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THE PROBLEM OF SEISMIC STRENGTHENING OF EXISTING BRIDGES

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ABSTRACT

The uncertainties, which result from earthquake, can be distinguished into two categories depending on the influence of these uncertainties on the actions (S_d) or on the resistance (R_d) of the cross section. In many strengthening and rehabilitation projects of buildings or bridges the crooked line solutions are proved to be more preferable than the straight line solutions, in the sense that the straight solution requires the increase of the seismic resistance of structures. In the present study an indirect rehabilitation technique, which aims at the seismic upgrade of existing bridges, is investigated. The aforementioned method aims at the reduction of the induced inertial loads through the restraining of the free seismic movement of the bridge by a group of micropiles, which develops the resistance of the backfill soil. The present study develops an existing "reference" bridge for which the two aforementioned rehabilitation methods -the conventional and the proposed non conventional- were implemented and checked, according to the current code provisions. The constructability and the low cost are noted as significant advantages of the proposed rehabilitation method, which proved to be adequate, according to the current codes' seismic performance requirements, and significantly efficient, in reducing the seismic displacements and actions.

Keywords: bridge, seismic retrofit, external, restrain, reduction, actions, non-conventional rehabilitation, plate, micropile, backfill

INTRODUCTION

For many years bridges were inadequately designed for earthquake resistance, due to the erroneous perception that their response was explicit and similar to the response of the single degree of freedom systems in each direction and by extension the seismic performance of bridges was expected to be satisfactory. However, the reality disproved the initial expectations since many bridges collapsed.

On the other hand, there are bridges whose deck consists of separate parts, due to the in-service constraints, which impose uncertainties as far as their seismic response concerns. Cast in situ and precast bridges with discontinuous decks are bridges whose superstructure consists of segments in series which are separated by narrow expansion joints of the order of 2-3cm. These joints were determined by the functional requirements of the bridge, in contrast to the modern codes' provisions, which take into account the seismic movements of the deck. The seismic response of those bridges is chaotic, (Pantelides & Ma, 1996; Chau et al., 2003), due to collisions that occur between the separate parts of the deck and, as a result, the modeling of such systems was unreliable.

The European Bridge Construction acquired an excellent code (Eurocode 8 Part 2, 2003), for the design of bridges for earthquake resistance, which, however, requires the free longitudinal movement of the deck during earthquake, even though the seismic combination requires that the width of the end

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expansion joints takes into account only 40% of the seismic movements. The absence of the abutments participation during earthquake puts into danger the backwall of the abutment, the expansion joints and the wing-walls. Structural configurations, like the ones presented in Figure 1, protect the aforementioned elements against the seismic event since the aforementioned damage possibility exists, (NCHRP 12-49, 1999).

Apart from the above mentioned consequences, it is obvious that the free longitudinal movement of the deck, which, as it is known, amplifies by 250% the input motion, is economically burdensome and affects aesthetics.

The existing techniques for bridge retrofitting utilize new materials and turns attention to the strengthening of existing elements aiming at a higher level of seismic performance of bridges, (Pantelides & Gergely, 2002; Sieble, 1994; Laursen et al., 1995). The earthquake retrofitting of seismically vulnerable bridges in many cases combines, (AASHTO LRFD, 2001; CalTrans, 2004), the connection of adjacent decks and the connection of the deck with the piers and/or the abutments by means of cable restrainers, (Saiidi at al., 2001; Des Roches, 2003), that prevent excessive relative displacement and reduce the possibility of unseating.

In conclusion, the present approach to the seismic retrofit of bridges proposes an indirect-external “stopper-restrainer” aiming at the restraint of the development of the free longitudinal deck’s movement and, by extension, to the reduction of the seismic actions. This can be achieved by utilizing the existing abutments, to participate during earthquake, by means of a plate which undertakes the collisions that occur during the seismic movement of the deck.

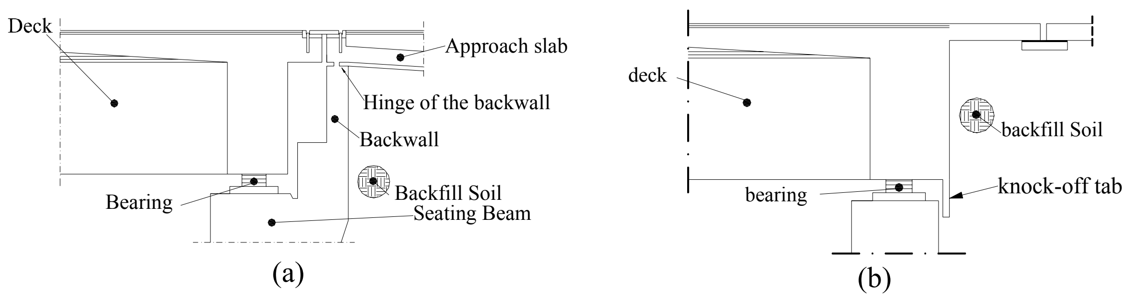

Figure 1. Protection of abutment critical members against excessive seismic displacements (a) Hinged backwall and (b) knock-off tab.

EXAMINATION OF THE STRENGTHENING REQUIREMENTS OF THE EXISTING BRIDGE AND RETROFITTING METHODOLOGIES

In the present study the strengthening requirement of the specific bridge, which is located in North Greece, crosses Aliakmonas River and was constructed in the early 80’ies, was extensively investigated. Non linear dynamic time history analysis was implemented and the bridge was subjected to the corresponding artificial earthquake motion that is compatible with the corresponding soil-dependent Eurocode 8 elastic spectrum, (Eurocode 8 Part 1, 2003). On the basis of the analysis results -distress of the piers and relative displacements of existing bearings- the deficiency of the bridge, according to current codes’ seismic performance requirements (Eurocode 8 Part 2, 2003), was concluded.

