An Innovative Friction-based Seismic Restrainer Utilizing Bridge Approach Embankments

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SUMMARY
An unconventional fusing mechanism reducing the longitudinal response of earthquake resistant bridges is presented. The suggested mechanism is an economical alternative to seismic isolation practice consisting of a concrete slab, connected to the bottom flange of the deck, embedded in the approach fill. The system resists to the deck seismic movements through friction forces developed at both ends of the bridge between the surfaces of the slab and the adjacent crushed material of the embankment. The performance of the proposed mechanism is investigated and a methodology for use with a dynamic response spectrum analysis is suggested and implemented. Furthermore, an experimental investigation was conducted for two loading speeds of a test specimen at a simple but realistic setup. Results of this very promising low-cost "damper" are presented.

Keywords: Abutment, Bridge, Embankment, Friction, Seismic isolation

1. INTRODUCTION

The separation of the bridge deck from the approach embankment using bearings and expansion joints at the abutments, in order to allow for the free expansion and contraction of the deck due to serviceability requirements (thermal effects, creep and shrinkage), is common practice in bridge engineering. The above configuration eliminates the possible advantages from the use of the approach embankments as anti-seismic restrainers which is however applicable, providing that the aforementioned serviceability requirements are properly accommodated. On the other hand, in case of a rigid connection between the deck and the abutment, the designer should pay special attention to the long-term build-up of soil pressures behind the abutment due to the wedging of the soil. The so called "ratcheting effect" was successfully faced by Horvath who proposed structural techniques in order to minimize the in-service distress of the abutments and their approach fills (Horvath J.S., 1998). The response of systems, consisting of compressible inclusion (EPS) between the abutment and the reinforced backfill was experimentally tested (Pötzl M. and Naumann F., 2005). The proposed techniques implemented in US and German bridges are shown in Figure 1 and 2 respectively.

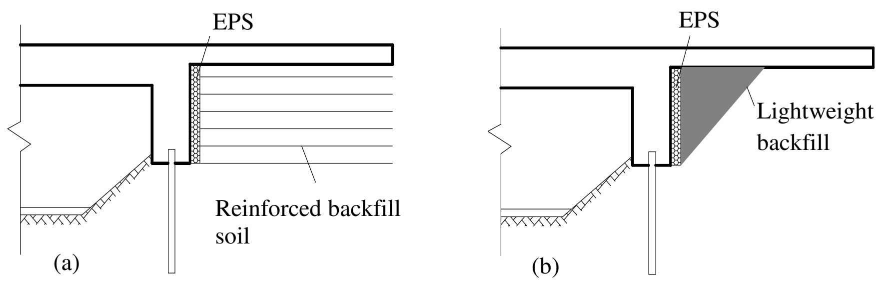


Figure 1. Structural techniques proposed by Horvath for the minimization of the ratcheting effect in US bridges: (a) reinforced backfill and (b) lightweight backfill

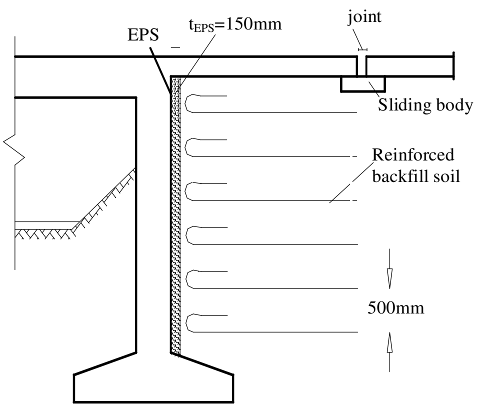


Figure 2. Compressible inclusion (EPS) between the reinforced backfill and the full height abutment (Germany)

More and more researchers acknowledge the enhancement of the bridge's earthquake resistance that can be achieved when taking into account the contribution of the embankment-bridge interaction (Zhang J. and Makris N. 2002, Mylonakis G. et al, 1999). According to recent studies (Mikami T. et al, 2003, Mitoulis S.A. And Tegos I.A., 2010, Tegou S.D. Et al, 2010), the bridge movements are generally reduced when utilizing the abutment and the approach embankment during the earthquake event. The effective participation of the above elements into the reduction of the bridge seismic actions, is the scope of an extensive research conducted in the laboratory of Reinforced Concrete and Masonry Structures of Aristotle University of Thessaloniki. A number of methods reducing the bridge pounding through the utilization of the abutments and the approach embankments as seismic restrainers, are further investigated in order to maximize the expected effect.

