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SEISMIC EVALUATION OF THE TOWERS OF AQABA-AMMAN 400 KV OVERHEAD TRANSMISSION LINE

"التقييم السيزمي لخط النقل (٤٠٠ك.ف.) من العقبة- عمان".

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ملخص

تدل الدراسات الزلزالية والتكتونية على أنه قد حدثت زلازل مدمرة بقوة أكبر أو يساوي ٦ درجات على طول حفرة الانهدام الاردني وان امكانية حدوثها في المستقبل واردة. وفي هذه الحالة سيكون لهذه الزلازل تأثير تدميري على أبراج الضغط العالي ٤٠٠كيلوفولت المقامة بين عمان والعقبة.

لقد تم تحليل حزمة ترددات النوع الاكثر شيوعا من هذه الابراج حيث استخدمت تقنية العناصر المحددة لايجاد الترددات الخمسة الاولى المصاحبة للاهتزازات الحرة لهذه الابراج وكذلك فقد جرت مقارنة هذه الترددات بترددات الامواج الزلزالية الناتجة عن زلازل محلية تم رصدها خلال العشر سنوات الماضية على محطة رصد الزلازل في الجامعة الاردنية. وقد كشفت هذه المقارنة النقاب عن الارتباط الجزئي بين ترددات هذه الابراج وترددات الارض المقامة عليها. يترتب على ذلك أنه في حالة حدوث هزات أرضية قوية فان الاستجابة الرنينية وتوابعها المدمرة يمكن توقعها.

Abstract: Seismicity and seismotectonic information indicate that destructive earthquakes ($M \geq 6$) have occurred all along the Jordan-Dead Sea transform and are likely to occur in the future. Any large future earthquakes that may occur between the Dead Sea and the Gulf of Aqaba will affect the towers and connections of this power line. Distances to the towers will vary from a few tens of kms to more than 200 km. The frequency band analysis of the towers is presented. Finite element technique is utilized as a solver for the free vibration of these towers. Only the frequencies of the first five modes associated with the free oscillation of the towers are determined at thus stage. These are compared with frequencies of both the body and surface waves associated with local earthquakes as recorded on the University of Jordan Seismological Station (UNJ). This comparison reveals partial correlation between the frequencies of the structures and their supporting ground. This implies that in the event of severe earthquakes the resonant response with all of its destructive consequences is to be expected.

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1. Introduction

The suspension towers of the 400 KV overhead transmission line constructed between Aqaba and Amman South Substation are designed to accommodate double circuit twin 560/50 ACSR/ACS conductors. The towers are stationed at approximately 350 m apart. Single and double hot rolled angle shapes of either mild or high strength steel are used in fabricating the towers. The strength and design criterion as per BSI [1] Specifications were utilized in sizing the tension and compression elements and their connections. It is worth noting that the analysis and design phases were carried out by Preece, Cardew and Rider Consultant Engineers [2]. Also, the varying environmental conditions between Aqaba and Amman and the relevant effects on the design criterion on the 400 KV transmission line were investigated by El-Zayyat [3].

In an attempt of triggering out the most severe conditions that the towers may experience, the earthquake option was considered by Preece et al [2]. However, in their assessment of earthquake loading the equivalent static loads, transversely and longitudinally, of 0.105 × tower weight were applied to the tower center of mass. This assessment seems to be crude and does not reflect the dominant parameters that characterize the structural response to earthquake excitations. Any rational analysis of earthquake induced forces should exhibit the prevailing structural dynamic properties coupled with the seismicity of the supporting ground.

The frequency band analysis of the towers for different loading conditions is presented in this paper. These are compared with the dominant frequency range of local earthquakes as recorded on the University of Jordan Seismological Station (UNJ). Results indicate partial correlation between these frequencies. This implies that in the event of severe earthquakes, the expected dynamic magnification factor in the absence of any reliable source of damping will be far beyond the capacity of the towers.

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2. Towers Description

The 400 KV overhead transmission line between Aqaba power station and Amman South Substation accommodates double circuit twin 560/50 ACSR/ACS conductors. The towers are fitted with two 7/8 (AWG) aluminium clad steel earth wire. The earth wires are located above the top insulator set attachment point of each circuit, but offset from the tower center line by at least 3 meters less than the top insulator attachment point. The span between towers varies with the type of tower as follows:

A) Standard Towers

Basic span : 410 m
Wind span : all towers - normal working : 450 m
- broken wire : 340 m
Weight span :
suspension towers : normal working: 820 m
broken wire : 615 m
Tension towers : - normal working :1230 m
- broken wire :1230 m
Negative weight span: -all tension towers = 300m
It should be noted that spans for broken wire conditions are applicable only for the conductors considered broken. Loadings for the intact conductors are to be based on normal working spans.

B) Special Towers

Basic Span: 410 m
Wind span - normal working : 450 m
broken wire : 340 m
Weight span - normal working : 820 m
- broken wire: 615 m

Statistical data regarding the number of towers constructed for each different type are as listed in Table 1. Reference to this table reveals that 85 % of the constructed towers are of the 4DL type. Fig. 1 shows the geometric configuration and detail of the standard 4DL tower.

