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Earthquake design of a viaduct with full seismic isolation of bridge deck

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A B S T R A C T

The Arachthos Bridge in Greece is about 1 km long and crosses the future Arachthos reservoir. This paper presents the results of the earthquake analysis of the bridge design that won an international design competition. The spans vary from 83 m to 107 m. The Y-shaped piers with heights of up to 80 m are founded on piles. Because of the high seismic stresses in the bridge piers, hydraulic dampers are needed in both the longitudinal and transverse directions. The dampers reduce the seismic stresses in the piers by about 50%. The optimisation of the seismic dampers is discussed in this paper. Two transverse seismic dampers are provided on each pier and one at each abutment. The seismic dampers allow relative movements between the bridge deck and the top of the bridge piers of up to ∓500 mm in the transverse direction. The longitudinal stability of the bridge girder under the static and dynamic loads is achieved by the piers, which are connected with the girder in the longitudinal direction, and the seismic dampers at the abutments. In the longitudinal direction, seismic movements of up to ∓250 mm are allowed. The longitudinal dampers at the ends of the bridge girder must allow both longitudinal and transverse movements. The dynamic analysis shows that maximum residual transverse movements of up to 200 mm are possible. Therefore, provision for the placement of hydraulic jacks is foreseen on the pier tops for re-centering the bridge deck after a strong earthquake. The stability of the bridge girder under the service loads is provided by shear keys, which are integrated in the pot bearings. Under the design earthquake or an earthquake exceeding the design earthquake, the bridge girder is prevented from falling down from the bearings.

A R T I C L E I N F O

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1. Introduction

The Arachthos Bridge, which is a part of the Egnatia Motorway in Greece, is about 1 km long, straight in plan and slightly sloping in the longitudinal direction. The bridge crosses the future Arachthos reservoir. This paper presents the results of the earthquake analysis of the bridge design that won an international design competition, in which aesthetics played an important role. The length of the bridge and the small height of the visible part of the piers above the water level, after the filling of the reservoir, led the designers to select a very slender prismatic structure supported on three-dimensional "sculptural" piers.

The bridge is up to 80 m above the ground level and the distance between the piers varies from 83 to 107 m. This distance complies with the most economic span lengths, which amounts to approximately 70 meters for free cantilever construction. The Y-shaped piers are founded on piles. The superstructure is composed of a post-tensioned single-cell concrete hollow box with cantilevering deck slabs. The total width of the bridge deck is 28 m.

The cross-section of the deck was designed to look slender from far away, as well as to be constructed and maintained easily. Special emphasis was paid on shaping the elements of the bridge and their details. The criteria for the design of these elements were, in order of importance: (i) aesthetics and pleasing overall design as

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well as attention to detailing, (ii) the structural behaviour of the bridge, under static and dynamic loads, and (iii) a simple construction process and cost considerations. The bridge has a unique and efficient design, which also creates a landmark in the area.

2. Seismic Isolation System

Because of the relatively low stiffness of the bridge system in the longitudinal and transverse directions and the resulting high flexural and axial stresses in the bridge piers, seismic dampers are needed in both the longitudinal and transverse directions. By means of hydraulic dampers with a friction-type hysteresis loop, the seismic stresses in the piers can be reduced by approximately 50%.

The hydraulic dampers have the advantage that no damping force is produced by slow movements, i.e. changes in the bridge deck caused by shrinkage, creep and temperature effects do not cause any loads on the abutments. The technical and economical feasibility of the dampers has been discussed with specialized manufacturers of seismic dampers.

Seismic dampers with a total damping force of 21 MN shall be provided at each abutment in the longitudinal direction. Six dampers with a damping force of at least 3.5 MN shall be provided. In general, the dampers shall only transfer compressive loads towards the abutments and exert only a small tensile force (maximum 5% to 10% of the compressive forces). However, during the bridge construction, at least two dampers at the fixed support is need to be designed to transmit both tensile and compressive forces.

In the longitudinal direction, the maximum static movements are +200 mm/-300 mm and the maximum allowable seismic movements are ∓250 mm. The expansion joints at the ends of the bridge girder shall be able to cope with the static movements. As damage of the expansion joints may be accepted under the design earthquake, the seismic design criteria of the expansion joint, which is not a vital element of the bridge, may be relaxed in order to achieve an economical solution.

