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Seismic behaviour of a bridge across the Strait of Gibraltar

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ABSTRACT: Among other alternatives, a bridge is being considered as a feasible solution for the permanent link between Europe and Africa across the Strait of Gibraltar. The most feasible solution consists of a multi span suspension bridge (three 3,500 m long main spans and two 1,500 m lateral spans) combined with two conventional offshore viaducts of a total length of 14 km. The suspension bridge is supported by concrete gravity four leg structures of a height of 340 m above the sea bed.

From a seismic point of view, some interesting problems have to be considered. Among others: (1) fluid-solid interaction in the gravity supports, (2) behaviour of an extremely flexible structure, (3) seismic interaction between the supports and the bridge and (4) relative comparison of actions due to ship impact, wind, wave, current and seismic exitation.

1. DESCRIPTION OF THE BRIDGE SOLUTION

To build a bridge across the Strait of Gibraltar, two main alignments are being considered. The so-called alignment 28 goes from Punta Paloma in Spain to Punta Malabata in Morocco; it is 28 km long and it crosses the Strait over a 300-m-deep sea. Alternatively, alignment 14 goes from Punta Cires to Punta Canales; it is only 14 Km long but the sea is up to 900 m deep although a two span solution (with a span length which would be close to 5000 m) can be designed with a central support founded at 450-m depth.

In the last 8 years, an important effort has been devoted by SECEG, SNED and their consultants, Carlos Fernández Casado S.A. (Spain), Cowiconsult AS (Denmark) and CID (Morocco), to define these solutions. An important number of parametric and feasibility studies have been performed to improve knowledge about the behaviour and properties of proposed solutions. The solution for alignment 28 will be presented here along with a description of its seismic behaviour.

If we focus our attention on the main suspension bridge which would be located at the center of the Strait, the main design/structural problems involved are:

- Substructure: supports have to be founded on a 300-m-deep seabed and have to withstand the weight of an extremely long span bridge as well as other external forces such as those produced by sea waves, earthquake, wind, currents and ship impact. Erection problems have also to be considered. These constraints are so important that it has to be demonstrated that such a structure is feasible.
- Superstructure: if we consider that the largest span under construction is "only" 1990-m long (Akashi Bridge, Japan), feasibility of the superstructure has also to be demonstrated, mainly with respect to wind stability and erection procedures.

At the present time a base solution has finally been selected to comply with all the constraints including the economical ones. The bridge would consist of a central 14-Km-long multispan suspension bridge with the following distribution of spans: 1750+3*3500+1750 m. On both sides, approach viaducts would connect the main bridge to both shores.

Foundations for the 4 main supports are located at a depth which ranges between 200 and 300 m. Offshore oil platforms experience has been applied to design these supports as gravity based concrete structures. They are four-legged frames which transmit loads to the foundation through four large cellular footings which are connected by transverse beams to form a rigid base. The top platform of this frame would be the foundation for the bridge pylons (Figure 1)[1].

The statical system of the suspension bridge would be based on the design of rigid A-shaped towers which could transmit unbalanced horizontal cable forces to the supports. Suspension scheme would be classical although some stays and inclined hangers may be added to improve static and dynamic behaviour of the main girder. The deck would allow partial vertical air flow through it to improve its flutter stability. Several alternatives are presently being investigated[2]. From

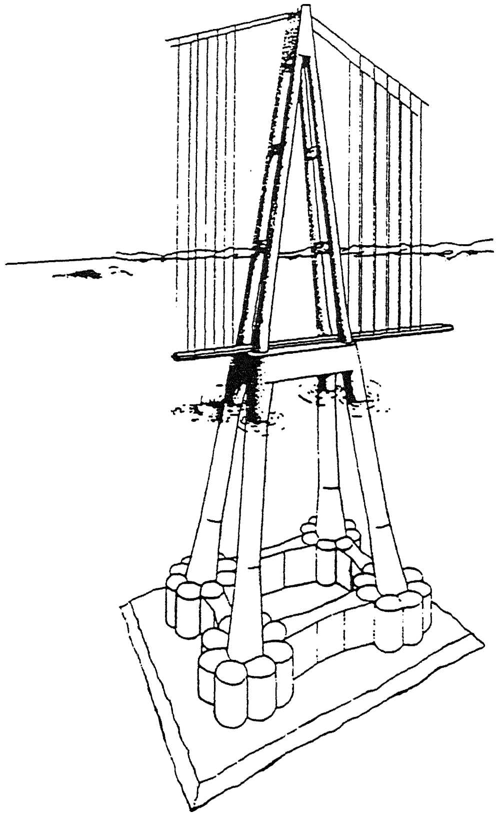

Figure 1. Pier and pylon for the Gibraltar Bridge.

a structural point of view it is interesting to note that, to get a stiffer statical system, a rigid connection between the cables and the girder has been designed at midspan as well as between the deck and the supports (although in this last case the connection would only be rigid for fast loads, including seismic forces).

