnishing lateral resistance, and

(iii) Consideration of highly loaded and critical sections with provision of reinforcement as required.

Chapter 2 has provided a good overview of structural action, mechanism of damage and modes of failure of buildings. From these studies, certain general principles have emerged:

(i) Structures should not be brittle or collapse suddenly. Rather, they should be tough, able to deflect or deform a considerable amount.

(ii) Resisting elements, such as bracing or shear walls, must be provided evenly throughout the building, in both directions side-to-side, as well as top to bottom.

(iii) All elements, such as walls and the roof, should be tied together so as to act as an integrated unit during earthquake shaking, transferring forces across connections and preventing separation.

(iv) The building must be well connected to a good foundation and the earth. Wet, soft soils should be avoided, and the foundation must be well tied together, as well as tied to the wall.

Where soft soils cannot be avoided, special strengthening must be provided.

(v) Care must be taken that all materials used are of good quality, and are protected from rain, sun, insects and other weakening actions, so that their strength lasts.

(vi) Unreinforced earth and masonry have no reliable strength in tension, and are brittle in compression. Generally, they must be suitably reinforced by steel or wood.

These principles will be discussed and illustrated in this Chapter.

3.2 CATEGORIES OF BUILDINGS

For categorising the buildings with the purpose of achieving seismic resistance at

Soft: Those soils, which have allowable bearing capacity less than or equal to 10 t/m^2.

Weak: Those soils, which are liable to large differential settlement, or liquefaction during an earthquake.

Buildings can be constructed on firm and soft soils but it will be dangerous to build them on weak soils. Hence appropriate soil investigations should be carried out to establish the allowable bearing capacity and nature of soil. Weak soils must be avoided or compacted to improve them so as to qualify as firm or soft.

3.2.4 Combination of parameters

For defining the categories of buildings for seismic strengthening purposes, four categories I to IV are defined in *Table* 3.1. in which category I will require maximum strengthening and category IV the least inputs. The general planning and designing principles are, however, equally applicable to them.

3.3. GENERAL PLANNING AND DESIGN ASPECTS

3.3.1. Plan of building

(i) Symmetry: The building as a whole or its various blocks should be kept symmetrical about both the axes. Asymmetry leads to torsion during earthquakes and is dangerous, *Fig* 3.1. Symmetry is also desirable in the placing and sizing of door and window openings, as far as possible.

(ii) Regularity: Simple rectangular shapes, *Fig* 3.2 *(a)* behave better in an earthquake than shapes with many projections *Fig* 3.2 *(b)*. Torsional effects of ground motion are pronounced in long narrow rectangular blocks. Therefore, it is desirable to restrict the length of a block to three times its width. If longer lengths are required two separate blocks with sufficient separation in between should be provided, *Fig* 3.2 *(c)*.

(iii) Separation of Blocks: Separation of a large building into several blocks may be required so as to obtain symmetry and regularity of each block.