In the present study, the approach embankments are properly utilized so as to create a dissipative mechanism capable of absorbing part of the induced seismic energy. The proposed fusing mechanism can effectively reduce the seismic displacements of the deck in the longitudinal direction, not affecting at the same time the serviceability performance of the bridge. It is noteworthy that with the use of the proposed system for a bridge about 200m long, even the immobilization of the bridge can be achieved during a longitudinal earthquake. This unconventional restrainer, applicable to any type of superstructure, is an economical and reliable equivalent alternative to the continuously expanding and expensive seismic isolation practice.

2. DESCRIPTION OF THE PROPOSED SEISMIC RESTRAINER

2.1. General

The basic objective of the proposed mechanism is to prevent the free oscillation of the bridge during an earthquake dissipating at the same time part of the induced seismic energy, and reducing thereby the seismic response of the critical structural members. The system, see Fig. 3, consists of a concrete slab, connected to the bottom flange of the deck, embedded in the approach fill. The width of the plate is equal to the clear distance between the wing-walls of the abutment, while the embedded length is proportional to the bridge's length. The constant weight of the soil above the plate, develops friction forces at both ends of the bridge between the interface of the plate and the embankment's crushed material, during any deck movement. The magnitude of the friction forces is constant and mainly related to the aforementioned depth and area of the plate, and also to the plate surface, the loading speed and the granulation of the adjacent material. These forces are easily overcome in the case of in-service constrained movements, such as creep, shrinkage and thermal effects. During an earthquake however, these forces resist to the longitudinal movement of the deck with a constant value and at the same direction once the system starts to oscillate. This simple friction-based mechanism, can thus be designed to effectively control the deck seismic displacements and contribute therefore to the reduction of the seismic actions of the piers (shear force and bending moment) and their foundations.

The above concept can easily be applied in both integral and simply supported bridges. The effect of the loading speed on the efficiency of the proposed mechanism is experimentally investigated in this paper.

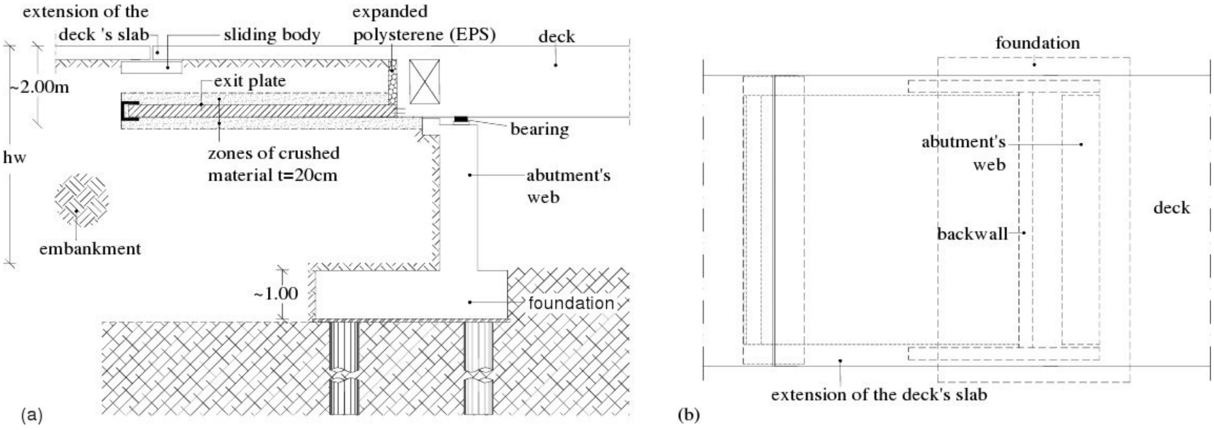


Figure 3. The proposed mechanism: (a) longitudinal section and, (b) plan view

2.2. Exit plate

The so called "exit plate" of the bridge deck, can be either cast in-situ or prefabricated, and is embedded at a depth of about 2.00m below the road surface. Its thickness is t_s=0.25m while the width is equal to the clear distance between the wing-walls, which are rigidly connected only to the abutment's web. Its length varies from 4.00m to 8.00m depending on the length of the bridge. The surface of the plate can be properly configured (i.e. wavy shape) or roughened so as to increase the friction coefficient at the interface, reducing thereby the necessary plate length.

