Safety Evaluation of Overhead Line Towers

M. P. Luong
CNRS-LMS, Ecole Polytechnique, Palaiseau, France

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M. P. Luong
Research Director, CNRS-LMS, Ecole Polytechnique, Palaiseau, France

SYNOPSIS A nondestructive vibratory testing using impulsive tension slacking has been devised for the quality and safety control of overhead line towers of Electricité de France. 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 slender structures and their foundations. This paper presents some significant results of the test program of safety evaluation of the pylon.

INTRODUCTION

Overhead 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 loading.
3. to investigate and develop simple experimental testing in order to obtain readily a vibratory signature for the control and inspection of the mechanical behaviour 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 behaviour 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.

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 :

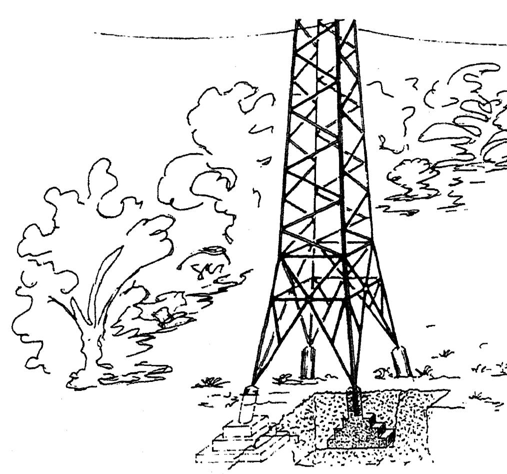

Fig. 1. Stepped or pedestal footings for overhead line tower

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 (Fig. 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.

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 (Fig. 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 top, friction along their sides, adhesion to the soil, or a combination of these means.

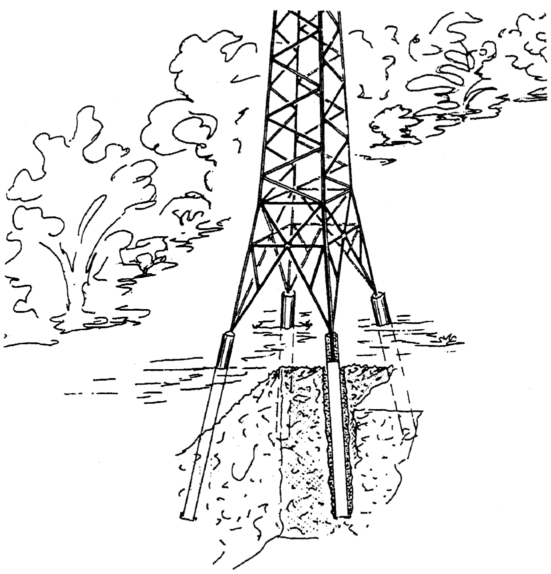

Fig. 2. Pile foundation for overhead line tower

Prestressed foundation

This novel principle of foundations, already in use for overhead line towers, is based on a prestressing technique (Fig. 3), 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 [Luong 1991].
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.

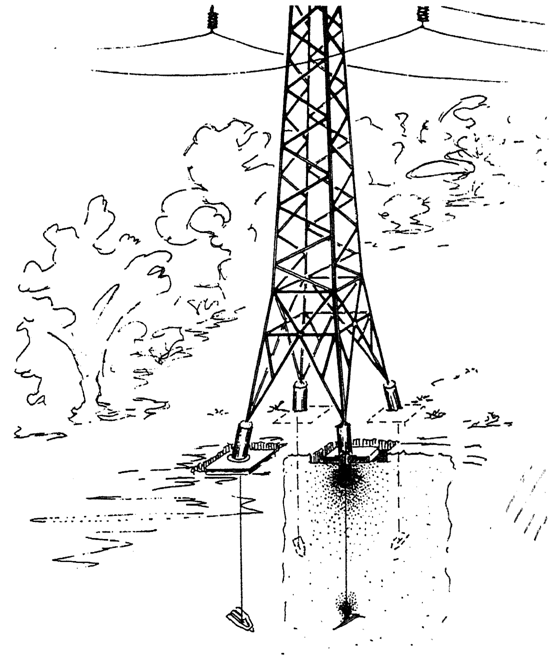

Fig. 3. The pylon foundation is stabilized by the prestressing forces

NON-DESTRUCTIVE TESTING OF SOIL-PYLON INTERACTION

An experimental frequency response technique using impulsive slacking from the top of the pylon has been applied for testing the behaviour 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 (Fig. 4).