2. DEFINITION OF LOADS

It is very important to define carefully the set of loads to be applied to such an important structure since these loads will govern its design. Hydrodynamic loads are moderate if we compare them with those which are considered for the design of oil platforms in the North Sea: the maximum current velocity at sea surface is 2.5 m/s and the 150-year sea wave height is 11 m.

The Strait is a well-known windy area because of the temperature difference between the Atlantic Ocean and the Mediterranean Sea and because of Venturi effects. Nevertheless, extreme winds are relatively moderate since design wind speed for static effects is 52 m/s at deck level.

But the most important load to be applied on the supports is resulting from ship impact events. Although a fully deterministic analysis would require to resist a 2100-MN force, a partially deterministic analysis has been adopted (at least during the feasibility studies) resulting in a 1200-MN statically equivalent load to be applied horizontally at sea level on any of the legs of the supports. Resistance to impact from submarines has also to be provided resulting in a very significant increase of wall thickness in all the elements of the supports.

With respect to seismic loads, since a specific seismic risk analysis has still to be done and since soil properties are not well known yet, a conservative approach has been adopted. AASHTO Regulations[3] have been followed combined with the draft of the new Spanish Seismic Code[4]. This draft code provides a specific description of response spectra to be used for far seismic events which have to be considered in the Strait of Gibraltar and would be most dangerous for a very slender structure such as an extremely long- span suspension bridge. Then, peak ground acceleration has been estimated as 0.117g for a 475 year return period. This acceleration is increased by 50% for a clayish soil, which has been found in the sea shore (this is the "worse" scenario which has been considered during the feasibility studies). Design response spectrum may be found in Figure 2.

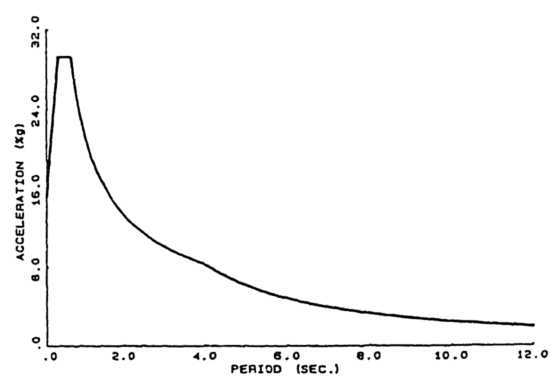

Figure 2. AASHTO design spectrum.

3. MODAL ANALYSIS

For such a complex structure special attention has to be paid to the structural models for dynamic analysis since two very different structures are connected: massive and rigid gravity-based supports and a flexible multispan suspension bridge. Three models of the bridge have been considered:

- A model of one support with its corresponding pylon without any connection to the bridge (Figure 3a).
- A model of a classical suspension bridge: 1 full span, 2 half-spans, 2 pylons and 2 gravity-based supports (Figure 3b).
- A model of the full 14-km-long bridge with its 4 pylons and its 4 gravity-based supports (Figure 3c).

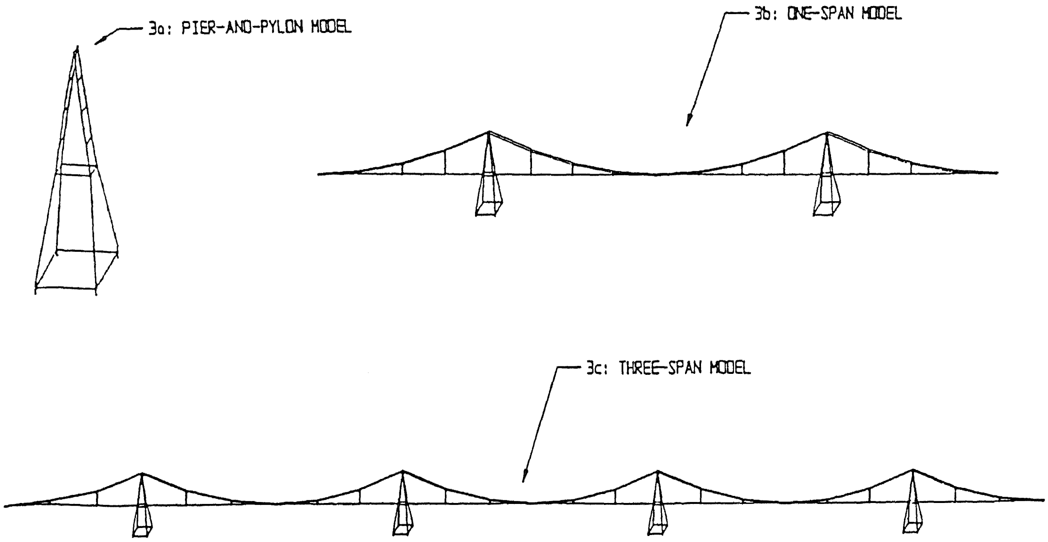

Figure 3. Finite elements models of the bridge.

