SLURRY PILES FOR ASEISMIC SHEARWALL FOUNDATIONS

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SUMMARY

Use of large reinforced concrete slurry wall trenches, called slurry piles, as piles for the foundations of shearwalls of aseismic tall buildings, is discussed. Discussions are oriented to present criteria adopted to obtain in-plan distribution of the slurry piles. Shape of cross section of shearwalls, effects of seismic moments, horizontal forces and vertical loads transmitted to the foundation top by the shearwall's base when subjected to earthquake actions, were considered. Foundations for box section, 'I', 'C' and 'U' shaped aseismic shearwalls of reinforced concrete tall buildings designed by the author following Venezuelan Seismic provisions (Ref.1), are also discussed. Foundations belong to constructed buildings whose shearwalls played main roles in their structural seismic resistance.

INTRODUCTION

Foundation design for aseismic structures combines the use of the foundation type selected according to the soil properties with lay-outs of structural components distributed in such a way that the desired structural response is obtained. The excellent behavior of reinforced concrete structures in which the seismic actions are resisted by coupled shearwalls or by structural systems integrated by lines of ductile frames interacting with shearwalls has been observed in buildings subjected to actual earthquakes. (Refs. 2,3).

Building structures sway when subjected to seismic actions. Presence of shearwalls are of principal interest to control these lateral deformations maintaining them between certain limits in order to get the desired dynamical response. Sources of shearwalls swaying can be originated when lacking of fixity are present at their bases. For this reason, it is important that the foundation offers a perfect structural fixity to the shearwall's base.

Structural requirements for shearwall foundations as well as the in-plan distribution and orientation of the slurry pile axes to give perfect fixity to the shearwall's base avoiding abrupt stiffness changes between the superstructure and the substructure at the foundation level, will be principal subjects of this paper.

SLURRY PILES

General Description and Construction

Slurry piles SP, are reinforced concrete elements used to transmit loads to subyacent soil layers of better load-carrying capacities. Their main

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advantages over circular piles are the shapes and dimensions which are possible to obtain with them as a consequence of the way they are constructed. Trenches with the desired shape for the section of SP are excavated into the ground filling the cavity with bentonite mud to prevent the instability of their walls.

It is possible to construct SP with transverse sections like long rectangles, open boxes and 'C', 'H', 'I', 'L' or 'T' shapes. When the depth of the cavity is reached, reinforcing bars forming cages are descended into it, pouring the concrete bottom-up using long tremies. Figure 1, shows the placement of the reinforcing cage for a rectangular slurry pile of 0.80 x 4.40 meters for the foundation of an 'U' shaped shearwall. (Ref.4).

Figure 2, shows six long SP placed in a rectangular plan for the foundation of two 'C' shaped shearwalls of an aseismic tall building recently built in Caracas, Venezuela, whose structure is formed by ductile reinforced concrete frames interacting with the 'C' shaped shearwalls. All SP are rectangular, four of them of 0.80 x 4.40 meters and the other two of 0.80 x 3.20 meters. Profundity of the SP tips is 30 meters below pile caps' bottoms. Buildings are shown in Fig. 7.

Static Properties

Strength of these sections is illustrated in Fig. 3, in which the interaction diagrams for combinations of ultimate moments in the two principal directions of the transverse section selected for various ultimate axial load levels, are shown. (Each quadrant corresponds to a different axial load level). Diagrams correspond to a slurry pile whose transverse section is an oblong rectangle of 0.60 x 1.80 meters, which is a tipical component of possible SP shapes listed before. Moments are expressed in metric Tons x Meters, and axial loads in metric Tons. Ultimate values were determined for two steel percentages of the longitudinal reinforcement : curves '1' of the diagrams correspond to $p = 0.55$ %, and curves '2' of the diagrams correspond to $p = 1.1$ %. The diagrams innermost curve correspond to the theoretical values of strength for the section without any longitudinal reinforcement. It is to be noted the large load capacity, strength, variety of shapes and dimensions of this type of structural sections.