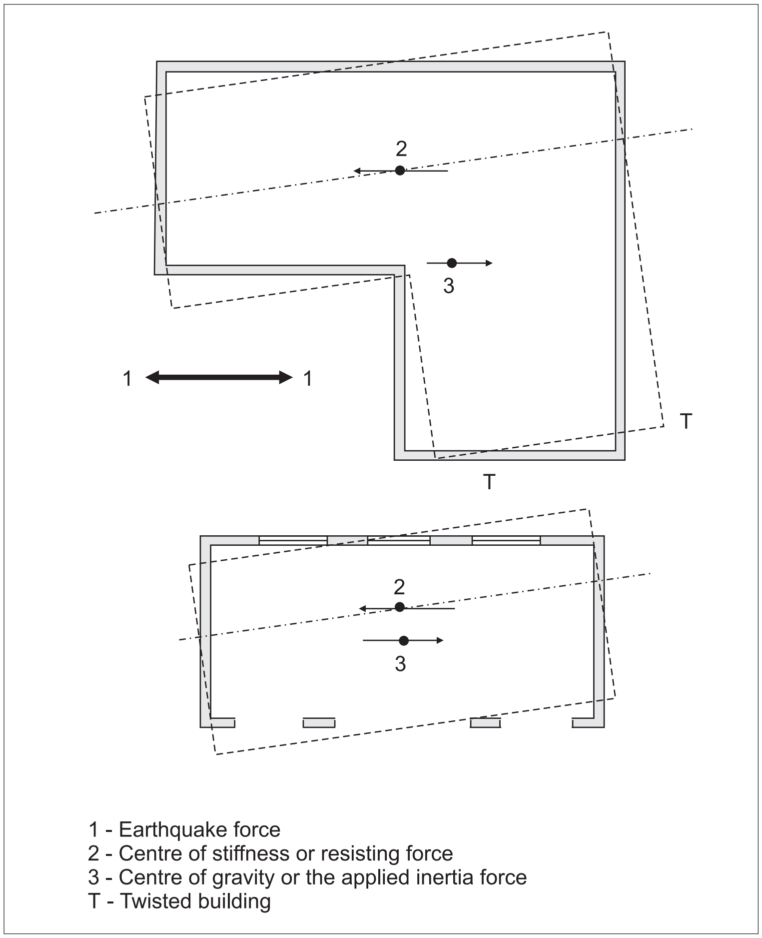

Fig 3.1 Torsion of unsymmetrical plans

For preventing hammering or pounding damage between blocks a physical separation of 3 to 4 cm throughout the height above the plinth level will be adequate as well as practical for upto 3 storeyed buildings, *Fig* 3.2 *(c)*.

The separation section can be treated just like expansion joint or it may be filled or covered with a weak material which would easily crush and crumble during earthquake shaking. Such separation may be considered in larger buildings since it may not be convenient in small buildings.

(iv) Simplicity: Ornamentation invo1ving large cornices, vertical or horizontal cantilever projections, facia stones and the like are dangerous and undesirable from a seismic viewpoint. Simplicity is the best approach.

Where ornamentation is insisted upon, it must be reinforced with steel, which should be properly em-

