Behaviour of a friction pile-box foundation in Mexico City during construction

Comportement pendant la construction de fondations mixtes radier-pieux flottants à Mexico

M. J. Mendoza – *Institute of Engineering, UNAM & CENAPRED, Mexico*
M. P. Romo – *Institute of Engineering, UNAM, Mexico*

ABSTRACT: The first geotechnical and seismic instrumentation placed in the prototype of a mixed foundation constituted by a box foundation and friction piles, in the difficult soft clayey soil of Mexico City, is described in this paper. Behavior of the foundation during construction is discussed taking into account the measured applied loads on friction piles,the contact pressure distribution at the raft foundation-subsoil interface, the piezometric heads in the subsoil water, and the foundation movements.

RESUME: Cette communication décrit le premier système d'auscultation géotechnique et sismique qui ait été installé sur des fondations mixtes radier-pieux flottants dans les difficiles argiles molles de Mexico. On révise le comportement des fondations durant la construction à partir de mesures portant sur des variables telles que la charge prise par les pieux, les pressions sur le radier, les pressions interticielles et les mouvements des fondations.

1 INTRODUCTION

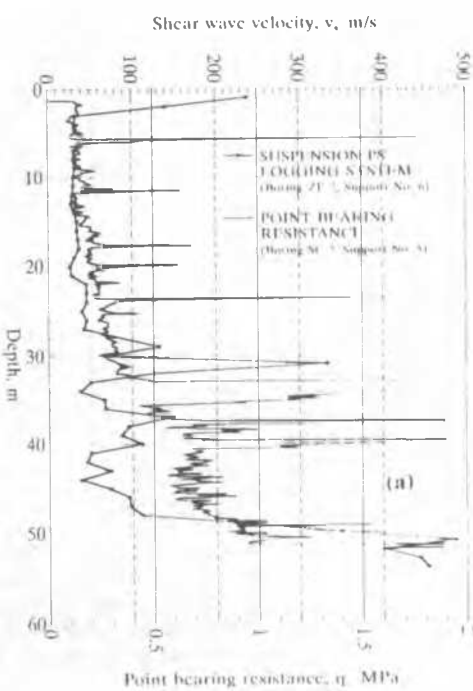
Among the types of foundation which are turned to in the lacustrine clay sediments in Mexico City, a mixed system constituted by a hollow box and friction piles has been the most common foundation for five to fifteen-floor buildings. However, due to the Michoacan earthquake in 1985 (M_s=8.1), 13% of these buildings, a figure truely high and unacceptable in engineering, suffered impressive settlements and tiltings, and severe structural damages; one building toppled due to foundation shear failure. Indeed, foundation engineering in Mexico City faces up to very difficult conditions, not only due to the presence of conspicuous soft and highly compressible clayey deposits, but due to regional subsidence and the occurrence of strong earthquakes. By the way, it is convenient to mention that these soils are not unique or different to other soft soils; they are, perhaps, just the extreme expresion of such kind of natural sediments.

As an answer to the above situation, more rigid regulations were imposed in the Mexico City Building Code to this type of foundation. Soon after the earthquake the inadequate behavior was associated to loss of skin resistance during the dynamic event, and lower reduction factors on this resistance were involved, in order to take into account this supposed effect on the load capacity of friction piles. Detailed review of case histories (Mendoza & Auvinet 1988) has shown that unsuitable behavior of buildings on this type of mixed foundation was related to reduced number or reduced skin area of piles developing skin stresses close to the ultimate skin resistance, eccentricities, flooded foundation boxes, and all of them associated to very high sustained contact stresses at the raft foundation-soil interface. In situ tests with short and isolated friction piles (Jaime et al. 1989) under repeated loads in Mexico City clay have pointed out that if the sum of sustained and cyclic semiamplitude is less or equal the ultimate static capacity, P_u, no reduction of load capacity was detected, with only a reduced settlement (about 1 cm); and only when the sum of loads reaches values between 1.15 P_u and 1.35 P_u, a clear reduction of skin load capacity and large settlements were measured. Furthermore, the increase of load capacity under dynamic loading due to rate effect is well known (Bea 1980), although it is also true that degradation of shear resistance because the level of strain and number of cycles aim at the reduction of load capacity.