Discretization of the piers and the pylons is more detailed than for the spans since most of the mass is accumulated there and it is necessary to determine a large number of modes to obtain reliable results in this case. Fluid-solid interaction has been taken into account in a simplified way by the added-mass concept by means of Morison's equation.

The first period of vibration for the support and the tower has been found to be 5.4 sec, although it is necessary to take into account as many as 50 modes (and a 0.35 sec period) to mobilize more than 90% of the mass of the structure. Among all these modes, the most significant from a seismic point of view are located at about 3-sec periods of vibration and correspond to the vibration of the pier.

In this analysis it has been supposed that the foundations are perfectly stiff which is an apparently reasonable hypothesis for such large footings. Nevertheless, the dimensions of the footings have been determined on the basis of a soft soil (what we call the "worse" scenario). If we take into account its possible flexibility, the fundamental period of vibration would jump up to 10.6 sec. This possibility has not been considered reasonable since the soft soil layer would only have a limited thickness but it shows how important it may be to have a better knowledge of the sea floor to design the supports not only from static strength criteria but also from its seismic behaviour.

The analysis of the one-span model gives a fundamental period of 35.1 sec corresponding to transverse vibration of the deck and the cables with almost no movement of the piers and the pylons. In this case it is necessary to determine as many as 230 modes of vibration to mobilize 90% of the mass of the bridge. Since the deck and the cables do not represent an important fraction of this mass, the period of the 230th mode is 0.32 sec, which is almost coincident with the corresponding value for the simplest model.

Results for the three-span model are very similar to those for the one-span model although the lower 230 modes would only mobilize 30% of the mass. For this reason most of seismic analyses have been only performed on the two simpler models (isolated support and one-span model).

4. RESPONSE SPECTRUM ANALYSIS

Seismic analysis of such an extraordinary structure will have to show how important the superstructure may be on the behaviour of the substructure. The pylon is much more flexible than its support and it will oscillate at smaller frequencies and with smaller spectral accelerations. Pylons are connected to the cables, which are massive (as compared to pylon's mass) and flexible. Then we have a three-part assembly with large differences in rigidity and mass between its components.

Multimode spectral analysis has been used to obtain an answer to all these questions. Results are summarized in the following table for two models (pier-and-pylon model and one-span model) and two earthquake directions (longitudinal and transverse with respect to bridge axis) in terms of selected displacements and member forces (Figure 4).

At first sight one may appreciate that results for both models are roughly comparable for most of the parameters which have been analyzed. Then it may be worthwhile to study only the simplest model, at least for parametric studies.

Nevertheless, some significant differences still exist between the two models. Displacements at top of pylon are larger for the simple model than for the one-span model. This means that the cables somewhat restrain

	Pier & Pylon Model	One-span Model
Maximum displacement at top of pier (m)		
longitudinal	0.19	0.27
transverse	0.26	0.25
Maximum displacement at top of pylon (m)		
longitudinal	0.86	0.34
transverse	0.42	0.27
Maximum displacement at center of span (m)		
longitudinal	-	0.35
transverse	-	1.85
Maximum vertical reaction in footings (MN)		
longitudinal	420	400
transverse	880	690
Maximum horizontal reaction in footings (MN)		
longitudinal	1710	1800
transverse	1520	2030
Maximum bending moment at base of pier leg (MNm)		
longitudinal	23310	26200
transverse	38020	34820

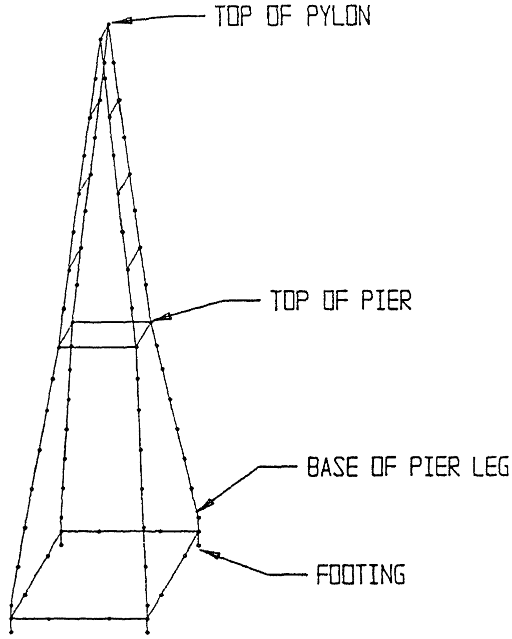

Figure 4. Critical points to be analyzed.

the tower deformation although their influence on the pier is less important.