Afterwards the nowadays seismic retrofitting alternative methodologies were examined. Initially, the seismic adequacy of the bridge was checked for the case that only the existing bearings were replaced by new type elastomeric or high damping rubber bearings. The aforementioned investigation was attempted considering that the cost and aesthetics burden of the conventional retrofitting of the bridge, meaning the strengthening of existing piers, is high.

The aforementioned bearings replacement by new elastomeric or high damping rubber bearings can follow two different alternatives for the isolation (Kelly 2001; Menshin Design, 1992): (a) a full base isolation, which leads to a significant increase of the period and, as a result, of the displacements of the structure and (b) the use of the isolators damping. The retrofitting of the bridge by the use of viscous dampers was rejected on account of the high finance cost of this methodology. The implementation of the two alternatives, for the seismic isolation of the existing bridge, concluded the deficiency of the piers as their capacity is reduced due to their self vibration induced distress. Also the examination of different types and total heights of the bearings elastomer come up to the same conclusion. It seems that the conventional rehabilitation methodology requires the strengthening of the existing piers and as a result to the strengthening of their foundations, which is economically burdensome or even unachievable.

The indirect retrofitting approach is described and analytically investigated below. The proposed indirect methodology proposes the construction of an external sub assemblage which participates during earthquake and restrains the free longitudinal and transversal movements of the deck.

DESCRIPTION AND OPTIMIZATION OF THE PROPOSED RETROFITTING METHOD OF THE "STOPPER-RESTRAINER"

In the present investigation, the accommodation of the in-service and the earthquake resistant requirements of existing bridges is attempted by a retrofitting sub-structure, Figures 2(a) and 2(b), which responds unilaterally in-service and during earthquake. The proposed intervention, which restrains the free longitudinal movement of the deck, is implemented by the construction of micropiles and their slab-pile cap. This pile cap has the ability to transfer the impulse, of the deck's collisions towards the backwall to the micropiles, which are located behind the abutment's foundation and activate the passive resistance of the backfill soil. These micropiles are arranged in a rhombic scheme, Figure 2(b). The retrofit method defined above also proposes the separation of the wing-walls from the abutment so as undesirable mode of failure of such elements is avoided and considers that the deck's continuity is provided. The last can be implemented by the development of steel blades which are bonded under the existing deck.

The transverse direction of the upgraded bridge, which is usually seismically advantageous in comparison with the longitudinal direction (wall-like or multi-column piers and stoppers-seismic links-), can be retrofitted by easily implemented structural methods: (a) The deck is proposed to be restrained by using the existing stoppers of the bridge. The stoppers were checked and found adequate for the transverse design earthquake. (b) The in-service needs of the bridge systems are arranged while in case of a transversal seismic movement the stoppers are activated and transmit the forces to the abutment, whose safety is also enhanced by implementing restraining piles from both sides of its foundation, Figure 2.

The suggested retrofitted bridge preserves an expansion joint over each abutment, which separates the backwalls from the deck, whose width is determined by the in-service requirements of the deck. In the present study, the determination of the in-service constraints of the superstructure takes into account only the thermal action, as creep and shrinkage were developed in the first 2-3 years of bridge service. The last observation is expected to increase the efficiency of the proposed retrofit technique as investigations, (Mitoulis & Tegos, 2005), concluded that the minimization of the joint leads to high abutments' participation during earthquake, (Unjoh et al., 2004; Tegos et. al, 2005).