Uncertainties and more stringent regulations have reduced the use of friction piles in the city, in comparison with the previous situation to that earthquake, even so, they still are a convenient solution for the unfavourable geotechnical conditions at the Lake Zone. Although field and laboratory work as well as analytical simulations have been done, a full and real evaluation of their behavior has not been carried out yet. Trying to fulfill this gap, geotechnical and seismic instruments have been arranged in a prototype of a friction pile-box foundation; brief descriptions of the foundation and instrumentation are included in this paper. Based on the records which were taken during construction, the behavior of the foundation in this stage is discussed. The prototype (15x22x3 m-foundation box with 77 friction piles down to 30 m) is the support of the central span of a vehicular and pedestrian bridge which is located in the Northeastern zone of Mexico City.

2 SCOPE

The behavior of this foundation during construction is discussed taking into account: a) the applied loads on some friction piles, both in their head as well as along their length, b) the contact pressure distribution between the raft foundation and the subsoil; c) the piezometric heads in the subsoil water below the foundation area; and d) ground and foundation movements. Measurements of applied loads or pressures were done with strain gages or vibrating based transducers. Having in mind that seismic condition is critical



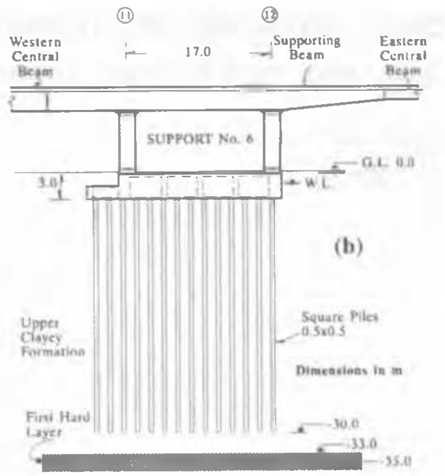


Fig 1 Geotechnical data of the site and lateral view of the instrumented mixed foundation and bridge superstructure

for this type of foundation in the city, particular emphasis was given to record the above mentioned variables at the very moment when an earthquake occurs, that is why these sensors are continuosly monitored through an automatic acquisition system, plugged in recently, controlled by a triaxial accelerograph. The construction stage of the bridge was over lately, and no important seismic events have happen since then. Performance of the foundation during the construction stage was closely monitored with manual digital recorders. The main objectives pursued with this instrumentation program are to learn more about the load-transfer mechanisms that develop among pile-soil and slab-soil. Thus, it is hoped that further light will be shed on the soil-pile-slab interaction problem, both in static and dynamic conditions.

3 SOIL SITE CONDITIONS

Three geotechnical zones are recognized in Mexico City (Marsal & Mazari, 1969). The Hill Zone (I) is characterized by well cemented pumice-type tuffs and dense sandy soils in the western part of the city, and basaltic lava flows to the south. Lake Zone (III) comprises very soft clayey deposits interbedded with thin lenses of sand or volcanic glass; these soils correspond to materials settled to the bottom of a former lake. Transition Zone (II) is characterized by even abrupt stratigraphical changes from place to place between those of Zones I and III. Mexico City soft clayey lacustrine soils are characterized by very high compressibility, low shear strength, normally or lightly overconsolidated behavior, very low shear wave velocities, thick deposits and quite high water contents, void ratios and plasticity indexes. These poor soil conditions are worsened by *i)* the regional ground subsidence of the Valley of Mexico, where the city is settled, with typical rates of 5 to 30 cm/year; this phenomenon is associated to the piezometric heads losses due to aquifers exploitation; and *ii)* the frequent occurrence of distant, strong earthquakes whose intensity is significantly increased by the clayey deposits. Foundations on point-bearing piles were used to support heavy buildings, making use of the FHL as the bearing stratum; however, they are rarely used now because regional subsidence induces an apparent emersion of the buildings, provoking unattractive appearance, undesirable differential movements on neighboring buildings and problems on service lines.

After a relatively thin dry crust, which was almost eliminated by the excavation, the site of interest is characterized by very soft and normally consolidated clayey deposits. Average undrained shear strength of undisturbed samples taken from UCF and measured in quick triaxial tests was 12 kPa. This indeed low strength is corroborated by the very low cone bearing resistance, as well as by the profile of shear wave velocities, Fig 1a. P and S-wave velocities were measured at each meter (Gutiérrez 1995) with the suspension P-S logging system through an upward movement of the probe, which includes wave source and receivers.