3. Seismicity and Seismotectonics

Instrumental seismicity information indicate that many earthquakes ($M \leq 6.25$) have occurred along the southern Jordan-Dead Sea transform during this century.

The largest ($M = 6.25$) occurred in 1927 and was epicentered some 25 Km north of the Dead Sea. The second largest ($M = 5.4$) occurred in the southern Dead Sea region in 1956. Seven earthquakes ($M = 4.5 - 5$) occurred in the Northern Gulf of Aqaba region in 1983. Studies on this seismicity clearly indicate a general correlation with the regional geology and tectonics. More than 75% of the seismicity seems to be epicentered along the transform proper with a noticeable correlation with its regional strike-slip faults, see Fig. 2.

Historical information indicate that within the last 20 centuries, 19 earthquakes ($M \geq 6$) have occurred in this region. Out of these, 12 can be confidently related to the transform proper including the largest ($M = 7.3$) which occurred in the year 746 and was epicentered in the vicinity of the 1927 earthquake [4,5,6]. Pre-historic information indicate that damaging earthquakes with magnitude as large as $M = 7.3$ have occurred along the southern segment of the transform. Evidences for these were presented by El-Isa and Mustafa [7] who calculated an average recurrence period of about 340 ±20 yr. for magnitudes greater than or equal to 6.5 .

Studies on the seismicity of the transform region indicate a reasonable correlation with the general tectonics, see Fig. 2 . All tectonic elements seem to be active in the present, but most activity seems to concentrate along the transform proper. More than 75% of the total seismic energy for the period 1903-1987 has been released from within the transform proper [3,8]. Thus, the transform represented by its regional strike-slip faults remains the major source of seismic risk in this region.

The Jordan-Dead Sea transform represents a major continental plate boundary that borders Jordan in the west. Over its 1100 km length, it links the plate convergence in southern Turkey to the Red Sea floor spreading in the south. In the last few decades, a number of geological [9,10,11] and geophysical evidences[3,8,12,13] were presented in support of a total multi-stage left-lateral shear of about 107 km. This shear is proposed to conform with the spreading and widening of the Red Sea and is accommodated by regional NNE trending strike-slip faults that are arranged en-echelon. Older deformational phases that affected the region have resulted in developing other regional fault systems that run in NE; NW and E-W directions.

Results from deep seismic soundings indicate that the transform is floored by a typical continental type of crust with a total thickness of about 35 km in Amman region that decreases gradually to about 32 km in the Aqaba region. Farther east in Jordan, the crust thickens gradually to more than 37 km in what is probably a transition towards a shield-type of crust [14,15]. Poisson's ratio and P-velocity distribution, together with focal-depth estimates of local earthquakes indicate that the upper-crust (18 km -21 km thickness) is rather ductile [13]. The recorded frequencies of the body and surface waves are listed in Table 2.

4. Structural Frequency Analysis

4.1 Analysis Methodology

The equations of motion for a freely vibrating undamped tower can be written as follows:

$$\left[M \right] \left\{ \ddot{u} \right\} + \left[K \right] \left\{ u \right\} = \left\{ 0 \right\} \tag{1}$$

Where $\left[M \right]$ and $\left[K \right]$ stand respectively for the mass and stiffness matrices of the tower, and the vectors $\left\{ \ddot{u} \right\}$ and $\left\{ u \right\}$ are the relative accelerations and displacements associated with the vibration of the system. In pursuing the eigenvalues and the corresponding eigenvectors , the following assumptions are made with view of reducing the degrees of freedom associated with the tower oscillation:

1. The restraints offered by the structural joints are ignored. This implies that the end of members coming in to the joint are free to rotate. Thus, each member of the tower can be categorized as a two-force member.

2. The contribution of the redundant (lacing) members to the structural stiffness matrix is suppressed, whereas, their contribution to the mass matrix is acknowledged. This assumption will greatly reduce the kinematics degree without sacrificing the accuracy of the analysis.

3. Consistent with the first assumption, three translational degrees of freedom are assigned to each structural joint.

4. The distributed mass of each member is lumped to the relevant nodes using the consistent mass approach [16]. Meanwhile, the masses of the permanently attached non-structural elements such as conductors, insulators and weight of the bolts and their gusset plates are treated as point masses on the relevant nodes. It should be noted that the last two assumptions, transform a structure with infinite degrees of freedom, due to the distributed masses, to one which has as many degrees of freedom as its unrestrained joint number × three.