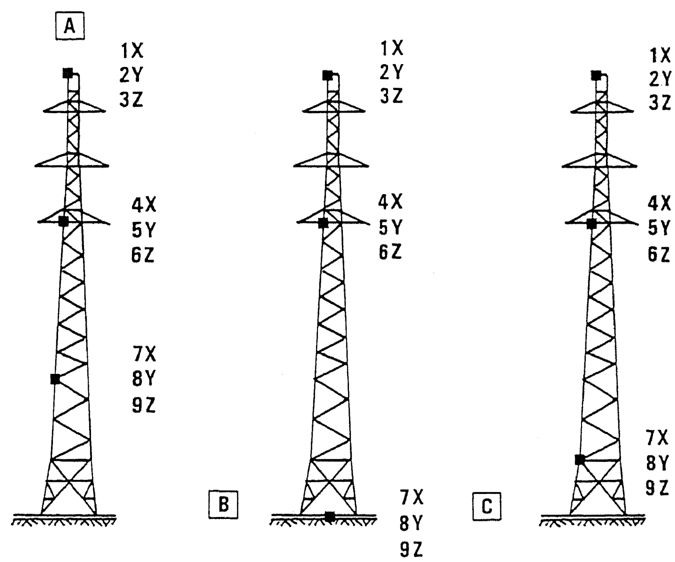

Fig. 4. Accelerometers glued at different locations on the pylon

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 exemple up to 30 kN (Fig. 5).

Fig. 5. Tensioning the cable for a slacking test

An explosive tie allows a sudden release of tension, inducing a rapid excitation on the pylon (Fig. 6). The pylon vibrates freely after tension release.

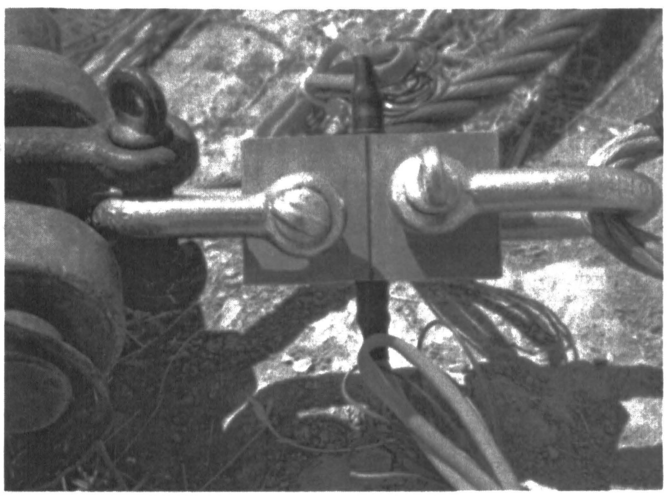

Fig. 6. Explosive tie allowing a sudden tension release

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 foundation (Fig. 7).

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. or sake of comparison, the impulsive slacking test has been also conducted on pylons resting on concrete stepped footings (Fig. 8) and on steel pile foundations (Fig. 9).

