Seismic Analysis

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Seismic Isolation of the Italian Bridge: A Case Study

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INTRODUCTION

The transversal communication between the Tirreno and the Adricatico coasts of the Italian peninsula, hindered by the presence of the Appennini mountain range, has been tackled quite late compared to the rest of the motorway network, in spite of its fundamental relevance for the socio-cultural development of the country. The designing and building processes of the connection between Abruzzo and Lazio regions began only in the early 70's, with the realization of A24 "Roma-L'Aquila-Teramo" and A25 "Teramo-Pescara" motorways.

Due to the complex orography of the terrain in question, the construction of several motorway bridges, artificial galleries and other structural works was necessary, bearing heavily on the costs and leading to the subdivision in multiple lots and a noticeable delay in the finishing of the works.

So much so that its completion is currently still in the construction phase, with the doubling of carriageways in the last single-carriageway tract going from Villa Vomano to Teramo. Its executive design has been prepared by Mario Petrangeli & Associates s.r.l. for Strada dei Parchi s.p.a. who currently manages the interested motorways in association with ANAS (a public limited company managing the majority of the Italian road and motorway network). Works, carried out by contractor TOTO s.p.a., amount to slightly more than 100 million Euros and comprise a natural gallery, about 800m long, and two viaducts for a total length of 3500m, as well as several minor works and landfills.

1. SEISMICITY OF THE ITALIAN TERRITORY

The Italian peninsula is subject to relevant seismic phenomena due to its location where the African, Euro-Asian and Adriatic tectonic plates meet, with their border developing exactly along the Appennini mountain range. The epicenter of the most significant seismic events of the 20th century is in fact in this area and they have been in 1908 – earthquake with epicenter in Messina, 83000 casualties; in 1915 –

Abruzzo, 30000 casualties; in 1976 – Friuli, 6,4° Richter scale earthquake, 982 casualties; in 1980 – Campania and Basilicata, 10° Mercalli scale, 3000 casualties.

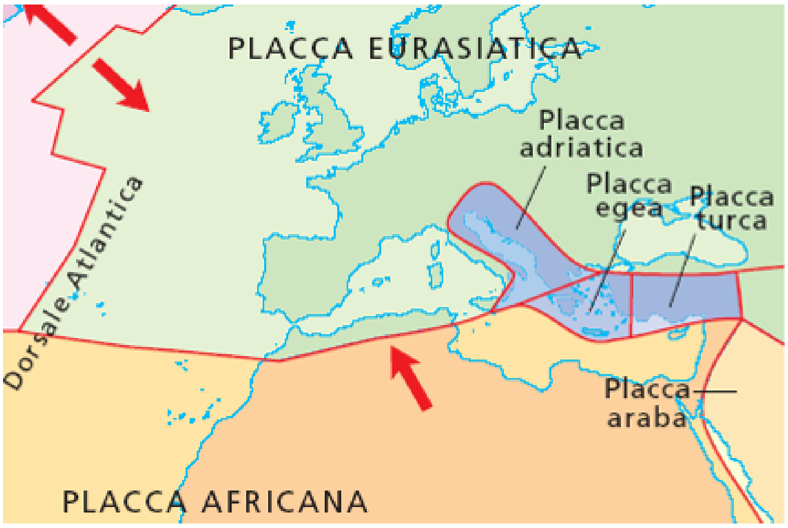


Figure 1. Tectonic plates

The evolution of the Italian seismic classification may be synthesized as shown in the following figure.

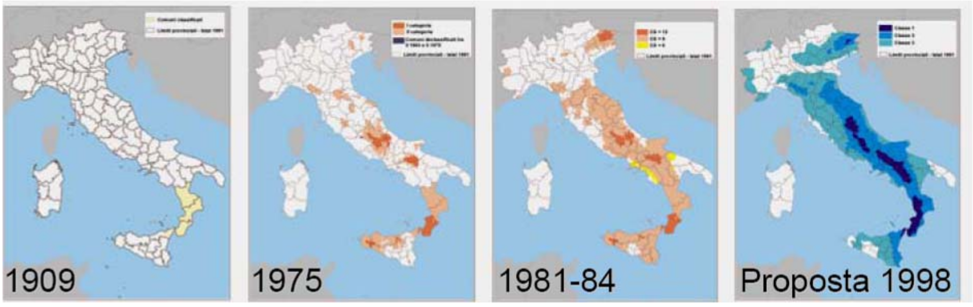


Figure 2. Evolution of the Italian seismic classification from 1909 (DPC-SSN)

Examining what happened during last century, it can be noticed that until 1980 classification followed the events, instead of foreseeing them. Only at the end of the 70’s, with the Geodynamic Finalized Project by CNR, which followed Friuli region earthquake of 1976, giving impulse to specific studies, danger level maps were created with proper scientific data and procedures. With these maps, between 1981 and 1984, a conspicuous portion of the territory previously considered non-seismic has been re-classified, extending from 25% to about 45% the portion of Italian territory classified in one of the three available categories.

