13 Mar 1991, 1:30 pm - 3:30 pm

Dynamic Behavior of Slender Structures on Their Prestressed Foundations

Phong M. Luong
Ecole Polytechnique, Palaiseau, France

Proceedings: Second International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, March 11-15, 1991, St. Louis, Missouri, Paper No. 5.74

Dynamic Behavior of Slender Structures on Their Prestressed Foundations

Phong M. Luong
Directeur de recherche CNRS-LMS, Ecole Polytechnique, Palaiseau, France

SYNOPSIS: A non-destructive vibratory testing, using impulsive tension slacking has been devised for the quality and safety control of overhead line towers. Several structural control experiments have been conducted on four-legged towers resting on three types of foundations: concrete stepped or pedestal blocks, steel piles and prestressed foundations. Experimental results have given significant vibratory signatures in close connection with the geotechnical response characteristics of both such slender structures and their foundations. The control of foundation mechanical behavior may be very useful in cases of earthquake resistant construction and design. This paper presents some significant results of the test program.

INTRODUCTION

Slender structures such as electric pylons or transmission line towers are commonly exposed to dynamic loading from several sources, including high winds, earthquake ground motions and others. The design task is made quite challenging by inherent constraints of economics, demand for extreme reliability and the considerable uncertainty in defining the dynamic loading which the structure must endure.

The major difficulties encountered in the application of modern control techniques to structural systems may be listed as follows :

1. Active control requires the ability to generate and apply large controlled forces to the structure.
2. Modern control theory often leads to feedback control laws, thus requiring on-line measurement or estimation of all the system state variables.
3. On-line control requires that both measurement and control be performed in real time.

From a practical standpoint, while the application of large control forces to a structure does not raise insurmountable difficulties, the generation of such forces over sustained periods of time, as necessitated by continuous optimal feedback control theory, may cause the concept of active control to become impracticable. To bypass this possible drawback, the approach under consideration attempts to use pulses of relatively short duration to control the structural system.

The objectives of this vibratory non-destructive testing were :

1. to characterize the soil-structure interaction of overhead line towers resting on different types of foundations such as traditional concrete footings, piles or prestressed foundations recently designed in France.
2. to verify the geotechnical performance of these foundations subjected to dynamic loadings.
3. to investigate and develop simple experimental testing in order to obtain readily a vibratory signature for the control and inspection of the mechanical behavior of the transmission tower.

In several cases, horizontal forces, for instance generated by winds, when loading on slender, high rise and light structures such as electric pylons or transmission line towers, induce onto their foundations both compressive and tensile loadings. Traditional building techniques employ huge heavy concrete blocks, large buried concrete plates or costly pile groups able to resist punching or pulling loads. When subjected to severe and diverse climatological variations or earthquake loadings, the geotechnical behavior of these slender structures can degenerate leading to failure.

The physical nature of the transmission line system restricted the dynamic excitation alternatives for testing. The classical procedures were sine dwell, sine sweep, fast sine sweep or chirp, random, impulse, etc. The technique in use is based on the release from an initial chosen tension similar to the twang-excitation method [Kemper et al 1981] based on a release from initial displacement of the structure.

The design of common foundations often requires a precise knowledge of mechanical and geotechnical characteristics, appropriate for a chosen location, necessary for their installation and their capacity to support the expected service loads. These conditions determine their proper foundation choice. Several design methods do exist, but they are often developed in very specific cases neglecting the actual stress-strain response of soil foundation and the 3-dimensional nature of loading conditions.

This paper presents some significant results of series of slacking tests conducted on overhead line towers of Electricité de France resting on three different types of foundations.

TOWER FOUNDATIONS

The transmission structures subject to vibratory testing involved in our test program are double-circuit, 63 kV, self-supporting, lattice-steel towers. These four-legged towers rest on three types of foundations :

Concrete foundation

The stresses of each pylon leg are distributed to a stepped or pedestal concrete footing designed to satisfy the limit total displacement to an acceptable small amount and eliminate differential settlements between parts of a structure as nearly as possible. As the pylon may be subjected to overturning forces, the footing has been designed on the assumption of linear variation of soil pressure and constructed with sufficient resistance to deformation. Stress in the longitudinal direction of the pylon leg is transferred to its pedestal by extending the longitudinal steel into the support (Figure 1). The stress transfer bar projects into the base a sufficient compression-embedment distance to transfer the stress in the column bar to the base concrete

