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Design of bridges utilizing a novel earthquake resistant abutment with high capacity wing walls

S.A. Mitoulis [a,*], M.D. Titirla [b], I.A. Tegos [b]

[a] Department of Civil and Environmental Engineering, University of Surrey, UK
[b] Laboratory of Reinforced Concrete and Masonry Structures, Department of Civil Engineering, School of Engineering, Aristotle University of Thessaloniki, Greece

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ABSTRACT

Abutments are not considered to participate strongly in the earthquake resisting system (ERS) of Eurocode-based designed bridges. However, previous studies showed that seat-type abutments can reduce effectively the seismic actions of bridges, especially when the openings at the expansion joints accommodate only the serviceability movements of the deck. Alongside, a wide field of study is open to new abutment configurations and innovation, as no unified procedure is available for their design and construction. In this framework, a new earthquake resistant abutment with high capacity wing walls is proposed and analytically investigated. The proposed abutment decouples the in-service response of the bridge from the backfill soil by small clearances at the expansion joints, which separate the deck from the abutment. During an earthquake the bridge movements are restrained by the high capacity wing walls and the backfill soil. The seismic performance of the new earthquake resistant abutment is evaluated by utilizing a benchmark bridge, whose design was based on Eurocodes, which has a relatively expensive isolation system with lead rubber bearings and dampers. Two alternative design schemes that utilized the seismic restraining effect of the proposed earthquake resistant abutment were re-designed and compared to the benchmark on the basis of seismic resistance and cost-effectiveness. The comparative results showed that the seismic participation of the proposed abutment with the backfill soil reduces effectively the seismic demand of the re-designed bridge schemes. Accordingly, the initial and the final bridge costs are effectively decreased, showing that the proposed unconventional design is a reliable scheme for future designs of bridges in earthquake-prone areas.

1. Introduction

The design of bridge abutments, either the seat-type or the integral ones, is traditionally based on the earth-retaining substructures design concepts and checks. Integral abutments' configuration, serviceability and seismic response have been extensively evaluated during the last years, either analytically [4] or experimentally [5,33]. On the other hand, only a few studies dealt with the conceptual design of seat-type abutments, on which the deck is typically resting on through bearings, while expansion joints separate the abutment from the superstructure. Hence, seat-type abutments are not considered to participate in the earthquake resisting system of the bridge, especially when the expansion joints account for the seismic movements of the deck. However, lateral earth pressures are expected to be developed behind seat-type abutments [30], which are depended upon the wall's height and movement towards the backfill soil [21]. Eurocode 8-Part 2 [18] discourages the seismic participation of the abutments, as it requires that the clearances, i.e. openings, at the expansion joints should take into account a fraction (40%) of the seismic movements of the deck. An additional penalty for bridges that are "locked in" by earthquake resistant abutments is that the bridge should remain essentially elastic during the design earthquake (Table 4.1 in Eurocode 8-Part 2 [18]). On the other hand, the codes in the USA [8,9,27,6] typically adjust in size the joint between the bridge superstructure and the abutment backwall from a few inches, in case only serviceability movements are taken into account, to a few feet for seismic effects. Usually, a compromise is adopted. The last design selection is considered to be rational, as the repair of the damaged backwall after a severe earthquake is considered to be relatively easy and inexpensive. AASHTO [1] also provides knock off detailing of the backwall, i.e. the backwall is designed to break free of its base support when struck by the deck during an earthquake. After the failure of the backwall, the wingwalls confine the backfill soil and, as such, the load transfer from the deck to

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* Corresponding author. Tel.: +44 7446887971.
E-mail address: s.mitoulis@surrey.ac.uk (S.A. Mitoulis).

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the wingwall in Caltrans abutments [30] is only through the compacted backfill.

As for the dynamic resistance of the backfill soil that is mobilized when the gaps at the expansion joints are closed during an earthquake, it seems that bridge engineers consider this resistance more of a second line of defense, rather than an earthquake resisting parameter. This is considered to be a rational design selection, as the reaction of the soil behind the abutments is inherently nonlinear and a function of the magnitude and nature of the wall displacement [7]. Hence, it is considered to be the biggest uncertainty in the design of bridges. Caltrans [10] and AASHTO [2], on the other hand, provide an analytical model for the estimation of the resistance of the abutment. The model results in force–deflection curves representing the resistance of the system that accounts for the projected width of the backwall and the abutment's height, while it seems to be independent from the dimensions and the cross sections of the abutment's web and the geometry of the wing walls. Hence, the Caltrans's effective abutment stiffness relies mostly on the resistance of the backwall, the piles and the backfill soil, which requires quite large deflections to be mobilized, rather than to the stiffness and damping of the wing walls.