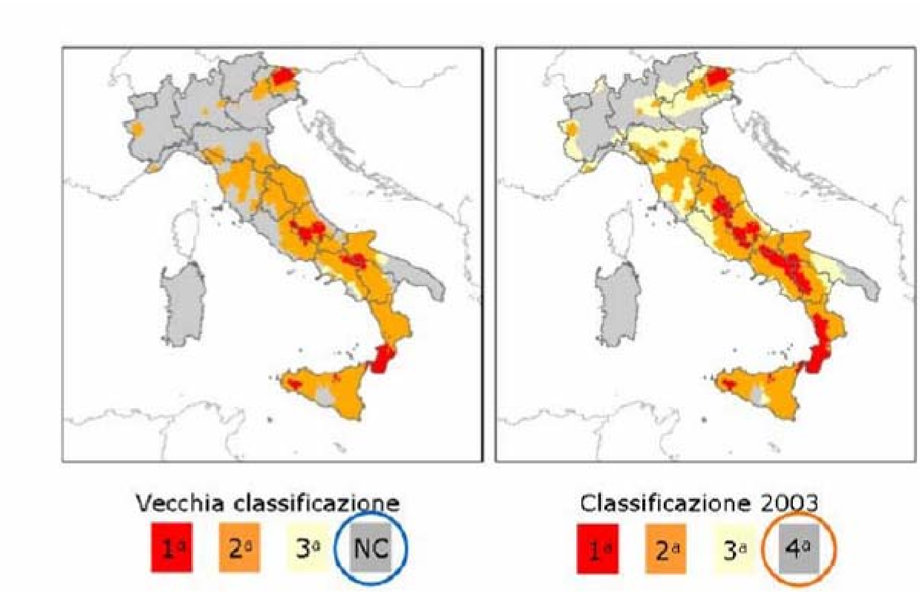


Figure 3. Comparison between old and new classification (DPC-SSN)

The new ordinance 3274 of 2003, brings to 67% the territory subject to seismic events and prescribes a minimum of one design seismic action for each new construction in non-seismic areas.

2. DESIGN CONSTRAINTS AND CHOICES

The design theme was atypical, as it concerned the doubling of existing roading. There had been two main critical aspects governing the design choices:

- constraints on the additional carriageways layout, which necessarily had to follow the existing one;
- the integration with the environmental context, with the necessity of keeping the structure coherent with what had been built previously in the area.

The Client input has obviously been to maintain span lengths, pier dimensions, general conformation and used materials of the existing viaducts. The roadbed of the new carriageway has been enlarged compared to the existing one and comprises of two 3,5m wide carriageways plus one 3,0m wide emergency lane, for a total width of 13m.

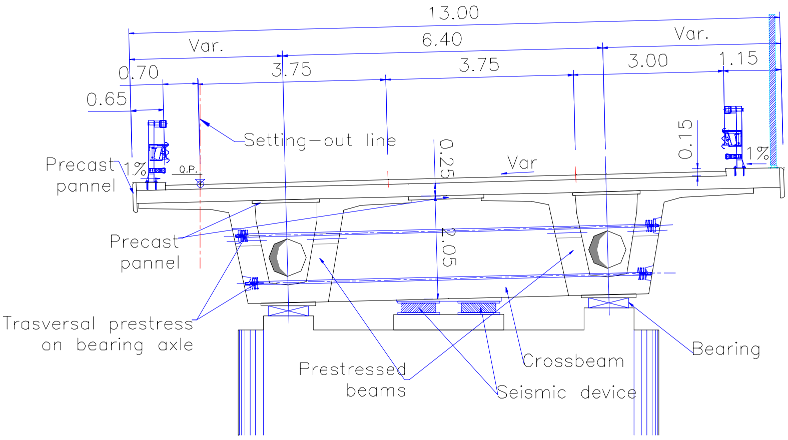


Figure 4. Transversal section

The choice made has been to maintain double box-girders in prestressed-concrete, similar in conformation and height to the nearby viaduct. The spans lengths have also been kept as similar as possible to the existing ones and such to guarantee the minimum axial difference between piers in order to avoid a visually unpleasant "wall effect" and in accordance with the horizontal alignment of the layout. Moreover, constructive requirements connected to beams prefabrication and more in general to construction cost-containment, as well as several interferences experienced at the piers basements, lead to the individuation of three classes of spans of 35,4m, 35m and 28m.

