Seismic design of bridges with seat-type abutments considering the participation of the abutments during earthquake excitation

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SUMMARY:
Abutments are not only earth-retaining systems, but also contribute to the earthquake resisting system (ERS) of bridges. The backfill-abutment-bridge interaction has been extensively discussed in international literature with emphasis on the seismic response and performance of bridges. Along these lines, the need arises to study the effect on the design of bridges considering the abutment-backfill seismic participation. To meet this objective, an extended parametric study was conducted on three real bridges with seat-type abutments, in which the system of the abutment with the backfill soil either participates or not in the ERS of bridges. Non-linear dynamic time history analysis was performed and revealed that in most cases the backfill-abutment-bridge interaction is beneficial, as the seismic demand of bridges was reduced. However, this beneficial effect was attenuated in longer bridges with tall piers, whose seismic actions can be increased under certain conditions.

Keywords: bridge; design; seat-type abutment; backfill; seismic participation

1. INTRODUCTION

Bridge abutments are earth-retaining sub-structures designed to provide unimpeded traffic access to and from the bridge. On the other hand, abutment response, soil-structure interaction and backfill resistance have been found by post-earthquake reconnaissance reports to significantly influence the response of an entire bridge system under moderate to strong intensity ground motions (Aviram et al. 2008). The influence of soil-structure-interaction on the dynamic response of bridges has been widely recognized in numerous research studies the last years. (Siddharthan et al. 1994; Goel et al., 1997, Mackie et al., 2002) and has been widely addressed the following years in instrumented bridge overpasses (Zhang et al., 2002; Inel et al., 2004). The known backfill-abutment-deck interaction constitutes a wide field of study not only in integral abutment bridges (Faraji et al., 2001; Arockiasamy et al. 2004; Dicleli, 2005), but also in bridges with seat-type abutments (Maragakis et al. 1989; Siddharthan et al. 2001) that are bridges whose deck is supported on the pier through bearings. In the latter case the typical backwall of the abutment is designed to break free of its base support when struck by a bridge deck (Stewart et al., 2007) mobilizing high values of the passive pressure of the backfill soil (Lemnitzer et al., 2009). Hence, refined modeling approaches of the backfill-abutment dynamic resistance are necessary in order to reveal the potential mechanisms triggered in the seismic assessment of bridges (Kappos et al., 2007; Kappos et al., 2009), as the participation of the system abutment-backfill in the ERS of bridges proved to reduce effectively not only the seismic displacements of bridges (Mylonakis et al., 1999; Mitoulis[a] et al., 2010) but also structural costs (Mitoulis[b] et al., 2010). The importance of including the flexibility and strength of supports at the abutments in dynamic analysis of highway bridges is also well recognized by various agencies such AASHTO (2002) and CalTrans (2006), however current design practice varies considerably on the use of the abutments as part of the ERS (NCHRP 472, 2002).
Different methods for the modeling of the dynamic abutment-backfill resistance exist in international bridge engineering practice. Simplified force-deflection relationships for modeling embankment-abutment systems were proposed by Sextos et al. (2008). Shamsabadi et al. (2007) used mobilized

logarithmic-spiral failure surfaces coupled with a modified hyperbolic soil stress-strain behaviour that is the LSH model to estimate abutment nonlinear force-displacement capacity as a function of wall displacement and backfill soil properties. The analytical force-displacement expressions, which model the capacity of the backfill soil were also validated using data from experiments (Shamsabadi et al., 2010). The experimental study used abutments of varying height and for different backfill types. Wilson et al. (2010) conducted full scale tests on a 1.7 m backwall and concluded that including a contribution, which represented the abutment resistance, can substantially reduce the predicted column displacement demand in bridges.

Finally, the expansion joints in current seat-type abutment bridges typically do not cover the total seismic displacement action (CalTrans, 2006; Eurocode 8 Part 2, 2005). The design of expansion joints takes into account a fraction or even neglects the seismic movements, due to technical and economic criteria (Gloyd, 1996). Therefore, the bridge design can follow different design alternatives namely: (a) either to isolate the deck from the backfill and the backwall of the abutment by using large clearances at the expansion joints or (b) to neglect or take into consideration a fraction of the seismic displacement action for the design of the expansion joints. In that case the bridge engineer should respect serviceability and provide appropriate openings at bridge abutments.