5. The offsetting transverse effect of the P-Δ is precluded.

The torsional resistance of angle type element is insignificant and this is coupled with bolt type connections. Thus, the truss-type element is justified. However, the torsional stiffness of the global structure is acknowledged by default through the adoption of the three dimensional modeling. torsional The synthesis of both the stiffness and consistent mass matrices follows the finite element formulation [16] for the three dimensional rod element . Accordingly, the element stiffness, K_l, and mass, M_l, coefficients in the local coordinate system, Fig. 3, may be expressed as follow:

$$K_l = \frac{EA}{L}\begin{bmatrix} 1 & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \qquad (2)$$

and

$$M_l = \frac{\rho AL}{6}\begin{bmatrix} 2 & 0 & 0 & 1 & 0 & 0 \\ 0 & 2 & 0 & 0 & 1 & 0 \\ 0 & 0 & 2 & 0 & 0 & 1 \\ 1 & 0 & 0 & 2 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 2 \end{bmatrix} \qquad (3)$$

Where the symbols A, E, L, and ρ denote:
A = cross-sectional area of the element in mm^2;
E = elastic section modulus taken to be = 2.1×10^5 N/mm^2; L = length of element in mm.; and
ρ = density of steel taken to be 7.81×10^{-8} $N.s^2/mm^4$.

The transformation from local to global coordinate systems is carried out using the transformation matrix G. Thus, the element stiffness and consistent mass matrices, K and M, are obtainable through the relations:

$$K = G^T K G \qquad (4)$$

and

$$M = G^T M G \qquad (5)$$

The geometric transformation matrix, G, is defined as follows:

$$G = \begin{bmatrix} \cos\theta xx & \cos\theta xy & \cos\theta xz & 0 & 0 & 0 \\ \cos\theta yx & \cos\theta yy & \cos\theta yz & 0 & 0 & 0 \\ \cos\theta zx & \cos\theta zy & \cos\theta zz & 0 & 0 & 0 \\ 0 & 0 & 0 & \cos\theta xx & \cos\theta xy & \cos\theta xz \\ 0 & 0 & 0 & \cos\theta yx & \cos\theta yy & \cos\theta yz \\ 0 & 0 & 0 & \cos\theta zx & \cos\theta zy & \cos\theta zz \end{bmatrix} \qquad (6)$$

The contribution of each element to the relevant joint is done through the allocation vector. The total mass matrix is obtained through the creation of a diagonal mass matrix to account for the lumped masses of the insulators, conductors . .. etc.

The computer program ASAS [16] which is implemented on the computer network of the University of Jordan is utilized to solve for the eigenvalues and eigenvectors associated with free vibration of the towers. The program is invoked by creating a data file which includes: nodal coordinates; pertinent physical properties of all elements comprising the tower; lumped masses; and constrained joints.

4.2 Analysis of Results

The standard towers designated as 4DL comprise about 85% of the totally constructed towers between Amman and Aqaba, see table (2). Thus, it was decided to pursue the dynamic analysis of this type of towers. Their geographical orientations together with the functional purposes dictate the increasing of the tower height by multiples of 3 m. This resulted in 4 different configurations of the basic 4DL towers. These towers are designated as 4DL+ 0, 4DL+3, 4DL+6 and 4DL+9, Fig. 4 .

For each tower, two sets of the frequency analysis were carried out utilizing the ASAS [16] computer program. In the first set, the tower is set into free vibration under its selfweight as well as the weight of permanently attached elements. Whereas, in the second set the locally anticipated snow loading on the conductors was added. The calculated frequencies of the first five modes for the four tower types are summarized in table (3). At this stage, however, calculations are restricted to the first five modes only as firstly, the attenuation of seismic waves is proportional to their frequency. Thus, seismic frequencies greater than 10 Hz are highly attenuated and/or absorbed during their passage. This is documented on UNJ, see also table (2); secondly, the calculated frequencies of higher mode of all tower types are greater than or equal to 9-10 Hz; thirdly, it is well-known fact that the first few modes of vibration accommodate in general more than 90% of the total response of a tower-type of structures [17].

The low frequencies of the free oscillation of the towers can be easily detected from table (3). Accordingly and in the event of severe excitation, the towers are expected to exhibit large lateral deformations. This means that even if the towers survive such large deformations, the integrity of the system will be questionable as the possibility of breakage in the conductors becomes feasible.

The fundamental frequencies of the towers are displayed in Fig. 5. This indicates that as the tower height increases, the fundamental frequency shows a compatible decrease. However, the 4DL+3 tower shows an abrupt decrease when compared to the rest of the towers. In order to justify such an observation, the relative stiffnesses and masses for all the towers are estimated as listed in Table 4. It is worth noting that the relative stiffness is defined ,herein ,as the force needed to force the top of the tower to displace a unit horizontally. It is clearly seen from table (4) that the stiffness of both the 4DL+0 and 4DL+3 towers are almost identical. This could be attributed to the slenderness of the extra elements added to the structure. Meanwhile, the mass of the 4DL+3 tower is considerably greater than that of the 4DL+0 tower. Thus, the stiffness mass ratio of the 4DL+3 tower is getting smaller which in turn decreases the frequency value.

