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Studies of Dynamic Response of a Guyed Tower

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The model of a deep-water pile-founded guyed tower is presented. Understanding of its dynamic behavior is gained through investigation of selected vibration characteristics. Effects of guying and foundation systems on the lateral and torsional modes of vibration are assessed; the dynamic stiffness of cables is addressed and the effects of cable inertia on tower response are investigated and the governing parameters identified. The pseudo-force method is applied to the transient nonlinear analysis of the guyed-tower system. The transient wave excitation is obtained from the Pierson-Moskowitz wave-energy spectrum and the wave forces from the linearized form of Morrison's equation.

Ein Modell eines in tiefem Wasser auf Pfählen fundierten, abgespannten Turmes wird vorgestellt. Einsicht in das dynamische Verhalten wird mittels Untersuchung ausgewählter Schwingungseigenschaften gewonnen. Die Einflüsse der Abspannung und der Fundation auf die Biege- und Torsionsschwingungen werden abgeschätzt; die dynamische Kabelsteifigkeit wird diskutiert und die Trägheitseinflüsse auf das Schwingungsverhalten des Turmes untersucht und die massgebenden Parameter festgestellt. Die Ersatzkräfte-Methode wird auf die transiente nichtlineare Analyse des Systems von Turm und Abspannung angewendet. Die Wellenerregung wird aus dem Pierson-Moskowitz Wellenenergie-Spektrum und die Wellenkräfte aus der linearisierten Morrison-Gleichung gewonnen.

Introduction

The extraction of oil has gained importance in the past few years. The discovery of fields in deep-water regions has set new challenges to engineers as it became apparent that traditional offshore structures would be, either in technical or financial terms, inadequate for the exploitation of these fields. As the behavior of platforms in deep waters is of a dynamic type, alternatives were sought in terms of dynamic response. In shallow waters, traditional fixed platforms have a small fundamental period of vibration T_{st} in comparison to a predominant period T_{wa} of the exciting waves. Their response is therefore close to the static response.

In deep waters, the same platforms have a fundamental period of vibration approaching the predominant periods of the exciting waves, thus bringing the structures into resonance or near resonance. Modifying the structures in order to have a sufficient reduction in the period ratio T_{st}/T_{wa} and thereby reducing the response is a way of overcoming the unacceptable resonance phenomenon. Another way is to increase the period ratio T_{st}/T_{wa}; the response is then of comparable magnitude to the static response or lower. The guyed tower is based on this latter concept. The structure is designed to be flexible enough to have a fundamental period of vibration larger than the predominant periods of the waves.

The deep-water guyed tower has been investigated by different authors, e. g. in [1 to 3]. A 113 meters prototype was installed in 1975 and the first full-scale guyed tower launched in 1983 in 305 meters of water [4 and 5]. This paper summarizes research performed with the objective of providing a better understanding of the dynamic behavior of guyed towers and of developing concepts useful in the design of such structures [6].

Model of Guyed Tower

The structure investigated is shown in Figure 1. It was developed during the course of a feasibility study by Brown & Root, Inc., Houston Texas. This structure is a 3-dimensional steel frame supported on piles and constrained laterally by the guying system.

Tower

The tower is 516.6 m high and is located in a water depth of 487.8 m. With the exception of the upper part of the structure which is somewhat longer in one direction, its plan dimensions are 36.6 m by 48.8 m. Disregarding the unsymmetrical arrangement of the transverse framing, the tower may be considered to be symmetric in the x-direction. In the y-direction, the structure is unsymmetric because of its longer dimensions near the deck and the eccentric arrangement of the main piles and conductors. All structural members are tubular and circular.