Two seismic dampers of the same type as for the longitudinal direction, with a damping force of 1 MN each, shall be provided in the transverse direction on each pier. In addition, one transverse damper of 1 MN is provided at each of the two abutments. The seismic dampers shall allow relative transverse sliding movements of the bridge deck with respect to the top of the bridge piers of up to ∓500 mm. This situation requires an increased sliding plate at the pot bearings. At the abutments, the maximum allowable transverse movement was taken as ∓300 mm.

In the design of the dampers, it shall be considered that the maximum static and dynamic movements do not occur at the same time. The dampers at the abutments must allow longitudinal and transverse movements. Hence, the seismic dampers in the longitudinal direction must be provided with spherical hinges in order to allow combined longitudinal and transverse movements at the ends of the bridge girder.

For the seismic monitoring, strong motion instruments (accelerometers) with event recording will be provided at the abutments and on selected piers.

The static and dynamic stability of the girder in the longitudinal direction is assured by means of the piers, which are connected with the bridge girder (piers P1 to P8) and the seismic dampers at the abutments. In order to stabilize the bridge deck in the transverse direction under transverse loads caused by wind, traffic, and small to moderate earthquakes, shear keys are provided with a predefined breaking force, which is almost equal to the damper force. The shear keys are integrated in the pot bearings. Under the design earthquake or an earthquake exceeding the design earthquake, the bridge girder is prevented from falling down from the bearings by the seismic dampers, i.e. the piston of the cylindrical damper touches the damper head.

3. Design Earthquakes

The peak ground accelerations of the design earthquake (embedment of pier foundations in rock) in horizontal and vertical directions are 0.16 g and 0.11 g respectively. In addition, an importance factor of 1.3 has to be taken into account for the seismic design of the bridge. The design earthquake motion is given in the form of an acceleration response spectrum for a damping ratio of 5%. The bridge has to be designed in such a way that no inelastic deformations occur in the structural elements of the bridge piers and the bridge girder under the design earthquake.

The peak ground acceleration of the earthquake action to be considered for the different construction stages of the bridge is 50% of that of the design earthquake, i.e. 0.08 g in horizontal direction and 0.056 g in vertical direction. This corresponds to an earthquake with an average return period of less than 100 years. In addition, the importance factor for the construction phase is taken as 1.0.

4. Specific Verifications

Specific verifications are required for the safety of the equipment on the bridge girder during construction under the wind and earthquake actions. For the seismic safety checks, the peak acceleration on the bridge deck, calculated for a structural model where the girder is fixed to the pier head, shall be used. As the eigenfrequencies of the equipment are much higher than those of the free-standing pier, it is sufficient to perform a pseudo-static analysis of the equipment.

To carry the horizontal wind and earthquake loads during the free cantilever construction of the bridge girder, the need for stabilizing of the piers by means of cables, which are connected to the corners of the pier head, has to be checked. If needed, the optimum layout of the stay cables has to be determined, and the corresponding anchor points must be provided on the ground. In view of the high mass of the bridge piers and the bridge girder, relatively high cable forces will result. The effect of the cable sag has to be taken into account in the analysis of the free-standing piers.

5. Analysis for Seismic Loads – Basic Assumptions

The basic assumptions of the structural modelling and dynamic analysis are as follows:

- The bridge deck and the piers are modelled using standard three-dimensional linear-elastic beam elements formulated on the basis of the Bernoulli-Euler beam theory, corrected for shear deformation effects. Each beam element has two nodes at the ends, and there are six degrees of freedom (i.e. three translations and three rotations) per node. (Fig. 1).