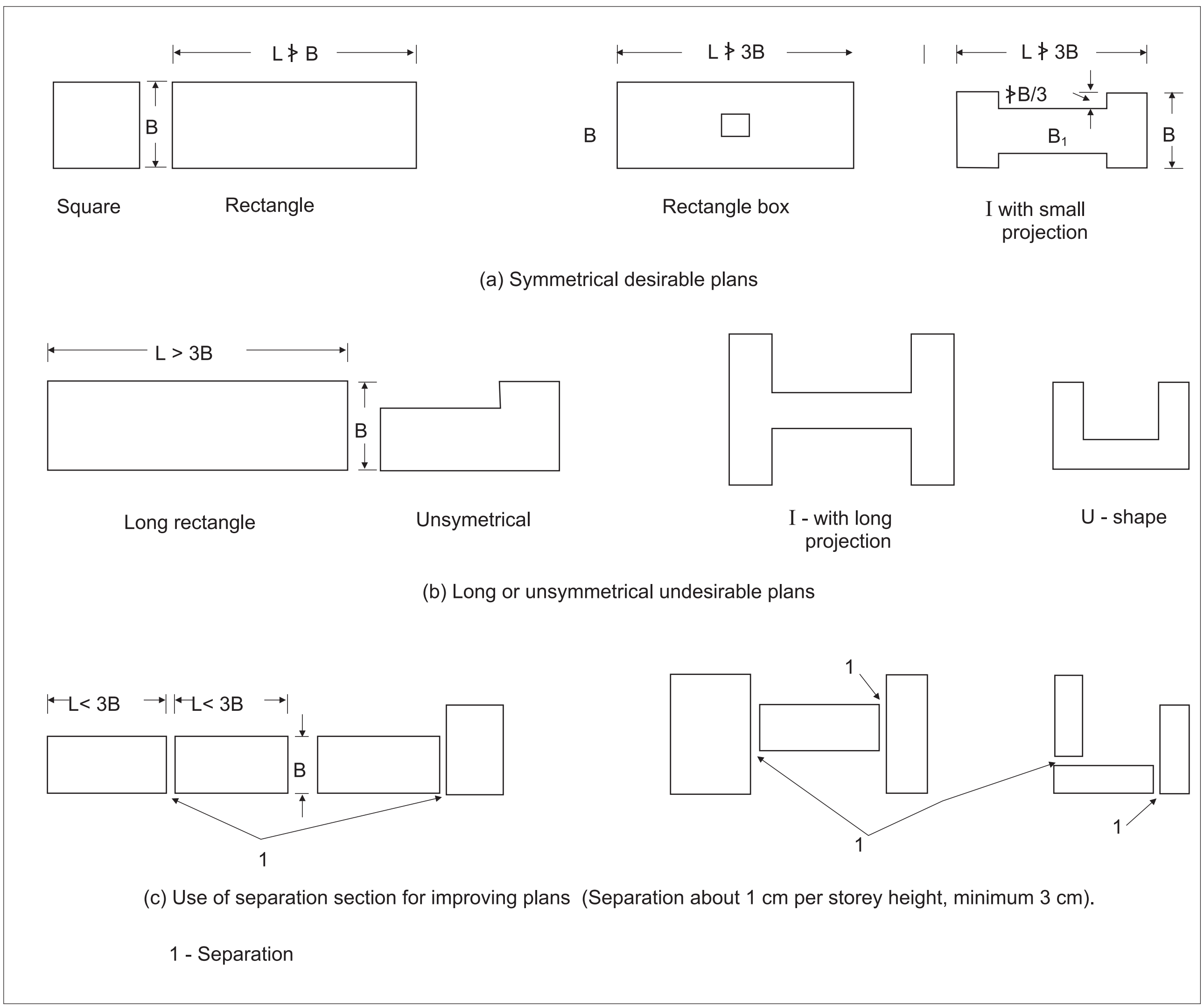

Fig 3.2 Plan of building blocks.

bedded or tied into the main structure of the building.

Note: If designed, a seismic coefficient about 5 times the coefficient used for designing the main structure should be used for cantilever ornamentation.

(v) Enclosed Area: A small building enclosure with properly interconnected walls acts like a rigid box since the earthquake strength which long walls derive from transverse walls increases as their length decreases.

Therefore structurally it will be advisable to have separately enclosed rooms rather than one long room, *Fig* 3.3. For unframed walls of thickness t and wall spacing of a, a ratio of $a/t = 40$ should be the upper limit between the cross walls for mortars of cement sand 1:6 or richer, and less for poor mortars. For larger panels or thinner walls, framing elements should be introduced as shown at *Fig* 3.3*(c)*.

(vi) Separate Buildings for Different Functions: In view of the difference in importance of hospitals, schools, assembly halls, residences, communication and security buildings, etc., it may be economical to plan separate blocks for different functions so as to affect economy in strengthening costs.

3.3.2 Choice of site

The choice of site for a building from the seismic point of view is mainly concerned with the stability of the ground. The following are important:

(i) Stability of Slope: Hillside slopes liable to slide during an earthquake should be avoided and only stable slopes should be chosen to locate the building. Also it will be preferable