2.3. Embankments

The approach embankment, into which the exit plate moves during the in-service and earthquake loading of the bridge, includes two layers of crushed material above and below the plate, as shown in Fig. 3. The optimal granulation of the two layers is to be experimentally investigated. It is noteworthy that the embankment is composed of common backfill material, without any special requirements, which would lead to an increase of the construction cost of the proposed system.

3. IN-SERVICE AND SEISMIC PERFORMANCE OF THE PROPOSED SYSTEM

It is well known that functionality opposes the earthquake resistance of bridges. As an example, while statical indeterminacy benefits the earthquake resistance, it opposes at the same time functionality. The extraction and contraction of the deck due to in-service loadings, causes subsequent entries and exits of the plate in the embankment, which result to the development of a constant force with a variable direction. This force which is applied at the level of the exit plate, eccentrically to the center of gravity of the cross section, causes changes in the axial forces and introduces moments, critical mainly when positive due to deck contraction, at the end support of the superstructure. These forces can be easily taken into account during the dimensioning of the structure.

As regards to the seismic contribution of the proposed fusing mechanism, the whole concept which is based on the development of a constant friction force F_f at both ends of the bridge and at the same direction, resisting to any seismic movement of the bridge deck, can be characterized as an "Egg of Columbus" alternative. In case of ground acceleration values lower than F_f/m_{tot}, where m_{tot} is the total bridge's mass, the system is not oscillated, but is moved parallel to the ground's motion. The oscillation of the system is activated when the ground acceleration exceeds the above value. During the seismic movement a constant friction force F_f is developed, which always resists to the system's oscillation. Two typical hysteresis loops are presented in Fig. 4, one of which refers to the initial bridge system, while the other refers to a bridge where the proposed mechanism is implemented. From this figure it can be derived that the additional percentage of the seismic energy that can be absorbed by the proposed system is equal to $100 \cdot F_f/[m_{tot} \cdot S_a(T)]$. According to the above quantification, ductile bridge structures with a behaviour factor q greater than 1.5, respond more effectively to the proposed enhancement than in the case of low ductility systems (i.e. precast bridge systems with $q<1.5$), due to the lower value of $S_a(T)$. However, the increased fundamental period of the latter systems, due to the support of the superstructure at the piers and the abutments on flexible elastometallic bearings, can provide an advantage which in many cases can cover the aforementioned difference.

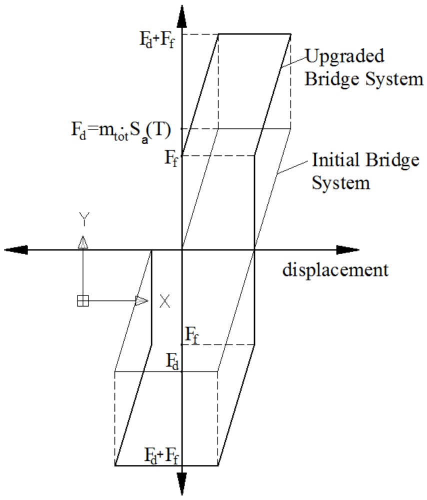


Figure 4. Typical hysteresis loops of the initial and the upgraded system

The developed constant friction force F_f is subtracted from the inertial force of the bridge, leading to a reduction of the ordinates of the response spectrum by F_f/m_{tot}. Therefore, a dynamic response spectrum analysis of the system can be easily implemented using a modified response spectrum. Eqn 3.1 quantifies the calculation of the ordinates of the above mentioned response spectrum, which is used for the dynamic analysis of bridge structures where the proposed mechanism is implemented.

$$DF_{inertial} = m_{tot} \cdot S_a(T) - F_f \quad (3.1)$$

where $S_a(T)$ is the spectral acceleration and $DF_{inertial}$ is the reduced inertial force due to the earthquake.