The design process has been long and complex and was concluded with the approval of the DEFINITIVE DESIGN after the completion of the Procedure of Evaluation of Environmental Impact (*design analysis from the environmental integration point of view carried out by Ministry of the Environment together with Territorial Superintendence for Artistic and Archeological Heritage, Local Authorities, etc*), and after CONFERENCE ON SERVICES (*a procedure during which the design has been introduced to local Authorities and all other public and private Administrations interested by the construction, under the mediation of Public Works Authority*),

The chosen solutions have not been dictated solely by the integration with what had been previously built, but also by matters of a more specifically structural nature. First of all, the presence of landslides for long portions of the layout, an issue tackled with solutions similar to those used by the existing viaducts: foundations on caissons 10 to 30m deep and 7 to 10m wide, variable according to the thickness landslide soil layers, with obvious negative effect on costs.

ISSN 1582-3024

Figure 5. Caissons

Solving the issues linked to the site seismicity has been lot more complex.

The area where the viaducts are erected is classified as part of zone II of seismic risk according to the latest zoning of the Italian territory, which confirmed the classification given by the previous normative. The Client insisted for the structure to be classified as strategic (infrastructure that must maintain its functionality even after a disastrous seismic event to guarantee continuity for emergency relief and communications) and as such to be dimensioned with an increasing coefficient for seismic actions of 30%.

In the following paragraphs the variation in the normative approach will be treated in greater detail, what is brought to attention at this stage thought is how the increased cost of the seismic actions to be considered according to the new normative, the peculiar orography of the territory with consequent alternation between short and stout piers and tall and slender ones, the limitations in the piers and foundations dimensions, all concurred in the necessity of reducing as much as possible the seismic phase actions, with the choice of the most efficient seismic decoupling devices available.

Another decisive design choice has been the reduction of expansion joints between spans. This is in accord with the present trend shared by the totality of infrastructures managements, which aims for the reduction of maintenance costs and is also corroborated by the experience accumulated over the years on bridges and motorway viaducts erected mostly according to the simply supported beam scheme that has expansion joints on every pier and abutments.

The length of the treated viaducts lead nevertheless to the necessity of introducing a number of intermediate joints due to two main reasons: (i) the limitation of excursion of the joints and the support devices, having a direct influence on the piers longitudinal dimensions; this aspect brought to a maximum limit of excursion in seismic phase of 250mm; (ii) and the necessity of limiting the longitudinal actions in seismic phase on the slab, which are obviously proportional to the mass connected to it and consequently to the number of connected spans.

On the basis of such considerations, the Sant’Antonio viaduct is divided into 5 minor viaducts with a maximum of 20 spans with continuous slabs, and each of these viaducts is linked in the longitudinal direction with 5 piers placed in their mid-spans.

3. BRIEF DESCRIPTION OF THE STRUCTURES

In this example are described the 777m long Vomano viaduct and the 2504m long Sant’Antonio viaduct which, together with Carestia Gallery represent the main structures for the completion of the doubling of Teramo – L’Aquila motorway in the Appennini tract, as shown in the layout plan below.