SHEARWALL FOUNDATION DESIGN

Actions generated by aseismic shearwalls on their foundation structures are similar to those exerted by conventional columns, except by the magnitude of horizontal forces and seismic moments transmitted to foundation tops by each one of these elements. Differences arise from the shear capacity and flexural stiffness offered by the shearwall to the structural system with which it interacts when it is subjected to horizontal actions.

Forces exerted by aseismic shearwalls on their foundations can always be reduced to a combination of vertical loads, seismic moments and horizontal forces. Seismic moments and high horizontal forces transmitted by the shearwalls' bases to pile caps strongly influence SP in-plan distribution, conditioning the relative orientation of their axes. As vertical loads are of second importance to the in-plan distribution of SP, details of their influence to foundation design of shearwalls will not be discussed.

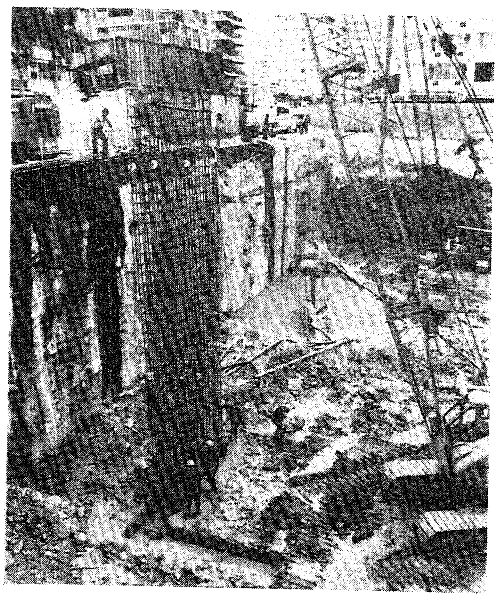

Fig. 1 - Placement of Reinforcing Cage. (Ref.4).

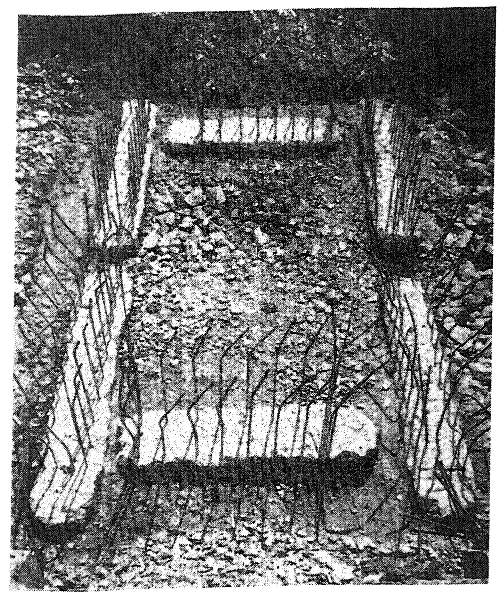

Fig. 2 - Built Slurry Piles for two C-shaped Shearwalls.