4. ANALYTICAL INVESTIGATION

4.1. Description of the "reference" bridges

The applicability and the seismic performance of the proposed mechanism were assessed utilizing two already designed and constructed bridges, an integral one at Arachthos-Peristeri section of Egnatia Odos, and a simply supported one at Skarfeia-Raches section of the PATHE Motorway. The final design of both bridges was carried out by METE SYSM S.A.

The reference integral bridge, see Fig. 5, has a total length of 240.0m and six spans (34+4x43+34=240m). The superstructure is continuous with a box-girder cross section and a total width equal to 13.5m (Fig. 5(b)). The deck is rigidly connected to the piers and rests on movable bearings at the abutments, where expansion joints also exist. The piers are wall-like columns with a rounded cross-section (Fig. 5(c)). The bridge is founded on a ground type B, according to the Greek seismic design code (corner periods T_B=0.15s and T_C=0.60s). The design ground acceleration was equal to 0.16g. The importance factor adopted was equal to γ_I=1.30 for bridges on Egnatia Motorway while the behaviour factors were equal to q_x=3.5 for the longitudinal direction and q_y=2.7 due to the relatively lower value of the transverse shear ratio ($\alpha_{s,y}$) at the transverse direction.

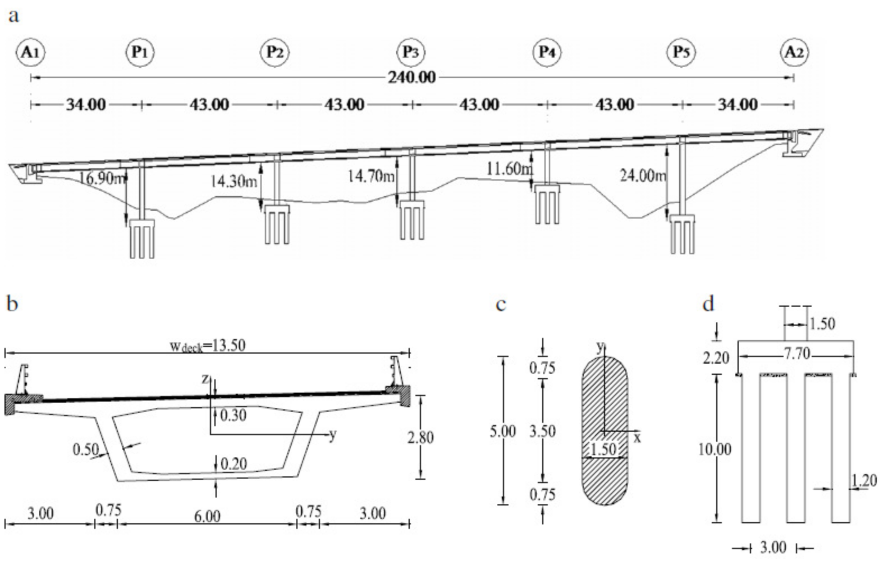


Figure 5. (a) Longitudinal section of the integral "reference" bridge (b) Deck Cross-section (c) Pier Cross-section (d) Foundation

The reference simply supported bridge, see Fig. 6, has a total length of 177.5m and five spans (34.75+3x36+34.75=177.5m). The width of the bridge is equal to 14.20m (Fig. 6(b)), and consists of six simply supported precast and prestressed I-beams, precast deck slabs and a cast in-situ part of the slab. The deck is supported on both the abutments and the piers through low damping rubber bearings. The piers (Fig. 6(c)) are hollow circular sections with an external diameter equal to 3.0m and a web thickness equal to 0.5m. The bridge is founded on a ground type B, according to the Greek seismic design code (corner periods T_B=0.15s and T_C=0.60s). The design ground acceleration was equal to 0.24g. The importance factor adopted was equal to γ_I=1.00 while the behaviour factors were equal to 1.0 for both horizontal directions.