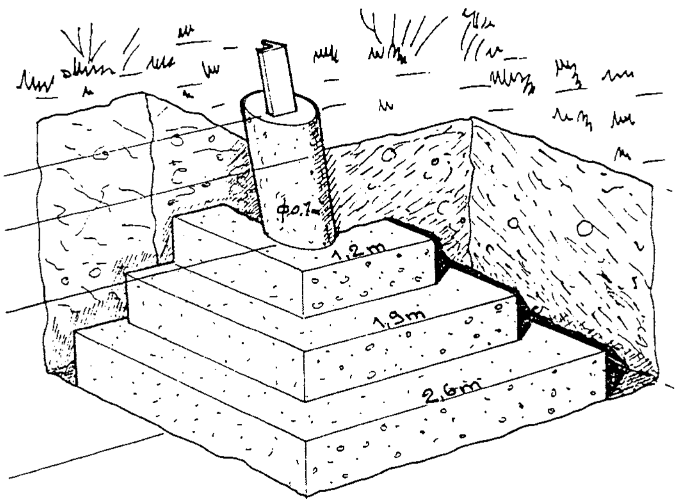

Fig. 1 Stepped or pedestal footing for overhead line tower.

Pile foundation

Piles have been used to resist uplift and overturning moments developed through friction along the sides of the piles and distribute loads over a sufficiently large vertical area (28 m) of relatively weak soil to enable it to support the loads safely (Figure 2). The safe friction values to use for the project has been determined by uplift tests. The compressive loads are supported through bearing at the tip, friction along their sides, adhesion to the soil, or a combination of these means.

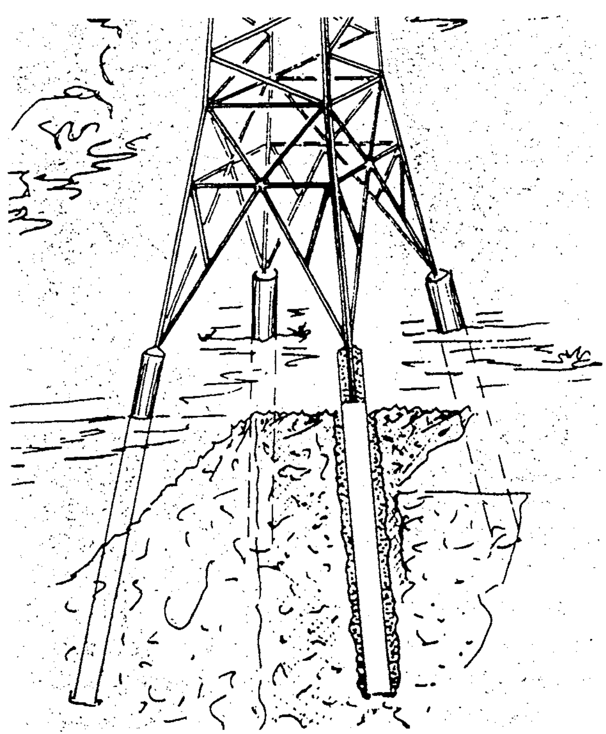

Fig. 2 Pile foundation for overhead line tower.

Prestressed foundations

This novel principle of foundations, already used for overhead line towers, is based on a prestressing technique, applied on the soil foundation in order to harden it, thus ensuring for the foundation a quasi elastic response to dead and live loads with higher deformation modulus and much smaller settlements.

* Soil mechanics background

It is known in soil mechanics that when a soil mass is prestressed, its domain of mechanical stability can be extended in a controlled manner. Soils often exhibit a rheological behavior that is difficult to control, a situation which makes the design of any associated structure a rather delicate affair. It is well known that a correctly executed mechanical hardening ensures an extended domain of pseudo elastic stability in which any external load generates only reversible and stable strains. Conventionally the stability domain of soil foundation is bound by an intrinsic curve deduced from triaxial tests. If the service loads are not included in this domain, the foundation cannot be built. On the contrary, a stable foundation can be realized when the stability domain is large enough to include the imposed loads. Thus the more extended the stability domain, the more various and severe loads can be sustained by the foundation. This is obtained by means of soil prestressing.

It can be seen on the stress-strain curve that a loading followed by unloading and reloading defines readily a hardening threshold (Figure 3) below which the rheological behavior of the material is practically elastic and reversible, i.e. stable.