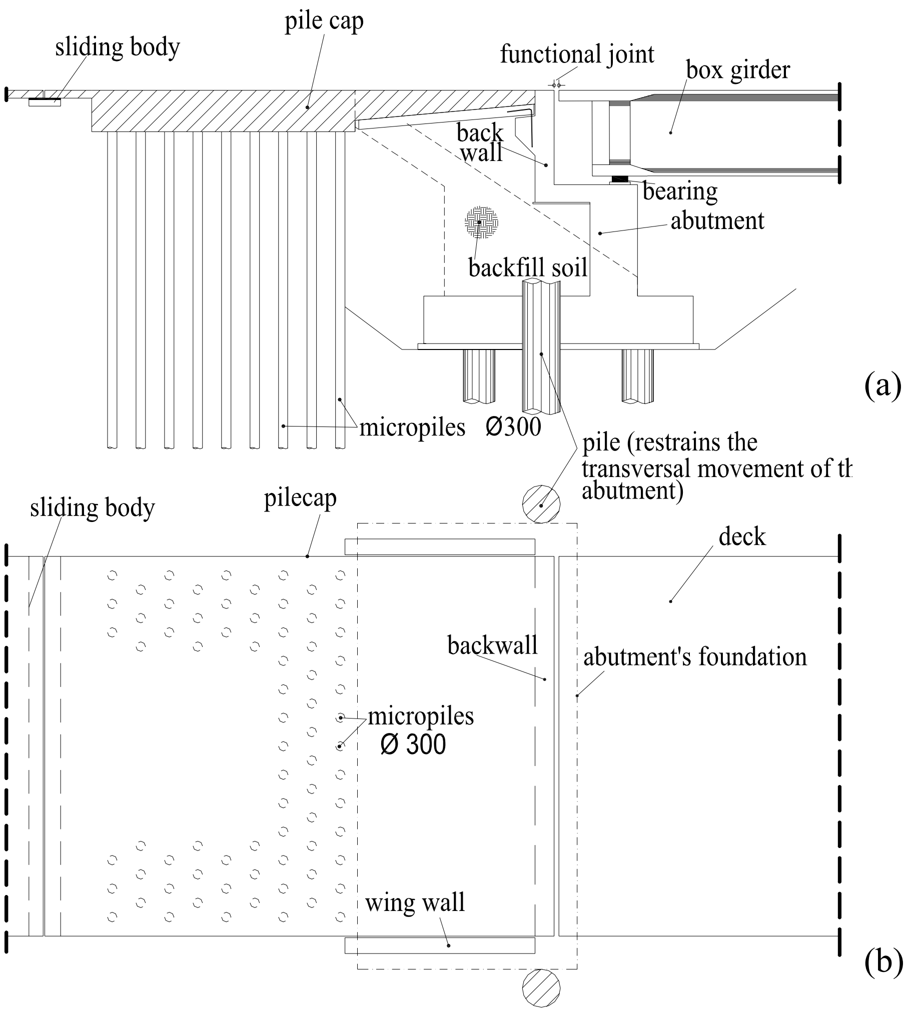

Figure 2. The proposed intervention at the abutment consisting of micropiles and their pile cap: (a) Longitudinal section (b) Plan view.

In the present study the intervention was considered to be implemented while the bridge temperature is equal to the average temperature of construction T_o, (Eurocode 1, 1991), which imposes constraint movements of the micropiles and compression of the deck during its expansion. The partial closure of the expansion joint induces additional criteria for the final choice of the width, due to the Serviceability Limit State's requirements. Apart from (a) the length of the continuous deck and (b) the thermal actions, also (c) the in-service compression of the deck, (d) the design of the "stopper-restrainer" meaning the allocation and the number of the proposed micropiles, (e) the ratcheting effects and (f) the properties of the backfill soil have been the most critical parameters which determined the width of the functional joints. The width of the preserved end joints can vary between zero (Δ=0) when the air shade temperature is $T \geq T_o$ and Δ=20mm when $T=T_{e,min}$.

EVALUATION OF THE PROPOSED BRIDGE INTERVENTION ON THE BASIS OF SERVICEABILITY REQUIREMENTS

The objective of the present research is to accommodate the in-service and the earthquake resistance requirements of existing bridges, in order to achieve the optimum seismic performance by implementing an external "stopper-restrainer". As it is reported, the determination of the expansion joint is a critical design selection which influences the seismic participation of the proposed retrofitting sub-structure. The determination of the joints' width took into account the aforementioned criteria and concluded that for the precast bridge of L=151m of length, which was the "reference" bridge case, for which the intervention system was designed, it is possible to close the joints while the shade air temperature is equal to the average temperature of construction, that is T_o=17°C. The last assumption leads to an upgraded bridge in which the joints are closed for temperatures higher than the average temperature during the intervention whereas are open for lower temperatures. In case the maximum width of the expansion joint is determined according to Eurocode 8 Part 2, (Eurocode 8 Part 2, 2003), which requires a 50% reduction of the thermal actions in the seismic combination, the analytical investigation has to examine both the seismic response of the upgraded system when (a) the joint is closed and (b) the joint has a width which takes the thermal actions into account reduced to 50% namely a joint corresponding to $\psi_{2T}*\Delta T_{N,con}=0,5\cdot25=12,5°C$, (Eurocode 1, 1991).

The aforementioned minimization of the joint requires the arrangement of the in-service problems: (a) The ratcheting effect, (Horvath 2000), (Lock et al., 2002), "behind" the micropiles was considered to be of minor importance as on the one hand, the micropiles allow the granular flow between them and on the other hand, the in-service movement of the micropiles is unilateral and as a result no space for the wedging of the soil is left "behind" them, (b) The serviceability constraint movement of the micropiles, due to the expansion of the deck, does not cause failure of the micropiles as adequate confinement in combination with longitudinal reinforcement of these elements provide that they respond in an elastic manner. Also it can be considered, (API, 1993; Kappos & Sextos, 2001) that the soil remains elastic for the considered constraint movements. (c) The in-service compression of the deck by an eccentric force, Figure 3, does not cause failure to the deck as the tension at the extreme tension fibre is reduced by the compressive stress caused by the same force.

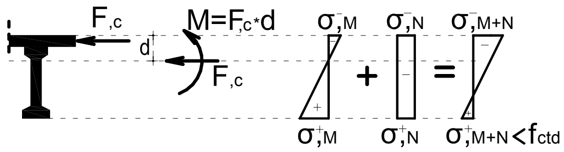

Figure 3. The distress of the deck due to the eccentric compression force developed during its expansion.

MODELING OF THE RETROFITTED BRIDGE-PARAMETERS OF THE ANALYTICAL STUDY

In the present study the adequacy of the proposed retrofitting technique was investigated. An existing "floating deck" bridge, Figures 4(a) and 4(b), was used as the "reference case". The class of Aliakmonas bridge is 60/30 according to DIN 1072. The superstructure consists of 3 prestressed precast beams with a discontinuous cast in situ deck. The total length of the deck is L=151m (5x30.2m). The piers are **I** shaped, Figure 4(c). The seismic action was taken into account by considering a coefficient ε_x=0.06 and ε_y=0.12 for the longitudinal and the transversal direction of the bridge correspondingly. The aforementioned coefficients correspond to ground accelerations $a_{g,x}$=0.10g and $a_{g,y}$=0.20g according to nowadays codes seismic actions. The design of the bridge according to the current provisions would require a ground acceleration equal to a_g=0.16g. The bridge is founded on soil type B according to Eurocode 8 Part 1.