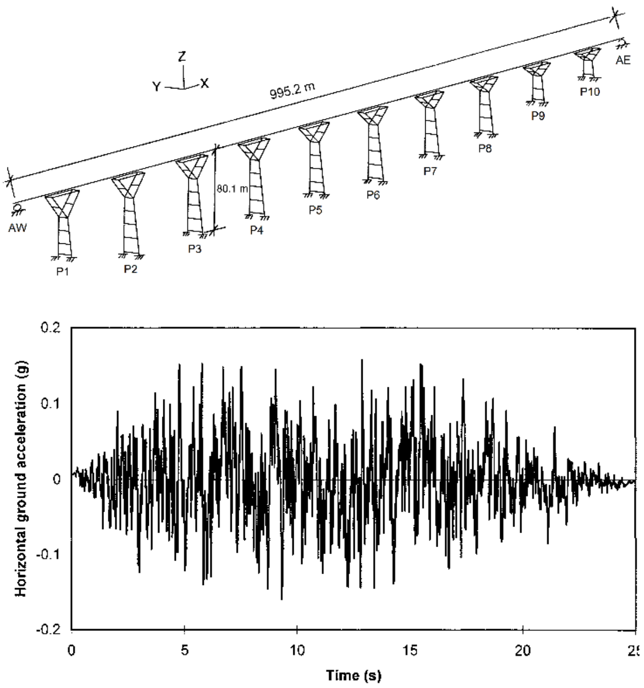

Fig. 1. Finite element model of Arachthos bridge and artificial accelerogram used for inelastic dynamic analysis.

- Strains, displacements and rotations are assumed to remain small.
- The dynamic modulus of elasticity of concrete is taken as 37 GPa.
- The effect of the water in the submerged portions of the piers is modelled by added masses.
- The mass of the 20% of the live (traffic) load has been considered in the dynamic model.
- All members, except the cross-beams in the piers, are assumed to be uncracked.
- The cracked flexural stiffness of the cross-beam section is assumed to be equal to 25% of the uncracked stiffness of the concrete section.
- The end zones of the main cross-beams of the piers are assumed to be rigid.
- All pier legs are assumed to be fixed at the base.
- At the abutments, the vertical displacement and the torsional rotation of the bridge are blocked.
- The longitudinal and transverse dampers are modelled as elasto-plastic elements. The damper forces of 2 MN in the transverse direction and 21 MN in the longitudinal direction include the effect of friction in the sliding bearings, which has the same hysteretic characteristics as the dampers.
- The bridge deck is supported vertically at four corners on the top of each pier. The deck can slide freely in the transverse direction at these bearings. Dampers control the transverse displacements of the bridge deck relative to the pier tops.
- The three components of the earthquake ground motion are represented by spectrum-compatible artificial accelerograms (Fig. 1).
- The ground motion is assumed to be uniform at all supports of the bridge.
- The Rayleigh damping model is used for the structural damping with 5% damping of the predominant structural modes.

The three-dimensional structural model used for the earthquake analysis comprises 991 nodes and 1172 elements. There are 5696 dynamic degrees of freedom in the structural model (Fig. 1). The earthquake response was computed by means of the computer program ADINA by direct integration with time steps of 0.01 s using the Newmark method.

6. Inelastic Seismic Analysis

An eigenfrequency analysis was carried out first to determine the eigenfrequencies and the modes of vibration of the bridge under small amplitude vibrations, i.e. when the shear keys in the pot bearings are still intact. This analysis allows the engineer to better understand the dynamic behaviour of the bridge and to determine the modes that mainly contribute to the dynamic response of the bridge under earthquake loads. Eigenfrequency analyses were also carried out for construction stages (Fig. 2).

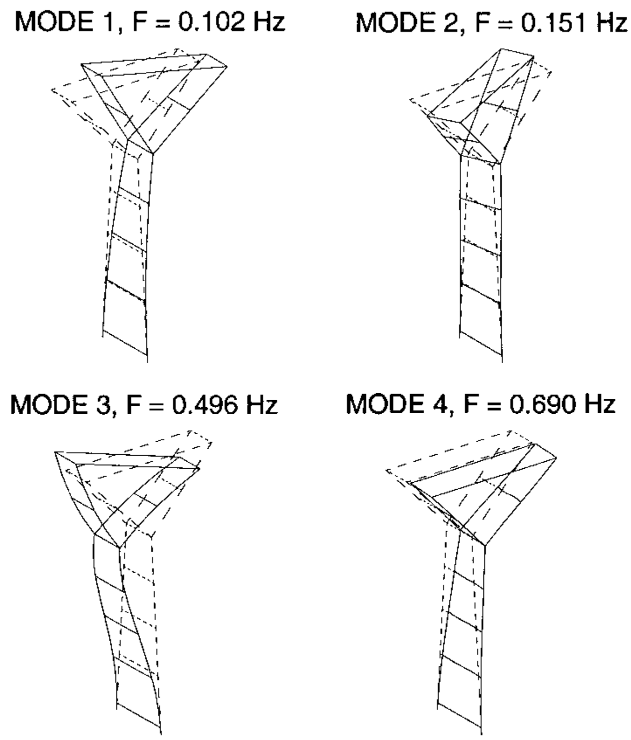

Fig. 2. Mode shapes and eigenfrequencies of highest free-standing pier during construction.