Foundation

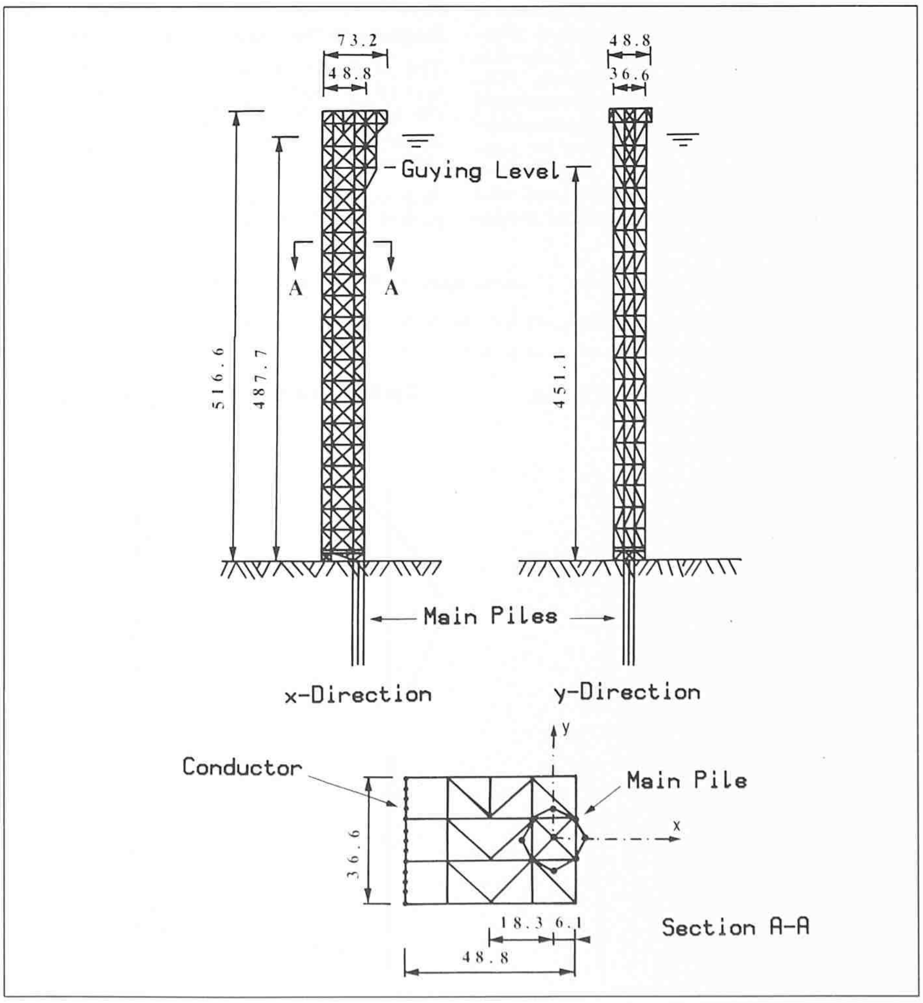
The foundation system is composed of 9 main piles arranged around, and at, the center of a circle on one side of the tower and of 8 shear piles uniformly spaced around the tower. The main piles are attached to the top of the tower and extend vertically through the tower to a depth of 121.9 m into the ground. The shear piles are 45.7 m long. The conductors located on the side of the structure opposite to the piles also contribute to the resistance of the foundation.

Guying system

12 pairs of coated steel cables of the spiral strand type are uniformly arranged around the structure with points of attachment to the tower at an elevation of 451.1 m from the base. Each individual cable is composed of 3 segments as illustrated in Figure 2. When the system is at rest, the lenght of the horizontal projection of the first segment is 966.2 m. The intermediate segment is the clump weight designed so as to minimize the increment in tension at large tower deflections and so as to reduce the vertical component of reaction at the anchor.