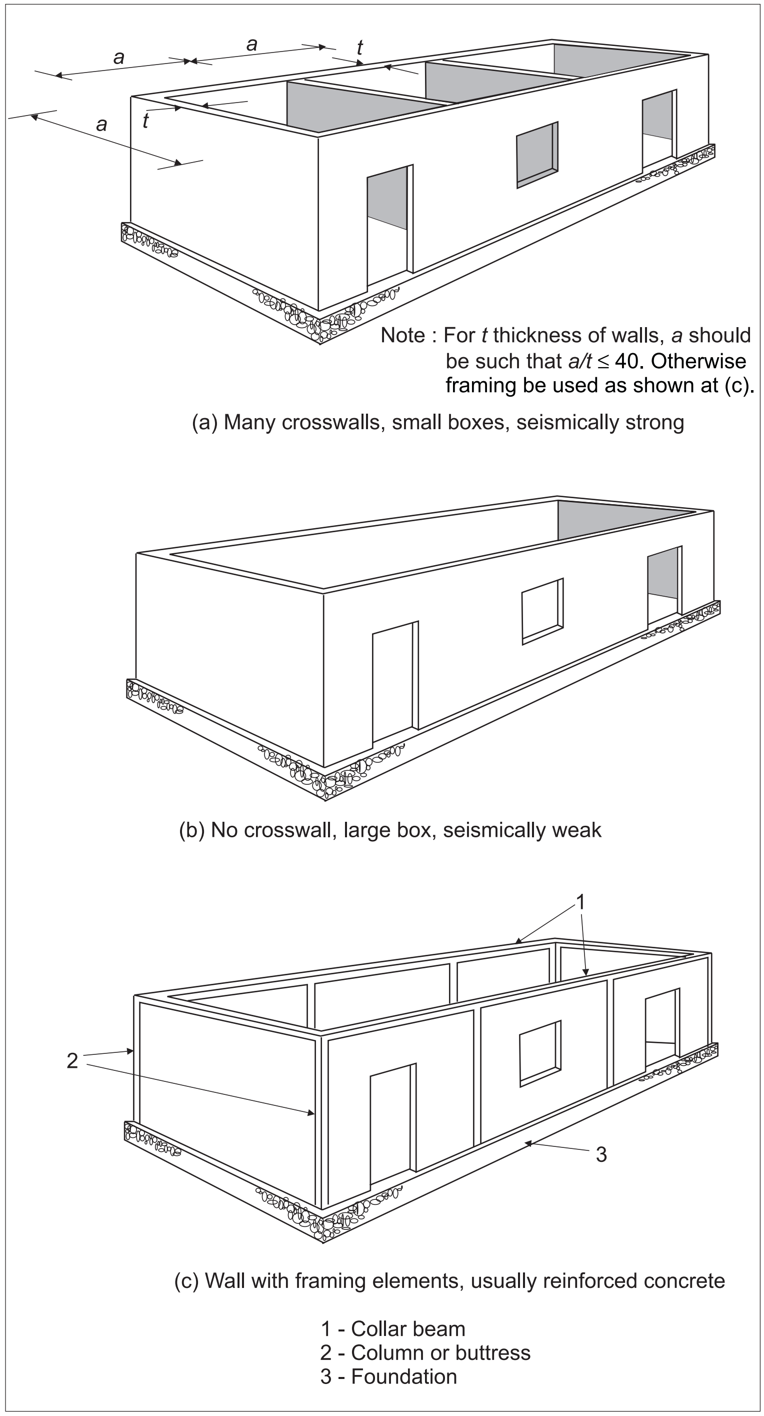

Fig 3.3 Enclosed area forming box units

to have several blocks on terraces than have one large block with footings at very different elevations. A site subject to the danger of rock falls has to be avoided.

(ii) Very Loose Sands or Sensitive Clays: These two types of soils are liable to be destroyed by the earthquake so much as to lose their original structure and thereby undergo compaction. This would result in large unequal settlements and damage the building. If the loose cohesionless soils are saturated with water they are apt to lose their shear resistance altogether during shaking and become liquefied.

Although such soils can be compacted, for small buildings the operation may be too costly and these soils are better avoided. For large building complexes, such as housing developments, new towns, etc., this factor should be thoroughly investigated and appropriate action taken.

Therefore a site with sufficient bearing capacity and free from the above defects should be chosen and its drainage condition improved so that no water accumulates and saturates the ground close to the footing level.

3.3.3. Structural design

Ductility (defined in Section 3.6) is the most desirable quality for good earthquake performance and can be incorporated to some extent in otherwise brittle masonry constructions by introduction of steel reinforcing bars at critical sections as indicated later in Chapters 4 and 5.

3.3.4 Fire resistance

It is not unusual during earthquakes that due to snapping of electrical fittings short circuiting takes place, or gas pipes may develop leaks and catch fire. Fire could also be started due to kerosene lamps and kitchen fires. The fire hazard sometimes could even be more serious than the earthquake damage. The buildings should therefore preferably be constructed of fire resistant materials.

3.4 STRUCTURAL FRAMING

There are basically two types structural framing possible to withstand gravity and seismic load, *viz.* bearing wall construction and framed construction. The framed construction may again consist of:

(i) Light framing members which must have diagonal bracing such as wood frames (see Chapter 6) or infill walls for lateral load resistance, *Fig* 3.3 *(c)*, or

(ii) Substantial rigid jointed beams and columns capable of resisting the lateral loads by themselves.