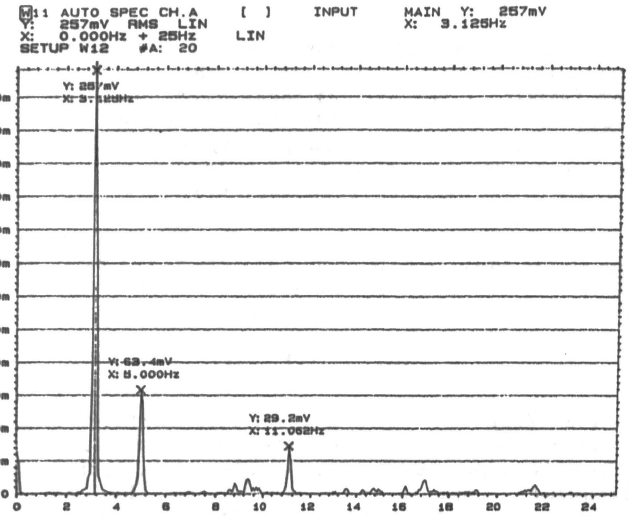

Fig. 7. Frequency response of a pylon resting on its prestressed foundation

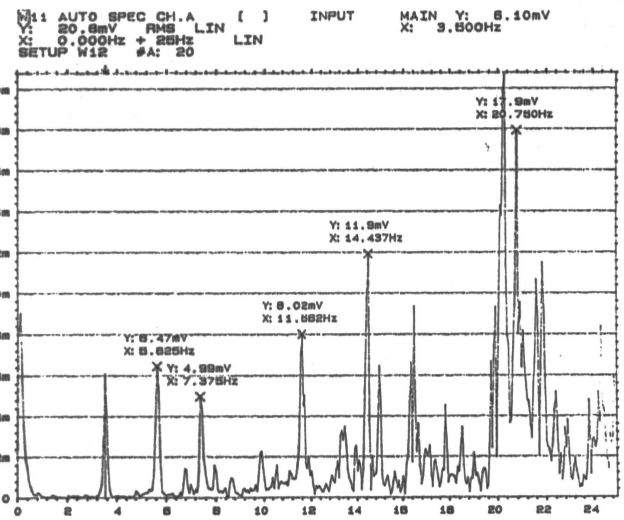

Fig. 8. Frequency response of a pylon resting on its concrete stepped footings

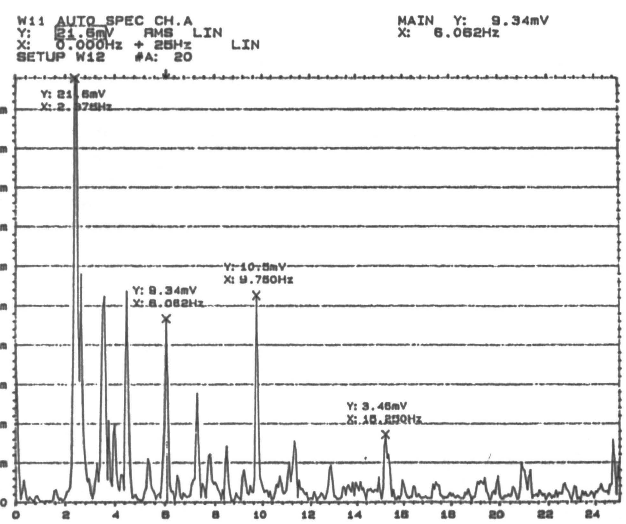

Fig. 9. Frequency response of a pylon resting on its steel pile foundations

NONLINEARITY DETECTION TECHNIQUE

In many situations, this impulse technique for structural frequency response testing is the simplest and fastest of the various techniques commonly used today. This transient excitation offers good estimates of the required frequency response information. However the nature of the excitation and response signals in the impulse technique requires special signal processing technique.

The frequency response function is defined in terms of the single input/single output system as the ratio of the Fourier transforms of the system output or response y(t) to the system input or excitation x(t).

$$H(f) = Y(f) \quad X(f)$$

where Y(f) and X(f) respectively denote Fourier transform of system output y(t) and system input x(t).

The only requirement for a complete description of the frequency response function are that the input and output signals be Fourier transformable, a condition that is met by all physically realizable systems, and that the input signal be non-zero at all frequencies of interest. If the system is nonlinear or time-variant, the frequency response function will not be unique, but will be a function of the amplitude of the input signal in the case of a nonlinear system and a function of time in the case of a system with time-varying properties.

In this study where pylons may be nonlinear structures, a nonlinear functional called Volterra series is used. In this functional, the total response of the system y(t) is decomposed into components of various orders.

$$y(t) = y_1(t) + y_2(t) + \ldots + y_n(t) \qquad (1)$$

Each component is defined by the functional

$$y_n(t) = \int_{-\infty}^{\infty}\cdots\int_{-\infty}^{\infty} h_n(\tau_1,\tau_2,\ldots\tau_n) \prod_{k=1}^{n} x(t-\tau_k)\, d\tau_k \qquad (2)$$

The first order component is decribed by linear convolution

$$y_1(t) = \int_{-\infty}^{\infty} h_1(\tau)x(t-\tau)d\tau \qquad (3)$$

If x(t) denotes the input function, $h_1(t)$ is the first order impulse response that describes the linear behaviour of the system.

For the other components, more than one time variables are necessary so that a multidimensional signal processing must be considered. As an example, let us describe the second order component (nonlinear) of the response. From Eq.(2) the following expression can be written :

$$y_2(t_1,t_2) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} h_2(\tau_1,\tau_2)x(t_1-\tau_1)x(t_2-\tau_2)\, d\tau_1 d\tau_2 \qquad (4)$$

where τ_1 and τ_2 are the two time variables, $h_2(\tau_1,\tau_2)$ is the second order impulse response). If this mathematical framework is valid for the study of the behaviour of the structure in the frequency domain, two dimensional Fourier transform is appropriate:

$$\mathcal{F}_2[h_2(\tau_1,\tau_2)] = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} h_2(\tau_1,\tau_2)\exp(-j\omega_1\tau_1-j\omega_2\tau_2)\, d\tau_1 d\tau_2 \qquad (5)$$

it is the definition of second order transfer function $\mathcal{H}_2$ with two circular frequency variables ω_1,ω_2. $\mathcal{F}$ is the Fourier transform operator.