Fig. 1. Guyed tower investigated with dimensions in m

Bild 1. Untersuchtes Modell eines abgespannten Turmes. Abmessungen in m



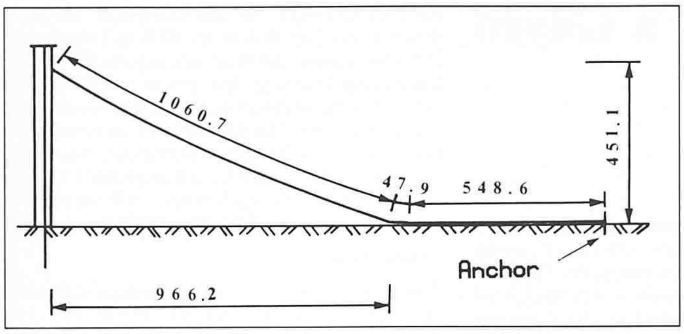


Fig. 2. Guying cable with unstretched segment lengths in m

Bild 2. Abspannkabel. Ungespannte Segmentlängen in m

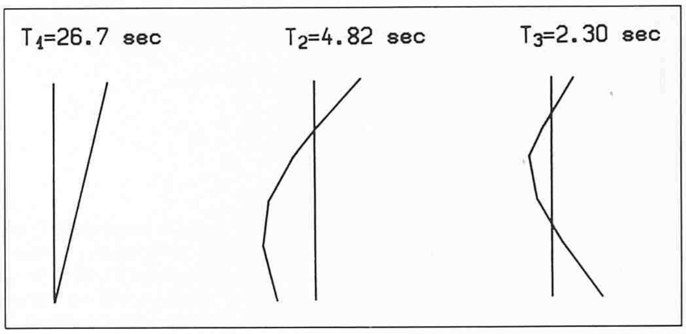


Fig. 3. Modes of vibration in x-direction

Bild 3. Schwingungsformen in x-Richtung

Model

The actual 3-dimensional structure is idealized for analysis purposes as a discrete cantilever stick model with 9 nodes distributed along its height. 3 degrees of freedom are assigned to each node, one in each of the lateral directions and a rotational one in the horizontal plane. The flexibility matrix of the model is determined from an analysis of the actual system and the inertia matrix by lumping the actual structural masses, the entrained masses of water and the hydrodynamic added masses at the individual nodes. The damping matrix is specified indirectly by modal damping ratios.

Periods and modes of vibration

For motion in the x-direction, the values of the first 3 natural periods of vibration are 26.7 sec., 4.82 sec and 2.30 sec., respectively. The associated modes are shown in Figure 3. The fundamental mode is essentially a straight line increasing from almost zero at the base to a maximum at the top. There is practically no structural deformation associated with it, the displacement being due almost exclusively to base rocking. The second and third modes are deformational modes with significant base lateral displacement. The modes in the y-direction are coupled lateral/torsional modes. The first 4 periods are 27.0 sec., 8.81 sec., 6.41 sec. and 3.49 sec., respectively. The associated modes are shown in Figure 4. The first mode is a predominantly lateral mode similar to the corresponding mode in the x-direction; the second mode is a torsional mode; and the third mode is a lateral deformational mode similar to the second mode in the x-direction.

Free-Vibration Characteristics

Knowledge of the free-vibration characteristics of a structure is of central importance to the understanding of its response to a dynamic excitation. The primary objective of this part of the study is to identify the parameters which affect the free-vibration characteristics of a pile-supported guyed tower and to assess their influence.

The following results are obtained by applying force and displacement methods of analysis:

Response in the symmetric x-direction

The fundamental mode of vibration is essentially a rigid-body mode increasing from the base to the top. This mode is affected mainly by the lateral stiffness of the guying system and by its location.

A good approximation to the fundamental period may be obtained by considering the tower to be a rigid bar hinged at the base, i. e. fixed against deflection but free against rotation. Improved accuracy may be achieved by incorporating the effect of the rocking stiffness of the foundation.

The second and higher modes are deformational modes which are sensitive to changes in the lateral stiffness of the foundation and in the stiffness of the tower but are insensitive to changes in the rocking stiffness of the foundation and in the stiffness of the guying system.

Response in the unsymmetric y-direction

The modes of vibration in this direction are generally coupled lateral/torsional modes.

The predominantly lateral modes and the associated periods are affected by changes in the stiffnesses of the guying system, tower and foundation in much the same way as in the symmetric x-direction. They are practically unaffected by changes in the torsional stiffness of either the guying system or the foundation.

The predominantly torsional mode (2nd mode) is practically unaffected by realistic changes in the lateral stiffness of the guying system. Although it is affected by changes in the torsional resistance of the guying system, unrealistically large changes in the stiffness are needed to produce substantial changes in response. This mode is affected by the torsional stiffness of the foundation, and it is

Fig. 4. Modes of vibration in y-direction. a) lateral deflection b) rotation x 18.3 m

Bild 4. Schwingungsformen in y-Richtung. a) seitliche Auslenkung, b) Verdrehung x 18,3 m