Along these lines, the need arises to shed an insight to the design of bridges with seat-type abutments considering the abutment-backfill seismic participation. To meet this objective, this paper investigates the influence of the seat-type abutment and the backfill soil on the design of the bridge, when considering different clearances at the expansion joints. The influence of the system abutment-backfill soil was assessed by an extended parametric study which employed three different highway bridges. The assessment was mainly performed on the basis of comparisons illustrating the response of bridges in which the abutment and the backfill soil were considered either to participate in the earthquake resisting system (ERS) of bridges or not. Useful conclusions in the field of bridge design as well on bridge performance with respect the backfill-abutment-bridge interaction are drawn.

2. DESCRIPTION OF BENCHMARK BRIDGES

Three bridges recently built along the Egnatia and the PATHE Motorways in Greece were utilised. The shorter one that was the bridge of Kleidi-Kouloura is a cast in situ bridge with a total of three spans and a length of 135.8m. Figure 1 illustrates the longitudinal section of the bridge and the cross sections of the deck and the pier. The bridge has a seat-type abutment, on which the deck is supported through two sliding bearings, while is rigidly connected to the piers. The backwall of the abutment had a height equal to 3.0 m and a thickness equal to 0.50m. The web of the abutment had a total height equal to 6.50 m. The clearance between the deck slab and the backwall was bridged by an expansion joint with a movement capacity ±100mm. The second bridge is located at Scarfeia-Raches territory of PATHE Motorway. It had five spans and a total length of 177.5 m. The deck consisted of precast and prestressed I-beams seated on the piers and abutments through low damping rubber (LDR) bearings. Figure 2 illustrates the geometrical layout of the bridge. The abutment of the bridge was a seat-type support with a stem wall. The height of the backwall was equal to 3.0 m and its thickness equal to 0.50 m. The web of the abutment had a total height equal to 4.50 m. Expansion joints with a movement capacity ±100 mm were installed. Finally, the balanced cantilevers of Malakasi-Grevena bridge were seated on the abutments through two sliding bearings, while were monolithically connected to the piers. The bridge had three spans and a total length of 349.0 m. Figure 3 illustrates the longitudinal section of the bridge, the deck cross sections at the mid-span and the cross section of the pier. The bridge has a seat-type abutment, Fig. 3. The backwall of the abutment has a height equal to 4.4 m and a thickness equal to 0.50 m. Expansion joints with a movement capacity ±320 mm (type:D640) separated the backwall from the deck slab.

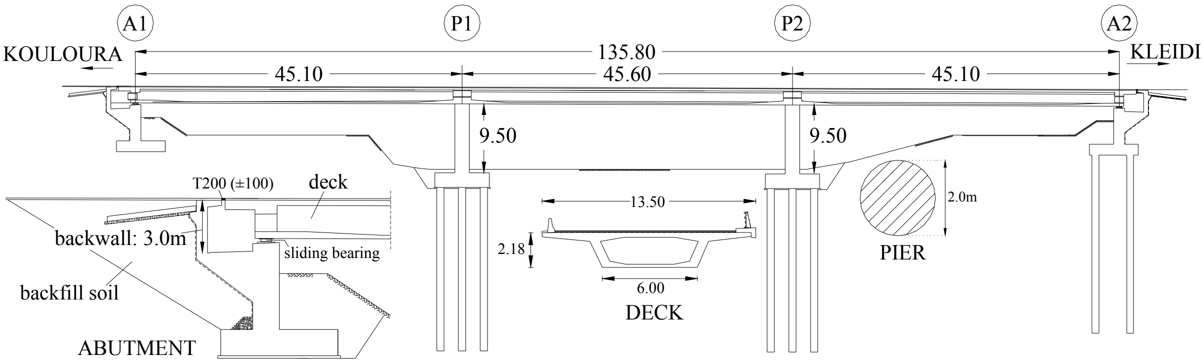

Figure 1. Longitudinal section of Kleidi-Kouloura bridge and the cross sections of the abutment, the deck at the mid-span and the pier.