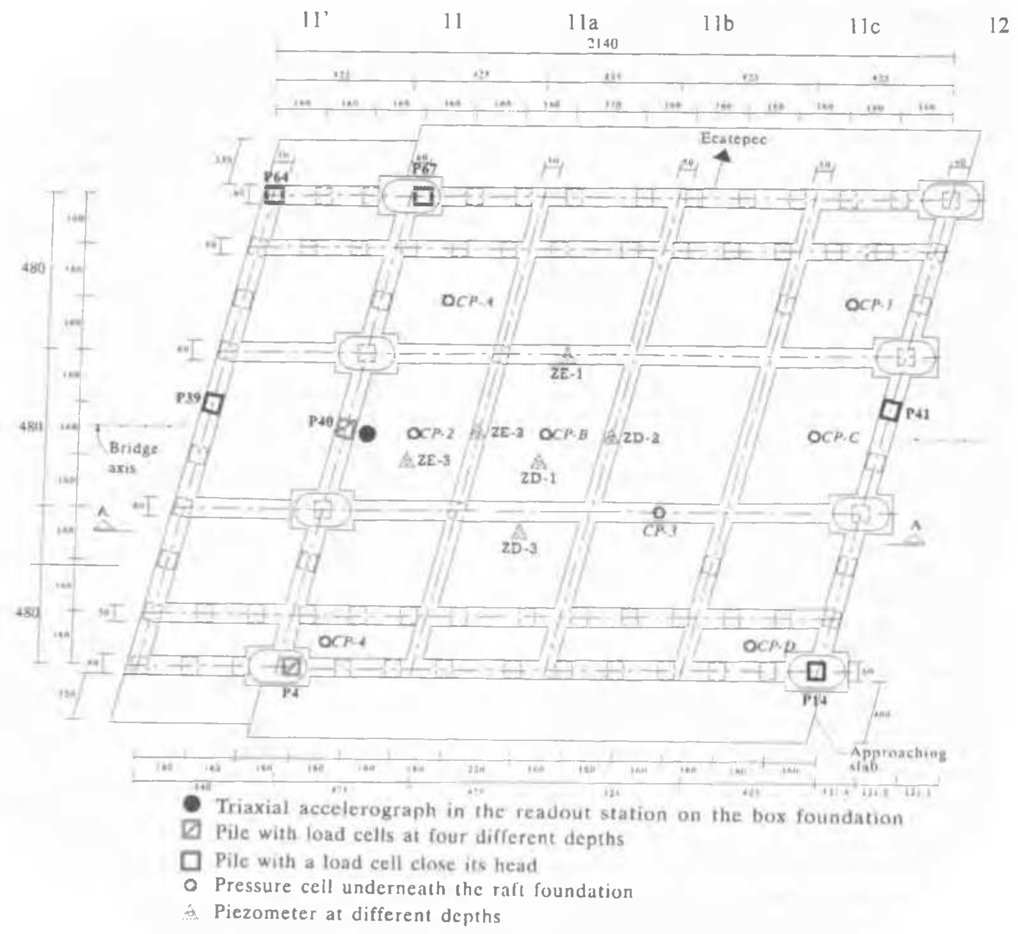


Fig 2. Plan of the instrumented friction pile-box foundation

4 INSTRUMENTED FOUNDATION

The selected prototype is the support No. 6 of the central span of a bridge located in the Northeastern zone of Mexico City; it crosses a wide avenue wherein the B-Line of the Metro is under construction, by surface in this portion. The bridge is 689 m long and was solved with eight supports and lightweight approaching ramps; each support has two transversal lines of cast in place reinforced concrete columns. Directly on columns, Fig 1b, supporting beams with cantiliver portions carry isostatic central beams; these structural elements are prefabricated and prestressed concrete hollow "T" shape beams. The Western span (central) between supports Nos. 5 and 6 is 56.8 m long, while the Eastern span is just 43.0 m long; heavier loads of the central span defines a shorter length for the Western cantiliver of the supporting beams and a larger raft foundation in that direction, in order to reduce eccentricities. Support No. 6 has 8 oblong columns in two lines, separated by 17.0 m; its foundation was solved with a 15 x 22 m rhomboidal in plan box due to the oblique crossing (104° 11') of the avenues, Fig 2, and 77 friction piles.The hollow box has 2.7 m-high and 0.5 or 0.6 m-wide foundation beams designed in both directions, upstanding the foundation slab; they were monolithicly cast to the reinforced raft which has a uniform thickness, 0.25 m. A second or cover slab, 0.22 m-thick, was cast on top of the beams, so forming a rigid box foundation or cellular raft.