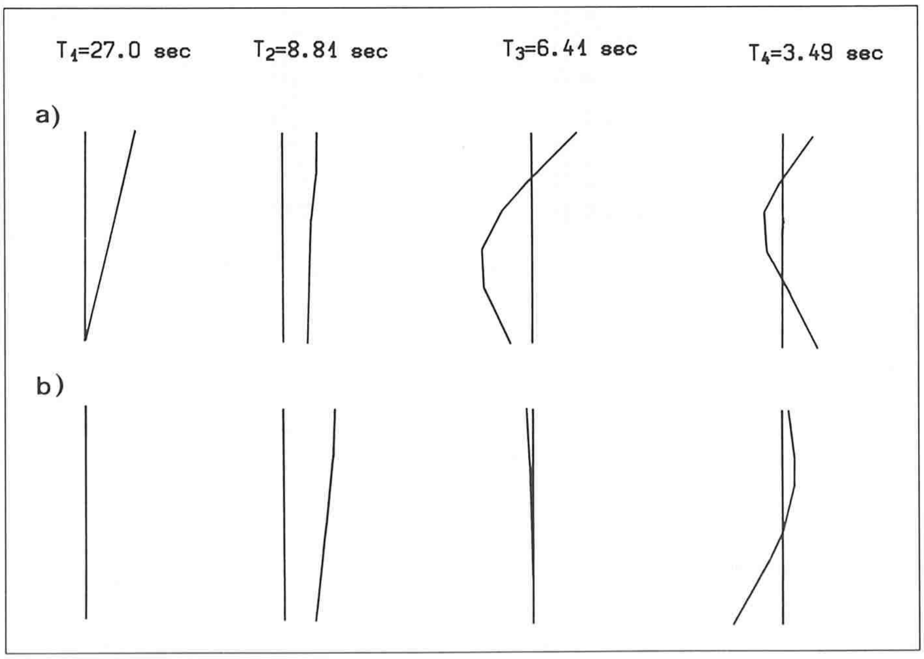
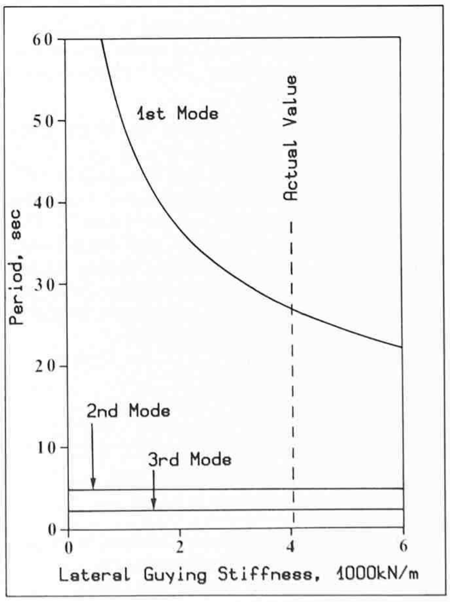


Fig. 5. Effect of lateral guying stiffness on natural periods of vibration in x-direction

Bild 5. Einfluss der Steifigkeit der seitlichen Abspannung auf die Schwingungsperiode in x-Richtung



this stiffness that should be used to monitor this particular mode.

As an example, the influence of the lateral guying stiffness on the natural periods of vibration in the x-direction is shown in Figure 5.

Dynamic Stiffness of Cables

A fundamental step in the analysis of the dynamic response of guyed towers is the evaluation of the dynamic stiffness of the guying cables in harmonic motion. This fairly theoretical part of the study has been documented in depth in the literature [7 and 8] and is not discussed here. Only the low-amplitude in-plane dynamic-stiffness curve applying to the parabolic characterization of an undamped cable of the guyed-tower system investigated is shown in Figure 6. The dynamic-stiffness value K is non-dimensionalized with respect to the static value $K_0 = 329$ kN/m and the circular frequency ω is non-dimensionalized with respect to the reference frequency $\omega_o = 0.167$ rad/sec.

Cable-Structure Interaction

The inertia of the guying cables affects the response of the dynamically excited guyed-tower system. In spite of this cable-structure interaction, the structural response is often computed under the assumption of massless cables. This part of the study examines the extent to which such an assumption is valid and determines which are the specific parameters governing the interaction.

