Engineering Structures 32 (2010) 1100–1112

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

An unconventional restraining system for limiting the seismic movements of isolated bridges

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ARTICLE INFO

Article history:
Received 22 January 2009
Received in revised form
24 November 2009
Accepted 22 December 2009
Available online 22 January 2010

Keywords:
Bridge
Serviceability
Continuity
Slab
Piles
Restrain
Movement
Backfill
Participation
Cost

ABSTRACT

An external restraining system with steel piles is introduced under the main objective of the study, which is the enhancement of the earthquake resistance of seismically isolated bridges. This objective is examined through the possibility of the improved seismic participation of the approach embankments, which are able to dissipate part of the induced seismic energy. The seismic participation of the embankments, which are seismically inactive, according to current conceptual design of bridges, is achieved through the extension of the continuous deck slab of the bridge onto the embankments and its restraint by the backfill through steel piles. The serviceability needs of the deck are accommodated by: (a) the flexibility of the steel piles, (b) the looseness of the backfill soil, (c) the partial replacement of the embankment's surface layers by expanded polystyrene (EPS) and (d) the in-service allowable cracking of the continuity slab. A parametric study was conducted and showed that the restraining system can effectively reduce the seismic displacements of the bridge. The proposed technique can be utilized in all bridge structures, and is more efficient in those exhibiting large displacements during an earthquake.

1. Introduction

The design of bridges has to accommodate both serviceability and earthquake resistance, which are conflicting components of the same problem and they impose opposite design requirements. Serviceability, which is mainly critical in the longitudinal direction of the bridge, requires the free contraction and expansion of the deck, due to the annual thermal cycle [1], shrinkage and creep [2] and prestressing. Serviceability is usually satisfied by the provision of flexible, as possible, bridge resisting systems, which usually lead to the use of bearings, expansion joints and piers which are oriented with their weak axis bending in the longitudinal direction of the bridge.

The role of the bearings is not only to accommodate serviceability movements. They mainly reduce the seismic actions transmitted to the piers and to the abutments by the seismically moving deck. This ability is either achieved by developing their shear flexibility, or indirectly, by shifting the fundamental period of the bridge away from the dominant periods of the response spectrum. Furthermore, bearings respond in an inelastic manner and dissipate part of the induced seismic energy of the bridge through their hysteretic behaviour. However, the use of a seismic isolation system in bridge structures leads to the inevitable use of a q-factor equal to 1 [3]. It follows that seismically isolated bridges are expected to respond in an elastic manner. The consequent elongation of the longitudinal period in bridges with seismic isolation, an effect which is known as "period shift effect" [4–6] induces another problem, which is related to the control of the, usually, excessive seismic displacements of the isolated deck. The "key point" for the control of these displacements is usually the increase in the damping of the structure [7]. Damping can be increased by specific types of bearings. Buckle and Mayes [8,9] suggested the use of lead rubber bearings in order to control displacements and distribute the lateral loads of bridges by controlling the stiffness of the bearing and the size of their lead core. Codes [3] usually handle the problem of excessive displacements by the use of expendable and relatively expensive seismic devices such as high damping bearings and viscous dampers.

The earthquake resistance of bridges can also be enhanced by monolithical, deck-pier connections. These rigid connections allow the use of piers' hysteretic behaviour. Therefore, the design spectra, which illustrate the design seismic actions, can be divided by a factor, known as the q [3] or R-factor [10]. However, monolithic

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doi:10.1016/j.engstruct.2009.12.036

deck-pier connections are restrained by structural methods, such as incremental launching or precast. It follows that, in many bridges the use of high damping bearings, dampers and seismic links is inevitable, since no other structural measure can be introduced in order to limit displacements.

In current Bridge Engineering, the expansion joints are supposed to uncouple the response of the deck from the abutment and the approach embankment. Specifically, the conventional design of bridges requires the use of expansion joints, which separate the deck from the abutment's backwall. The clearances at the expansion joints are determined by taking into account the in-service [11,12] and part of the seismic displacements of the deck [3]. The selection of smaller clearances is related to technical and economical criteria, as the cost of providing a road joint to accommodate large seismic deflections may be prohibitive and usually a compromise is adopted [12]. The aforementioned criterion can lead to the seismic interaction of the deck with the abutment's backwall and with the embankment "behind" it. Furthermore, the backwall is usually connected to the stiff wing-walls, whose interaction with the deck can lead, in some cases, in stability problems of the abutment, namely in slumping and rotations [13,14]. Despite the fact that this possibility exists, no measures against this event are taken.

