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The dynamic behaviour of Archimede's Bridges: Numerical simulation and design implications

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Abstract

In the paper the activity of the research group in the field of the dynamic behaviour of Archimede's Bridges is reviewed. The scope is twofold; on one hand the implications, in terms of structural analysis and design, of the results of this activity are summarized and discussed. On the other hand the needs for future research are defined.

The general criteria adopted in the simulation of the dynamic response of the Archimede's Bridge are first summarized. Attention is focused on "slow" dynamic actions; loading conditions due to impacts and internal or external explosions are thus not considered.

The problem of seismic response is subsequently addressed; the problem of transverse response is discussed, especially in light of the anchoring system typology. It is then commented how another critical issue can be represented by the longitudinal motion of very long tunnels and, on design grounds, by the way of providing adequate restraint. Finally the aspects related to hydrodynamic excitation due to seabed motion (tsunamis and "seaquake") are briefly presented especially in light of research development.

The dynamic behaviour under wave and current excitation is addressed in the second part; the adopted wave models are briefly described along with the criteria for defining hydrodynamic forces; some results are shown illustrating the response to exceptional wind waves, with particular reference to the motion of the anchoring elements.

The issue of vortex induced vibration is then treated, showing how long anchoring elements can be dangerously prone to activation of large oscillations, with the additional problem of high Reynolds numbers characterizing the fluid-structure interaction. The numerical procedure which has been developed for simulating the phenomenon is illustrated along with some example of application to simple problems.

Finally, some general considerations relating dynamic performance and basic design choices are proposed.

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Keywords: structural dynamics; non-linear response; seismic excitation; wave forces; vortex-induced-vibration

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1. Introduction

The Archimedes Bridge (AB) is an intrinsically flexible and slender structural system, whose performance under dynamic loads represents one of the most important factors affecting both feasibility and basic design choices. When compared to other more traditional options for crossing sea straits or, more generally, waterways, it can be observed that the AB shares some of the problems affecting other flexible systems such as suspended or cable-stayed bridges. The dynamic behaviour of the latter systems, in particular, shows some features which are typical of ABs as well; in both systems the interaction between the main element (deck or tunnel) and the supporting elements (stays or anchoring elements) plays an important role.

Both systems can claim a good performance against seismic events, even though none can be regarded as a ductile or dissipative structure, this being usually a desirable property for anti-seismic designs. Both systems can be prone to fluid-structure interaction effects (aerodynamic or hydrodynamic); in fact, the design of suspended or cable-stayed bridges can be significantly governed by aeroelastic considerations related to flutter behavior. The AB concept, in this respect, seem to be more “robust”; however, the behaviour of long anchoring elements under vortex shedding excitation deserves a very careful treatment, also in consideration of the high Reynolds number values characterizing the problem.

Aerial and Archimedes bridges obviously show much different aspects in relation to “fast dynamics” problems, related to vehicle impacts and to the vulnerability to intentional attacks; it must be observed, in this light, that the AB safety, though not affected by the risk of impact by flying objects, can be harmed by external underwater explosions, this being a very difficult problem to be tackled by simulation.

For long crossings, many aspects related to feasibility, economy and environmental impact are in favor of the AB solution; to allow for a practical exploitation of this advantages, a significant amount of research has been performed, in the last years, for gaining a deeper confidence in the structural behavior and in the safety features of ABs. In this light this paper reviews the activity of the research group which has been active at DIS-Politecnico di Milano, also in relation to the sino-italian cooperation and to the SIJLAB project. Design implications of the obtained results are highlighted, along with the need for further research and development.

2. Structural configuration and modeling

The studies reviewed in this paper and the related considerations refer to a design solution having the following characteristics:

- (1) The tunnel axis is rectilinear and horizontal; the tunnel itself acts as a continuous beam.
- (2) The anchoring system is provided by means of slender elements lying in a plane which is orthogonal to the tunnel axis; the elements can be cables or bars. In the latter case the choice of hollow sections can lead to almost neutral conditions for the anchor elements under self weight and buoyancy effects, this resulting in an approximately straight configuration which positively affects the transverse initial stiffness of the AB.
- (3) In longitudinal (axial) direction the tunnel is restrained at one of the end section and left free at the other end.