Only two parameters control cable-structure interaction. The first parameter is the ratio of the static stiffness of the guying system to the tower stiffness corresponding to a specific configuration, in the present analysis selected as being one of the natural modes of vibration of the tower constrained by the massless guying system. This stiffness parameter specifies to which extent the guying stiffness contributes to the overall stiffness and thereby gives an indication of the potential importance of the interaction. The second parameter is the ratio of a characteristic frequency of the guying system to the natural frequency of the particular tower mode considered. From a knowledge of this frequency parameter and of the dimensionless dynamic-stiffness curve of the guying cables such as the one shown in Figure 6, it can be seen if large variations in the dynamic-stiffness value occur in the frequency regions at which the response of the tower is mass controlled or to the contrary in the frequency regions at which it is sensitive to variations in the value of the guying stiffness.

The analysis performed for the actual guyed-tower system indicates that the fundamental modes of vibration in both the x- and y-directions are potentially sensitive to cable inertia because of their large stiffness ratio. However, substantial differences between static and dynamic guying stiffnesses occur in the frequency regions at which the response of these modes is mass controlled. The higher modes of vibration are practically not affected by cable inertia because the guying stiffness makes a negligible contribution to the overall stiffness. The static guying stiffness may therefore be used to analyse the structural response of the guyed-tower system considered.

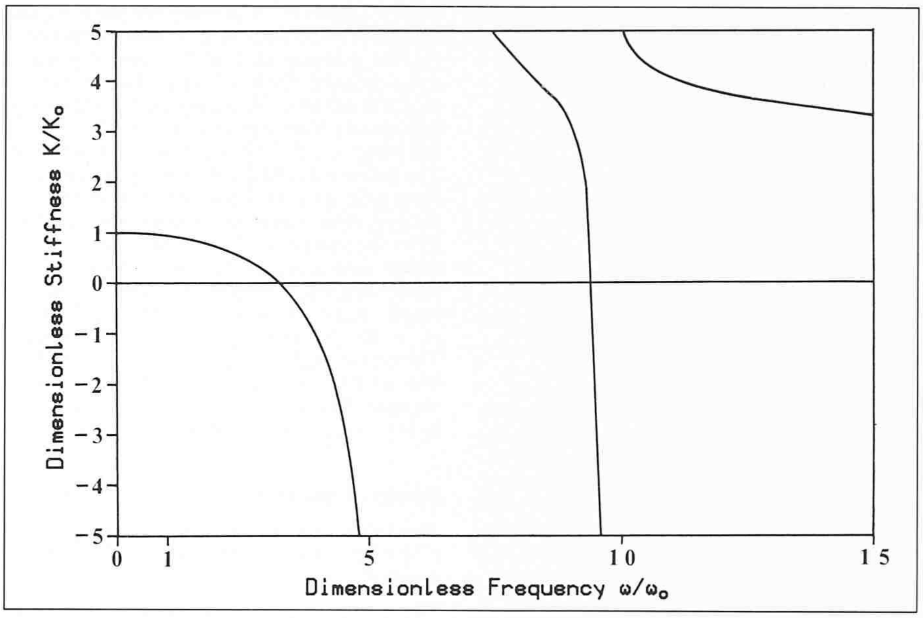


Fig. 6. Dynamic stiffness of undamped guying cable

Bild 6. Dynamische Steifigkeit des ungedämpften Abspannkabels

Fig. 7. Frequency-response curve for fundamental mode of undamped guyed-tower system in x-direction