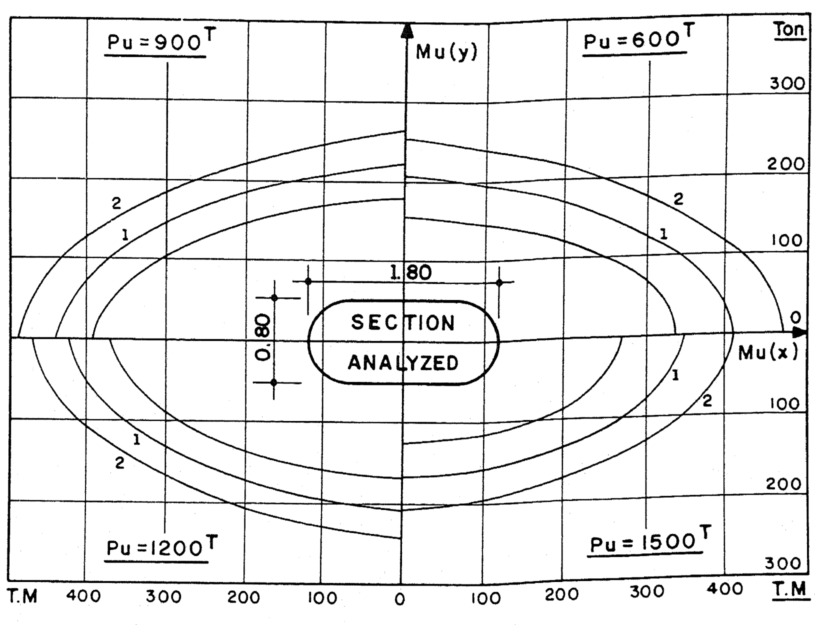

Fig. 3 - Interaction Diagrams. (Sections of the Interaction Volume).

Seismic Moments

Seismic moments can be resisted by slurry piles groups in two ways:

1. As in general design practice for columns founded on circular piles, placing the SP group where they can generate couple reactions large enough to resist the design moments. (Ref.5).

2. Using the large flexural capacity of SP groups, capacity that was illustrated in Fig. 3, for an oblong rectangular pile of 0.80 x 1.80 meters. Use of this flexural capacity requires orienting the transverse sections of SP with the plane containing their largest dimensions parallel to the plane containing the design moments.

   Flexural capacity of long rectangular SP, or of groups of them can reach significant values, being a basic difference with circular piles whose flexural capacities can not always be used for foundation design. (Ref.5). The orientation of SP axes follow specific structural requirements because their load capacity is independent from their relative orientation in the soil.

Horizontal Forces

Seismic actions generate very high horizontal forces at shearwall's bases of tall buildings producing lateral displacements and deformations on the foundations. Actually, seismic motions induce soil-structure interaction, which in turn produce inertial forces and lateral deformations in the structural complex.

If there are abrupt structural stiffness changes at foundation level, as consequence of wrong orientation of SP axes, the lateral sway of the SP group may be inadequately large, originating an undesirable behavior at the transition between the superstructure and the substructure. Consequences of this behavior can be diminished or even avoided, if the larger dimensions of the SP are oriented in planes parallel to the direction of the acting horizontal forces. This requirement is similar to N° 2, above.

Both design requirements can be easily fulfilled if the inertia moments of the SP group in each direction, are equal or larger than the correspondent inertia moments of the transverse section of the upper shearwall. Designing the SP group in a geometrical configuration similar to the transverse section of the shearwall to be founded on them, is a practical rule to meet the structural design orientation requirements.

Notes on Soil-Structure Interaction

Conventional piles cause large soil deformations before developing their limited resistance to actions perpendicular to their axes. Shearwalls interacting with frames can not always deal with these large deformations of their supporting piles. Traditional solutions call for use of battered piles or transmitting horizontal actions to other resistant members of the structure.

Long rectangular SP subjected to horizontal actions in the directions of their largest dimension behave into the soil as rigid bodies. Due to this behavior they can always resist the applied horizontal forces with minor deformations of the surrounding soil. It appears as if the stiffer behavior of SP groups would produce more undesirable dynamical responses of the soil-structure complex than those produced if the structure were founded on conventional piles. Lateral deformations needed on piles to get lower responses can not be accommodated by shearwall's foundations without resulting abrupt changes of structural stiffness between the super and the substructure.

EXAMPLES

Designs of shearwall foundations that will be shown, belong to various constructed buildings designed by the author following Venezuelan Seismic Code (Ref.1), built in Caracas, Venezuela, during the period 1970 - 1982.

I-Shaped Shearwall. (Ref.6)

Foundation shown in Fig. 4, belong to one of the two central I-shaped shearwalls which interact in the structure of an A-Shaped 32-Story reinforced concrete building 120 meters tall. (Ref.6) Three rectangular slurry piles were used in this foundation, one unit of 0.80 x 5.60 meters placed below each I's flange, and one unit of 0.80 x 3.80 meters placed below the I's web. Note the similar configuration of shearwall and the SP group.