Special dissipation devices can be provided at the restrained end to avoid transmission of excessive axial force.

In such configuration, and for the type of loadings here considered, the tunnel dynamic response in the transverse-vertical plane is mainly affected by the behaviour of the anchor elements. In this light extensive analytical and numerical work has been performed by this research group aiming to the development of efficient and reliable numerical tools for modeling these elements.

For the bar case two models have been set; the first one (NWB element [1, 2]) is capable of representing the entire anchor element, under the hypothesis of hinged end sections and constant axial force. The NWB element, though simplified, can capture the interaction between the transverse local oscillation of the bar, introduced through a variable number of local coordinates and shape functions, and the time varying axial force. The second model is a 3D beam finite element based on a corotational formulation [3]; upon discretization of the bar in a sufficient number of elements, the model allows for representing arbitrary large motions, though retaining the small deformation assumption.

For the case of submerged tunnels anchored by cables [8, 18], a previously developed finite element [4, 5] has been adopted, especially in view of comparing the structural performance resulting from the two design strategies. This is a three-node cable element formulated in the large displacement and small deformation hypothesis.

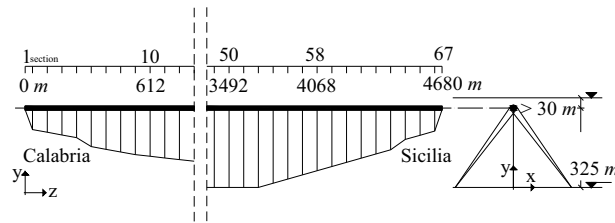


Fig. 1. Schematic view of Messina Strait crossing

In all the studies here reviewed the following hypotheses and criteria have been adopted when a dynamic model of the complete structural system has been set:

- (1) the tunnel is modeled as a single elastic beam; shear deformability is included; tunnel masses are lumped at anchoring sections;
- (2) soil-structure interaction effects are introduced by means of a lumped-parameter approach, encompassing frequency-independent spring and dashpots.
- (3) structural damping is introduced in a quite refined way and according to different strategies, depending on the model adopted for the anchoring system.

Most of the analysis done to test the developed numerical models were relative to a design proposal (see Fig. 1) for the Messina Strait Crossing between Punta S. Ranieri and Catona (4680 m) [12]. More recently the dynamic behaviour [8, 18] of the AB prototype designed within the SIJLAB project [13] was investigated.

3. Structural behavior against dynamic loading

In Table 1 the main sources of dynamic excitation affecting an AB design are summarized with reference to environmental actions and to “slow” dynamics problems. In the table the main anticipated design issues are summarized for each action. The acronym RD is referred to the need of further research, while “design solution” (appearing in the last column) is related to the choice between cables and hollow section bars as anchor elements.

3.1. Earthquakes (ground transmission)

The design of an AB against seismic loads moves from the consideration that a structural system of this type cannot be regarded as dissipative, as intended by modern codes. No inelastic deformation, in fact, can be allowed in the tunnel due to tightness requirements; anchor elements, on the other hand are in general made by cables or very slender beams, whose inelastic behaviour can be hardly exploited as a reliable dissipative mechanism. This means that the seismic design of ABs is essentially elastic; in this situation the computation of dynamic response becomes very important, especially for avoiding unnecessary conservatism.

In this light, the earthquake response of Submerged Floating Tunnels has been object of several studies by this research group; multiple-support seismic input was adopted in all analyses, by means of artificially generated time histories of ground displacement and velocity. Generation was performed in accordance with a stochastic model describing, through suitable coherency functions, the spatial correlation structure of free-field ground motion. The generation procedure has been recently improved within the SIJLAB research activity [18].