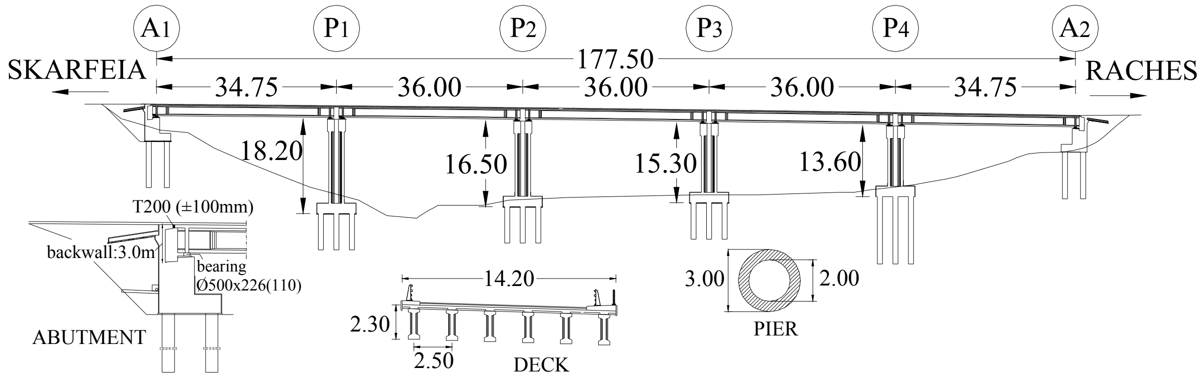

Figure 2. Longitudinal section of Scarfeia-Raches bridge and the cross sections of the abutment, the deck at the mid-span and the pier.

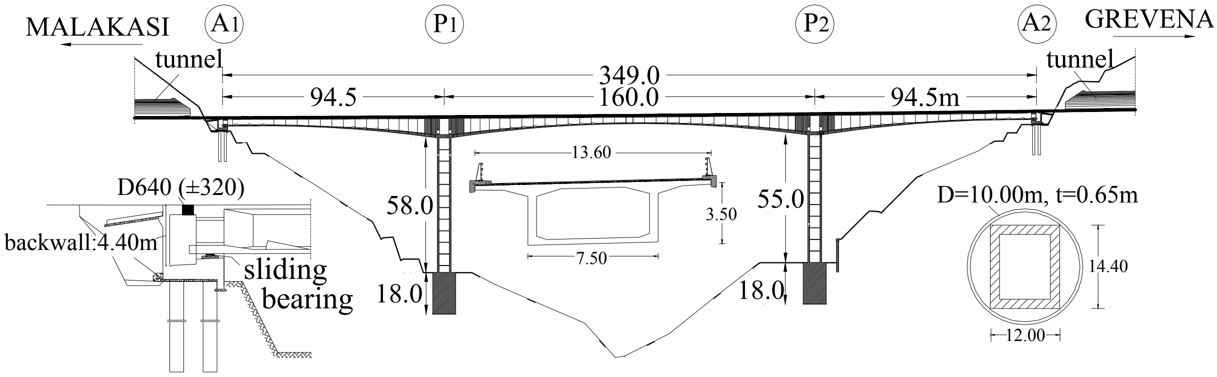

Figure 3. Longitudinal section of Malakasi-Grevena bridge and the cross sections of the abutment, the deck at the mid-span and the pier.

3. MODELING OF THE ANALYSED BRIDGE SYSTEMS

The three bridges were modelled and analysed in two different ways: (a) Firstly, the benchmark bridges were modelled without considering the abutment-backfill seismic participation. The analytical models were validated by the refined analysis conducted during the final design of the real bridge structures. (b) Secondly, all bridges were re-analysed accounting for the participation of the system abutment-backfill during earthquake. In this second analytical study the system of the backfill and the backwall were considered to participate in the ERS of bridges when the expansion joints close, namely, when the deck moves towards the abutment and closes the expansion joints. Both bridge models, namely the ones with and the others without abutment-backfill seismic participation, had the same geometry, namely the same total lengths, cross sections of the deck and piers and the same foundations.

3.1. Modeling of benchmark bridges

The analysis of the benchmark bridges used simplified stick models. In Fig. 4 the stick model of the Kleidi-Kouloura bridge is given. The deck of the bridge was modelled by frame elements. The deck was seated on slide supports at the abutments, as the deck of the as-built bridge is supported on two sliding bearings. Its transverse displacements were restrained at the abutments, due to the utilization of transverse stoppers that are seismic links (Eurocode 8 Part 2, 2005).The deck to pier rigid connection and the stiff zones, which were rigid sections, are illustrated in the Detail 1 of Fig. 4. Frames were used for the modeling of the piers connected in series with non-linear rotational spring elements, which modelled the possible plastic hinges at piers' top and bottom, as shown in Details 1 and 2 of Fig. 4. The required moment-curvature (M-φ) curves of piers' top and bottom sections were calculated by means of RCCOLA-90 (Kappos A.J., 2002). The soil spring values modeling the flexibility of the foundation were obtained by the geotechnical in-situ tests conducted during the final design of the as-built bridge. The rest two benchmark bridges were modelled by using similar modeling techniques. Non linear dynamic time history analysis was used using the SAP 2000 (Computers and Structures, 2010) commercially available software.