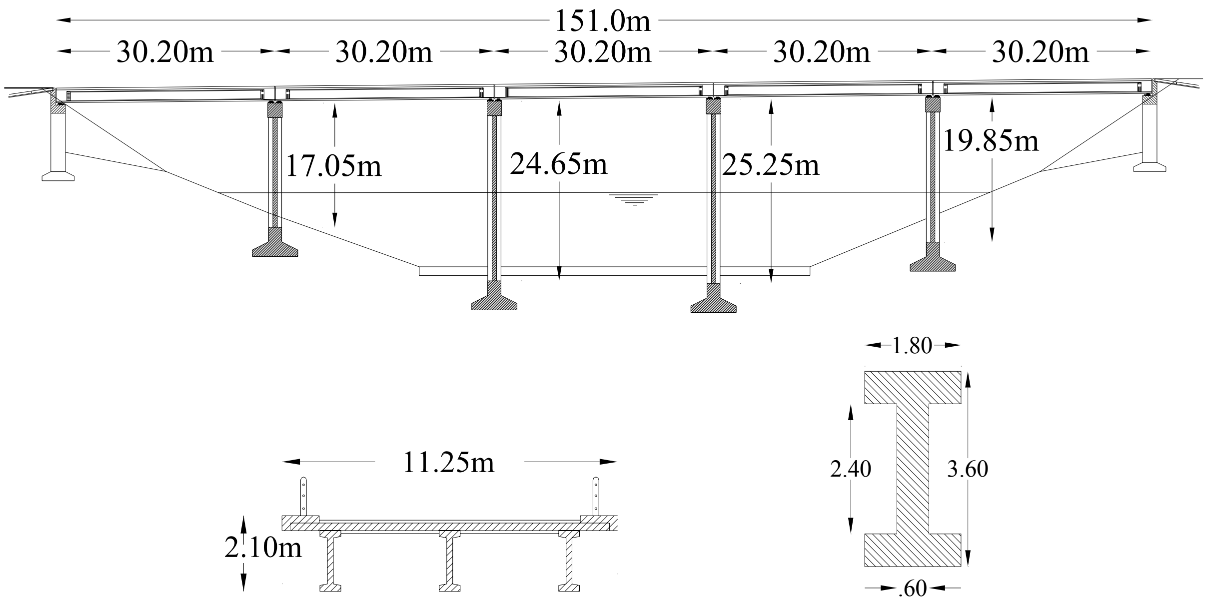

Figure 4. The "reference" real bridge, (a) Longitudinal section, (b) Cross section of the deck and (c) Cross section of the piers.

The authors of the present investigation had at their disposal the design of the existing bridge according to which the system was modeled. Figures 5(a) and 5(b) illustrate the model of the upgraded bridge, whose abutment is retrofitted by 74 micropiles with a pile cap slab connected with the existing backwall. The superstructure was modeled by a "stick model" and the existing bearings by bilinear springs. The micropiles were modeled by 10 circular frame elements of 1m of length. The diameter of the micropiles was considered to be d=0,30m and the commonly adopted bilinear P-y curve was assumed for the modeling of the springs corresponding to the soil resistance, (API, 1993). In the elastic range, the discrete soil spring stiffness k was specified according to the in situ geotechnical tests performed at the embankments. The soil is assumed to enter the inelastic range at a deformation D_y = 25 mm, whereas for the second branch of the P-y curve, the soil stiffness is reduced to 25% of the initial stiffness. The piers were considered to remain elastic during earthquake, as the deck is floating on bearings and the use of a q-factor equal to 1 is inevitable. Three non-linear contact elements were used in each joint, Figure 5(b), which joints separate the deck from the pile cap of the micropiles. The analytical investigation was performed by means of non-linear dynamic time history analysis implemented with the FE commercial code SAP 2000, (SAP 2000).

In order to determine the limits of the capabilities of the proposed retrofitting methodology, three different parameters, which are affecting the efficiency of the suggested intervention, were examined:

a) The ***width of the joint***, existing between the backwall and the deck, at the beginning of the seismic event and which separates the backwall from the deck. Analysis of bridge systems performed considering that the joints are closed or have a gap corresponding to a thermal contraction equal to $\Delta T_{N,con}=12,5^oC$ and $\Delta T_{N,con}=25^oC$. Also the undesirable case of the maximum gap was analyzed for completeness.
b) The ***Ground Type***. Ground Types B and C of Eurocode 8 were considered and the bridge was subjected to the corresponding artificial earthquake motion that is compatible with the corresponding soil-dependent Eurocode 8 elastic spectrum.
c) The ***Peak Ground Acceleration*** was adopted equal to a_g=0.16g or 0.24g while the 15 artificial records were generated with the computer code ASING, (Sextos et al., 2003).