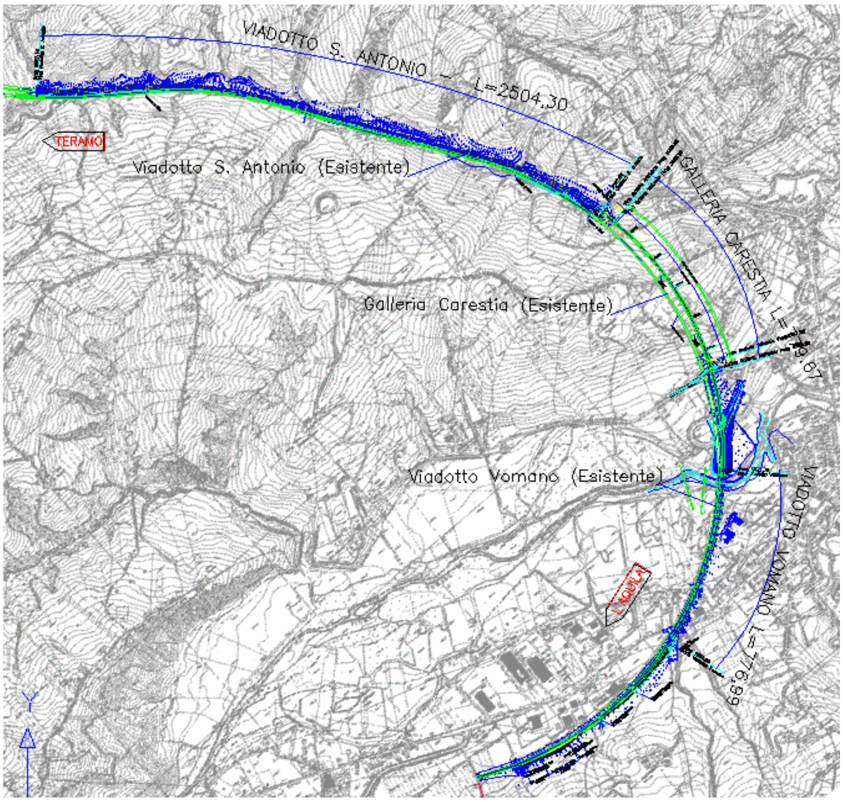


Figure 6. Appenine tract of A24 layout plan

The Vomano viaduct is composed by eighteen 35,4m long and two 28m long simply supported prestressed concrete spans, with continuous slab and no expansion joints, whereas Sant'Antonio viaduct is composed by seventy-two 35,4m or 35m long spans with three expansion joints. Decks are identical for both viaducts and are made of two box-girders 2,05m high, pre-fabricated in situ and prestressed with pre-tensioned strands, and cast in place of two cross-beams at support axis and of the 0,25m thick slab. (see figure 4)

The terrain morphology lead to a great variability of piers heights (4m to 18m), which have a 8,40x3,60m pseudo-rectangular hollow section, with 60cm thick walls.

The choice of viaduct foundation typology was influenced by the presence of landslide soil layers, so that it was necessary to use foundations on caissons of variable diameter and depth as already done with the twin viaduct; such caissons are butted 3m deep into the marlstone substrata.

In other places instead it was opted for more economical foundations on large diameter piles.

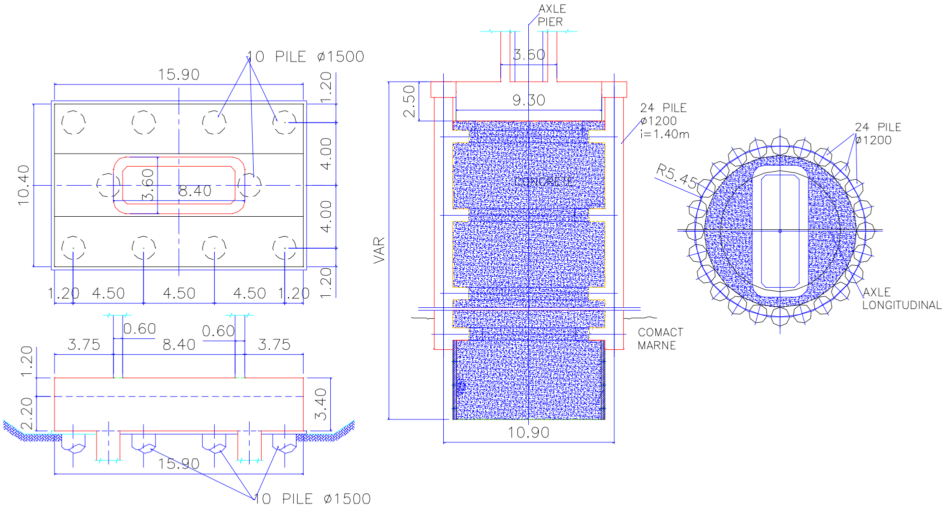


Figure 7. Foundations on plinth and Caisson

The supports scheme of a typical viaduct is shown in the following figures.