3.2. Modeling of bridges system with abutment-backfill participation

The bridge models, which accounted for the abutment-backfill seismic participation, included the stick models of the benchmark bridges with the addition of the abutment and the backfill models. Hence: (a) the abutment's stiffness, (b) the backfill soil resistance and mass and (c) the friction effects between the backfill and the wing walls and between the first and the approach slab as well as the (c) masses of the wing walls and the approach slab were modelled. Indicatively Figure 5 shows the modeling performed. The resistance of the backwall was taken into account by considering a simplified stick model considering either the: (a) the CalTrans (2006) model or (b) the more rigorous LSH model suggested by Shamsabadi et al. (2007). Modeling of the possible impacts at expansion joints utilised the Anagnostopoulos impact model (2004). The expansion joint clearance (Δ) was considered to vary at the beginning of the seismic event. More specifically, the clearances were considered to vary between two values that were attached the names Δ_{min} and Δ_{max}. The calculation of the clearances required by the serviceability induced movements is given in Table 1. It is noted that two different design cases DC_1 and DC_2 were examined, which represent the two extreme design cases that are the maximum expansion or contraction of the deck at the beginning of earthquake excitation. These cases influence significantly the clearances at the expansion joints and hence affect strongly the possible deck-abutment interaction effects that occur during earthquake.

Table 1. Serviceability design of bridge expansion joints and determination of the clearances at the expansion joints (Mitoulis[c] et al., 2010).

Bridge ID#		**B1 Kleidi-Kouloura**	**B2 Skarfeia-Raches**	**B3 Malakasi-Grevena**
	Thermal expansion and contraction: $\Delta T_{N,exp} = \Delta T_{N,con} = \pm 25\,^{o}C$			
$\Delta_{,exp} = \Delta_{,con}$ (mm)		17 mm	22 mm	44 mm
	Creep, shrinkage and prestressing equivalent contraction, $\Delta T_{N,eq} = 30\,^{o}C$			
$\Delta_{,eq}$ (mm)		20 mm	27 mm	52 mm
[1] Δ_{min}(mm)	***DC₁*:**	**3 mm**	**4 mm**	**9 mm**
[2] Δ_{max}(mm)	***DC₂*:**	**37 mm**	**49 mm**	**96 mm**

[1] The bridge is expanded due to maximum expansion (DC_1: $\Delta_{min} = \Delta_{,eq} - \Delta_{,exp}$)
[2] The bridge is contracted due to maximum contraction (DC_2: $\Delta_{max} = \Delta_{,con} + \Delta T_{N,eq}$)

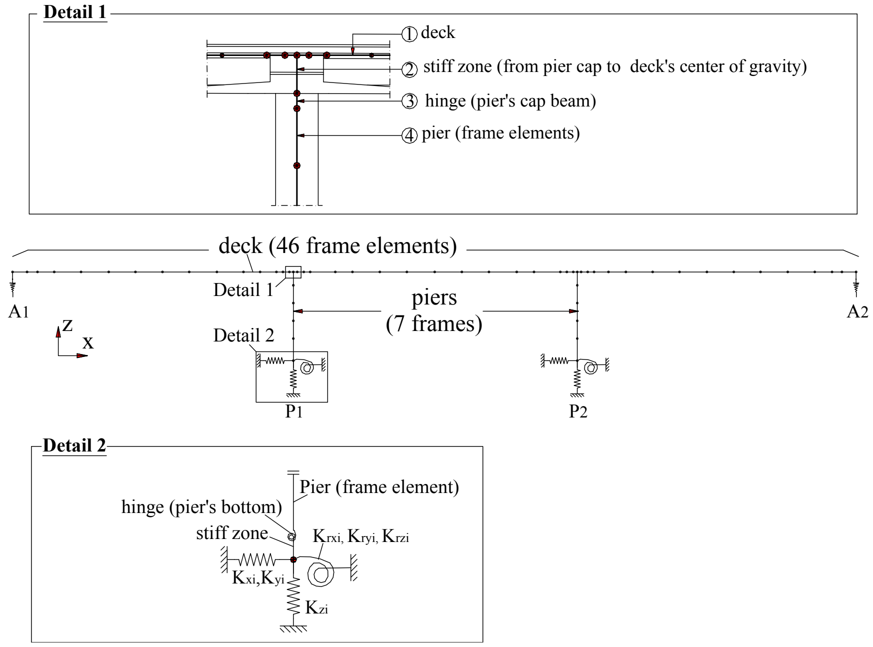

Figure 4. The stick model of Kleidi-Kouloura bridge without abutment-backfill participation, **Detail 1:** Modeling of the monolithic deck to pier connection, **Detail 2:** Modeling of the foundation and the possible hinge of the pier's bottom.