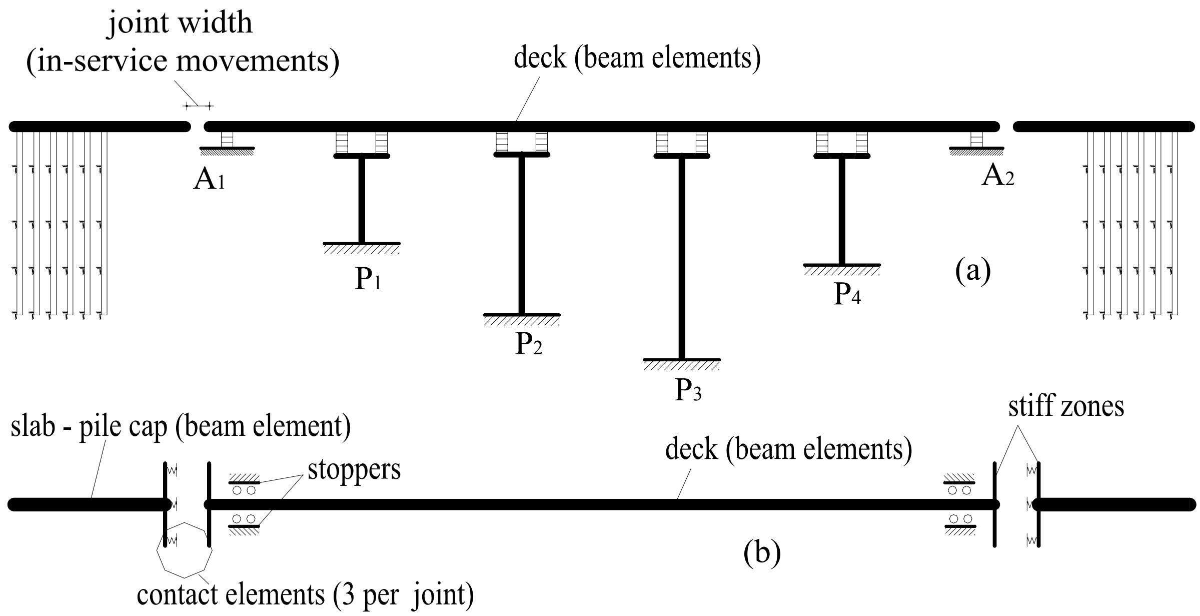

Figure 5. The model of the upgraded bridge with the micropiles and their pile cap, (a) Longitudinal section, (b) Plan view.

IMPLEMENTATION OF THE PROPOSED INDIRECT SEISMIC RETROFITTING METHODOLOGY-PARAMETRIC STUDY

In the present paragraph, the results of the investigation, concerning the adequacy of the proposed seismic retrofitting methodology, which can be implemented in existing bridges, are presented. The bridge was checked for the adequacy of: (a) the existing piers' moment and shear strength and of (b) the existing bearings for the displacements of the longitudinal design earthquake. The moment and shear strength of the piers were calculated according to the current codes' provisions, (Eurocode 2, 2003). The aforementioned estimation of the shear strength is conservative (Priestley et al., 1994). It is reminded that the existing stoppers -seismic links- of the bridge were considered to be seismically active and restrain shear strain of the bearings during the transverse design earthquake.

Figure 6 illustrates the shear capacity (V_{Rx}) and the shear actions for the longitudinal design earthquake ($V_{x,x}$) when the end joints have three different widths Δ, which are determined by the in-service needs of the continuous deck. It is obvious that the restraining of the longitudinal movement of the deck by the proposed system also restrains the piers' shear actions which are significantly small in comparison with their shear capacity in the same direction. It is reminded that the use of a q-factor equal to 1 is inevitable, as the deck is supported on piers through bearings and also capacity design is not required. The last note justifies the check of the piers cross sections against the seismic shear actions resulted from the analysis, which are given in Figure 6.

Figure 7 illustrates the shear capacity (V_{Ry}) and the shear actions for the design earthquake in the transverse direction ($V_{x,x}$) when the end joints have three different widths Δ. It is observed that the shear capacity of pier M_1 is marginally greater than the corresponding shear action when the width of the joint, existing at the beginning of the seismic event, is Δ=20mm. It is reminded that the joint has the aforementioned width in case of an extreme thermal contraction of the bridge.

In Figures 8 and 9 the moment capacities (M_{Ry} & M_{Rx}) and the corresponding moment actions of the retrofitted bridge piers ($M_{y,x}$ & $M_{x,y}$) are given. The actions $M_{y,x}$ and $M_{x,y}$ are developed during the longitudinal and the transversal design earthquake correspondingly. It is obvious that the flexural resistance of the piers is adequate and their strengthening is avoided due to the beneficial participation of the proposed restraining system.

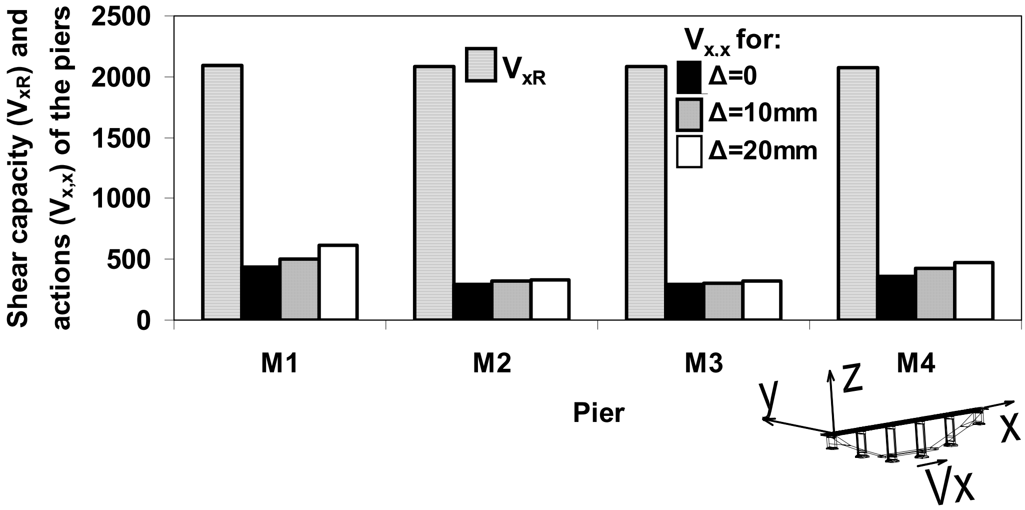

Figure 6. The shear capacity (V_{xR}) and the shear actions ($V_{x,x}$) of the piers for the longitudinal design earthquake (KN). (Ground Type B, α_g=0.16g).