Table 1. Dynamic loading on Archimedes Bridges

Phenomenon	Treatment	Impact on safety/serviceability	Design implications
<i>Earthquake (ground transmission)</i>	Numerical simulation	Resistance	Section, end connections, connections between modules (tunnel); section, end connections (anchors), foundations
<i>Earthquake (water transmission) – “seaquake”</i>	Numerical simulation (RD) Physical testing (RD)	Resistance	Section and connections between modules (tunnel); section, end connections (anchors), foundations
<i>Earthquake - tsunamis</i>	Numerical simulation (RD)	Resistance	Still to be defined
<i>Wind waves</i>	Numerical simulation	Fatigue (anchoring system) Comfort (tunnel)	Design solution, end connections (anchors) Depth below water table (tunnel)
<i>Current (vortex shedding)</i>	Numerical simulation (RD) Physical testing (RD)	Fatigue (anchoring system) Comfort (tunnel)	Design solution end connections and section shape (anchors)
<i>Secondary waves</i>	Numerical simulation (RD)	Resistance	Still to be defined
<i>Traffic (structure-vehicle interaction)</i>	Numerical simulation (RD)	Fatigue (anchoring system) Comfort (tunnel)	Design solution, end connections (anchors)

The results obtained for the Messina Crossing example show how the transverse behavior of a long AB is mainly affected by the local performance of the anchoring system. The most critical aspect, in this respect, seems to be represented by the large stresses occurring in the anchor bars close to the tunnel ends, where the elastic limit of the material was largely exceeded in the quoted example. The comparison between the design solutions encompassing, for the anchoring system, hollow-section bars or cables [9] has shown similar performances when the response to ultimate seismic conditions is considered.

The simulation of the longitudinal behavior of a long AB has essentially put in evidence two problems. The first is related to the “internal resonance” effect occurring between the local oscillations of the anchor bars and the axial modes of the tunnel, resulting in significant amplifications of the response. Activation of the phenomenon for other sources of excitation must be carefully studied.

A second aspect is related to the design strategy to be adopted for the axial restraint of the tunnel ends, which must be free to accommodate thermal effects and anticipated variations in the distance between the connected shores. The problem is the same as typically encountered in long continuous-deck bridges; in fact, the choice of a rigid connection at one end, with the other end free, results in very high axial forces, both in the deck and in the restraint and abutment, at the fixed side. At the same time, some longitudinal restraint must be provided both for the behaviour under normal loads and to avoid excessive bridge-abutment relative motion under design seismic actions.

In [14] the seismic response has been simulated, for the Messina Strait example, by adopting different longitudinal end conditions, namely free-free, free-fixed, free-dissipator, dissipator-dissipator. The dissipation device here considered is similar to the one introduced in the SIJLAB prototype design [8,13]; this is a elastic-plastic spring with kinematic hardening. The yielding displacement has been set to 0.1 m and the hardening ratio to 15%, while three values of the yielding force, equal to 2, 5 and 10% of the tunnel weight, have been considered for the Messina Strait example. When dissipators were positioned at both ends half the stiffness and yielding force were assumed.

The results obtained, though preliminary, show that the double-dissipator solution performs better than the one with a single dissipator at one end; it is also confirmed how the free-free solution should be carefully studied, especially in relation to behaviour in serviceability conditions and to the need of providing a sufficient amount of self-centering capability.

3.2. Earthquakes (water transmission): “seaquake”

The term seaquake denotes here the hydrodynamic excitation related to the vertical transmission of compressive fluid waves from the sea bottom, which moves under seismic conditions, to the tunnel. It is deemed that the phenomenon can result in significant overstress, especially on the anchor elements and on the foundations.

The numerical simulation of the phenomenon, involving delicate fluid-structure interaction aspects, seems to be quite complex. Specific research is needed in the field, to the aim of testing available computational tools and of developing simplified computational approaches. The feasibility of physical tests on a shaking table should be also investigated.

3.3. Earthquakes (water transmission): tsunamis

Most of the research performed worldwide in the last period on the tsunamis phenomenon is related to the estimation of coastal “runup” causing damage and victims. The behavior of coastal infrastructures has been investigated to a much lesser extent.