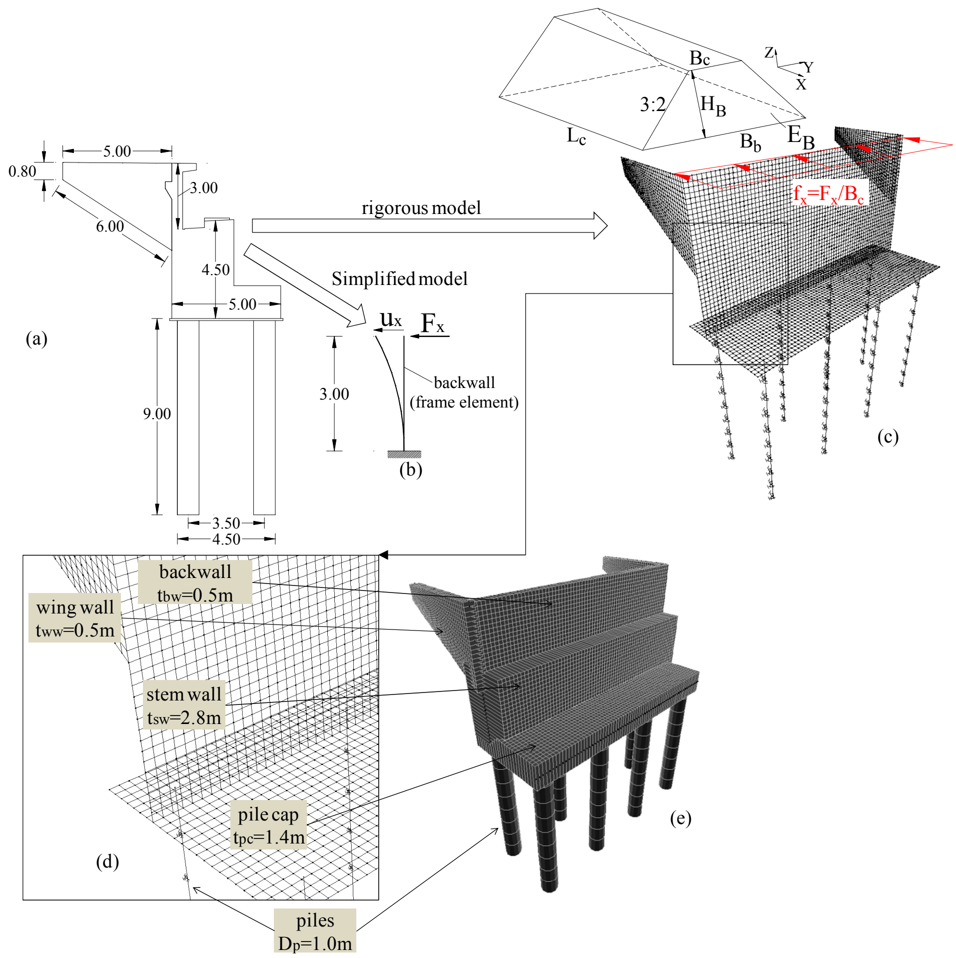

Figure 5. (a) Longitudinal section of the Skarfeia-Raches bridge abutment, (b) the simplified stick model, (c) the rigorous model and the geometry of the mobilized backfill soil, (d) **Detail**: The thicknesses of the shell elements and the diameter of the piles, (e) Extruded view of the abutment.

4. RESULTS AND DISCUSSION

The bridge earthquake resisting system became stiffer when the abutment and the backfill soil considered to participate during earthquake. Indicatively, the first longitudinal modal period of the Skarfeia-Raches bridge was found to be reduced from 1.73 s to 1.25 s that corresponded to a reduction up to 28 %. The last finding is illustrated by the response pseudo-accelerations spectra given in Fig. 6, which showed that the corresponding accelerations were increased from 12.9 to 19.6 m/s^2, when the abutment-backfill system participated during earthquake.
The influence of the abutment-backfill participation in the ERS of the bridge was mainly assessed by calculating the percentage reductions in the longitudinal movements of the bridge deck and in the bending moments of the piers. The comparisons were performed by following the two different bridge modeling approaches described above. The ratio of the displacement percentage reduction Δu_x *(%)*. Similarly, the corresponding ratio of the piers' bending moments was the ratio ΔM_y *(%)*.