In the stress space, the mechanical hardening generates a domain of stability and integrity for the material, that is bound by the corresponding hardening curves. In this hardened domain, the material presents advantageously a quasi elastic behavior, easy to be taken into account in design codes.

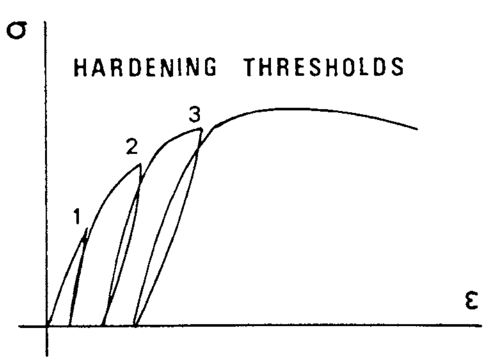

Fig. 3 Hardening thresholds of soil mechanical behavior.

The requirements in service define for a structure a loading domain that must be confined in the hardened domain bound by the hardening curves. The more stable the behavior of the whole soil-structure, the more distant the loading domain from the limits of intrinsic stability.

This can be obtained by soil prestressing. Graphically, this corresponds to a horizontal displacement of the vertical axis of Mohr diagram toward the tensile region unacceptable for soils (Figure 4). The magnitude of the displacement vector represents the prestressing force required for withstanding the imposed loads.

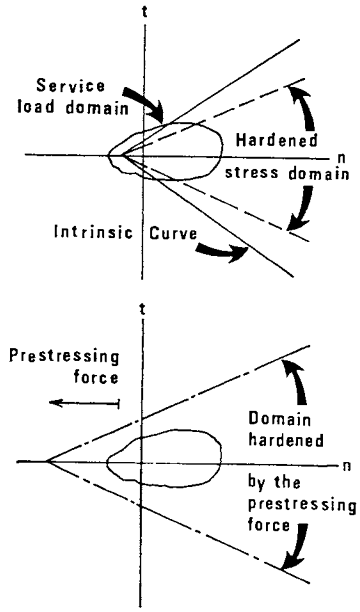

Fig. 4 The pylon foundation may be stable thanks to the prestressing force.

The overhead towers foundations are principally subjected to uplift, compressive loads and/or overturning. They are thus essentially stretched, compressed or bent. These requirements define a loading domain to be imposed on the foundation. This domain determines the magnitude of the recommended prestressing force used firstly to harden the foundation material and secondly to consolidate its stability domain.

* Centrifuge simulation of prestressed foundation

To establish the correct design by means of numerical techniques is rather delicate because of the geometrical interaction of neighboring supports loaded in tension and in compression. This is a three-dimensional configuration difficult to deal with. In addition the self-weight-induced stresses appropriate to the prototype earth structures exert in this case very strong influences [Mandel 1962]. These methods are useful only if the essential nature of soil and structure is properly reproduced in the numerical models. Experimental modeling and simulation are therefore vital to a fuller understanding of the problem.

An experimental study has been carried out in centrifuge, in order to determine the basic data required for a clear understanding of the dynamic, vibratory, cyclic and transient responses of pylons resting on their prestressed foundations. This may lead to an optimal and precise design, thus ensuring the safe and economical constructions and also the satisfactory performance of overhead line towers.

An anchoring system is used to load the squared metallic plate resting on the soil. Prestressing forces are applied on the plate by means of four springs. This loading generates a mechanical hardening on the soil foundation. This results in a supporting soil stiffer in appearance, whose mechanical behavior is quasi elastic.

The response is recorded by acceleration, displacement and force transducers. A force transducer, placed between the electromagnetic excitor and the pylon model, gave the force loading signal. A displacement transducer and three 3D-accelerometers were installed on the anchored plate. The analysis of the results has been focussed on the appearance of non-linear phenomena which announce the beginning of loss of structural stability.

Tests were carried out under forced vibrations at fixed frequency for different force intensities. The comparative analysis conducted in centrifuge has shown that the gravity foundation worked correctly when subject to the motions of low amplitude, that the pile foundation presented a more stable mechanical behavior. But when subject to greater excitory motions, the pile foundation would fail at a given loading threshold. Finally the prestressed foundations using four 160 kN (16 tons) prestressing forces have shown the predicted best mechanical behavior and this for different intensities of loading excitation.