With respect to reactions, interpretation of the results may become more difficult. Transverse earthquake gives higher vertical reactions than longitudinal earthquake and this is due to the dimensions of the pier at sea bottom level (longitudinal dimension is larger than transverse dimension in this particular case).

Going from the pier-and-pylon model to the one-span model increases base shear although this increase is much larger for the transverse earthquake than for the longitudinal earthquake. The reason is probably due to the fact that the one-span model is rigidly supported at both ends to represent the anchorages and most of seismic forces applied to cables and deck are absorbed at these end supports.

In the case of the transverse earthquake the connection between the piers and the anchorages is more flexible and then less effective from a structural point of view.

The decrease in base bending moments which may be found in comparing results for the two models and for the transverse earthquake may be related to the supporting effect of the cables on the top of the pylon as it was previously seen for displacements.

The fact of considering cables and deck increases the total mass of the bridge and consequently also seismic forces but these forces are applied at a lower level than seismic forces on the pylon and the resulting overturning moment becomes lower.

There is also an important contribution from the design spectrum since modal accelerations are lower for the one-span model.

An important fact to be checked is the relative magnitude of all the external actions which are applied on the bridge. Maximum vertical reactions at the footings are:

Wind:	220 MN
Sea waves:	40 MN
Ship impact:	760 MN
Earthquake:	880 MN

while bending moments at pier's column base are

Wind:	560 MNm
Sea waves:	4500 MNm
Ship impact:	54710 MNm
Earthquake:	38020 MNm

It appears that earthquake will be the governing action for the design of foundations while most of the pier design will be governed by ship impact loads. Nevertheless we should point out that it has to be determined how safe against ship impacts the bridge needs to be, how effective the corresponding barrier has to be and finally how important the ductility of such a structure would be. Although we still do not have an answer to these questions, previous results indicate that ship impact is the main load case to be investigated in the case of a bridge across the Strait of Gibraltar.

If we focus on transverse displacements at midspan, wind forces would deform the deck about 10 times more than earthquake forces depending on the design of the cross section. Then, even if a minimum acceleration would be specified in the design spectrum, strength requirements for the deck would be governed by wind forces. With respect to the pylons, the differences are not so dramatic since the corresponding spectral acceleration is more significant than for the deck, but wind forces are still governing the design. As an example, the bending moments at the base of the pylon are 650 MNm for earthquake and 2145 MNm for wind.

5. STEP BY STEP ANALYSIS

As it has been shown previously, response spectrum analysis may give surprising results which are sometimes difficult to explain. Then step by step analyses have been undergone to try to better understand the seismic behaviour of this bridge. Besides this reason, it is also interesting to investigate the effect of unphased excitation for a long-span bridge.

The acceleration record was generated by superposition of sinusoidal components and it was adjusted to obtain a response spectrum which is very similar to the design spectrum (Figure 5). For so doing, a long record was selected (30 sec.) and it was modulated by a parabolic build-up function in the first 2 seconds and by an exponential decay function in the last 10 seconds (Figure 6).

For the uniform excitation in the pier-and-pylon model, it is interesting to note how the pier and the pylon deform according to their corresponding fundamental periods of vibration (about 5 sec. for the pylon and 3 sec. for the pier) as it may be observed in Figure 7 for transverse displacements at top of pier and at top of pylon. The same effect may be found on the one-span model for the displacement at mid-span (Figure 8) which builds-up at a much slower rate: the maximum transverse displacement at mid-span is obtained at time t=26 sec, when the earthquake vibration is almost finished.

Multi-support excitation has been analyzed in a very simple way to ascertain its potential importance. The same accelerogram has been used in all the supports although they have been shifted according to a previously fixed wave velocity. Two reasonable values have been chosen for this velocity: 1000 and 2000 m/s.

In the pier-and-pylon model, the distance between the supports is 200 m and the corresponding time shift would only be less than 0.5 sec. The step by step analysis gives very similar results for the uniformly excited model and for the multi-excited model (Figure 9). We should choose much lower wave velocities (less than 300 m/s) to get significant differences and these values are not very reasonable.