4.1. Seismic movements of the deck

Figure 7 shows the percentage reductions in the longitudinal movements Δu_x *(%)* of Kleidi-Kouloura bridge for clearances at the expansion joints equal to Δ_{min}= 3mm and Δ_{max}= 37mm. The two figures were summarized by the diagram on the right, which shows the average percentage reductions. The modeling of the backfill resistance used the CalTrans soil model, as shown in Fig. 7. The figure corresponded to a design ground acceleration 0.16 g. The comparative diagrams showed that the longitudinal displacements of the Kleidi-Kouloura bridge were reduced from 12 to 33 % when the clearance at the expansion joints was equal to the minimum requirement according to serviceability, namely Δ=Δ_{min}= 3 mm. The corresponding percentage movement reductions were 6 up to 17 % in case the larger expansion joint Δ_{max}= 37 mm was considered, namely in case the deck was contracted due to creep, shrinkage and thermal effects. It was evident that the seismic contribution of the system abutment-backfill was more effective when the smaller clearance Δ_{min} was considered. The average displacement reductions showed that the abutment-backfill seismic participation led to a 25 % reduction in case a soil type A was considered, while the movements were up to 11 % reduced for the soft soil type C.
The study of the higher seismic action that was 0.24 g instead of 0.16 g led to the finding that the higher the seismic action the more effective the seismic participation of the abutment-backfill was. The displacements of the deck were more effectively reduced when the bridge was founded on the stiffer soil type A, as the movements in that case were reduced up to 25 % (average value). The bridge movement reductions were up to 23 % (average value) in case soil type C was considered. The movement reductions of the bridge were also calculated in case the expansion joints account for a fraction of 0.40 of the seismic movements, which corresponded to clearances at the expansion joints equal to 100 mm. It was found that the seismic participation of the system abutment-backfill was effectively reduced. Thus, an up to 5% reduction in the bridge deck movements was observed.

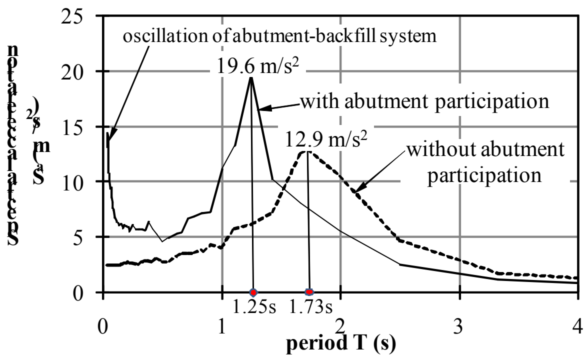

Figure 6. The structural pseudo-accelerations spectra of Skarfeia-Raches bridge with and without abutment-backfill seismic participation (longitudinal direction, ground type: C, ground acceleration: 0.24g).

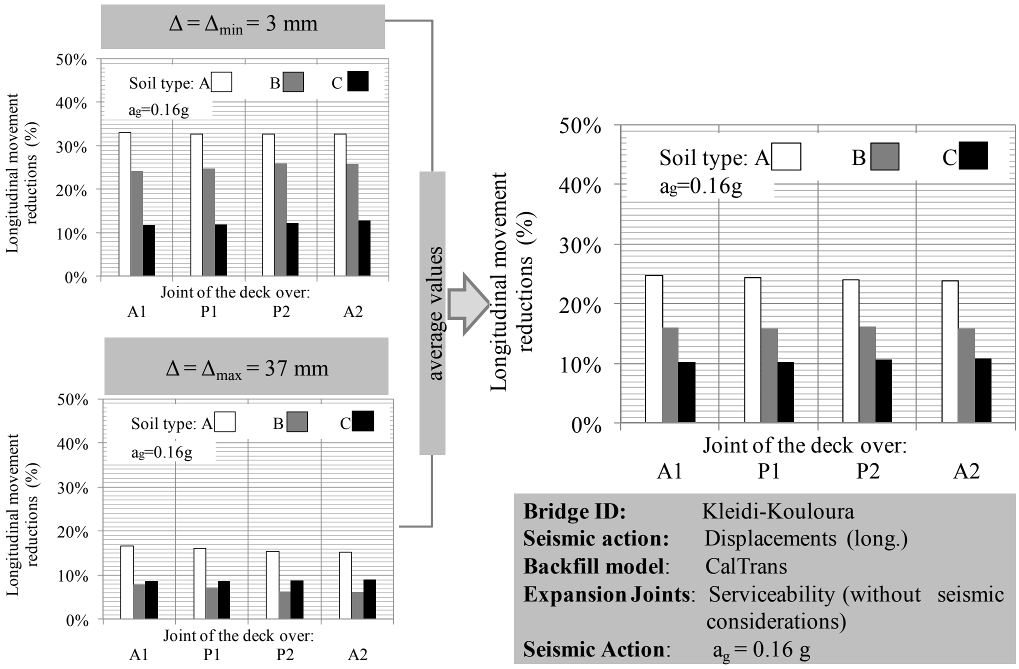

Figure 7. The percentage reductions in the longitudinal movements (*Δu_x (%)*) of Kleidi-Kouloura bridge for Δ_{min} and Δ_{max} and the average percentage movement reductions for modeling of the backfill resistance with the CalTrans model (a_g = 0.16 g).