It is generally agreed that the frequency content of seismic waves resulting from an earthquake is important as much as their peak ground motions they cause.. This was illustrated by a number of recent catastrophic earthquakes, particularly the 1985 Mexico city earthquake [18]. Therefore, the calculated frequencies of the towers and the observed frequencies of the seismic phases as recorded on UNJ from local earthquakes are plotted on the frequency spectra of Fig. 6 . The frequency band of the surface waves rather than the average values is displayed in Fig. 6. It can be easily depicted from this spectra that the ground shaking at distances greater than 200 Km away from the epicenter has a predominant frequency that is coincided with that of the fundamental mode of all the tower types. This coincidence may result in a resonant response which will lead to disastrous consequences. It should be mentioned that such coincidence was the sole cause of the serious damage of the medium height range buildings in the Mexico city [18]. For shorter epicentral distances, the frequency of the second mode of vibration falls within the frequency content of nearly the body and surface waves. At distances less than 50 km, the frequencies of the fourth and possibly the fifth modes coincide with the predominant, frequencies of all phases. This indicates that any rational analysis should not preclude the contribution of, at least, the second or even higher modes. This is particularly true due to the fact that the epicenter of possible future earthquakes should be expected anywhere all along the Jordan transform. As the power line runs almost parallel to the transform and a few tens of kilometers to the east, then one should expect epicentral distances to the towers that range from a few 10s of kms up to more than 300 km. It is worth noting that the design and analysis by Preece et al [2] were based on the equivalent static load technique. The latter technique, in general, capitalizes only on the first mode in estimating and distributing the lateral earthquake forces. The results of the frequency analysis as presented in this paper represent a first step toward a comprehensive dynamic analysis. Seismic risk evaluation, assessment of lateral forces and their distribution and the contribution of individual modes are in progress. This project will be ultimately concluded by providing a response-spectra chart that can be utilized in the design of similar structures.

5. Conclusions

Studies on the seismicity of the region and the dynamic characteristic of the 400 KV Aqaba-Amman line revealed the following conclusions:

1. Instrumental and historical seismicity information indicate the possibility of

the occurrence of severe earthquakes ($M \geq 6$) in the southern Dead Sea transform region in the future.

2. The eigenvalue analysis shows that the towers are flexible in the sense that the fundamental frequency for all the analyzed towers is too low. This criterion may jeopardize the integrity of the system.
3. Comparison of the structures and their supporting ground frequencies triggers out the possibility of resonant response in the event of destructive earthquakes.
4. The design of such essential facilities should include the effect of higher modes of vibration, up to at least mode 5.
5. The anticipated resonant response need to be explored further with the view of proposing a remedy for this serious problem.

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Table 1: The Towers Classification and Their Numbers

Location	4DT	4D1	4D2	4D3	4DL	4D6	4D9
Aqaba - Maa'n	2	40	10	5	250	10	1
Maa'n - Qtran	3	22	3	3	263	-	-
Qatran - Amman	1	18	2	1	168	6	-

Table 2: The Dominant Frequencies of Seismic Phases as Recorded on UNJ

Epicentral Area	Epicent. Dist. from UNJ in KM	Dominant Frequencies in Hz		
		P-Waves	S-Waves	Surface Waves
Northern D.Sea	50	8-10	6-8	3-5
Dead Sea	70	5-9	4-7	3-4
Tiberias	110	6-7	3-6	2-3
Beasan	120	6-7	5-6	3-4
Dead Sea	120	5-6	4-5	3-4
Southern D. Sea	150	5-6	4-5	3-4
Syria/Palestine NNW of Amman	150	5-6	4-5	4-5
NE Amman	180	4-5	3-4	1-2
Syria	190	4-5	3-4	1-2
Syria	200	5-6	3-4	1-2
Araba	200	5-7	4-5	2-3
Azraq	220	3-4	4-5	1-3
Palestine/Lebanon	240	5-6	3-5	1-2
Aqaba	380	1-5	0.5-3	3-1
Cyprus	450	.8-4	0.4-3	4-1.5
Gulf of Suez	480	1-4	2-3	1-2
N.Red Sea	800	1.3-3	.3-2	.4-1

Table 3: A summary of The Calculated Towers Frequencies

Tower	Load	Freq. of Mode No. in Hz				
		1	2	3	4	5
4DL+0	W/O Snow	1.2	4.3	9.2	10.	12.5
	W. Snow	1.0	3.7	7.8	9.1	10.7
4DL+3	W/O Snow	.79	1.3	5.1	8.3	9.2
	W. Snow	.76	1.07	4.4	7.8	8.4
4DL+6	W/O Snow	1.0	3.8	7.6	8.3	13.0
	W. Snow	0.84	3.2	6.6	7.9	10.7
4DL+9	W/O Snow	1.1	3.7	6.5	8.3	12.0
	W. Snow	0.91	3.2	6.3	7.1	10.8

Table 4: Relative Stiffnesses and Masses as Estimated for the 4DL-Type Towers

Tower	$K_{rel.}$ N/mm	$M_{rel.}$ N-s/mm^2	First Mode Freq. in Hz
4DL+0	220.8	14.00	1.20
4DL+3	224.0	18.40	.79
4DL+6	168.3	15.64	1.00
4DL+9	139.1	15.70	1.10