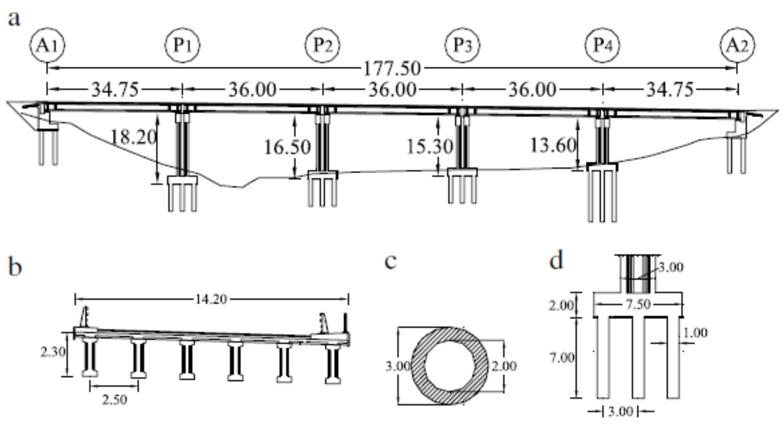


Figure 6. (a) Longitudinal section of the simply supported "reference" bridge (b) Deck Cross-section (c) Pier Cross-section (d) Foundation

4.2. Analytical modeling of the analysed bridges

The deck of the bridges, "reference" and enhanced, was modeled by frame elements (see Fig. 7 and 8), which have the section properties of the corresponding deck. The effective stiffness of the prestressed deck is taken equal to that of the uncracked section. The piers were also modeled by frame elements. Their effective stiffness was taken equal to $EI_{eff}=M_y/\varphi_y$, where M_y is the yield moment and φ_y is the corresponding curvature derived from fibre analysis with the program RCCOLA (Kappos A.J., 2002). The integral bridge is simply supported at the abutment. For the simply supported bridge, the bearings are properly modeled by link elements, which model the corresponding translational and rotational stiffnesses of each bearing. These values were calculated according to Naeim and Kelly model (Naeim F., Kell J.M., 1999). The flexibility of the foundations was taken into account by assigning six spring elements – three translational and three rotational – with a stiffness equal to that of the final design.

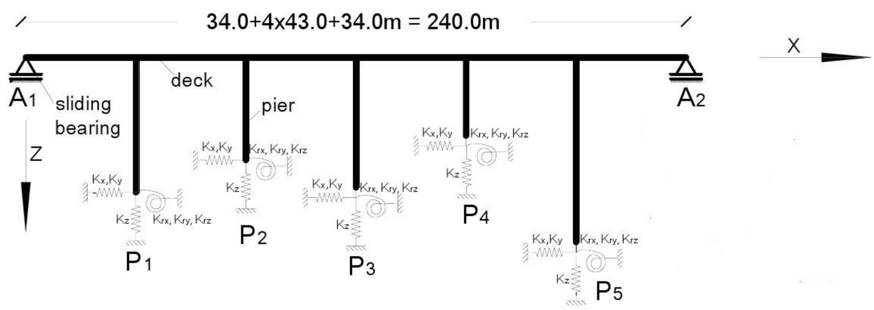


Figure 7. Model of the integral bridge

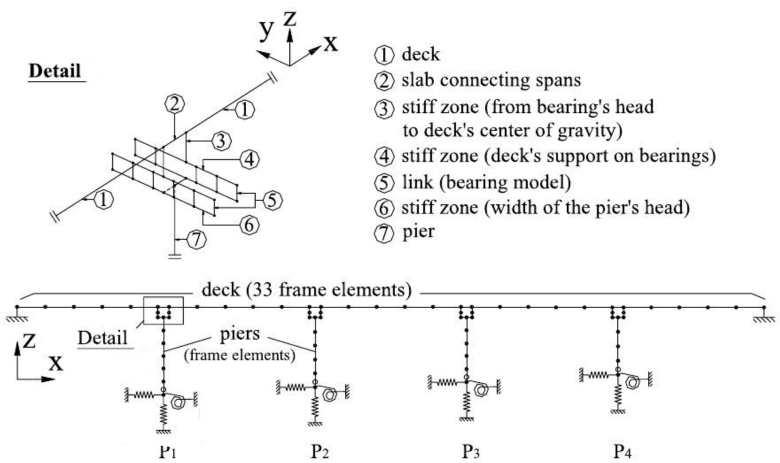


Figure 8. Model of the simply supported bridge

The influence of the friction resisting forces developed at the exit plate was taken into account using a modified response spectrum (see Section 3) according to the Greek seismic design code. The coefficient of friction was taken equal to μ=0.4. A number of modified response spectrums were calculated for different values of the exit plate's area and for both reference bridges.