The latter will be required for large column free spaces such as assembly halls.

The framed constructions can be used for a greater number of storeys compared to bearing wall construction. The strength and ductility can be better controlled in framed construction through design. The strength of the framed construction is not affected by the size and number of openings. Such frames fall in the category of engineered construction, hence outside the scope of the present book.

3.5 REQUIREMENTS OF STRUCTURAL SAFETY

As a result of the discussion of structural action and mechanism of failure of Chapter 2, the following main requirements of structural safety of buildings can be arrived at.

(i) A free standing wall must be designed to be safe as a vertical cantilever.

This requirement will be difficult to achieve in un-reinforced masonry in Zone A. Therefore all partitions inside the buildings must be held on the sides as well as top. Parapets of category I and II buildings must be reinforced and held to the main structural slabs or frames.

(ii) Horizontal reinforcement in walls is required for transferring their own out-of-plane inertia load horizontally to the shear walls.

(iii) The walls must be effectively tied together to avoid separation at vertical joints due to ground shaking.

(iv) Shear walls must be present along both axes of the building.

(v) A shear wall must be capable of resisting all horizontal forces due to its own mass and those transmitted to it.

(vi) Roof or floor elements must be tied together and be capable of exhibiting diaphragm action.

(vii) Trusses must be anchored to the supporting walls and have an arrangement for transferring their inertia force to the end walls.

The strengthening measures necessary to meet these safety requirements are presented in the following Chapters for various building types. In view of the low seismicity of Zone D, no strengthening measures from seismic consideration are considered necessary except an emphasis on good quality of construction. The following recommendations are therefore intended for Zones A, B and C. For this purpose certain categories of construction in a number of situations were defined in *Table* 3.1.

3.6 CONCEPTS OF DUCTILITY, DEFORMABILITY AND DAMAGEABILITY

Desirable properties of earthquake-resistant design include ductility, deformability and damageability. Ductility and deformability are interrelated concepts signifying the ability of a structure to sustain large deformations without collapse. Damageability refers to the ability of a struc-

Table 3.1 Categories of buildings for strengthening purposes

Category	*Combination of conditions for the Category*
I	Important building on soft soil in zone A
II	Important building on firm soil in zone A Important building on soft soil in zone B Ordinary building on soft soil in zone A
III	Important building on firm soil in zone B Important building on soft soil in zone C Ordinary building on firm soil in zone A Ordinary building on soft soil in zone B
IV	Important building on firm soil in zone C Ordinary building on firm soil in zone B Ordinary building on firm soil in zone C

Notes: *(i)* Seismic zones A, B and C and important buildings are defined in Section 3.2.

(ii) Firm soil refers to those having safe bearing value more than 10 t/m^2 and soft those less than 10 t/m^2.

(iii) Weak soils liable to compaction and liquefaction under earthquake condition are not covered here.

ture to undergo substantial damage, without partial or total collapse. This is desirable because it means that structures can absorb more damage, and because it permits the deformations to be observed and repairs or evacuation to proceed, prior to collapse. In this sense, a warning is received and lives are saved.

3.6.1 Ductility

Formally, ductility refers to the ratio of the displacement just prior to ultimate displacement or collapse to the displacement at first damage or yield. Some materials are inherently ductile, such as steel, wrought iron and wood. Other materials are not ductile (this is termed brittle), such as cast iron, plain masonry, adobe or concrete, that is, they break suddenly, without warning. Brittle materials can be made ductile, usually by the addition of modest amounts of ductile materials, Such as wood elements in adobe construction, or steel reinforcing in masonry and concrete constructions.

For these ductile materials to achieve a ductile effect in the overall behaviour of the component, they must be proportioned and placed so that they come in tension and are subjected to yielding. Thus, a necessary requirement for good earthquake-resistant design is to have sufficient ductile materials at points of tensile stresses.