Bild 7. Frequenz-Antwortkurve der Grundschwingung in x-Richtung

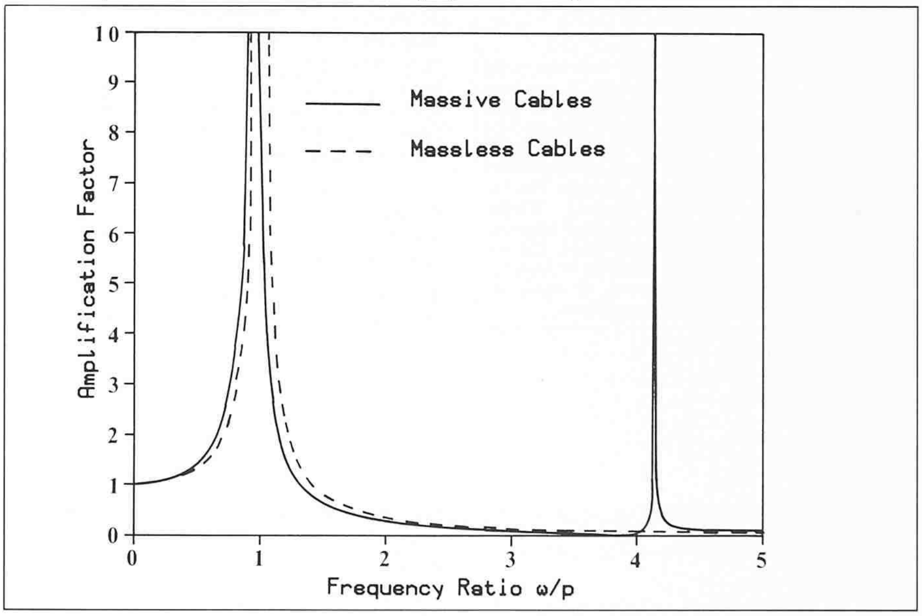
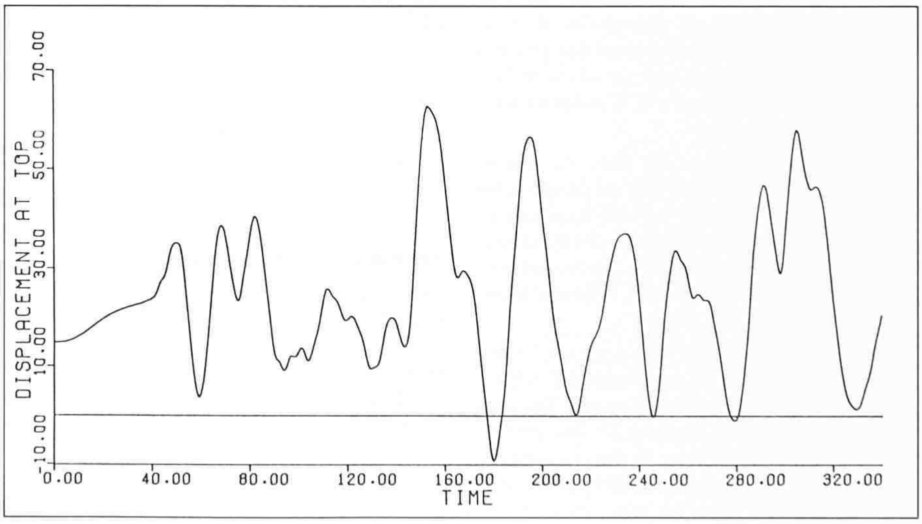


Fig. 8. Top displacement in ft versus time in sec (1 ft = .30 m)

Bild 8. Auslenkung an der Turmspitze in ft (0,30 m) über der Zeit in s



As an example the frequency-response curve of the fundamental mode of vibration of the tower in the x-direction is shown in Figure 7 for the undamped condition.

Transient Analysis of Guyed Tower

A thorough understanding of the behavior of guyed-tower systems requires studies of their response to wind, current and waves. They are performed in this part of the study.

Method of analysis

The major sources of structural nonlinearities are localized at the level of the guying system and possibly at the foundation. The modal pseudo-force method is thus chosen to perform the transient analysis. The same modes of vibration and natural frequencies are used during the entire analysis and all the structural, geometric and force nonlinearities are treated as an excitation. The equation of motion is solved by using the exact piecewise linear method of integration.

Excitations

The fluid forces acting on the structure are obtained from the linearized form of *Morrison's* equation. The fluid velocity in this equation is the sum of the time-independent current velocity and of the time-dependent wave-induced fluid velocity. The current is represented by a fluid particle velocity varying linearly from a maximum of 1.2 m/sec at the mean water level to zero at the sea bed. The wave-induced fluid velocity is generated from a linear *Airy* wave for deep-water conditions. The wave amplitudes are obtained from the one-sided *Pierson-Moskowitz* wave-energy spectrum expressed in terms of the significant wave height, H_s, and of the average wave period, T_o. The values of $H_s = 10.7$ m and $T_o = 12$ sec are utilized. The phase angles necessary for the specification of the waves are selected in a random manner. The wind action is represented by a lateral static force of 890 kN acting at the top

Acknowledgements

This paper summarizes the study reported in [6] which has been performed under a research project directed by Prof. *A. S. Veletsos* at Rice University, Houston Texas and sponsored by Brown & Root, Inc., Houston Texas. Financial support has been provided by Rice University and the "Bata Schuh Stiftung", Zurich. The International Communication Agency, Washington DC provided travel grants and financial support; this support was placed under the administrative direction of the Institute of International Education. The generosity of these organizations is gratefully acknowledged.