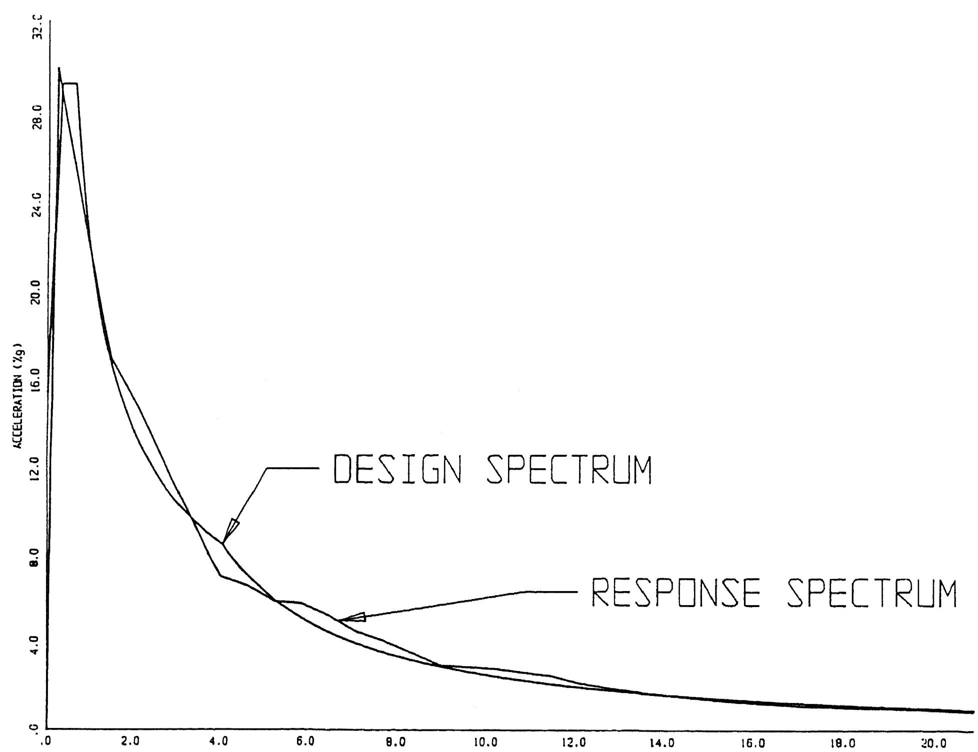

Figure 5. Response spectrum of the artificial accelerogram.

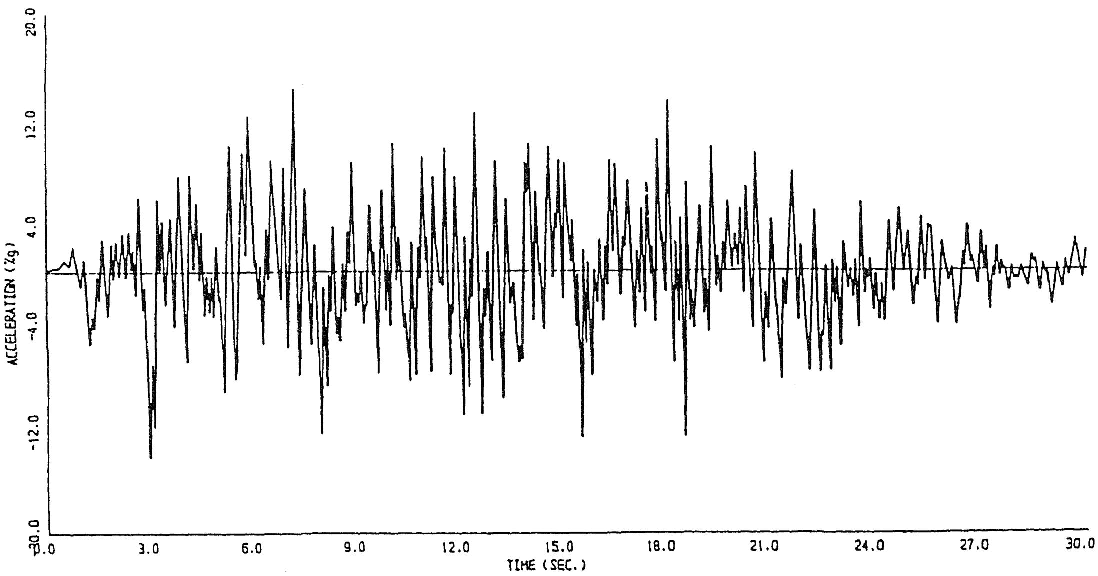

Figure 6. Artificial accelerogram.