- For the longitudinal direction, each sub-viaduct is connected to 5 piers placed near the mid-span of the viaduct itself by means of double-effect, elastic behavior isolating devices; on other piers and on the abutments there are instead mobile supports with maximum excursions of ±260mm;

- for the transversal direction, an elastic bonding device of variable rigidity according to pier height is placed on each pier; fixed bonds are instead placed on abutments and expansion joints piers.

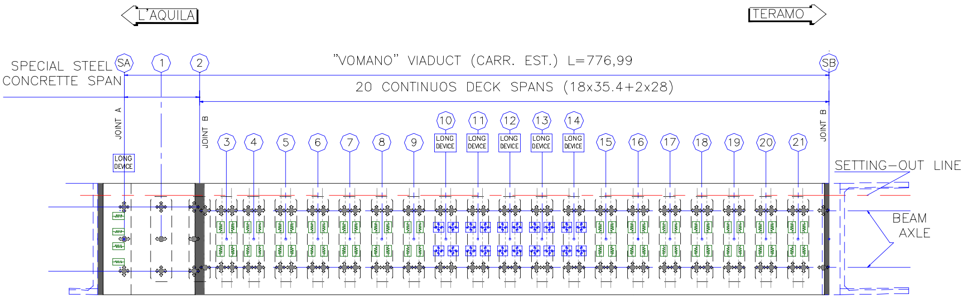
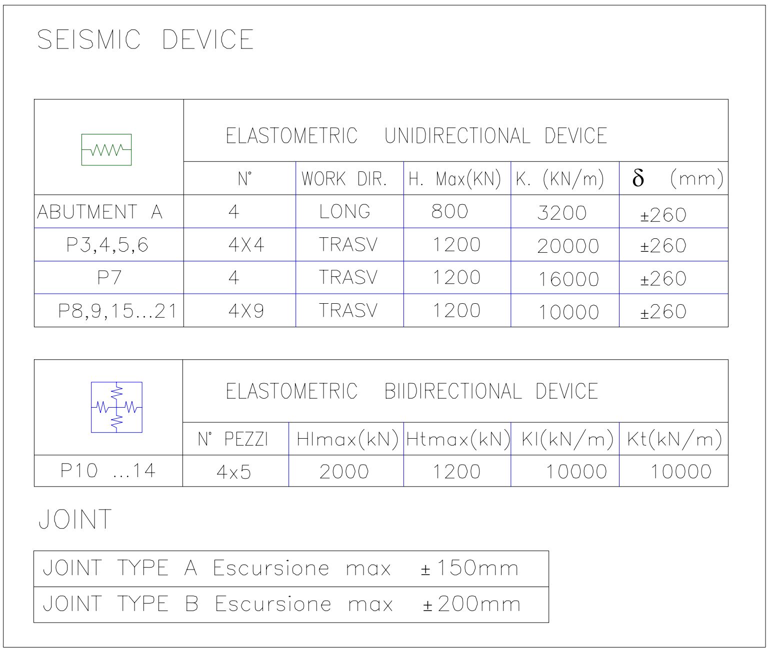


Figure 8. Supports scheme

Table 1. Characteristics of the seismic devices used



SEISMIC DEVICE

	ELASTOMETRIC UNIDIRECTIONAL DEVICE				
	N°	WORK DIR.	H. Max(kN)	K. (kN/m)	δ (mm)
ABUTMENT A	4	LONG	800	3200	±260
P3,4,5,6	4X4	TRASV	1200	20000	±260
P7	4	TRASV	1200	16000	±260
P8,9,15...21	4X9	TRASV	1200	10000	±260

	ELASTOMETRIC BIIDIRECTIONAL DEVICE				
	N° PEZZI	Hlmax(kN)	Htmax(kN)	Kl(kN/m)	Kt(kN/m)
P10 ...14	4x5	2000	1200	10000	10000

JOINT

JOINT TYPE A Escursione max	±150mm
JOINT TYPE B Escursione max	±200mm

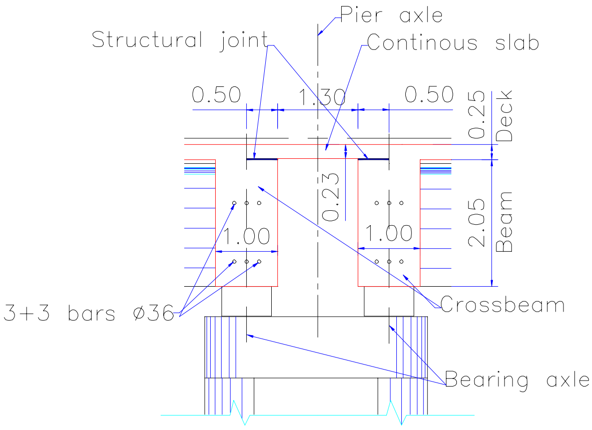


Figure 9. Continuity slab

The longitudinal expansion joints are dimensioned to guarantee creep due to normal service and frequent seism, implicitly accepting the cost of substitution in case of an exceptional seismic event which might break them.