3.6.2 Deformability

Deformability is a less formal term referring to the ability of a structure to displace or deform substantial amounts without collapsing. Besides inherently relying on ductility of materials and components, deformability requires that structures be well-proportioned, regular and well tied together so that excessive stress concentrations are avoided and forces are capable of being transmitted from one component to another even through large deformations.

Ductility is a term applied to material and structures, while deformability is applicable only to structures.

Even when ductile materials are present in sufficient amounts in structural components such as beams and walls, overall structural deformability requires that geometrical and material instability be avoided. That is, components must have proper aspect ratios (that is not be too high), must be adequately connected to resisting elements (for example sufficient wall ties for a masonry wall, tying it to floors, roof and shear walls), and must be well tied together (for example positive connection at beam seats, so that deformations do not permit a beam to simply fall off a post) so as to permit large deformations and dynamic motions to occur without sudden collapse.

3.6.3 Damageability

Damageability is also a desirable quality for construction, and refers to the ability of a structure to undergo substantial damages, without partial or total collapse

A key to good damageability is redundancy, or provision of several supports for key structural members, such as ridge beams, and avoidance of central columns or walls supporting excessively large portions of a building. A key to achieving good damageability is to always ask the question, “if this beam or column, wall connection, foundation, etc. fails, what is the consequence?”. If the consequence is total collapse of the structure, additional supports or alternative structural layouts should be examined, or an additional factor of safety be furnished for such critical members or connections.

3.7 CONCEPT OF ISOLATION

The foregoing discussion of earthquake-resistant design has emphasized the traditional approach of resisting the forces an earthquake imposes on a structure. An alternative approach which is presently emerging is to avoid these forces, by isolation of the structure from the ground motions which actually impose the forces on the structure.

This is termed base-isolation. For simple buildings, base- friction isolation may be achieved by reducing the coefficient of friction between the structure and its foundation, or by placing a flexible connection between the structure and its foundation.

For reduction of the coefficient of friction between the structure and its foundation, one suggested technique is to place two layers of good quality plastic between the structure and its foundation, so that the plastic layers may slide over each other.

Flexible connections between the structure and its foundation are also difficult to achieve on a permanent basis. One technique that has been used for generations has been to build a house on short posts resting on large stones, so that under earthquake motions, the posts are effectively pin-connected at the top and bottom and the structure can rock to and fro somewhat. This has the advantage of substantially reducing the lateral forces, effectively isolating the structure from the high amplitude high frequency motions. Unfortunately, traditional applications of this technique usually do not account for occasional large displacements of this pin-connected mechanism, due to rare very large earthquakes or unusually large low-frequency content in the ground motion, so that when lateral displacements reach a certain point, collapse results. A solution to this problem would be provision of a plinth slightly below the level of the top of the posts, so that when the posts rock too far, the structure is only dropped a centimeter or so.

3.8 FOUNDATIONS

For the purpose of making a building truly earthquake resistant, it will be necessary to choose an appropriate foundation type for it. Since loads from typical low height buildings will be light, providing the required bearing area will not usually be a problem. The depth of footing in the soil should go below the zone of deep freezing in cold countries and below the level of shrinkage cracks in clayey soils. For choosing the type of footing from the earthquake angle, the soils may be grouped as Firm and Soft (see Section 3.2.3) avoiding the weak soil unless compacted and brought to Soft or Firm condition.

3.8.1 Firm soil

In firm soil conditions, any type of footing (individual or strip type) can be used. It should of course have a firm base of lime or cement concrete with requisite width over which the construction of the footing may start. It will be desirable to connect the individual reinforced concrete column footings in Zone A by means of RC beams just below plinth level intersecting at right angles.

3.8.2 Soft soil

In soft soil, it will be desirable to use a plinth band in all walls and where necessary to connect the individual column footings by means of plinth beams as suggested above. It may be mentioned that continuous reinforced concrete footings are considered to be most effective from earthquake considerations as well as to avoid differential settlements under normal vertical loads. Details of plinth band and continuous RC footings are presented in Chapters 4 and 9 respectively.

These should ordinarily be provided continuously under all the walls. Continuous footing should be reinforced both in the top and bottom faces, width of the footing should be wide enough to make the contact pressures uniform, and the depth of footing should be below the lowest level of weathering.

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