$$\mathcal{H}_2(\omega_1,\omega_2) = \mathcal{F}_2[\, h_2(\tau_1,\tau_2)\,] \qquad (6)$$

In this application, a single impulse is taken as input

$$x(t) = a\,\delta(t-T)$$

Then from (1) and (2)

$$y(t) = \sum_{i=1}^{n} y_i(t) = \sum_{i=1}^{n}\int_{-\infty}^{\infty}\cdots\int_{-\infty}^{\infty} h_i(\tau_1,\tau_2,\ldots\tau_i) \prod_{k=1}^{i} a\,\delta(t-T-\tau_k)\, d\tau_k = \sum_{i=1}^{n} a^i\, h_i(t-T) \qquad (7)$$

When m time tests are conducted using a single impulse of m different levels, then (7) can be shown in :

$$y^m(t) = \sum_{i=1}^{n} a_m{}^i\, h_i(t-T) \qquad (8)$$

where m indicates *mth* test. Eq.(8) can also be presented under matrix form :

$$\{\, y \,\} = [\, a \,]\{\, h \,\} \qquad (9)$$

where

$$\{y\} = \left(y^1(t), y^2(t), \ldots y^m(t)\right)^T ,$$

$$\{h\} = \left(h_1(t-T), h_2(t-T), \ldots, h_n(t-T)\right)^T \qquad (10)$$

$$[a] = \begin{bmatrix} a_1{}^1 & a_1{}^2 & \ldots\ldots & a_1{}^n \\ a_2{}^1 & a_2{}^2 & \ldots\ldots & a_2{}^n \\ \ldots & \ldots & \ldots & \ldots \\ a_m{}^1 & a_m{}^2 & \ldots\ldots & a_m{}^n \end{bmatrix} \qquad (11)$$

or

$$\{\, h \,\} = \left[\, a \,\right]^{-1} \{\, y \,\} \qquad (12)$$

The resolution of this equation permits us to obtain the impulse response of various orders with only one time variable (Fig. 10 and Fig. 11).

For further research, it is necessary to take a input signal with two impulses, three impulses ... etc.

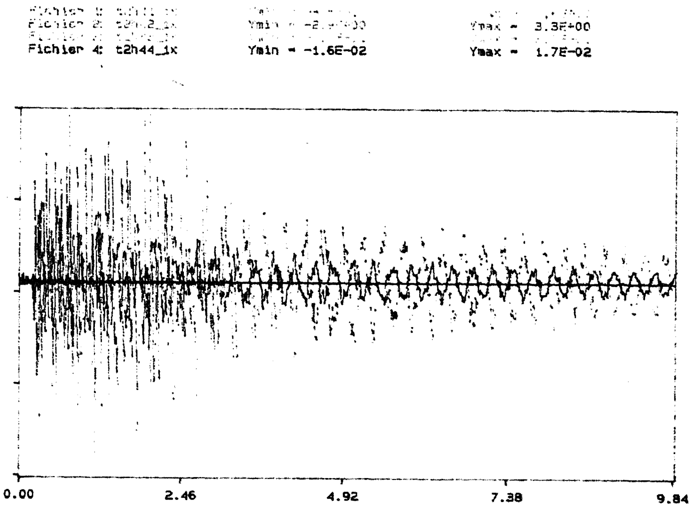

Fig. 10. Time response of a pylon, resting on its concrete foundation, subject to a slacking test

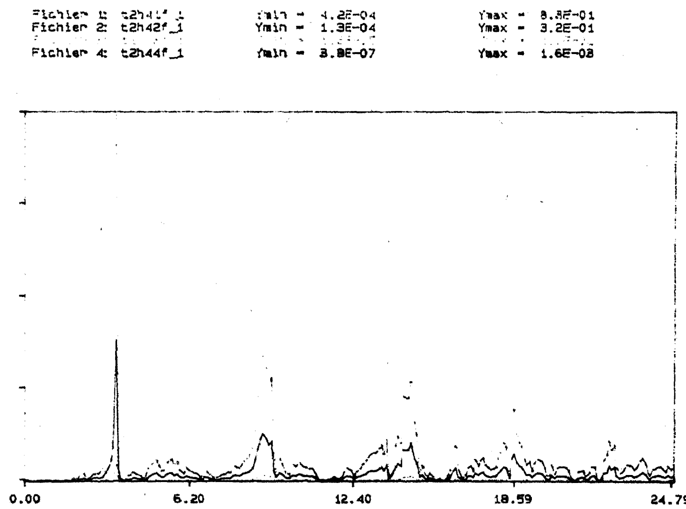

Fig. 11. Frequency response of the same pylon excited by the slacking test

DATA PROCESSING TECHNIQUE VALIDATION

This specific data processing technique has been validated by three slacking tests on a pylon resting on pile foundation.