The design remarks commented above can be characterized as conventional Bridge Engineering design, in the sense that the current codes for the design of bridge structures [3,15] suggest the use of seismic isolation devices, expansion joints and, when the structural system includes rigid deck-pier connections, the development of the hysteretic behaviour of the piers. However, new initiatives have been taken by some bridge designers to improve the bridge's seismic response by changing the overall bridge system [16], aiming to control its seismic response. It is noted that only a few bridge design concepts combine unconventional earthquake resistant structures with the current code provisions. For instance, the development of the backfill's dynamic resistance, namely its stiffness and damping properties, can be useful, especially in case of seismically isolated bridges, in which the control of the displacements is important. This possibility seems to be an interesting design improvement as, on the one hand, viscous dampers are usually expensive and their replacement during the life of the bridge is inevitable. On the other hand, recent studies showed that the embankment can lead to significant reductions in the seismic displacements of bridges, mainly in the longitudinal direction of the bridge [17–20]. The development of the resistance of the backfill and the abutment's backwall, in a controllable way, namely by introducing a capacity design philosophy, in order to avoid undesirable slumping and rotations of the abutment, can lead to an efficient control of the movements of the bridge deck, and, in turn, to cost-effective bridges design alternatives [21]. It is noted that the capacity, namely the stiffness and the deformability of the system abutment-backfill can be estimated either by international codes [22,23] or literature [24].

The present study proposes a new external restraining system, which aims at reducing the seismic actions of seismically isolated bridge systems with the assistance of the backfills. The proposed external system consists of the extension of the deck slab of the bridge onto the backfills and its restrain by IPE-steel piles, which are driven in the backfill. The extension of the slab is the so-called "continuity slab" because it eliminates the expansion joint between the abutment's backwall and the deck. This external system is expected to reduce the seismic displacements of the deck by utilizing the restrain of the piles by the backfill soil. The system can be implemented in all bridge structures whose deck slab is continuous, namely in bridges whose deck is either supported on the piers and on the abutments through bearings or is monolithically connected to them.

The objective of the paper is: (a) to bring to light unconventional bridge seismic design concepts, which can be useful for the future design of bridge systems, (b) to assess the seismic response of the unconventional bridge system, in which the restraining system is participating strongly during earthquake. The assessment is mainly carried out by comparing the response, the constructability and the cost-effectiveness of the unconventional bridge with the conventional one; (c) to identify the earthquake resistance efficiency of the restraining system; (d) to determine which configuration of the piles, namely material and geometry, length and location, is the most efficient in terms of serviceability and earthquake resistance; (e) to optimize the stiffness of the backfill, in terms of soil properties or by using flexible materials, which are popular in Geotechnical Engineering such as expanded polystyrene-EPS; (f) to estimate the cost of the proposed system in comparison to conventional seismic isolation, which requires the use of bearings.

2. Description of the "reference" bridge

The present study used an isolated bridge of the P.A.TH.E Motorway, which is located in the Skarfeia-Raches territory in Greece, Fig. 1(a). The bridge was considered to be the "reference" case of the study. It is straight, has five spans and a total length equal to 177.5 m. The two end spans have a length equal to 34.75 m, while the three central spans are 36.0 m long. The deck of the bridge, Fig. 1(b), consists of six prestressed and precast I-beams, precast deck slabs and cast in-situ part of the slab. Its width is equal to 14.2 m. The deck is seated on both the abutments and the piers through low damping rubber bearings. The bearings have a circular cross section with a diameter equal to 500 mm and 450 mm, while the total thickness of their elastomeric rubber is 110 mm and 99 mm at the abutments and at the piers correspondingly. The piers are hollow circular sections, Fig. 1(c), with an external diameter equal to 3.0 m and a web thickness equal to 0.5 m. The piers are founded on 3 × 3 pile groups, Fig. 1(d), which are connected to 7.5 × 7.5 m pile-caps. The diameter of the piles is 1.0 m and their length is 7.0 m for piers P_1, P_2 and P_3 and 13.0 m for pier P_4. The abutment is a conventional seat-type abutment, which provides the required clearance at the expansion joint, according to Eurocode 8 [3], between the deck slab and its backwall. The abutments restrain the movements of the deck in the transverse direction of the bridge, as capacity design stoppers are installed on them. Stoppers, which restrain the transverse movements of the deck, were also used on the piers. The bridge is founded on Eurocode's 8 [25] ground type B and a design ground acceleration equal to 0.24g was used in the final design. The importance factor adopted was equal to 1.0, while the behaviour factors were equal to 1.0 in the longitudinal, the transverse and the vertical direction of the bridge.

The bridge described above was considered to illustrate the conventional design, while the so-called unconventional bridge is the same bridge with the additional equipment of the external restraining systems at both ends of the bridge, namely the continuity slab and the restraining IPE-steel piles.

3. Description and optimization of the external restraining system

The proposed restraining system given in Fig. 2 consists of three parts: (a) the extension of the deck slab onto the backfill soil, which is the so-called "continuity slab", (b) the restraining IPE-steel piles, which are driven in the appropriately selected backfill material and (c) the abutment, which is a conventional stub abutment with the seating beam and the backwall. The abutment with the reinforced backfill "behind" it also participate