The piles were driven in two segments 15 m each, down to 30 m-depth, keeping a 3 m-gap between piles tip and FHL in order to accommodate future regional subsidence and foundation settlements. Piles driving was carried out before excavation in order to reduce the heave at the excavation bottom, and to reduce the time the excavation was kept open The piles coincide in plan with the foundation beams, and their design was oriented to include them as much as possible close to longitudinal edges, keeping in mind the overturning seismic moments in the transversal direction to the bridge. Reinforced concrete piles were precast in place, with a square cross section, 50 cm by side. An auger preboring, 50 cm ϕ, was made through the top 4 to 5 m; afterwards, a Delmag No. 33 piling hammer was used, although very few, controlled and reduced blows, an average value of 20, were in general necessary to give; as a matter of fact, piles were tied up with steel cables for not to loose the design tip level.

5 GEOTECHNICAL AND SEISMIC INSTRUMENTS

The geotechnical and seismic sensors were installed as follows: 13 load cells, 8 earth pressure cells, 6 piezometers and a triaxial arrangement of accelerometers. Two independent and redundant instrumentation systems, one automatic and other manual, were adopted for this project taking into account a long-term monitoring. The automatic system is oriented to record the response during a strong motion; the manual system is meant to be for measuring the performance of the foundation system under "static" conditions. Geotechnical sensors for the automatic system are of strain gage basis (SG), of convenient dynamic response, while vibrating wire transducers (VW) were considered more stable for long-term monitoring. Sensors were monitored during the construction stage by means of a conventional strain indicator readout box for SG, and frequency indicator readout box for VW instruments, both of manual type. Full and accurate calibrations were done in the laboratory, before construction, of each sensor, making use precisely of the same manual and automatic recorders to be employed in the field, reproducing gains, gage factors, input voltages and placing conditions.

The recording system is quite similar to those of accelerographic stations; in addition to the accelerometers signals, it will record those of geotechnical sensors both to predefined intervals, as well as to a certain threshold acceleration. To the authors' knowledge this instrumentation project is without precedents worldwide; previous studies in prototypes have been oriented for the static and long-term performance (Cook et al. 1981, Hansbo & Jendeby 1983; Rickard *et al.*, 1985, Sommer *et al.*, 1985; Yamashita & Kakurai, 1991, among others).

Load cells. Rugged waterproof load cells were selected; their load element with a maximum capacity of 1.78 MN is a spool of high strength steel. These sensors were integrated to seven piles (Fig 2) close to their head; in addition, three more load cells at different depths were included in two of these instrumented piles. These cells were carefully integrated to pile segments placing each one between steel plates attached and lightly precompressed by 6 high strength galvanized steel bolts. More details are given in a previous paper (Mendoza & Romo 1996).

Earth pressure cells. The cells consist of two circular stainless steel thin plates welded together around their periphery and spaced apart by a narrow cavity filled with an stable degassed liquid, which is connected to the pressure transducer through a stainless steel tubing. External total pressure acting normal to the plane of the cell are balanced by an equal pressure induced in the internal fluid. The cells were horizontally placed 10 cm beneath the raft foundation within a sand bed.

Piezometers. These sensors were placed at different depths in a small core beneath the box, Fig 2. Each piezometer was carefully saturated in order to assure a quick response (Hartlén 1985), and brought down in different boreholes to avoid possible interconnections between them; the boreholes were stabilized with water and two piezometers were located in clayey strata.

Accelerograph. A high resolution accelerograph including built-in triaxial servo accelerometers have been fixed to a concrete pedestal within the readout station which was built on the box foundation. This Integrated Digital System (IDS) produces a data record in battery backed-up CMOS RAM of seismic events; it continuously amplifies, filters and converts (1000 samples/ second/ channel) the sensor output to 16 bit digital form and sends the data, along with the synchronized internal time to a digital delay.

Digital recorders. Instead accelerometers, digital recorders will have signal conditioned inputs for external geotechnical sensors. Fifteen geotechnical sensors will be monitored by five automatic digital recorders (three per instrument) which will be in a slave-master network with the triaxial accelerograph, under common timing for sample synchronization.