4. SEISMIC ISOLATION

As it's widely known, the seismic isolation of a structure represents a very efficient technique to guarantee security against collapses and damages to persons and/or other structures in case of a catastrophic seismic event, and it is therefore expressively suggested by normative, especially in sites of medium to high seismicity. In the case of bridges and viaducts such technique finds its natural implementation due to their "mono-dimensional" conformation and their structural response. The new Italian seismic legislation, adhering to international regulations and specifically to the Eurocodes approach, proposes two main methodological approaches for the dimensioning of bridges under seismic actions: "elastic" or "ductile".

The "ductile" approach has never managed to be properly implemented due to its lesser cost-effectiveness particularly for the dimensioning of foundations works. The ductile approach consists in dimensioning the works with a "design" spectrum reduced, in comparison to the elastic one predicted for the site, by a structural coefficient "q>1"; the reduction varies according to several characteristics such as the capacity of the sub-structures to guarantee a pronounced ductile behavior. Such attitude for a structure consists in its ability to guarantee great deformation in post-elastic phase before reaching the breaking threshold and is exemplified by the

ISSN 1582-3024

formation of plastic hinges where the beneficial effect of energy dissipation is concentrated. About this, together with dispositions and constructive details widely codified by normative for different structures, the conformation and dimensioning of the sub-structures is of paramount importance. Viaducts with tall and slender piers (high H/b ratio), can be dimensioned with high structural coefficients (4,5); whereas with short and stout piers or, as the case in exam, with alternation or great irregularity of height and distribution of rigidity, lower structural coefficients are applied (1,5-2).

In the case of the viaducts in exam, the peculiar orographic conformation of the site has required short and stout piers alternated to much more slender ones and, more in general, a not-homogeneous distribution of rigidity, which impaired the regularity criteria determining reduced structural coefficients, which in turn readdressed the calculation to an “elastic” approach. The following picture shows the comparison between the two spectra.

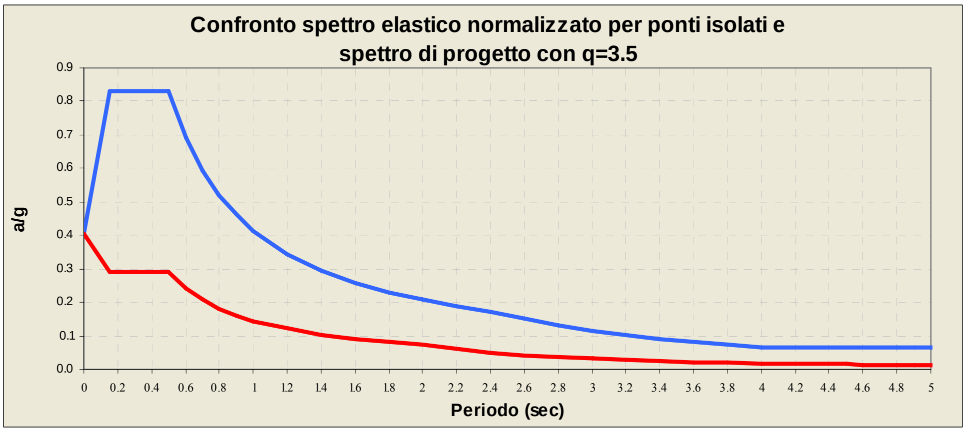


Figure 10. Comparison between “ductile” and “elastic” approaches

It is evident how the “elastic” approach is more demanding; in some cases it might then be more cost-efficient the use of passive control techniques of structural response such to reduce the seismic effects. There are several solutions that have been developed over the years and in this field the Italian experience is at the forefront with many companies manufacturing advanced systems.

In the case in exam the isolation technique has been applied which consists in the use, between two structural portions, of decoupling devices able to modify the response of the structure subject to seismic action. The isolated structure must remain in an essentially elastic phase and, because of this, structural coefficients of q>1,5 are not allowed, so that their structural behavior during seismic event can be univocally determined.