The displacement limiting effect of the abutment-backfill system was also established in the bridges of large total lengths that were the Skarfeia-Raches and the balanced cantilever bridge of Malakasi-Grevena. The analyses showed that the mobilization of the abutment and the backfill soil during earthquake reduced the displacements of the Skarfeia-Raches bridge deck up to 28 %. The influence of the soil type was also not uniform, as the reductions in the deck movements were up to 23, 13 and 16% when soil type A, B and C were adopted correspondingly. The last percentages correspond to the modeling of the backfill soil by the CalTrans model. It was also established that, in all bridge cases, the smaller the expansion joint the more efficient was the reduction in the displacements of the deck. The analytical results showed that the movements of Scarfeia-Raches bridge were more effectively reduced in case the LSH model was employed at the analysis. More specifically, the reductions were up to 22, 25 and 18 % (average values) when soil types A, B and C were considered correspondingly. The differences observed in the seismic displacements of the bridge due to the backfill model that was employed in the analyses were not considered to be significant. The reductions in the movements of the Malakasi-Grevena bridge, which was the longest among the analysed bridge systems, were found to be up to 10, 6 and 8 % for soil types A, B and C correspondingly (average values), when the model of CalTrans was applied for the modeling of the abutment resistance. The corresponding reductions were found to be 11, 15 and 19% (average values) in case the LSH model was used in the analysis.

In most cases, the movement reductions in different bridges led to the finding that the longer the bridge the less significant was the seismic participation of the system abutment-backfill. This seemed to be rational due to the fact that the clearances at the expansion joints were required to be larger due to the larger serviceability movements of the deck. Consequently, the influence of the abutment and the backfill on the seismic response of bridges was reduced in longer bridges. As far as the backfill model concerns, it was found that the LSH backfill model caused a more significant reduction in the seismic movements of the deck in most cases. This was found to be attributed to the fact that the LSH model mobilized a relatively high passive soil pressure, that was K_p>10, of the backfill soil even for a relatively small backwall movement (< 60mm) towards the backfill soil. This had also been established by the experimental results conducted by Lemnitzer et al. (2009). On the other hand, the CalTrans model required an almost 200 mm movement of a backwall of 3.0 m high towards the backfill soil in order to develop its maximum passive resistance. Hence, the bridges analyzed did not mobilize the total resistance of the backfill soil when the CalTrans model was employed, as their displacements towards the backfill soil were found to be smaller than 200 mm in most cases. The last remarks seem to verify the increased efficiency of the system abutment-backfill when employing the LSH backfill soil model.

4.2. Bending moments of the piers

Figure 8 shows that the bending moments of the Skarfeia-Raches bridge were reduced up to 19 % (average value) in case the bridge was founded on soil types A or B and up to 23 % in case the softer soil type C was considered. The figure illustrates the bending moments of the piers' base, that were represented by $P_{1,b}$, $P_{2,b}$, $P_{3,b}$, $P_{4,b}$. Finally, the bending moments of the Malakasi-Grevena bridge piers were found to be either reduced, by up to 8 %, or increased, by up to 5 %. In most cases studied, the seismic participation of the abutment and the backfill soil reduced the displacements and the seismic