For sake of ready comparison between the three types of foundations, horizontal, transversal and vertical displacement measurements as recorded in flight have been calculated as for full scale prototype in order to obtain a better subsequent analysis with field tests on actual pylons in service. F_p denotes the prestressing force, F the vibratory amplitude of the applied load, b a characteristic size of the pylon and d the measured displacements. The vibratory motion of the pylon is characterized by bending **B**, rotation **R** and stamping **S** (Figure 5).

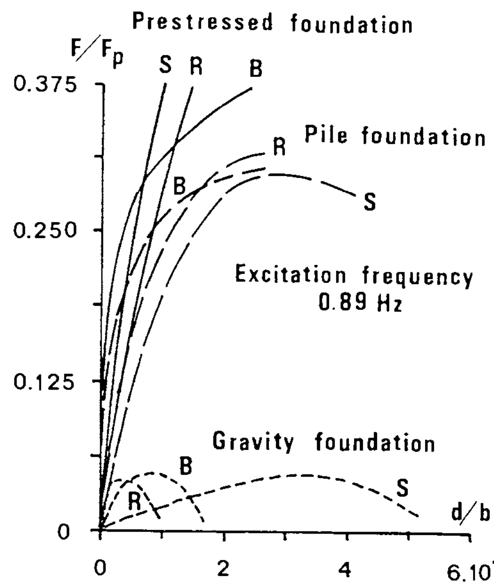

Fig. 5 Comparison of the mechanical responses of three types of pylon foundations.

Performed tests have permitted the assessment of the role of the prestressing force F_p on the mechanical behavior of the prestressed foundation. A significant influence of the prestressing force is observed on the amplitude of the excitation within the stability domain.

The experimental results obtained from centrifuge simulation show the following principal trends :

a. the domain of mechanical stability of the prestressed soil mass is enlarged with the magnitude of the prestressing force,

b. the rheological behavior of the prestressed soil mass within the stability domain is quasi elastic,

c. with a small amplitude prestressing force used for the tests (160 kN), the mechanical behavior of the prestressed foundation proves to be better than the pile group foundation and much more reliable than the buried concrete block foundation.

This centrifuge simulation offers the great advantage of suggesting a ready choice either of excitation force or prestressing force within the stability domain of the prestressed foundation where the mechanical behavior is quasi elastic.

* Working up the prestressed foundation

The study performed in centrifuge reinforces the conceptual predictions of this novel type of foundation. It permits to specify the design method of a prestressed foundation that has been effectively installed on several overhead lines of the Electricité de France.

The used anchoring system (Figure 6) belongs to a family of high performance anchorage devices suitable for any type of soils [Habib et al 1982], which are easy to use with known driving in or propulsion processes.

Fig. 6 High capacity anchoring system.

It comprises (1) an anchorage element adapted for penetrating into the ground under the driving action, (2) one articulated element pivotably connected to the main body by a flexible connection. It further combines the following characteristics : a cranted shape of the articulated element and the location of the centre of gravity between the fastening point being situated on each side of the driving plane. They are especially designed for low required energies when driving into the soil.

Anchoring ultimate resistance was defined as that maximal tension load causing admissible displacement on the anchoring line. In fact this value is given by the soil uplift resistance where the anchoring device must withstand tensile forces. It depends mainly on the mechanical properties of surrounding soil, embedment, active anchoring area and roughness of the surface.

Several laboratory and field tests show that at a shallow embedment ratios of up to three, uplift resistance exhibits a well-defined peak resistance. For embedment ratios greater than five, the anchoring system resistances exhibit oscillatory behavior at large displacements. This demonstrates the existence of a critical depth from which the anchoring mechanism works entirely in subsoil. The holding capacity of the tested anchoring device embedded in a cohesionless soil is then approximately given by $T_p = \gamma' D S A_p$ where γ' is the effective unit weight of the soil, D the embedment, S the effective area of the anchoring system and A_p a dimensionless coefficient dependent on soil mechanical characteristics and on relative embedment.

A great number of full scale test results have demonstrated the remarkable performance of this new type of anchor and illustrate that :

a. anchoring is possible even in compact soil for which the use of classical anchoring systems is excluded ;

b. the holding capacity is offered even in superficial heterogeneous soil ;

c. the vertical pulling forces simplify the use of this anchoring device ;

d. the low weight of this anchoring device leads to an excellent efficiency coefficient : a 800 N anchoring device withstanding a vertical pulling capacity gives an efficiency of nearly 500.