The nature of such devices can vary (elastic, elastic-plastic, elastic-viscous), depending on the required effect. For the viaducts in exam simple elastic devices in vulcanized rubber with shear behavior were used, and they isolate the macro-viaducts in both longitudinal and transversal directions.

The usage of elastic-plastic devices would have allowed for example the introduction of a threshold to the forces transmitted by the device itself and thus to limit the stresses to the substructures with a general increase of the allowed displacements on the joints, as well as the costs and maintenance expenses.

In the following notes, a brief comparison between the various approaches mentioned above is given, showing the cost-effectiveness of seismic isolation in situations analogous to those of the viaducts in exam, re-enacting the logic progression of the chosen solutions.

INPUT DATA

- Infrastructure typology: roadway viaduct on 35,4m long spans, with 11,20m wide roadbed comprising two 3,5m carriageways plus 3,0m emergency lane;
- Structural typology: p.c. viaduct with prefabricated beams and cast in place continuous slab; total length of macro-viaduct: 660m; weight: 155000kN;
- Seismic zoning: site in zone II (ag=0,25), terrain type E (S=1,25), strategic work (I=1,3).

DESIGN CONSTRAINTS

- Landslide surface soil; necessity of limiting foundations stresses;
- Limiting of deck-pier relative displacements ($\delta_{max} = 25$cm);
- Span lengths fixed to follow the existing twin viaduct.

DESIGN APPROACHES

A. Isolated structure: intervention aimed at modifying the structural response → isolated structure → long. isolation or transv. isolation or long.+transv. isolation

B. Non-isolated structure: determination of fixed elements on which “release” the horizontal actions;

    B1. slender piers (design spectrum approach → constructive details to guarantee sufficient ductility → structural factor q>1 → criteria of resistance hierarchy check;

    B2. stout piers or abutments → structure must remain in elastic phase → q=1-1,5.

Case A1 – ELASTIC ISOLATORS

N° FIXED PIERS= 5 piers= 17,7m

Devices= elastic devices with double rigidity effect= 40000kN/m/pier

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Total rigidity kTot= 200000kN/m

Elementary oscillator vibration period $T0 = 2\pi\sqrt{m/kTot} = 1{,}77$ sec

Seismic analysis → elastic spectrum for isolated bridges:

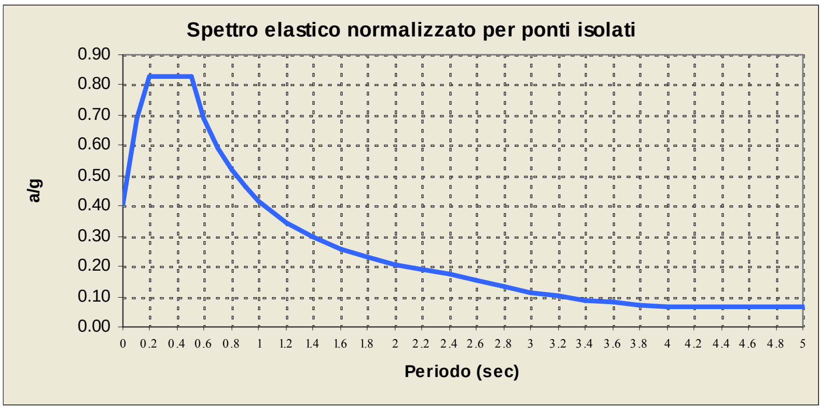

Figure 11. Elastic spectrum for isolated bridges

a/g=0,25, S=1,25, $\gamma I = 1{,}3$, $\mu = 10\%$

Corresponding spectral ordinate → S(T0)= 0,2343 → H= 1550000 x 0,2343 ≈ 36200kN

For each pier H= 36200/5 * 1,15 (coefficiente di sovra-resistenza)= 8326kN

Maximum seismic displacement $\delta l = 208$mm

Case A2 – ELASTIC-PLASTIC ISOLATORS

It is possible to identify two variants:

- to connect the same 5 piers as in the previous example;
- to create a seismic retaining device on one of the abutments.

In the first case the same condition as in case A1 is obtained, but with slightly more expensive supplying costs and higher maintenance costs, with the end result of a reduction in actions transmitted to the sub-structures, but with larger displacements.

The second case would be of difficult application in the situation in exam due to the viaduct length and the displacements geometric limit.

Pros: limitation of design actions on substructures and foundations, lesser cost and complexity of piers ordinary reinforcement.