4.3. Analytical results

The earthquake response of the bridges was analysed using the FEM code SAP 2000. Linear dynamic response spectrum analysis was implemented in every case. The performance of the proposed mechanism was assessed calculating the percentage reduction of the deck displacements and of the internal forces at the base of the piers, between the reference and the enhanced bridge, for the design earthquake.

For this case study, an exit plate with an area of 8x8=64m^2 was taken into account. The displacements were reduced by 45% for the integral bridge and 52% for the simply supported one. At the same time, the internal forces at the base of the piers were reduced by 60% for the integral bridge and 55% for the simply supported one. The increased fundamental period and the reduced mass of the simply supported bridge proved to be beneficial for the effectiveness of the mechanism.

5. EXPERIMENTAL INVESTIGATION

5.1. Experimental Setup

The experimental setup includes a suitable system, without parasitic frictions, in conjunction with a double acting hydraulic actuator, see Fig. 9 and 10. The system basically consists of two steel frames and a rectangular 1.00x0.60m concrete slab, 0.18m thick located in between the two frames. Two layers of gravel fill the empty space above and below the slab. The double acting hydraulic actuator is properly connected to the slab's edge to apply a quasi-static cyclic loading to the plate. The diameter of the gravel is between 8 and 16 mm. The total dead load imposed on the concrete slab is 7kN to account for the overlying soil of the embankment. The experiment was repeated for two loading speeds, namely, the slow speed which represents the movement of the plate during serviceability loading, and the fast speed which represents the seismic loading of the slab.

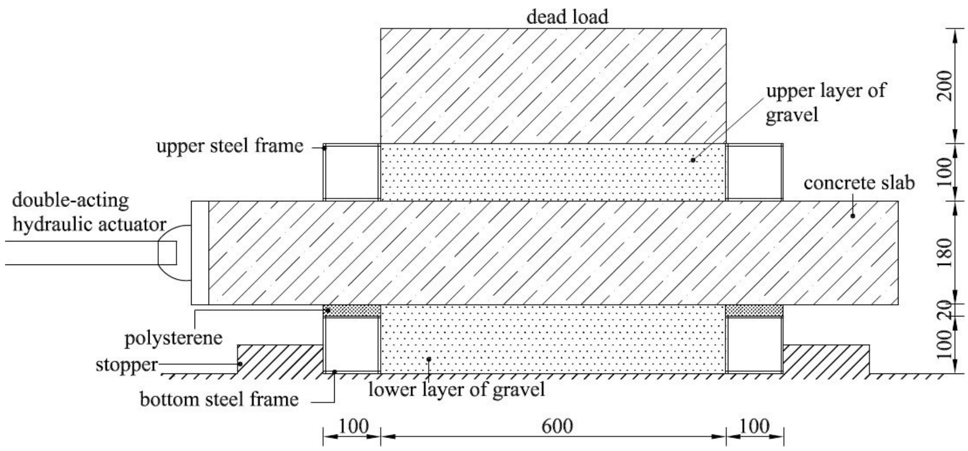
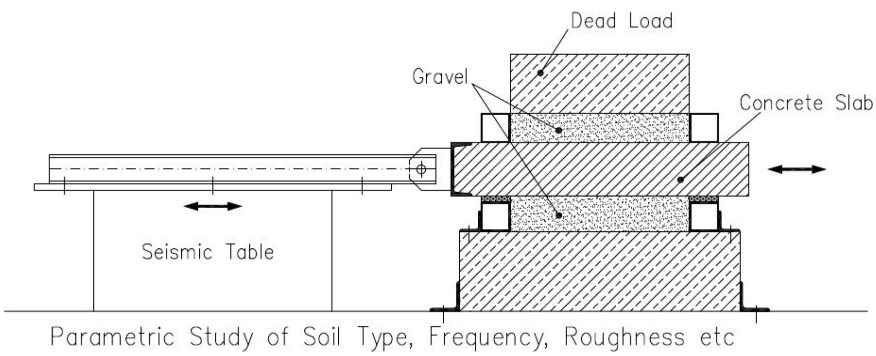