In [15] a preliminary study regarding the forces transmitted by a tsunamis wave to a tunnel located in the Messina Strait has been performed. The essential limitation of this study is related to 2D analysis; under this hypothesis, the classical Laitone theory of solitary waves has been adopted along with the Morison equation. The results obtained, which must be regarded as very preliminary, show the occurrence of very small transverse displacements for the tunnel. Larger effects occur when the propagation of the wave has a significant component along the tunnel axis; on design grounds, this raises some questions related to the longitudinal restraint of the tunnel.

This writers believe, however, that the problem needs a high degree of attention with respect to 3D effects; geometrical effects occurring in the propagation of a tsunamis wave through a sea strait, for example, could result in significant amplifications of the actions transmitted to an AB crossing.

3.4. Wind waves excitation

The problem of dynamic excitation due to wind waves has been treated in quite extensive research work (see for example [2, 9]). Response has been computed by step-by-step simulation; wave forces have been modeled by adopting the Morison equation, which is justified, when the forces on the tunnel are considered, only for very large waves; fully non-linear drag forces have been retained in the analysis. The models for wave loading are consistent to the hypothesis of a crossing in deep water, the random sea level is simulated according to the Multivariable Stationary Model [10], accounting for waves having different frequency and direction; artificial wave profiles were generated according to the harmonic superposition technique. Subsequently, wave kinematics has been modeled following Airy linear theory.

The result generally show how, given the tunnel depth below the water table, the tunnel displacement components are rather limited even in the case exceptional waves, especially if compared to design seismic effects. On the contrary, lateral displacements of the tethering elements can be of the same order of magnitude as in the seismic case. The comparison between the two tethering solutions [9], in addition, shows how, if the equal strength criterion is adopted, the cable solution undergoes much larger displacements, mainly due to catenary effects, both in exceptional sea conditions and under “normal” waves (significant height equal to 1 m). The latter condition deserves, in the writers’ opinion additional research effort; in fact, the tunnel performance under wave loading in serviceability conditions should be studied, considering diffraction effects, for estimating fatigue life of the structure and comfort for the occupants. The analysis could be simplified assuming linear behaviour, thus allowing for the use of a frequency domain approach.

3.5. Current and vortex shedding effects

Current effect is deemed to be important in view of the phenomenon of vortex induced vibration (VIV). The problem appears to be critical especially for long tethering elements, which are prone transversal oscillations in the low-frequency range. These oscillations can undergo coupling with the vortex shedding frequency; additional “internal resonance” effects could occur due other low-frequency oscillatory phenomena, such as tunnel forced

motion due to wave loading and tunnel longitudinal free vibration. The latter is obviously strongly affected by the end restraint condition.

The preceding considerations support the belief that global modeling, even though simplified, is necessary to estimate structural response to vortex-induced excitation. In this light the adoption of so called “fluid oscillator” models appears to be a reasonable compromise between accuracy and computational efficiency. In previous research the model proposed by Belloli et al. [11] has been assumed in its essential physical properties; a different formulation, however, has been proposed, based on a distributed approach replacing the original lumped-parameter model. In the proposed procedure a distributed vortex layer (DVL, see Fig. 2) runs parallel to the elastic bar, represented through the NWB element, exchanging non-linear viscous and elastic fictitious forces. The DVL is in turn connected to the reference system by means of a continuous layer of non-linear springs and dashpots. The latter show a cubic force-velocity relationship, characterized by negative initial tangent damping and thus feeding energy into the system for small motions; for larger velocities the cubic damping term makes the fluid-structure energy flux decrease until equilibrium is reached against structural dissipation.

The model needs experimental data for calibrating its mechanical parameters; in [6, 7, 16] examples are given of the model performance against experimental results and theoretical considerations, showing how the main characteristics of self-sustaining and self-limited of the vortex shedding phenomenon are effectively reproduced. In Fig. 3, for example, typical diagrams relating non-dimensional amplitude and shedding frequency to fluid velocity are shown. Nevertheless, an additional research effort appears to be worthwhile to the aim of better characterizing the dependency on initial conditions and some aspects related to fluid-dynamic damping.