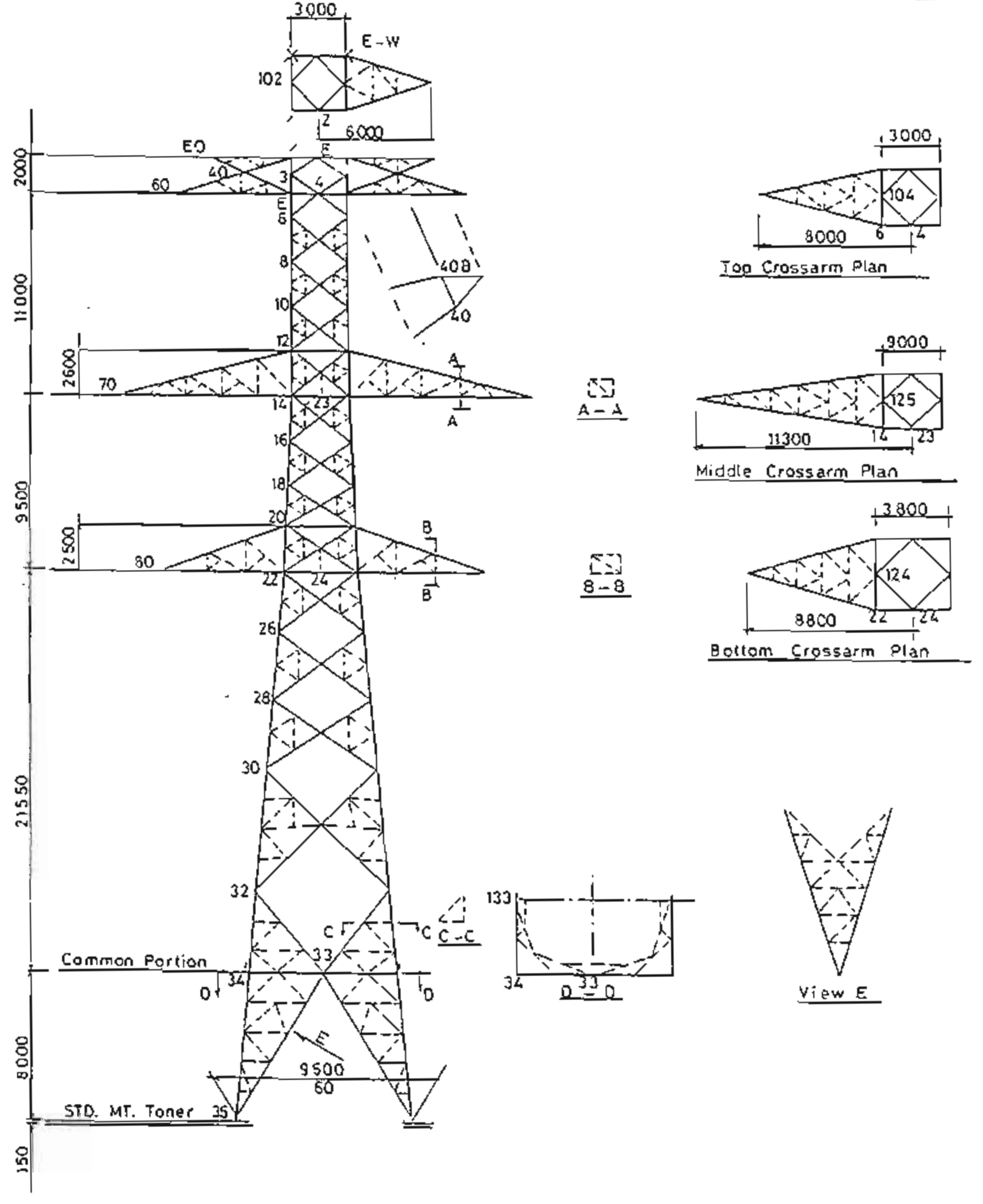

Fig. 1: Details of the 4DL Standard Tower

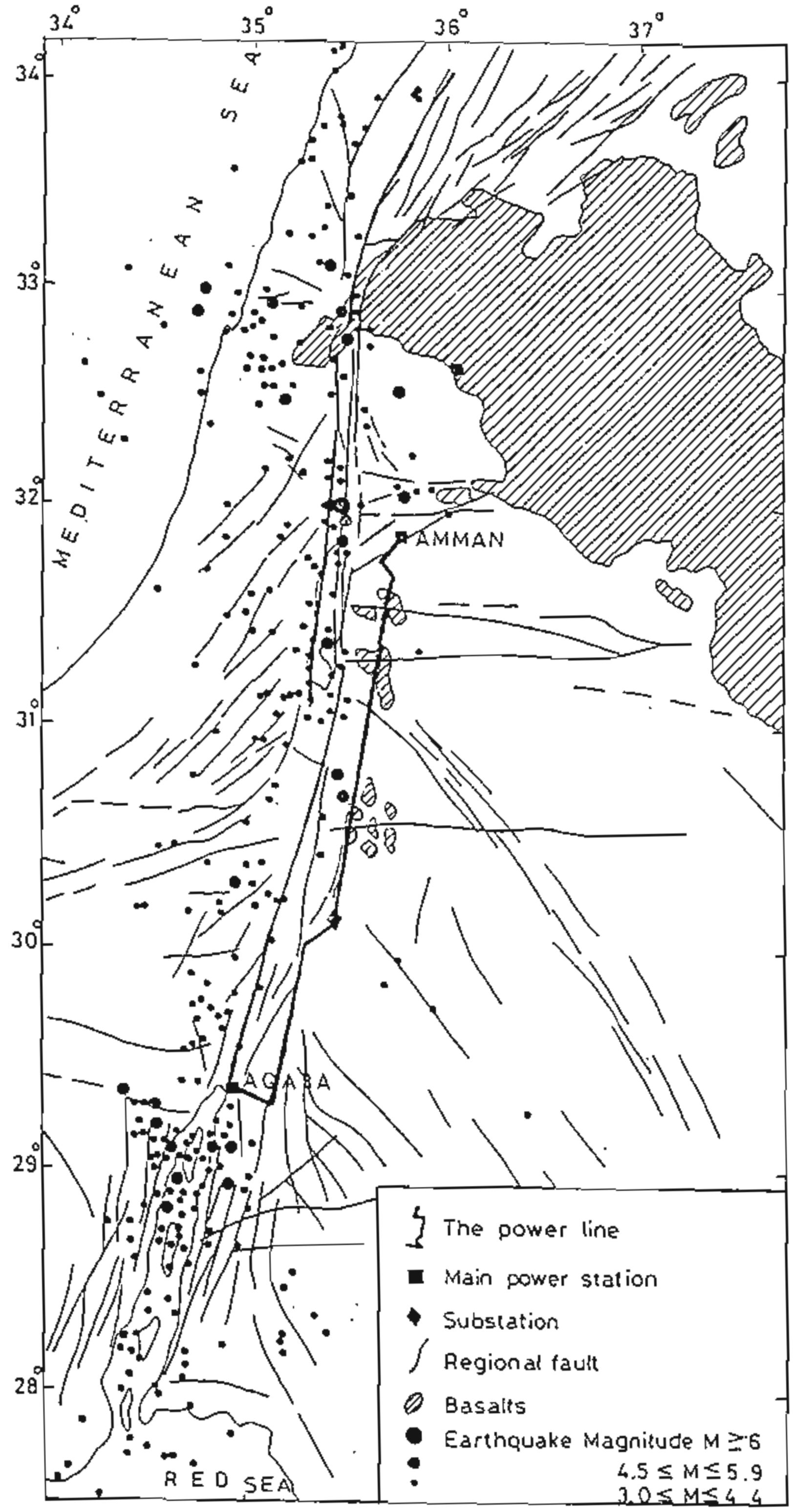

Fig. 2: A tectonic Map of The Jordan-Dead Sea Transform Region showing