U-Shaped Shearwall. (Ref.4)

Foundation shown in Fig. 5, supports each one of the four U-shaped shearwalls placed at the corners of a 28-Story reinforced concrete building of cross-shaped plan. (Ref.4). Each shearwall is founded in four rectangular SP, three of them of 0.80 x 5.40 meters and the remaining of 0.80 x 4.40 meters. The picture shown in Fig. 1, shows the placement of the reinforcing-cage of the smaller pile. These rectangular SP were placed along the axes of flanges and webs of the U-shaped shearwall in order to avoid abrupt stiffness changes at foundation level.

C-Shaped Shearwall.

In the SP's general description paragraph in this paper, the foundations for two C-shaped shearwalls were described. See Fig. 2. The corresponding pile caps are shown in Fig. 6, and the constructed buildings in Fig. 7. It is to be mentioned that the tie beams of this cap, placed below the 'C' flanges, must be designed as coupling beams between shearwalls. (Ref.3).

Shearwall of Square Open Box section

The structure of the building shown in Fig. 9, has one shearwall shaped as a square open box section at each corner of its symmetrical plan. Each box shearwall was founded on four equal rectangular SP of 0.60 x 4.40 meters, placed in a way that SP resemble the upper shearwall shape, as it is shown in Fig. 8.

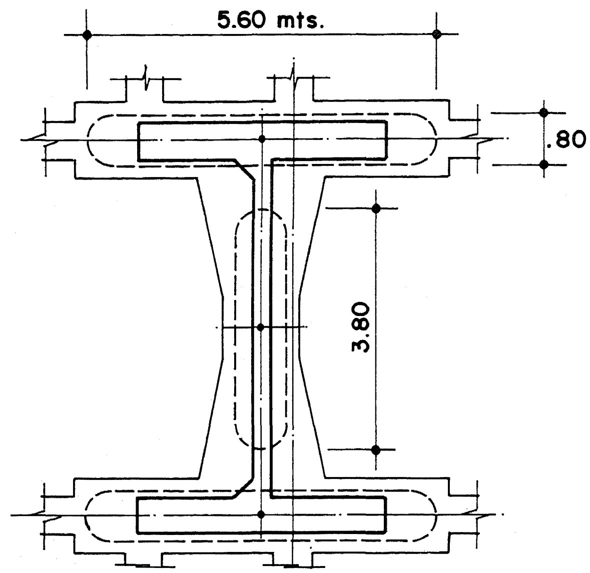

Fig. 4 - I-Shaped Shearwall Foundation. (Ref.6).

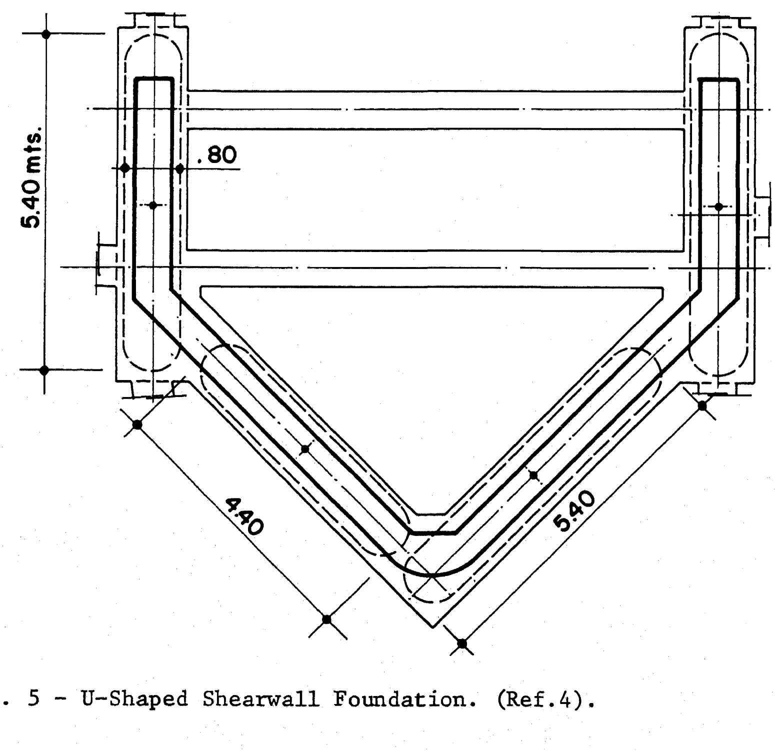

Fig. 5 - U-Shaped Shearwall Foundation. (Ref.4).