Figure 9. Cross Section of the Experimental Setup

(a)



(b)

Figure 10. View of the Experimental Setups (a) Initial Setup (b) Final Setup

5.2. Test results

The hysteresis loops derived from the response of the system to the loading, for the two different loading speeds, are presented in Fig. 11. The frictional resistance in the first case, see Fig. 11(a), which refers to the slow loading of the system (158 mm/min) was almost 13,5kN. The corresponding frictional resistance for the fast loading (1800 mm/min) case, see Fig. 11(b), was almost 15kN. The area enclosed by the envelope of the hysteresis loop, is quite large and indicates that the energy dissipation is significant in both cases.

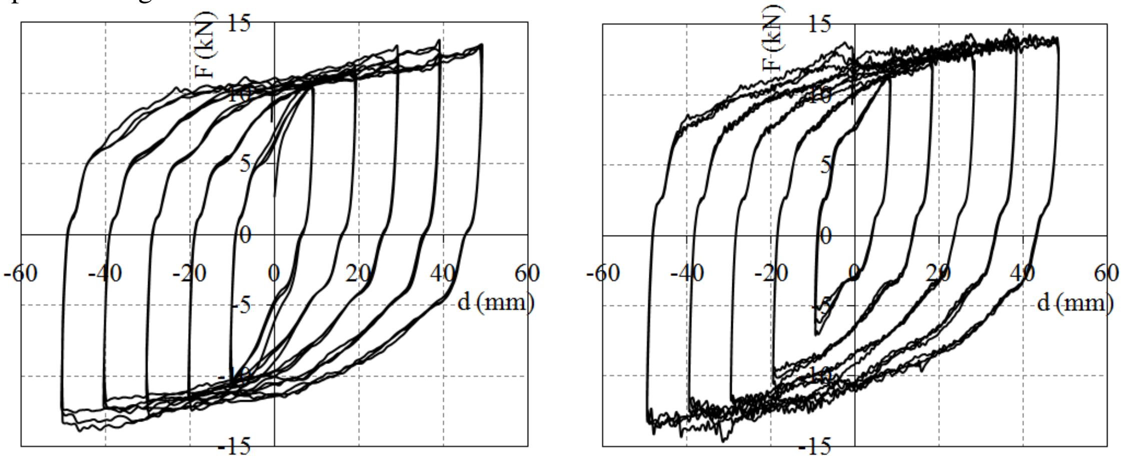


Figure 11. Hysteresis loops: (a) slow loading (158mm/min), (b) fast loading (1800mm/min)

6. CONCLUSIONS

The seismic efficiency of the proposed fusing mechanism was experimentally investigated. The mechanism consists of a concrete slab, the so called “exit plate”, connected to the bottom flange of the deck, which is embedded in the approach fill. When the deck moves due to an earthquake, the system resists to the seismic movements through the friction which is developed at the interface between the exit plate and the crushed material of the embankment. Friction forces developed due to in-service loading can be easily taken into account during the dimensioning of the structure. The experimental investigation reached to the following conclusions:

- The resultant hysteresis loops are impressive, and can be contrasted with the seismic efficiency of the most efficient seismic dampers. A significant amount of the seismic energy induced can thus be dissipated by the proposed system.

- According to the results, the friction resistance is increased about 10% due to the increase of the loading’s speed. The friction coefficient is increased by the same percentage. This obvious influence is expected to be much higher for realistic speed values of the seismic loading.

- The friction resistance of the plate’s surface, which is about two times the imposed dead load, results to a measured value for the coefficient of friction between the concrete surface and the gravel’s layer of about 1.00.

The proposed mechanism, as described above, and as confirmed by the analytical investigation, is a feasible and cost-effective method to enhance the longitudinal seismic response of both integral as well as simply supported bridges, of practically any length, by reducing the displacements and the internal forces. It can also be used for existing bridges when properly adjusted.

A more extensive investigation, both experimental and analytical, of the promising mechanism is already conducted in the laboratory of Reinforced Concrete and Masonry Structures of Aristotle

University of Thessaloniki, to study the effect of a number of parameters involved and prove the effectiveness and applicability of the system.

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