Results of analysis

The following conclusions follow from the numerous calculations performed for the x-direction:

The vertical forces substantially affect the fundamental period of vibration and the response of the tower.

The assumption of a constant vertical cable reaction for the guying system produces insignificant errors in response.

When performing a modal pseudo-force analysis of the guyed tower, it is necessary to consider at least the first two modes of vibration. The fundamental mode typically controls the deflections in the upper part of the tower, while the second mode affects the deflection at the base and the member forces. This has been investigated further in [9].

The drag component of the wave-induced forces dominates the inertia component by an approximate ratio of 3 to 1 for a drag coefficient of $c_d = 1.0$

The nonlinearities of the guying system affect the response to various extents depending on whether it operates mostly in the nearly linear range or not.

In Figure 8, the response time-history of top displacement in the x-direction is shown for the tower subjected to the combined action of wind, current and waves.

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Wettbewerbe

International Concept Design Competition for Advanced Information City

The Japan Association for Planning Administration (JAPA) and the Mainichi Newspapers have launched an international ideas competition to solicit conceptual designs and plans for several themes for an advanced information city, focused on Kawasaki City (Japan).

The UIA was informed only after the competition had been launched and its programme *does not conform* to the revised Regulations for International Competitions in Architecture and Town-Planning, approved by UNESCO and which the UIA is bound to see respected.

The composition of the jury does not in fact offer the guarantee of international representation urged by these regulations. The conditions for the adjudication do not respect the soverainty of the jury in the sense that a pre-selection will be carried out by a committee independant of the jury. Finally the promotors of the competition make no committment as to the future or the carrying out of the winning project, and the sum of the prize money does not suffice, given the amount of work required of the competitors.

For these reasons the International Union of Architects cannot support this competition and warns architects intending to participate, that they do so at their own risk, and that in the event of problems with the promoter during or after the competition, the UIA will in no case be able to intervene in defense of their interests.

Union Internationale des Architectes (UIA)

Sportanlage Trottacher in Kloten

Die Stadt Kloten veranstaltet einen öffentlichen Projektwettbewerb für die Sportanlage Trottachter (1. Etappe), verbunden mit einem Ideenwettbewerb für Vorschläge zur künftigen Gesamtgestaltung der Sport- und Erholungsanlage Trottacher (weitere Etappen).

Teilnahmeberechtigt sind Architekten, die seit mindestens dem 1. Juli 1985 ihren Wohn- oder Geschäftssitz in Kloten oder in den angrenzenden Gemeinden Winkel, Lufingen, Oberembrach, Nürensdorf, Bassersdorf, Dietlikon, Wallisellen, Opfikon, Rümlang oder Oberglatt haben. Zusätzlich sind folgende Archiekten eingeladen (Preisträger im Wettbewerb «Gwerfi»): Theo Hotz AG, Zürich, Peter Uster, Hinteregg, und René Wagner, Küsnacht, Werkgruppe für Architektur + Planung, Zürich, Atelier WW, Walter Wäschle und Urs Wüst, Zürich, Nikolaus Hajnos, Zürich, Christian Hurter, Wädenswil, Walter Schindler, Zürich, Aurelio Galfetti, Bellinzona, und Livio Vacchini, Locarno, und zusätzlich Rudolf Meuli, Minusio.

Ein Bewerber kann Spezialisten einer anderen Fachrichtung (Landschaftsplaner, Ingenieur usw.) beiziehen, auch wenn diese die Teilnahmebedingungen nicht erfüllen; ein Spezialist, dessen Name zu nennen ist, darf nur für einen Bewerber tätig sein.

Es gelten ausdrücklich die Bestimmungen der Ordnung für Architekturwettbewerbe SIA 152 und der Kommentar zu Art. 27.

Fachpreisrichter sind Max Schlup, Biel, Christian Stern, Zürich, Max Ziegler, Zürich; Ersatzfachpreisrichter: Fritz Schwarz, Zürich.