1. A first slacking test with a tension T = 5 kN has given the following natural frequencies :
   - Bending $N_b = 3.0$ Hz
   - Torsion $N_t = 5.8$ Hz
   - Stamping $N_s = 8.6$ Hz

2. A second slacking test with the same tension T = 5 kN with unscrewed node in the pylon gave the same natural frequencies.

3. A third slacking test with the same tension T = 5 kN with rescrewed node showed the same natural frequencies.

When calculating the quantity $\mathcal{N}$ = (nonlinear energy) / (linear energy),

$$\mathcal{N} = \left[\int_0^T |\ h_2(t)\ |^2\, dt\right] \Big/ \left[\int_0^T |\ h_1(t)\ |^2\, dt\right]$$

it can be found respectively :

1.	$\mathcal{N}_i$	0.97
2.	$\mathcal{N}_u$	2.05
3.	$\mathcal{N}_r$	0.96

Thus it can be seen for this case that the ratio $\mathcal{N}$ between the nonlinear energy of order two and the linear energy, is a more sensitive parameter than the natural frequencies.

CONCLUDING REMARKS

The purpose of these tests was to characterize the dynamic geotechnical properties transmission line towers in service.

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.

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 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 Fig. 12. It permits to follow the evolution of the pylon behaviour as regard to fatigue or damage.

The control of foundation mechanical behaviour 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 or small interference with the earthquake frequency characteristics.

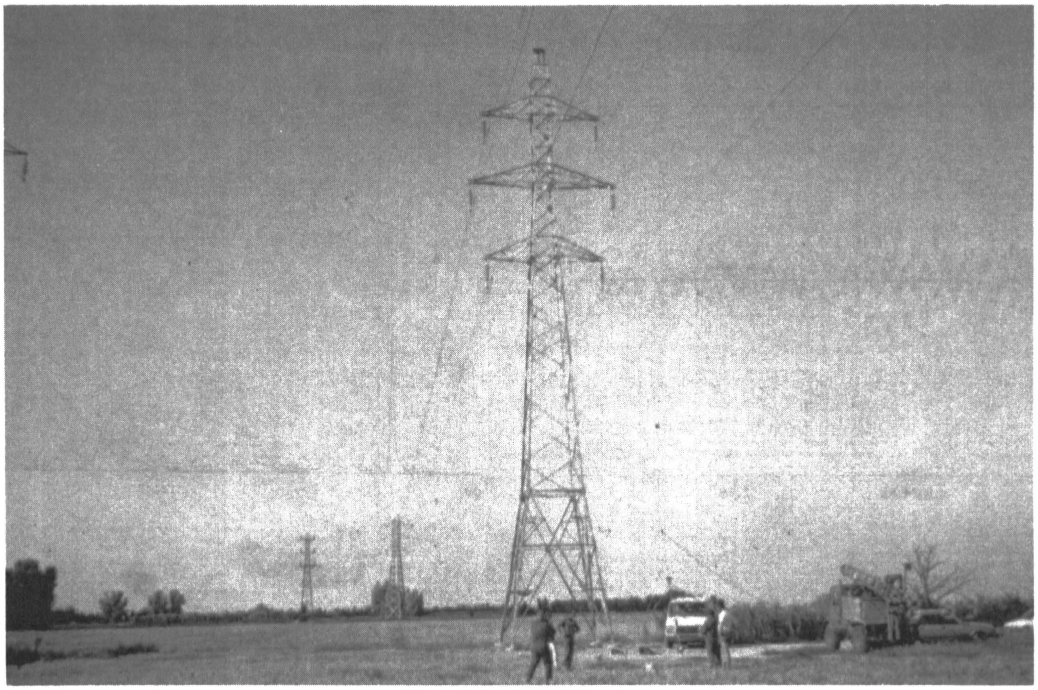

Fig. 12. Routine slacking test for the quality control of overhead line tower

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