To work up the prestressed foundation for an electric pylon, a concrete slab is laid on the ground and a prestressing force is applied between the anchoring device and the slab (Figure 7).

Fig. 7 Prestressing force tensioning.

The prestressing force hardens the soil, thus increasing the elastic soil modulus and decreasing the settlements induced within the foundation by the service loadings. This has been demonstrated on various types of subsoil as shown for instance on the Figure 8 where E_p and p_ℓ are pressuremeter characteristics.

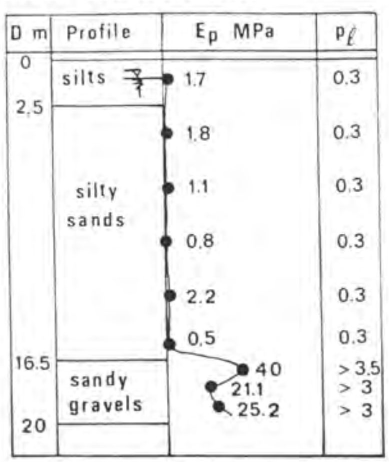

Fig. 8 Characteristic subsoil of the Jonquières-Arles overhead electric line.

NON-DESTRUCTIVE TESTING OF SOIL-PYLON INTERACTION

An experimental frequency response technique by impulsive slacking from the top of the pylon has been applied for testing the behavior of the three types of pylon resting on their respective foundations.
Several 3D-accelerometers affixed at different locations on the pylon record the vibratory motions (Figure 9).

Fig. 9 Accelerometers glued at different locations on the pylon.

A cable was attached on the top of the pylon. It is then fixed in the ground by a small anchoring device, distant from the pylon foundation. A tension system allows to increase the cable tension to a relatively low value for example up to 30 kN (Figure 10).

Fig. 10 Tensioning the cable for a slacking test.

An explosive tie allows a sudden release of tension, inducing a rapid excitation on the pylon (Figure 11). The pylon vibrates freely after tension release.

Fig. 11 Explosive tie allowing a sudden tension release.

Data reduction of acceleration signals by Fast Fourier Transforms gives the frequency response spectra which are, of course, the vibratory signature of the pylon resting on its prestressed foundations (Figure 12).

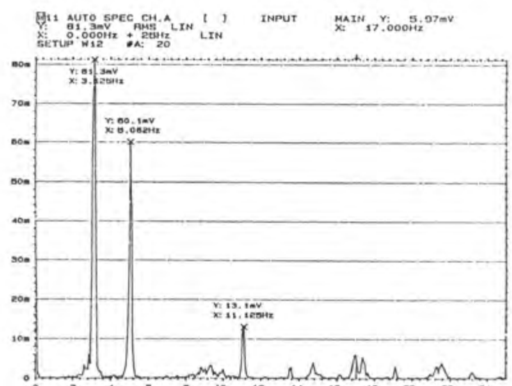

Fig. 12 Frequency response of a pylon resting on its prestressed foundations.

These plots of frequency versus vibrational amplitude in arbitrary units provide vibration signatures of the soil-structure interaction characterizing the mechanical performance of the pylon resting on its prestressed foundations. Of course, this non-destructive test can be applied also to others types of slender structures, because the vibration signature plots pinpoint vibration frequencies and indicate conditions such as poor workmanship, damage in structure or in subsoil. As a periodic maintenance activity, changes in subsequent plots permit early detection and identification of damage. For sake of comparison, the impulsive slacking test has been also conducted on pylons resting on concrete stepped footings (Figure 13) and on steel pile foundations (Figure 14).

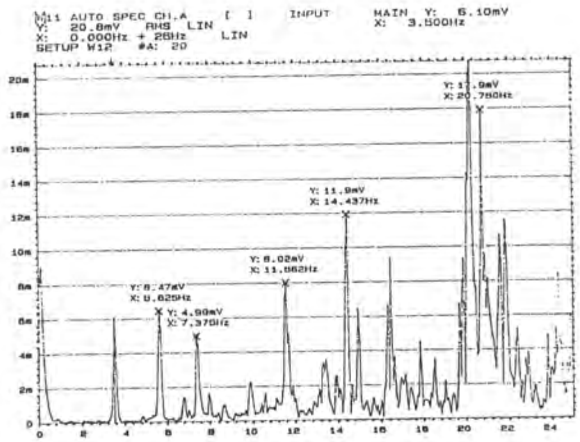

Fig. 13 Frequency response spectrum of a pylon resting on its concrete stepped footings.