the seismicity for the Period 1903-1987.

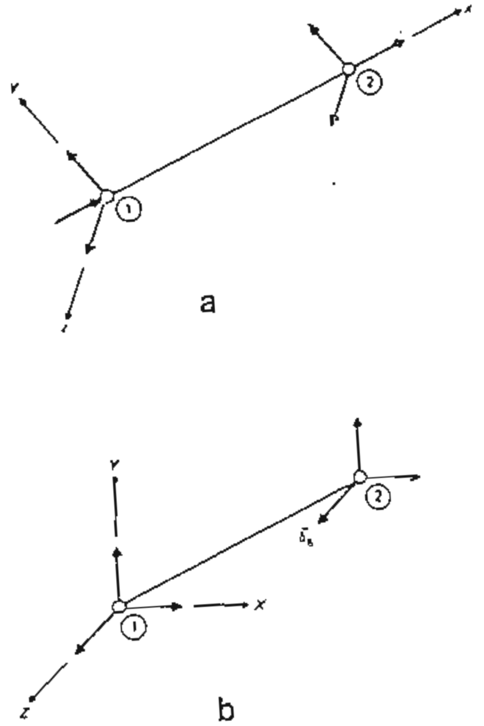

Fig. 3: Member of A space Truss Showing Nodal coordinates.a) In The Local System. b) In the Global System.