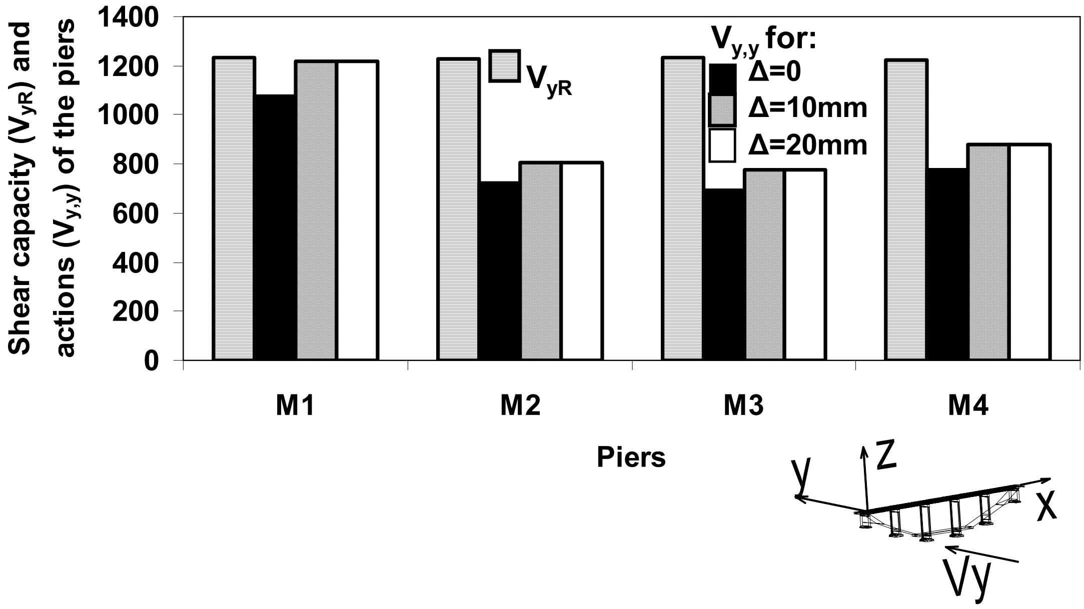

Figure 7. The shear capacity (V_{yR}) and the shear actions ($V_{y,y}$) of the piers for the transverse design earthquake (KN). (Ground Type B, α_g=0.16g).

Apart from the piers also the adequacy of the existing bearings was checked for the seismic displacement actions, according to the Eurocode 8 Part 2, (Eurocode 8 Part 2, 2003). The check concluded that the bearings are sufficient when the retrofitted bridge develops the restraining system of micropiles during earthquake. It seems that the significant reduction of the deck's longitudinal movement, which is of the order of 70%, also restrains the need for voluminous bearings, whose total height is mainly determined by the seismic displacement actions, d_{Ed}. The identification of the former verification is illustrated in Figure 10, which gives the maximum allowable (ε_{smax}) and the developed (ε_{sx}) shear strain $\varepsilon_s=d_{Edx}/\Sigma t_i$ of the bearings due to the longitudinal design earthquake. It is obvious that the code's requirement is easily satisfied.

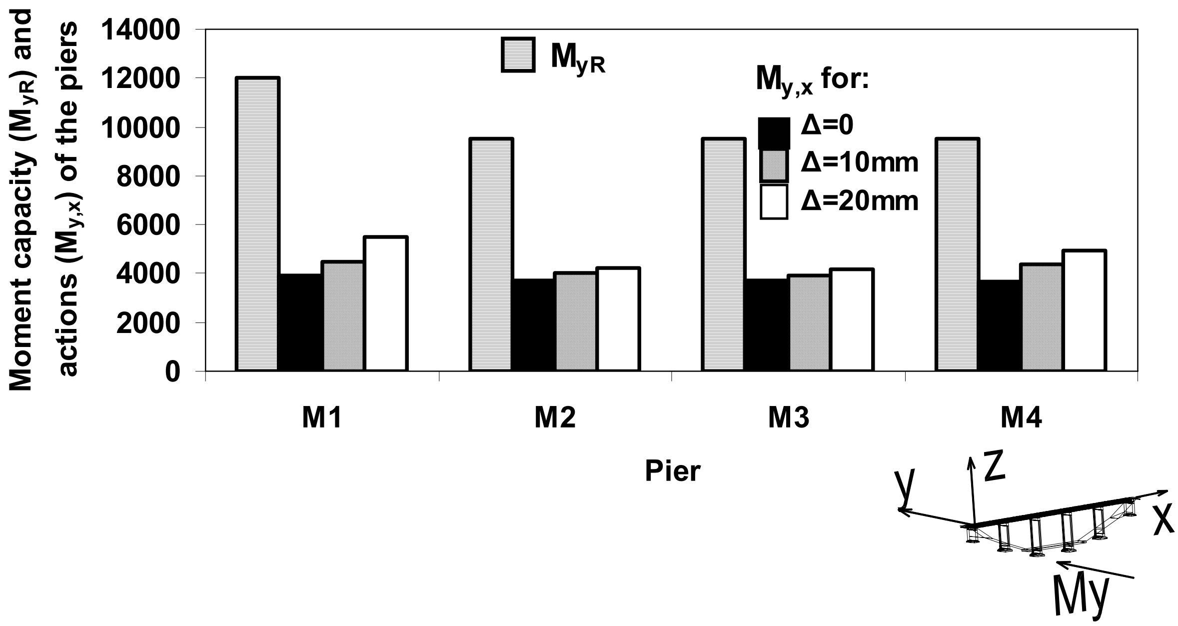

Figure 8. The moment capacity (M_{yR}) and the moment actions ($M_{y,\chi}$) of the piers for the longitudinal design earthquake (KNm). (Ground Type B, α_g=0.16g).