6 OBSERVED BEHAVIOR

6.1 Loads on piles

The measured applied loads on instrumented piles' head during construction and beginning of operation is depicted in Fig 3. All load cell were preloaded with about 60 kN when they were attached to the piles segments. It is interesting to notice the load variations; however, whereas the quotient between the maximun and minimun loads was 2.35 at the end of 1995, when the bridge was open to traffic it was 1.56 only. It is clear that as the foundation has experienced movements and the residual stresses have relaxed, the tendency is to reach more uniform loads on piles. A preliminar analysis does not let us to establish definitive trends, because a particular arrangement of piles in which more of them were concentrated to the edges. The measured loads do not point out clear symmetries; not withstanding, we can distinguish that the extreme piles P4 and P64 in the transversal direction close to the long span, support the two largest loads. Furthermore, the extreme piles P39 and P41 in the longitudinal direction are required with the two lowest loads.

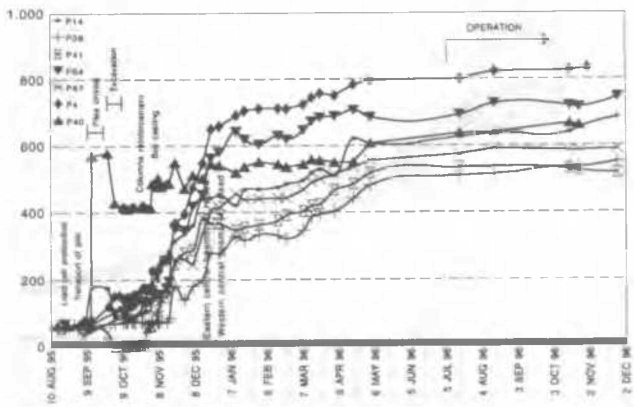


Fig 3. Measured loads on piles during construction

6.2 Total pressures at the soil-raft interface

Evolution of the applied total pressures in the soil-raft contact during construction and the beginning of the bridge operation is shown in Fig 4. In a similar way to loads on piles, pressures at different points exhibit different values, defining no uniform contact stresses; the mean value to the end of construction was 24 kPa, which corresponds to 70% of the total pressure to the grade level before excavation. The first pressure represents about 15% of the total applied load; although the contribution of piles and raft varies during construction (Rickard *et al* 1985), upon completition it has been found with much more stiffer clays (Cooke *et al.*, 1981) that the raft typically takes 25% to 40% of the total load, the remainder being supported by the piles.

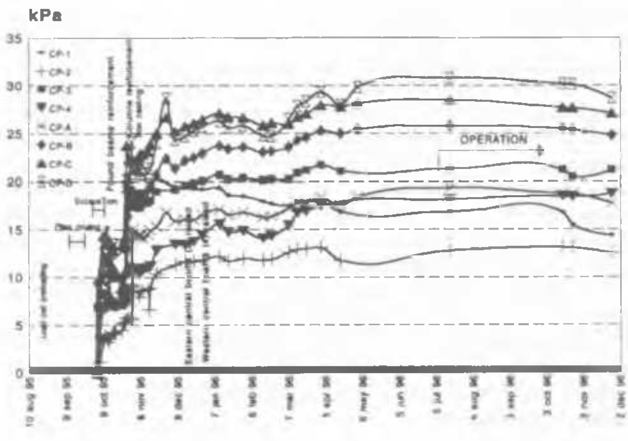


Fig 4. Measured pressures in the soil-raft contact during construction

An immediate increase of pressure was detected when raft and foundation beams were placed; afterwards, a low reduction corresponding to the reaction of piles, and then, a sudden rise when the box foundation was cast, in two stages. Once the box was hardened and the columns were erected, it was observed the work of the rigid box, transfering loads to piles. As the loads of the superstructure increase, it is evident that contact pressures grow, but with a lower rate than loads on piles; that means that the substantial weigth of the bridge is taken by the piles.

Without doubt, interaction phenomena and load sharing mechanism between piles and the close areas of the raft foundation develop, as can be appreciated by Figs 3 and 4. The measured loads on piles P4, P40 and P64 were the largest, defining in that portion the lowest pressures on the contact; on the contrary, loads on piles of the east side were lower than the mean value of all of them, and the largest raft pressures were there. The presence of 7 piles at the centre of axis 11 and 11a, in comparison with the 2 piles in the axis 11c, determines that those piles have been taking larger loads, and may be contributing to the formation of a clear "valley" in the pressure distribution towards the west side.