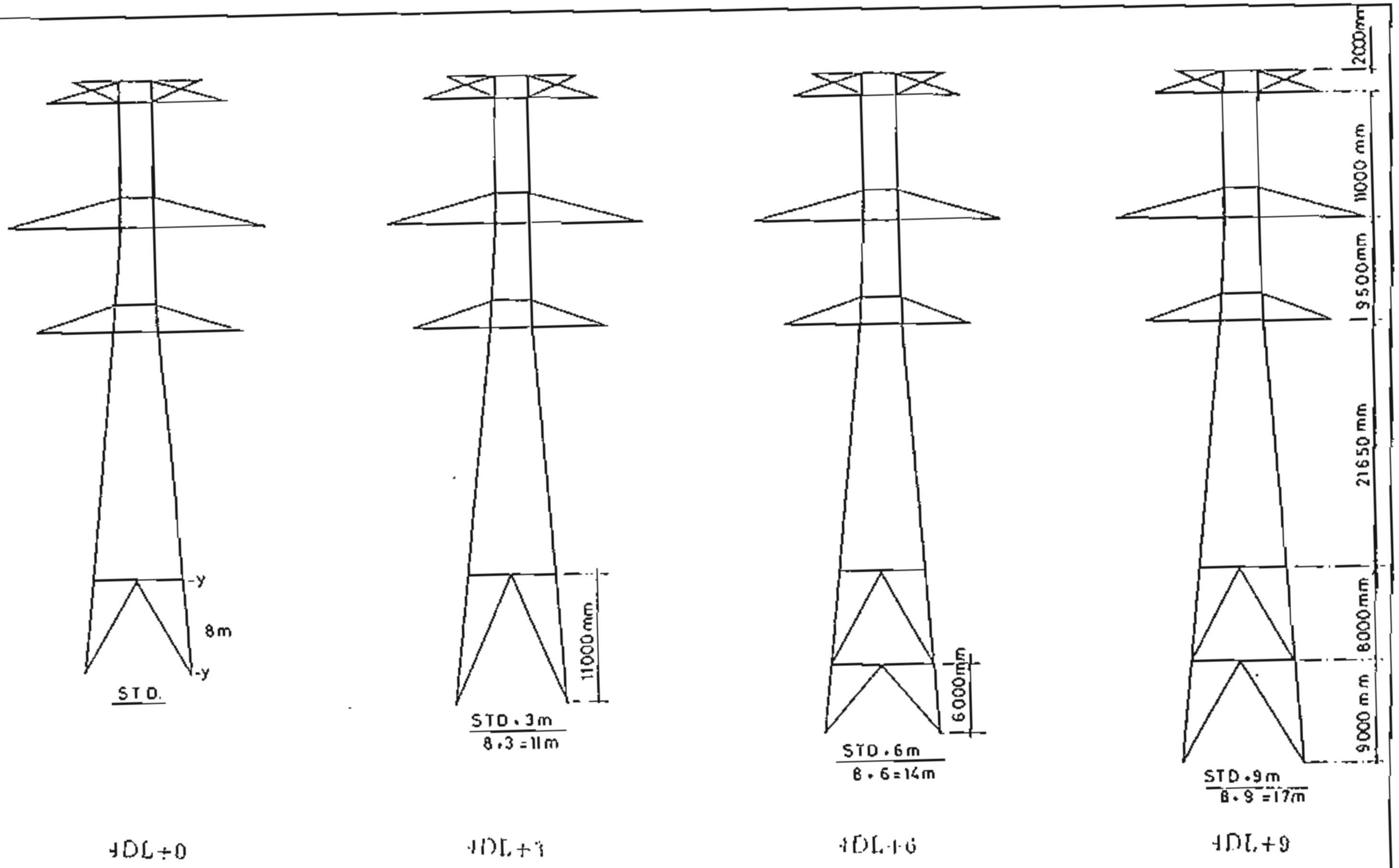

Fig. 4: The General Layout of the 4 Versions of the 4DL standard Tower.