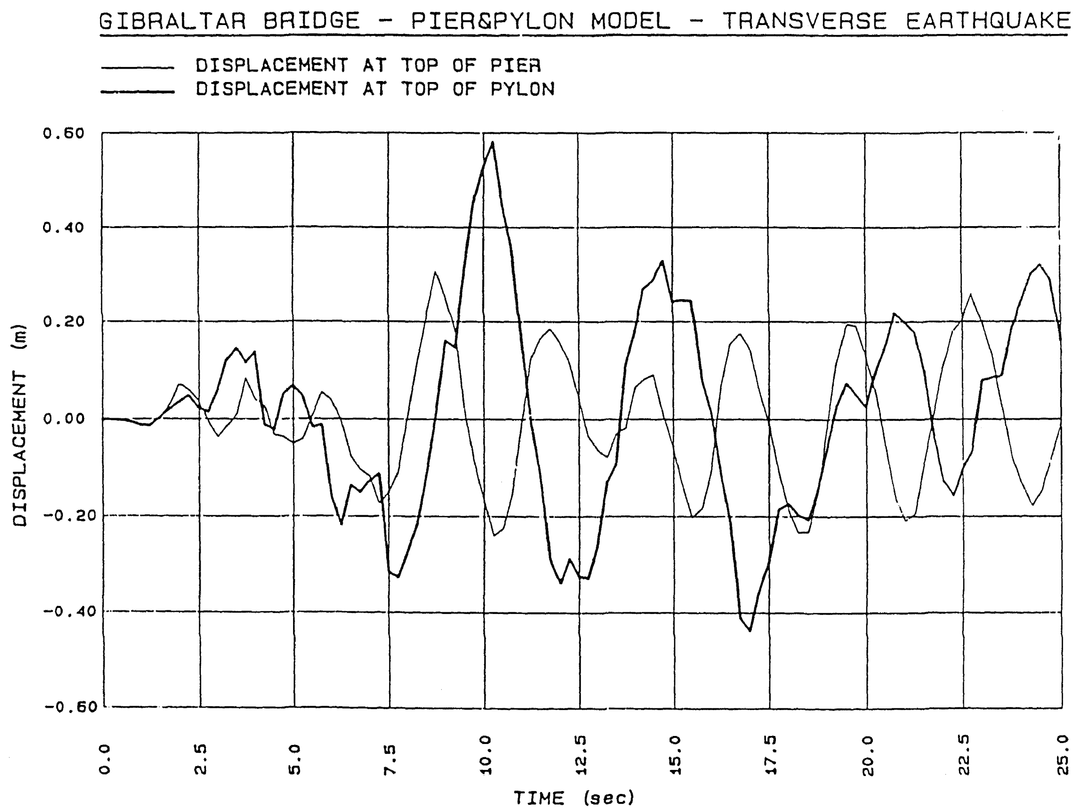

Figure 7. Displacement response for the pier and pylon model.

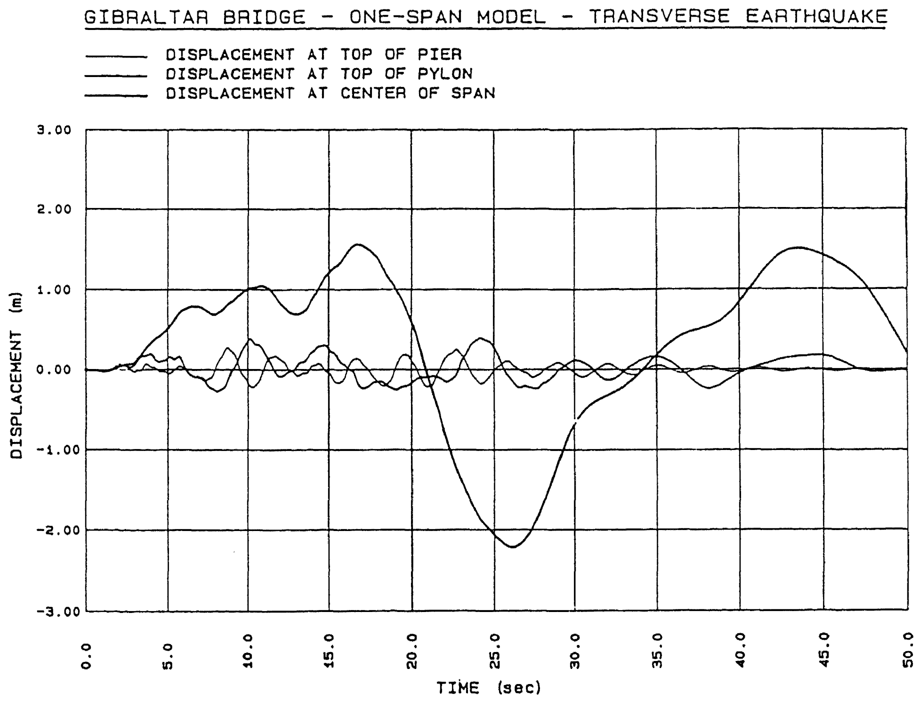

Figure 8. Displacement response for the one-span model.