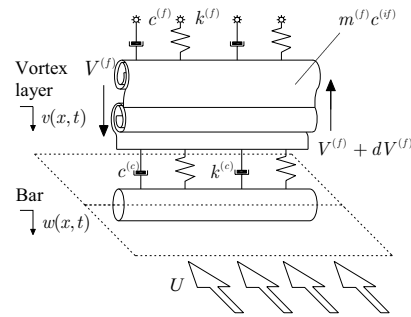


Fig. 2. Distributed Vortex Layer (DVL) model

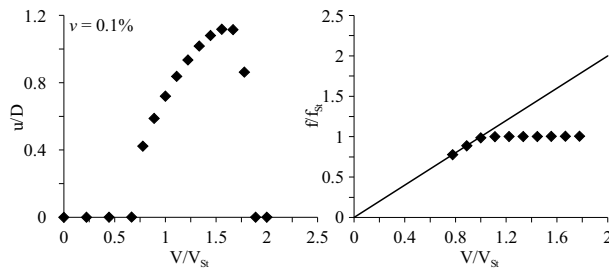


Fig. 3. Normalized amplitude and frequency at the steady state response of a cylinder at the 1st mode resonant condition

It can be noted, finally, that equivalent mechanical models like the one here adopted are usually set and calibrated with reference to fluid velocities in the subcritical range; the problem of vortex shedding at higher Reynolds number, as the ones occurring in Archimedes Bridges still needs experimental and numerical research activity.

3.6. Secondary (internal) waves

The term “internal” refer to waves oscillating within a fluid medium rather than at its surface. They can occur due to mixing of fluids characterized by different density values; in seas this can be caused by temperature or salinity effects. Internal waves have been observed in a number of cases, including Gibraltar and Messina Straits.

The effect of the phenomenon on a submerged structure like an AB still deserves attention by the scientific community of structural engineers.

3.7. Traffic (vehicle-structure interaction)

Oscillations due to dynamic interaction with moving vehicles is an aspect which deserves investigation in relation to fatigue considerations and comfort requirements for people travelling through the tunnel. The latter aspect seems to be of utmost importance for an innovative infrastructure whose psychological acceptance from the community must be ensured by all technical means.

The problem can be faced by means of numerical simulation; within this field, a targeted numerical procedure is under development [17] within this research group as well; the procedure can account for all relevant effects, including road roughness. Up to now it has been applied to linearized systems; extension to non-linear vehicle or structural behavior can be performed without excessive modification.

4. Conclusions

Some aspects related to the dynamic behavior of Archimedes Bridges under environmental actions have been reviewed in the paper, along with the research activity which has been performed, in the last decade, at this Department. In some cases the need for further research activity has been highlighted; for other aspects the results obtained allow for some consideration regarding important design choices. This seems to be the case, for example, when the typology of the anchoring elements is to be selected. For deep water crossings the adoption of bars having hollow sections seems to be particularly attractive; in fact, avoiding catenary effects due to dead weight, this solution leads to higher initial stiffness with respect to vertical and transverse dynamic loads, thus resulting in a better performance in serviceability conditions.

It can be also observed, in this respect, that the adoption of anchor bars having some compressive resistance (especially close to the tunnel ends where water depth is usually reduced) could be beneficial if loading conditions encompassing partial flooding of the tunnel were to be considered.

Less definitive considerations can be made for the choice of the tunnel end restraint in longitudinal direction, especially when very long tunnels are considered. In such case the design and operation of a single dissipative device is likely to be problematic given the involved amount of force and energy.

Fluid-dynamic interaction aspects seem to be the ones in which additional research efforts are still needed, both in the field of vortex induced vibration related to current and in the area of earthquake-related phenomena such as seaquake and tsunamis. Structure-vehicle interaction deserves close attention, especially in relation to comfort.

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