Hence, current code-design and state-of-practice have minimized the role of the seat-type abutment to a, say, earth retaining structure, rather than to an element that can participate strongly to the earthquake resisting system (ERS) of the bridge. However, recent research outcomes showed that the seismic demand and the structural cost of bridges can be reduced, when considering the seismic participation of the abutment and the backfill soil [20,23,12,26,28]. Hence, the design of a new seat-abutment that on the one hand accommodates the in-service movements of the deck, while providing an additional high capacity lateral support to the bridge, seems to be suggestive for future design of earthquake resistant bridges. In this framework, a new seat-type abutment having high capacity wing walls is studied. The abutment accommodates the serviceability movements of the deck, by limited openings at the expansion joints, while enhancing earthquake resistance, by participating strongly to the ERS of the bridge during an earthquake. This is achieved by a slight reformation of the abutment's wing walls, which are designed to respond as high capacity external stoppers. The reformed abutment restrains the longitudinal movements of the deck mostly by relying mostly on the capacity of the reinforced concrete members of the abutment, rather than on the resistance of the backfill soil, that is the typical case for seat-type abutments. The design concept is validated through a benchmark, heavy substructured bridge. Different design schemes were analyzed and assessed by rigorous non-linear dynamic history analyses, incorporating both geometrical and structural non-linearities. Comparisons were performed on the basis of the seismic performance of the bridge, while estimations of the structural and the final costs including maintenance were conducted. The study showed that the high capacity wing walls can be a feasible and cost effective scheme to enhance future designs of bridges in earthquake-prone areas.

2. Benchmark and re-designed bridge schemes

2.1. Description of the benchmark bridge BM_0

The seismically isolated bridge, given in Fig. 1, was used as benchmark (BM_0). The bridge is straight, has four spans and a total length 168 m. A movable scaffolding system was used for the construction of the bridge. The two end spans are 39 m long, while the two intermediate spans have span lengths 45 m. The deck is a box girder with a constant cross section along the bridge, as shown in detail 3 of Fig. 1, has a total width equal to 13.4 m and a depth 3.6 m. The piers, shown in detail 4 of Fig. 1, are hollow rectangular cross sections with dimensions 3.0 m by 5.5 m in the longitudinal and transverse direction of the bride respectively, while the thickness of the box is 0.45 m. The piers are founded on 4 by 4 pile groups. The pile-cap of the foundation has in-plan dimensions 11.0 by 11.0 m and a depth equal to 1.50 m. The piles are 15 m long and their diameter is 0.8 m. The deck is seated on both the abutments and piers through two lead rubber bearings. The bearings dimensions in plan 900×900 mm and 1200×1200 mm on the piers and on the abutments respectively, the total thickness of the elastomeric rubber is 231 mm and 286 mm, while the diameter of their lead is 200 mm and 250 mm correspondingly.

Two viscous dampers were installed at each seat-type abutment to restrain excessive deck displacements in the longitudinal direction of the bridge, as shown in Fig. 1. The figure also shows the damper's hysteresis loops and the corresponding response of the bearing. The damping coefficient of the dampers is $c = 2350$ kN s/m and their exponent of velocity $\alpha = 0.15$. The abutment, which is illustrated in detail 1 of Fig. 1, is a typical seat-type abutment and provides an expansion joint between the deck slab and its backwall. The movement capacity of this joint is ±250 mm. The design of the expansion joints took into account 40% of the seismic movement of the deck as prescribed by Eurocode 8 Part 2 [18] as well as the serviceability induced constraint movements [13] of creep, shrinkage, prestressing and 50% of the thermal movements of the deck. Seismic links according to Eurocode 8 Part 2 [18] also known as shear keys in AASHTO [2] and Caltrans [10], restrain the transverse seismic movements of the deck over its sequential supports, i.e. the piers and the abutments. The bridge is founded on ground type B [17], according to the geotechnical in situ tests. Soil type B corresponds to an average shear wave velocity between 360 m/s and 800 m/s, $N_{SPT} > 50$ blows/300 mm and to an undrained shear strength $c_u > 250$ kPa. The design ground acceleration adopted equal to 0.24 g, the importance factor $\gamma_I = 1.3$, while the behavior factors were equal to 1.0 for all directions of the bridge seismic loading (longitudinal, transverse and vertical) as Eurocode 8 Part 2 [18] requires that isolated bridges should respond essentially elastic. The q-factors are related to the seismic response modification R-factors of AASHTO's Bridge Design Specifications section 3.10.7 [2].

2.2. The proposed earthquake resistant abutment

The seismic efficiency of the earthquake resistant abutment, illustrated in Fig. 2, was examined analytically. The abutment is similar to the seat-type abutments met at bridges in Europe [23] and USA [10,32]. The unconventional abutment decouples the in-service response of the bridge from the backfill soil, by utilizing an expansion joint that accommodates only serviceability movements of the deck, according to Caltrans [10]. The wing walls have a dual role, as on the one hand retain the backfill soil, while on the other hand participate in the ERS of the bridge. The wing walls are oriented with their strong axis bending in the longitudinal direction of the bridge to increase their longitudinal resistance. The thickness of the wing walls was selected 0.50 m, while this can be appropriately adjusted in case of different bridge systems. A high capacity beam-stopper, shown in Fig. 2, was designed to connect the two wing walls, as they should be able to receive not only the impulse of the deck in the longitudinal direction of the bridge, but also large eccentric loads, due to possible eccentric collisions of the deck towards the backwall. A capacity design procedure was adopted for the foundation of the abutment to provide 40% overstrength factor as compared to the total capacity of the two wing walls. A hinged slab is installed behind the pile cap of the abutment's foundation to enhance the foundation's translation resistance, which relies on the increased friction of this slab, which