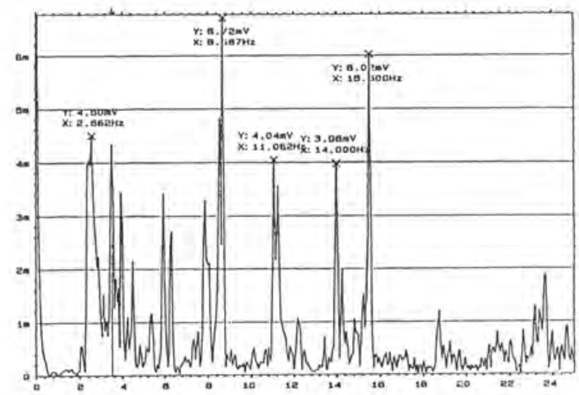

Fig. 14 Frequency response spectrum of a pylon resting on its steel pile foundations.

Several tests on different pylons resting on their prestressed foundations have evidenced that the prestressed foundation presents a quasi elastic behavior as indicated by the sharp peaks in the frequency response spectra (Figure 15).

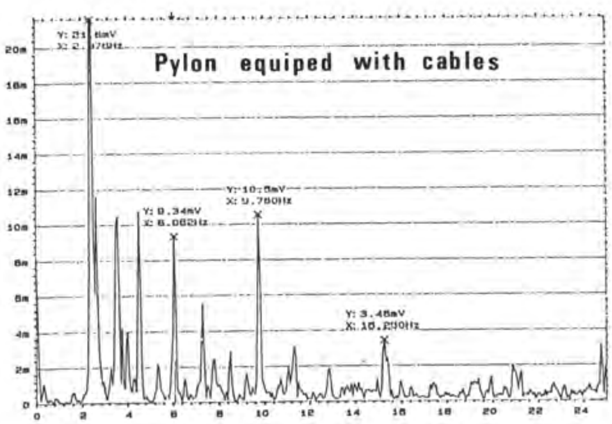

Fig. 15 Frequency response spectrum of a pylon in service resting on its prestressed foundations.

Several non-destructive tests have been carried out on overhead pylons in use with an analysis of their free vibrations. The use of impact excitation together with a Fast Fourier Transform based spectrum analyzer to determine the dynamic characteristics of structures is potentially a very attractive technique. An impact gives an excitation across a broad frequency range. It is therefore possible to investigate the whole frequency range of interest in a single test.

Experimental determination of the vibratory signature of such a slender structure resting on its prestressed foundations, subsequent to a sudden release of tension at its summit, reveals to be a very promising technique for integrity control and inspection. This test is very simple and rapidly executed since the need for connecting and aligning a shaker is eliminated. It can be used as routine test as shown in Figure 16.

Fig. 16 Routine slacking test for the quality control of overhead line tower.

It permits to follow the evolution of the pylon behavior as regard to fatigue or damage. This can be obtained by identification of the nature of non-linearities detected on the recorded signals [Bourdin et al 1989].

The control of foundation mechanical behavior is very useful in cases of earthquake resistant construction and design because it is possible to modify - by changing the prestressing force - the frequency spectrum of the soil-structure response such that there is no interference with the earthquake frequency characteristics.

In parallel, a numerical simulation has been carried out using the CADSAP system to analyse the vibratory behaviour of the pylon resting on its prestressed foundations (Figure 17). The structure was modeled by beams elements. The supports being considered rigidly or elastically connected in order to take into account the soil-structure interaction. Treating the foundation soil as brick elements, the calculation can take into account non-linear soil behavior. The numerical modeling has given the first six resonnant modes which can be superimposed in a modal calculation.

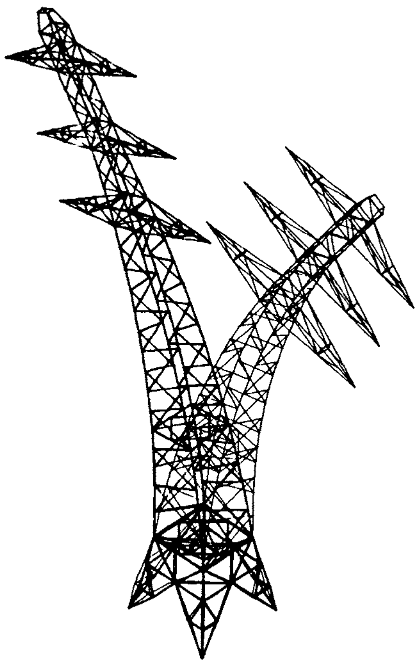

Fig. 17 Numerical simulation of the pylon vibratory response.