The seismic design was based on the results of inelastic earthquake analyses using eleven statistically independent sets of artificially-generated, spectrum-compatible earthquakes. Due to the non-linear behaviour of the seismic dampers, all seismic analyses have to be carried out in the time domain using a direct integration method (Figs. 3 to 5).

Non-linear analyses can be numerically quite sensitive; therefore, a number of numerical checks were necessary to confirm the reliability of the results. For the Arachthos Bridge, the following numerical checks were carried out:

- Reduction of time step from 0.02 s to 0.004 s
- Change of numerical integration method (Newmark method and Wilson-theta-method)
- Effect of error criterion (energy, displacement tolerance, etc.)
- Equilibrium iteration with Newton-Raphson method, etc.

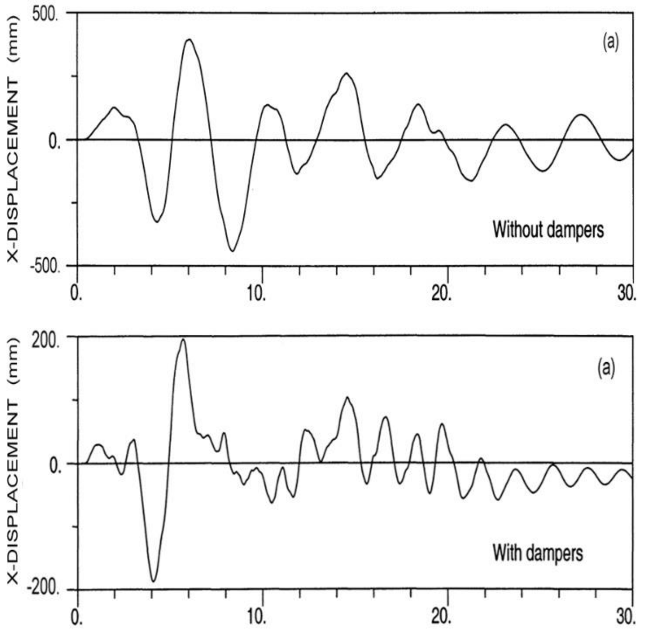

Fig. 3. Comparison of time histories of longitudinal displacement of bridge girder at abutment without (top) and with damper (bottom) (displacements in mm).

7. Design Considerations

In accordance with Eurocode 8 (2005), the results (bending and torsional moments, axial forces, shear forces, displacements, accelerations, relative movements of bearings and expansion joints, forces in dampers, etc.) of the eleven nonlinear earthquake analyses were averaged for the purpose of the seismic design of the bridge.

The bridge girder and the piers are designed to behave fully elastically under the design earthquake. Any damage will be confined to the pot bearings, where the shear keys will have to be replaced and the displaced bridge girder has to be moved to its original position by means of hydraulic jacks. In addition, local damage can be expected at the expansion joints. This seismic design concept will ensure that the bridge can be used safely during and after the design earthquake. The bridge is also expected to behave satisfactorily during an earthquake exceeding the design earthquake, as the design earthquake and the dynamic modelling of the bridge include a number of rather conservative assumptions, e.g. the uniform ground motion, which leads to an overestimate of the longitudinal and transverse movements of the bridge girder on the bearings.