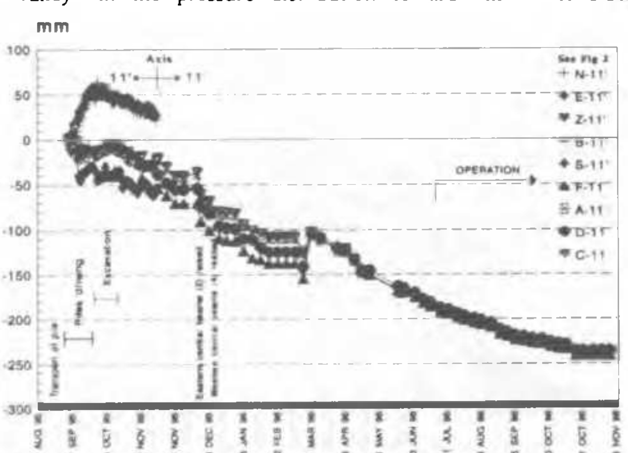


Fig 5. Vertical movements of the ground and foundation

The vertical movements of the foundation during construction and the beginning of operation, through axis 11, is depicted in Fig 5. It is clear the ground heave due to piles driving without previous excavation. The concavity of the settlements curves some months after the bridge was open to traffic points out that foundation movements are tending to reach less than 30 cm. These large settlements are not uncommon in the very soft deposits of Mexico City.

7 CONCLUSIONS

Multiple uncertainties in the performance and design of piled box foundations were detected after the Michoacan earthquakes in 1985; reduction of them is the aim of the instrumentation project which is described herein. The use of instrumentation within a prototype of this kind of foundation on the very soft clayey deposits of Mexico City will provide with further information to improve our knowledge about the load sharing mechanism between piles and raft foundation; without doubt, just one instrumented prototype is not enough. When the bridge was open to traffic, piles supported 85% of the total reaction of the mixed foundation; the rest is the contribution of the raft. Both loads on piles and contact pressures at the raft exhibit diversity in their respective values, but with a tendency to reach more uniform conditions with time.

ACNOWLEDGMENTS

The described work has been carried out as a joint venture between National Center for Disaster Prevention (CENAPRED), Institute of Engineering (II-UNAM), and the Government of Mexico City (DDF), with the very important sponsorship from the Japan International Cooperation Agency (JICA). Mr Daniel Ruiz-Fernández, Secretary General for Public Works (DDF) has been an enthusiastic promoter of the project. The authors gratefully acknowledge the assistance of M. Orozco, L. Domínguez, I. Noriega and J.M. Velasco.

REFERENCES

Bea, R.G. (1980). "Dynamic response of piles in offshore platforms", ASCE Nat. Convention, Hollywood Fl:203-224

Cook, R.W., D.W. Bryden-Smith, M.N. Gooch, and D.F. Sillett (1981). "Some observations of the foundation loading and settlement of a multi-storey building on a piled raft foundation in London clay", *Proc. I.C.E.* (70), Part 1, 433-468

Gutiérrez, C. (1995). "Profile of seismic waves velocities in the ZE-2 borehole at the Campestre bridge site, Metropolitan B-Line" (In Spanish), Internal Report, CENAPRED

Hansbo, S. and L. Jendeby (1983). "A case study of two alternative foundation principles: conventional friction piling and creep piling", Vag ocht Vattenbyggaren, No. 7-8

Hartlén, J. (1985). "Discussion to Session 2D: Field instrumentation and field measurements", *Proc. 11th ICSMFE*, San Francisco, Vol 4:2696-2698

Jaime, A., M. P. Romo and D. Reséndiz (1990). "Behavior of friction piles in Mexico City clay", *J of Geotech Engrg*, Vol 116, No. 6

Marsal, R.J. and M. Mazari (1969). *The Subsoil of Mexico City*, National University of México

Mendoza, M.J. and G. Auvinet (1988). "The Mexico earthquake of September 19, 1985: Behavior of building foundations in Mexico City", *Earthquake Spectra Journal*, EERI, Vol 4, No. 4, 835-853

Mendoza, M.J. and M.P. Romo (1996). "Geoseismic instrumentation of a friction pile-box foundation", Paper No. 1892, *CD-Proc. 11th WCEE*, Acapulco. Elsevier Science Ltd.

Rickard, C.E., B. Manie, G. Price, N.E. Simons, I. Wardle and C.R.I. Clayton (1985). "Interaction of a piled raft foundation at Basildon, UK", *Proc. 11th ICSMFE*, Vol 4:2235-2238

Sommer, H., P. Wittmann and P. Ripper (1985). "Piled raft foundation of a tall building in Frankfurt clay", *Proc. 11th ICSMFE*, San Francisco, Vol 4:2253-2257

Yamashita, K. and M. Kakurai (1991). "Settlement behavior of the raft foundation with friction piles", *4th Int. DFI Conference* Balkema