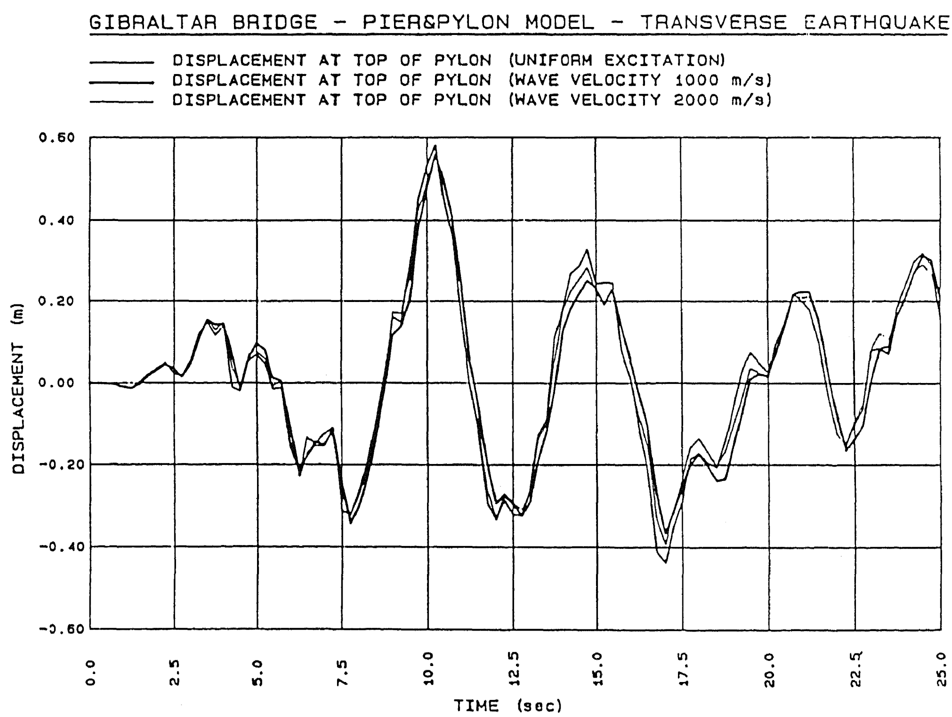

Figure 9. Displacement response for non-uniform excitation.