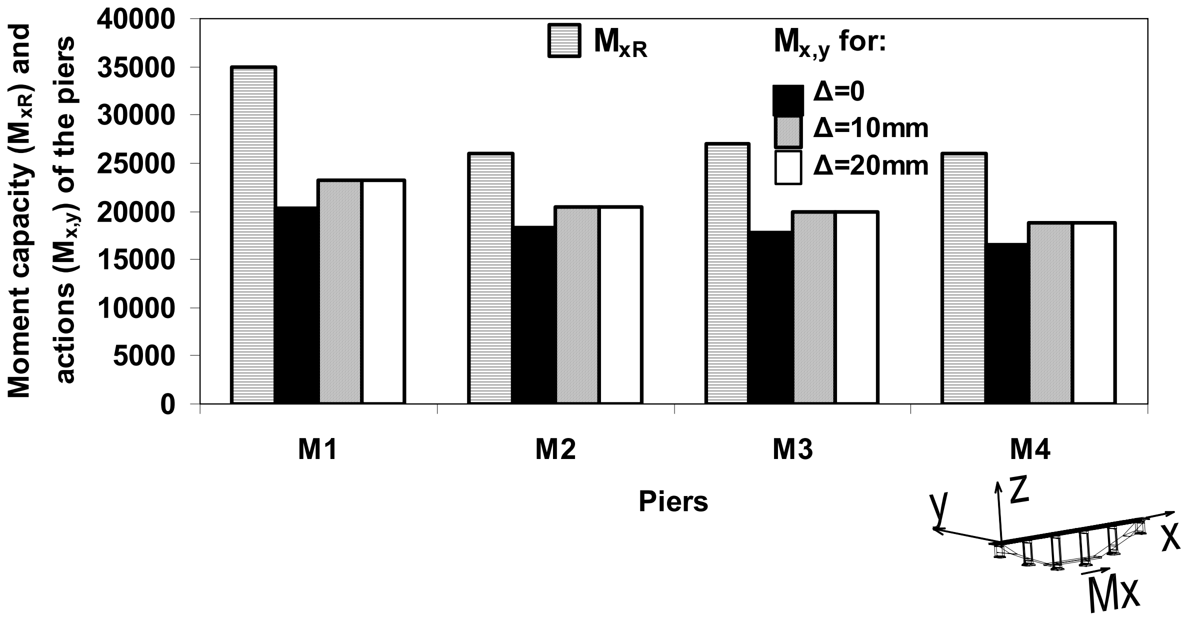

Figure 9. The moment capacity (M_{xR}) and the moment actions ($M_{x,y}$) of the piers for the transverse design earthquake (KNm). (Ground Type B, α_g=0.16g).

The examination of Figures 6,7,8 and 9, in which the seismic actions of the piers, for the longitudinal and the transverse design earthquake, are illustrated lead to conclusions concerning the influence of the joints width on the seismic restraining efficiency of the proposed sub-assemblage. It is noted that the width of the end joints, which separate the abutment backwall from the deck, can be closed during earthquake, in the desirable case that $T_e \geq T_o$, or have a maximum width equal to Δ=20mm, in the undesirable case of deck's maximum contraction. The aforementioned figures show that the desirable restraining effect of the external system is up to 20% reduced when the width of the joints is increased from Δ=0 to Δ=20mm.

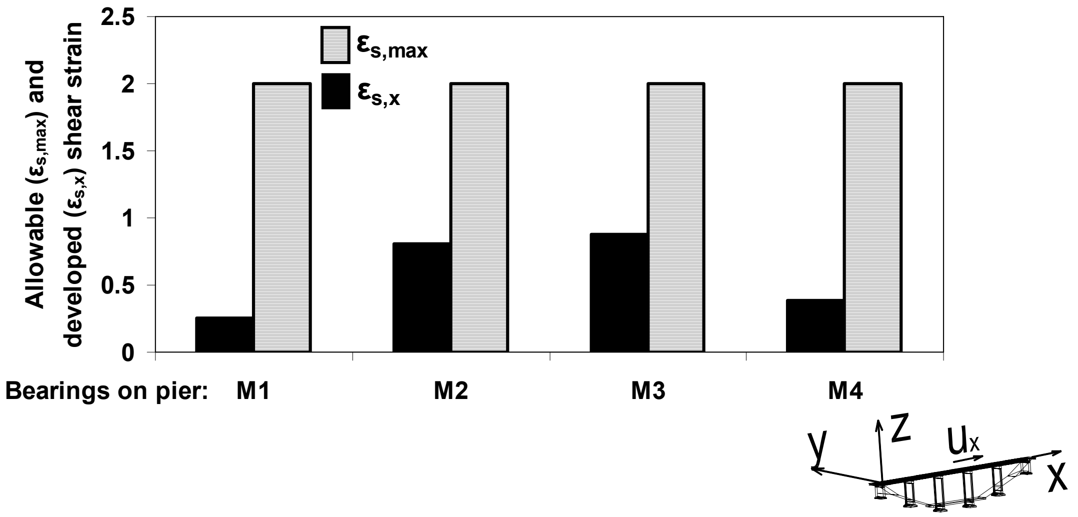

Figure 10. The maximum values of allowable ($\varepsilon_{s,max}$) and developed ($\varepsilon_{s,x}$) shear strains of the bearings for the longitudinal design earthquake. (Ground Type B, α_g=0.16g).