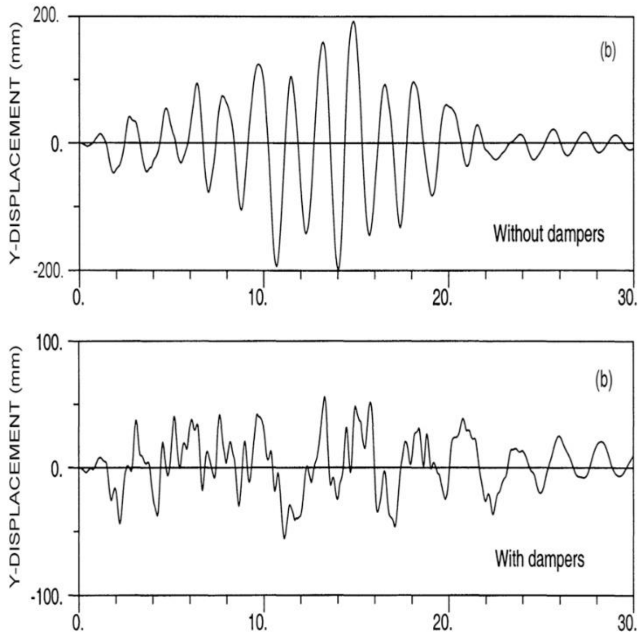

Fig. 4. Comparison of time histories of transverse displacement of top of highest pier without (top) and with damper (bottom) (displacements in mm).

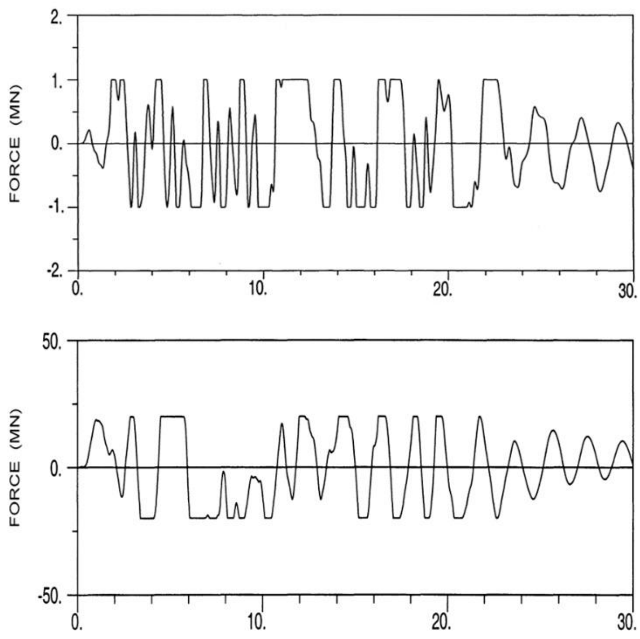

Fig. 5. Comparison of time histories of force in single transverse damper on highest pier (top) and total force in the longitudinal dampers at the abutment (bottom) (damper forces in MN).

8. Conclusions

By means of isolation of the bridge girder from the supports, the seismic forces can be greatly reduced in large continuous girder bridges susceptible to dynamic actions. The isolation is achieved by hydraulic dampers (other types of dampers may also be suitable), which are located at the bridge bearings.

In the case of the proposed Arachthos Bridge project, the seismic forces in the Y-shaped high piers with heights of up to 80 m could be reduced by about 50% as compared to the bridge without dampers. The maximum dynamic deflection of the pier heads transverse to the bridge axis could even be reduced by 75%. The maximum transverse and longitudinal sliding movements on the bearings due to the earthquake shaking were calculated as ∓40 cm and ∓24 cm, respectively, which are within the allowable limits.

Because of the nonlinear characteristics of the dampers with an almost rectangular hysteretic loop under the seismic action, extensive nonlinear dynamic analyses were carried out for the optimization of the dampers and for the calculation of the seismic design forces and deformations. It is obvious that seismic dampers do not only protect a bridge from large seismic forces but also result in a very economical solution, as modifications in the structural system of a bridge might be much more expensive than the installation of dampers. In the case of Arachthos, it was required that the bridge behaves elastically under the design earthquake, a requirement which is hard to fulfil with conventional design options. It must be added that the design response spectrum had very high spectral accelerations at low frequencies, which made the installation of dampers even more advantageous.

Instead of the winning bridge design, whose earthquake design is described in this paper, the owner decided to go for a more conventional bridge with a less challenging and aesthetic design.

References

Eurocode 8 (2005). Design of Structures for Earthquake Resistance. Part 2: Bridges, prEN 1998-2, European Committee for Standardization (CEN), Brussels.

Malla S, Wieland M (2003). Study on the dynamic behaviour of a base-isolated viaduct (in German), Current Status of Bridge Dynamics, SIA-Dokumentation D 0198, Zurich, Switzerland.