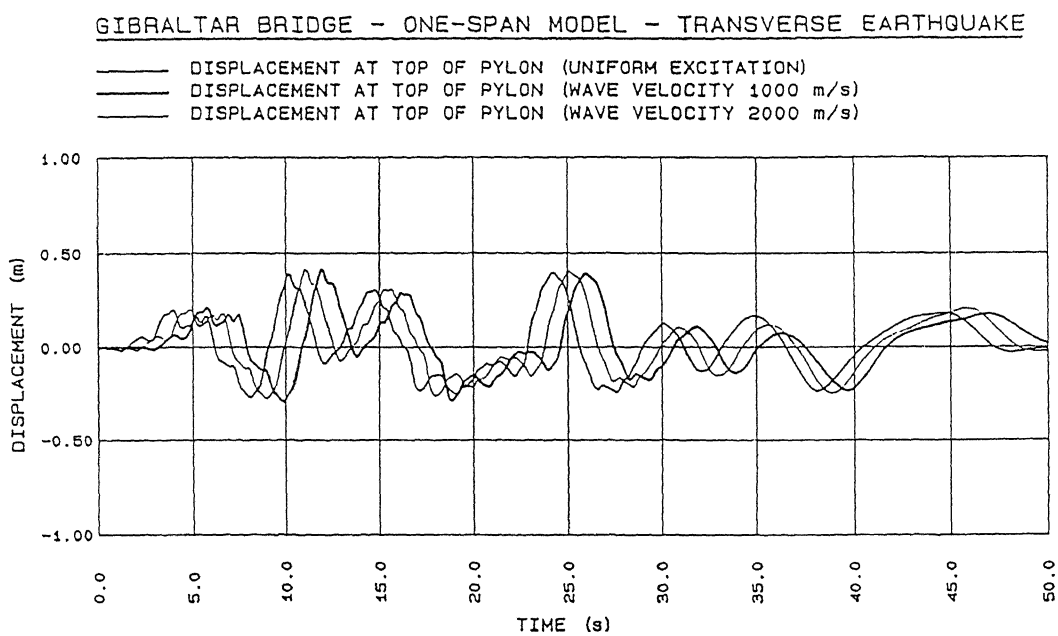

Figure 10. Displacement response for non-uniform excitation

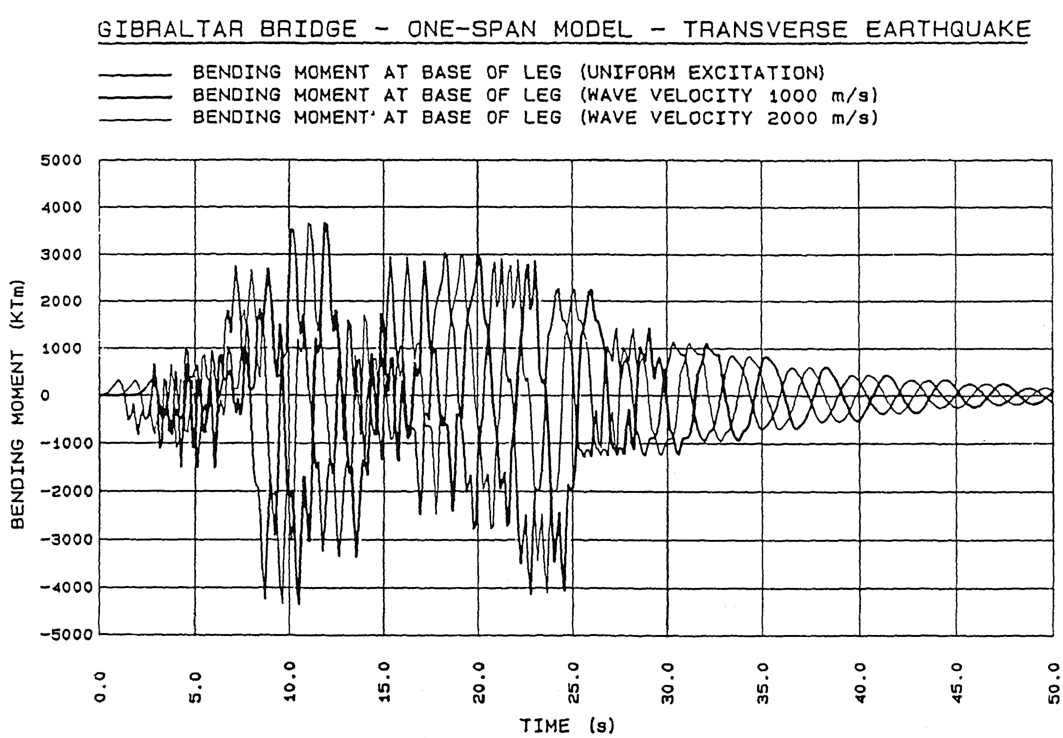

Figure 11. Bending moment response for non-uniform excitation.

In the case of the one-span model, the distance between the supports is much larger and the corresponding time shift may be very important (3.5 seconds for the main span and a 1000 m/s seismic wave velocity). Nevertheless, the structure is also very flexible and it can accommodate quite easily displacement differences between the supports. Step-by-step analysis shows that member forces do not change very significantly if we change the wave velocity (Figures 10 and 11).

6. CONCLUSIONS

It has been shown that seismic forces are very important for an ultra long span bridge even in an area with a moderate seismic risk such as the Strait of Gibraltar. Nevertheless, in our case wind forces are governing the design of the deck and the pylon, and ship impact forces are governing the design of the piers.

In the future development of this project, some other aspects related to seismic engineering have to be studied:

- Design criteria have to be established for this particular structure to allow a coherent treatment of all the forces which have to be considered. Standard specifications such as AASHTO, BS or EN are not valid in a design phase of this project.
- Non-linear response of the structure should be studied to determine its level of ductility as well as the level of ductility which could be considered in the analysis (repairing the pier legs would be so difficult that it would possibly be necessary to keep them in the elastic range.)
- The soil-structure interaction is also very important, but a better knowledge of the sea bottom would be necessary to undergo more detailed studies on this topic.

A large project like the Gibraltar Strait Bridge drives us to revise some fundamental aspects of seismic engineering since many generally accepted ideas may not be applicable in this case.

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