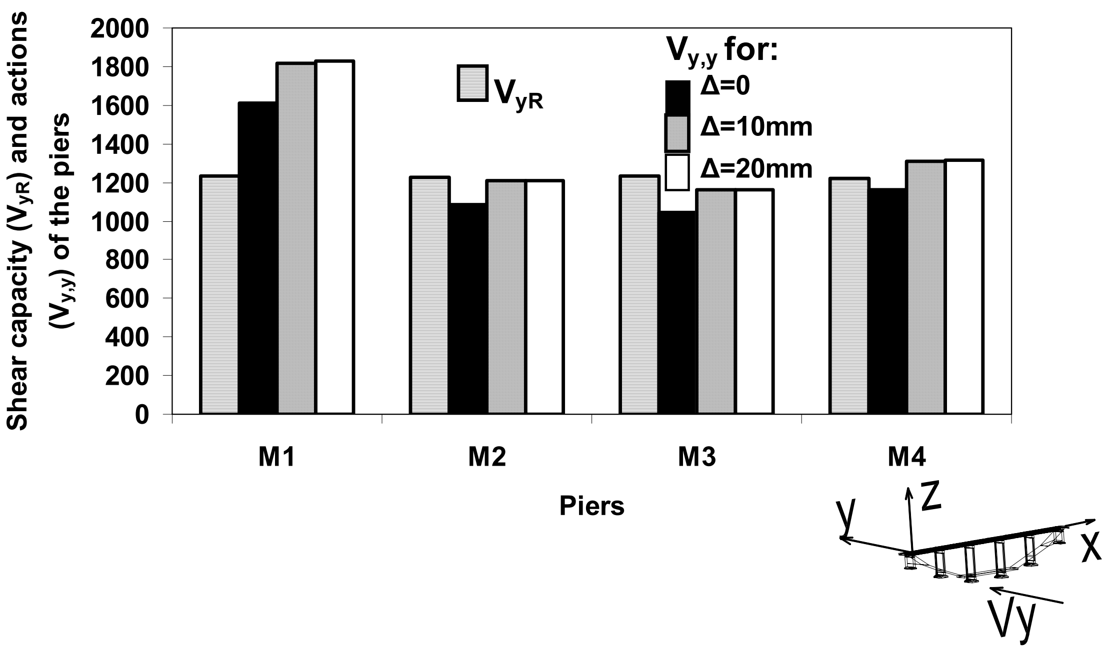

Figure 11. The shear capacity (V_{yR}) and the shear actions ($V_{y,y}$) of the piers for the transverse design earthquake (KN). (Ground Type B, α_g=0.24g).

The existing bridge was also found to have inadequate overlap lengths of the deck on the supports and mainly on the piers. The decks retrofitting by providing its continuity, the development of the existing seismic links and the significant reduction of the deck's longitudinal and transversal seismic movement, resulting from the restraining effect of the proposed system, are considered to be adequate measures against unseating under the design earthquake.

The investigation concerning the sufficiency of the retrofitted bridge for the higher seismicity α_g=0.24g and for the soft ground type C concluded that the proposed seismic upgrade through the micropiles restraining effect is not adequate. The seismic shear actions ($V_{y,y}$) of the piers are greater than their shear resistance (V_{Ry}) for the transverse design earthquake. Figure 11 shows the aforementioned adequacy of the proposed bridge rehabilitation methodology for the case of the higher seismicity. It seems that even the desirable closure of the end joints can not enhance the shear actions of the shorter piers M_1 and M_4.

The contrast of Figures 6,7 and 8,9 can give an explanation of the aforementioned retrofitting inadequacy, which was observed in the transverse direction of the piers. The proposed restraining system performs efficiently against the longitudinal movements while its efficiency is reduced for the transversal movements of the deck. This is attributed to the fact that the micropiles' translational stiffness is participating in the longitudinal design earthquake while their smaller rotational stiffness about the vertical axis is activated during the transversal deck's movement. Moreover, the deck is moving as a rigid body, in the longitudinal direction, while the transversal movement is governed by deformations, which determine the overall displacement by up to 70%, (Goel, 1997). These flexural deformations also increase the piers' actions. The aforementioned effects are of minor importance in shorter bridges, (Mitoulis & Tegos, 2005).

CONCLUSIONS

The present investigation proposes a non-conventional retrofitting method which aims at the reduction of the induced inertial loads. The method can be implemented in bridges whose deck consists of discrete segments separated by expansion joints. The quantitative analysis of the two alternative rehabilitation techniques, one conventional and one non-conventional, came up to the following conclusions:

1) Any rehabilitation technique has to provide deck's slab continuity, by eliminating the existing expansion joints which separate the bridge segments, in order to avoid the chaotic response of bridges whose deck is not continuous.
2) The conventional rehabilitation technique can not achieve the currents' codes seismic performance requirements. The conventional rehabilitation method has to retrofit the piers and their foundations.
3) The proposed rehabilitation technique, which reduces the seismic actions instead of strengthening the existing bridge members, proved to be significantly efficient as the seismic performance of the rehabilitated bridge is adequate according to the current codes' provisions.
4) The proposed retrofitting methodology is more efficient, both in the longitudinal and in the transverse direction, in shorter bridges. However, appropriate configuration of the embankments and selection of the micropiles restraining system can enhance the seismic performance of longer bridges.

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