Cons: large displacements, greater cost for expansion joints.

Case B1 – NON-ISOLATED STRUCTURE IN DUCTILE APPROACH: q>1

N# FIXED PIERS= 5/h= 17,5m

Joint devices: fixed joint on central pier and impulsive type couplers on the two couple of adjacent piers.

Pier stem rigidity: Jpier= 23,4m^4; k= 3EJ/h3= 4,4E + 0,5kN/m

Total rigidity kTot= 2,2E + 0,6kN/m

Elementary oscillator vibration period T0= 2 π √ m/kTot= 0,53sec

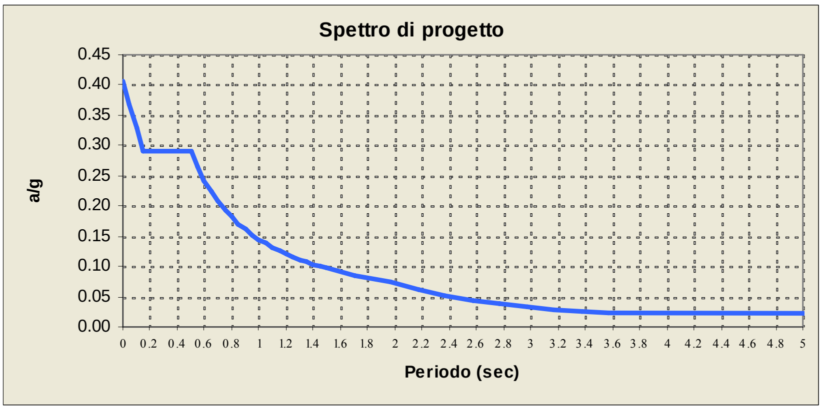

Figure 12. Design spectrum

Seismic action → Design spectrum with q= 3,5: a/g=0,25, S=1,25, γI= 1,3, μ= 5%,

Corresponding spectrum ordinate → S(T0)= 0,273 → H= 1550000 x 0,273 ≈ 42315kN

For each pier H= 42315 / 5= 8463kN

Pros: limitation on displacements and reduction of actions for checks of piers sections;

Cons: coupling devices cost, greater cost of piers ordinary reinforcement to guarantee sufficient ductility, greater actions on foundations with consequent cost increase.

Case B2 – NON-ISOLATED STRUCTURE WITH STOUT SUBSTRUCTURES (piers or abutments)

Horizontal actions too great → modification of structural scheme and/or lighter deck.

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5. CONSTRUCTION METHODS

The erection of the structure in exam imposed a careful study of the building site activities, especially in the case of Sant'Antonio viaduct. This was due to the presence of an existing viaduct in service and a torrential river which, in several occasions, interfered with the foundations of the new viaduct.

To complicate the situation further, was the presence of large portions of landslide soil layers that, as well as influencing the choice of foundations as mentioned above, required expensive and difficult site protection works (Φ1000 pile bulkheads).

Two building sites were appointed: the main one placed in correspondence with Vomano viaduct was used as prefabrication and stocking site for the prestressed beams; these were later launched by means of a metallic launching equipment.

Figure 13. Caisson foundation

Figure 14. Beams prefabrication site

Figure 15. Launching of a beam

Figure 16. Launching of a beam

6. CONCLUSIONS

What explained above, even with such ordinary structural typology, could be an example of correct design approach, which is to aim toward the right mediation between structural and security requirements, as well as limiting construction and maintenance costs of the structure to be erected. Concerning this, the introduction of new legislation brought on a real revolution in design approach that involved non only new works, but also those already erected which now have to be conformed to new dispositions.

Seismic isolation finds wide application in this area. There are several examples of this kind of interventions on existing motorway viaducts, some of them designed by the author, that making use of seismic isolation allowed the structure adjustment to the new legislation and further development of the motorway networks, while sensibly limiting costs. In some cases for example it was possible to maintain foundations and substructures, limiting interventions to decks by modifying or changing them with lighter ones (steel – concrete).

Figure 17. Application example of seismic isolation of existing viaducts by decks substitution and deployment of elastic-plastic dissipators on abutments

Generally speaking, it is possible to synthesize the Italian experience in bridge seismic isolation by defining it a relatively less expensive technique which, in association with a correct design approach as well as a correct construction procedure, allows to effectively and elegantly solve the issue of conformation to seismic regulation even for large structures.