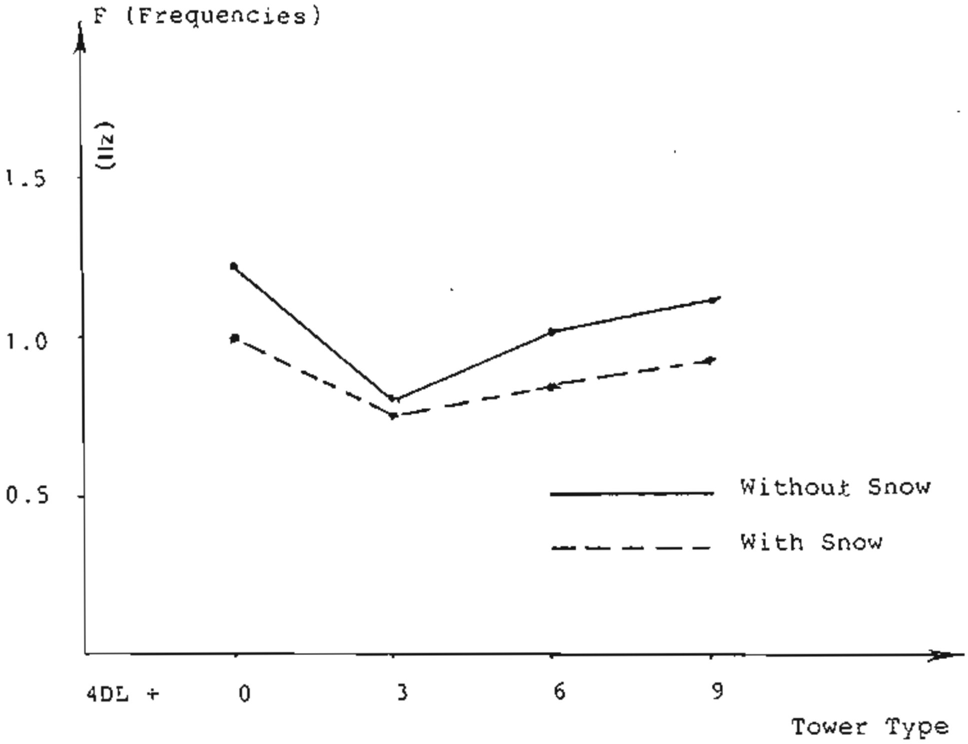

Fig. 5: **Calculated** Fundamental Frequencies of the 4DL types.

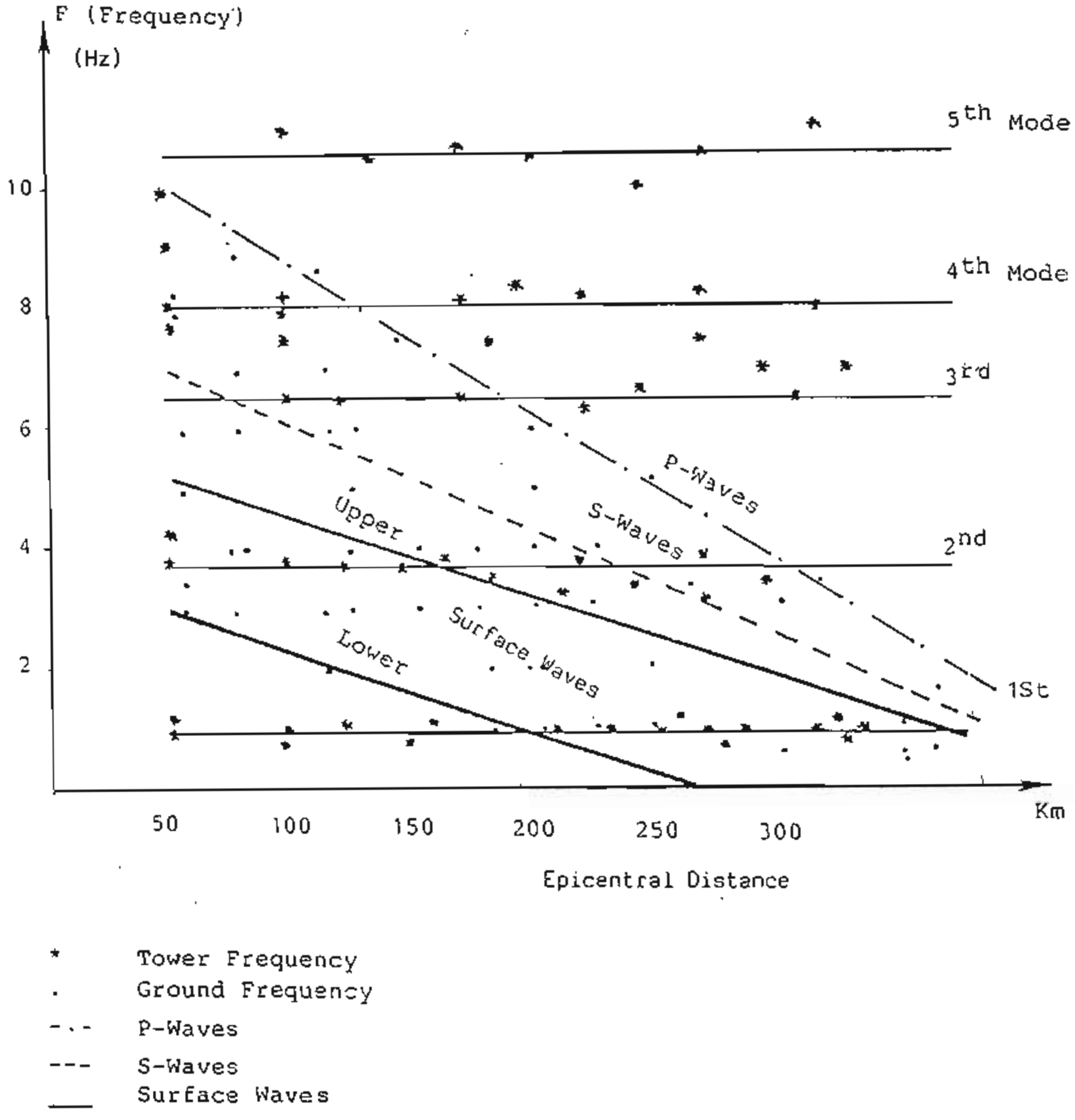

Fig. 6: Calculated and Observed frequency spectra for the tower-types and seismic phases.