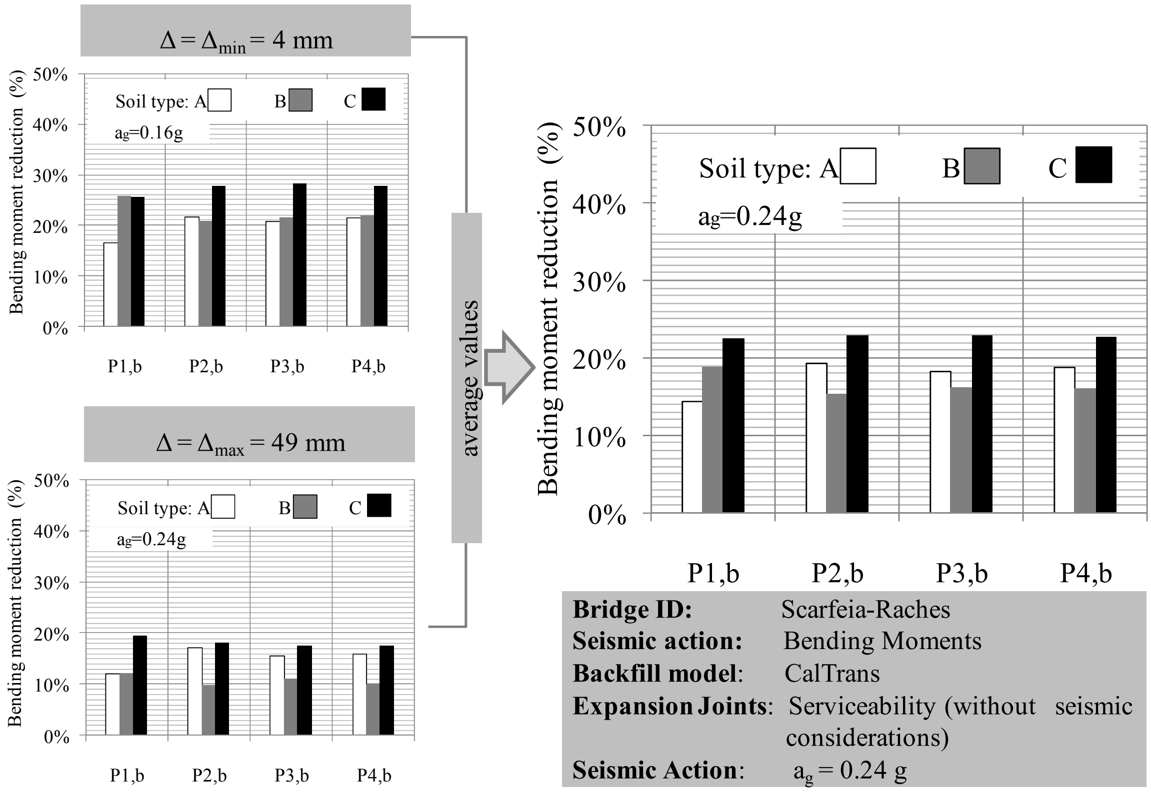

Figure 8.The percentage reductions in bending moments of Scarfeia-Raches bridge piers for Δ_{min} and Δ_{max} and the average percentage moment reductions for modeling of the backfill resistance with the CalTrans model (a_g = 0.24 g).

demand of the piers. However, the participation of the abutment and the backfill caused increases in the bending moments of the Malakasi-Grevena bridge piers by up to 8 %, in case soil type B was adopted and for Δ_{min} = 96 mm. This was found to be attributed to the increase in the spectral accelerations of the bridge when the deck interacted with abutment and the backfill. Therefore, the inertial loading of the two tall piers of the bridge induced relatively high bending moments that were not counterbalanced by the favorable reduction in the seismic movements of the deck. In all other cases the piers' bending moments were found to be reduced.

5. CONCLUSIONS

The design of bridges with seat-type abutments considering the abutment-backfill seismic contribution was investigated with three different highway bridges. The study aimed at assessing the modifications in their seismic response when the seat-type abutment and the backfill soil participated in their earthquake resisting system. Different bridge total lengths, clearances at the expansion joints, backfill soil models and multiple seismic actions were parametrically investigated. The study came with the following conclusions:

In case the expansion joints were designed according to Eurocode 8 Part 2, that was to take into account a 0.40 fraction of the seismic movements of the deck, it was found that the impact of the backfill-abutment-deck interaction on bridge seismic response was relatively low. It seemed that in that case the collisions of the deck to the backwall were negligible.

The total length of the bridge was also found to influence strongly the prospective backfill-abutment-bridge interaction. The influence of the length of the bridge was found to be indirect in the sense the clearances required at the expansion joints due to serviceability were larger when the length of the bridge was increased. Furthermore, the dynamic stiffness and mobilized mass of the abutment and the backfill soil became less significant in comparison to the total stiffness and mass of the bridge, when the length of the bridge was increased. This reflected on the reduction in the seismic displacements of the deck and bending moments of the piers, which were found to be less effective in longer bridges. More specifically, the displacements were reduced up to 35, 28 and 10 % in case of bridges of 135.8, 177.5 and 349.0 m long. The corresponding reductions in the bending moments of the piers were 18, 18 and 8%.

The model of the backfill soil was found to influence slightly the response of shorter bridges, namely the Kleidi-Kouloura and the Skarfeia-Raches bridge systems. The displacements and the bending moments of the piers were found to be reduced by almost the same percentage, whether the LSH or the CalTrans soil model was used. The influence of the backfill soil model was more significant in the long bridge of Malakasi-Grevena in which the LSH model reduced up to 19 % the longitudinal seismic displacements of the deck, while the corresponding reduction was 10 % in case the CalTrans model was used. The corresponding reductions in the bending moments of the piers were17 % and 10 % when using the LSH and the CalTrans model correspondingly.

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