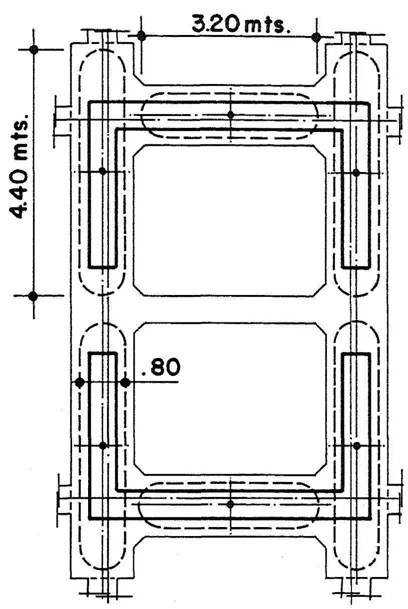

Fig. 6 - Foundation for two
C-shaped Shearwalls.

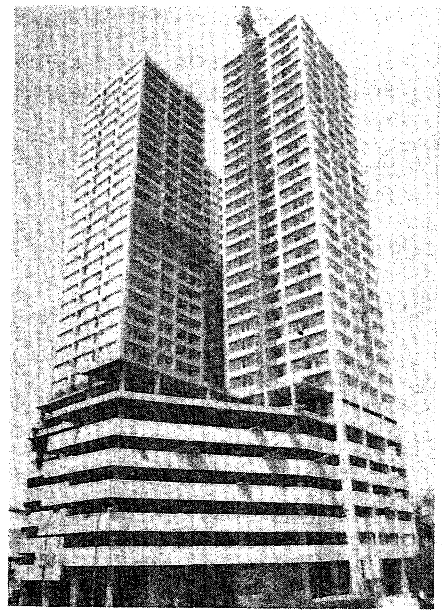

Fig. 7 - Buildings with central
cores shown in Fig. 6.

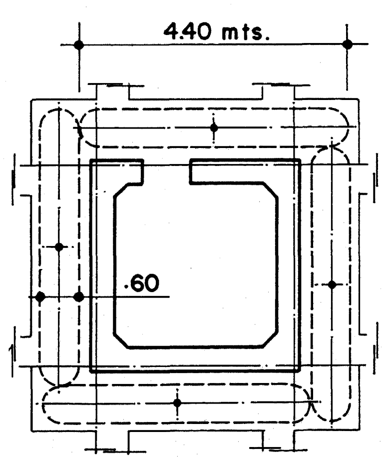

Fig. 8 - Foundation for an open
Box-shaped Shearwall.

Fig. 9 - Building with corner
Box-shaped Shearwalls.

CONCLUSIONS

This paper resumes the author's experience using SP as structural components of aseismic tall building shearwall foundations. Some conclusions related to structural design are:

Slurry piles are structural elements with large axial load capacity, excellent flexural strength and sufficient shear capacity when they are subjected to actions perpendicular to their axes. Diversity of shapes and dimensions make their use specially adequate to resist the high forces acting at shearwall's bases of aseismic tall buildings. Lay-out and geometrical configuration of foundation caps result on compact dimensions.

Undesirable stiffness changes between the super and the substructure are avoided when slurry piles are correctly oriented in-plan. The orientation of SP for convenient lay-outs is a function of structural requirements because their load capacity is independent from their axes orientation.

Stiff SP would behave as long shearwalls built into the soil. It is not possible to determine actual responses of upper structures founded on these elements without taking into account soil interaction. Usual assumptions regarding the fixity of shearwall and column bases, normally adopted in mathematical models for analysis, are better satisfied by slurry piles correctly oriented in actual foundations.

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