CONCLUDING REMARKS

The purpose of these tests was to characterize the dynamic geotechnical properties transmission line towers in service, especially in case of prestressed foundations.

Tests on laboratory or centrifuge scale models have shown the value of using prestressed foundations in soft soils. Observed settlements, even in cases of tests carried out until failure, seem to be very small if compared to the strength values. This is readily obtained thanks to soil foundation hardening.

The mechanical behavior of prestressed foundations by driven anchorings appears to be very satisfactory in different sites presenting gravelly, sandy and clayey soils.

Several slacking tests have been conducted on overhead pylons in use with an analysis of their free vibrations. This non-destructive testing technique reveals to be a very interesting method for the integrity control and inspection of slender structures. It allows to follow the evolution of the pylon behavior as regard to fatigue or damage occurrence.

The control of soil-structure interaction behavior is very useful in cases of earthquake resistant construction and design because it is possible to modify - by changing the prestressing force - the frequency spectrum of the soil-structure response such that there occurs small interference with the earthquake frequency characteristics.

Acknowledgement - The support and interest of Electricité de France CRTT Sud-Est and Technologies Spéciales Ingéniérie for this work are gratefully acknowledged.

REFERENCES

Berthomieux G. 1976. Modèles tridimensionnels de fondations de pylônes sollicités horizontalement. Thèse de 3e cycle, 21-09-1976, Université de Grenoble.

Bourdin B., Luong M.P. & Morlier P. 1989. Characterization of non-linearities occurred during forced vibration tests in centrifuge. Rev. Franç. Géotech. n° 47, 39-59.

Bustamante M., Frossard A., Gouvenot D. & Sage D. 1986. Nouvelles fondations de supports aériens. Journées d'Etudes sur les Fondations des Supports Aériens. ESE, 27-11-1986, Gif-sur-Yvette.

Ewins D.J. 1978. Whys and wherefores of modal testing. J. Soc. Environmental Engineers, June 1978.

Ewins D.J. & Sidhu J. 1982. Modal testing and the linearity of structures. Mécanique Matériaux Electricité, J. d'Etude GAMI, Juin 1982.

Gagneux M. 1986. Evolution dans le calcul et choix des fondations des supports aériens HT, THT à l'Electricité de France. Journées d'Etudes sur les Fondations des Supports Aériens. ESE, 27-11-1986, Gif-sur-Yvette.

Goyder H.G.D. 1984. Foolproof for frequency response measurements. Proc. of 2nd Intern. Conf. on Recent Advances in Structural Dynamics, Southampton, April 1984.

Habib P., Le Tirant P. and Luong M.P. 1982. Anchors and model tests of high capacity anchorings. Geotechnics in a marine environment. Bulletin Technique du Bureau Veritas, January 1982, 5-15.

Halvorsen W.G., Brown D.L. 1977. Impulse Technique for Structural Response Testing. Sound and Vibration, November 1977, 8-21.

Instructions de 1953. Instructions provisoires relatives à l'emploi du béton précontraint dans les ouvrages dépendant du Ministère des Travaux Publics, des Transports et du Tourisme" annexées à la Circulaire N° 141 du 26 Octobre 1953.

Kemper, L.Jr., Stroud, R.C. and Smith, S. 1981. Transmission line dynamic/static structural testing. J. Struct. Div. ASCE, 107(ST10), October 1981.

Luong M.P. 1986. Simulation des forces de masse. Annales de l'ITBTP, Essais et Mesures N° 442, Février 1986.

Mandel J. 1962. Essais sur modèles réduits en mécanique des terrains - Etude des conditions de similitude. Revue de l'Industrie Minérale, N° 9, Vol. 44.

Plumelle C. & Lapeyre J.L. 1986. Les fondations des supports aériens. Journées d'Etudes sur les Fondations des Supports Aériens. ESE, 27-11-1986, Gif-sur-Yvette.

Ramsey K.A. 1975. Effective measurements for structural dynamics testing : Part I". Sound and Vibration, Vol.9, N° 11.

Sutherland H.B. 1988. Uplift resistance of soils. Géotechnique 38, N° 4, p.493-516.