UDC 624.21:624.04:550.34.03
Review paper
Received: 02.09.2002.

Engineering modelling of seismically isolated viaducts

Tatjana Isaković and **Matej Fischinger**
University of Ljubljana, Faculty of Civil and Geodetic Engineering, Jamova 2, SI-1000 Ljubljana, SLOVENIA
e-mail: tatjana.isakovic@fgg.uni-lj.si; matej.fischinger@fgg.uni-lj.si

SUMMARY

The basic principle of seismic isolation is simple: to reduce seismic actions applied to the structure using special isolation devices. First, since the seismic isolation is a relatively new technology this basic principle is described in the paper. Then some recommendations for modelling the isolation devices are given.

Isolated bridges are sensitive to several parameters, which usually do not affect the structures without isolation. Therefore more exact methods of analysis and models are usually necessary for the isolated structures. Especially important are precise models of pier foundations and the ground, the earthquake load in the long period range, a friction in sliding bearings, and column masses.

The influence of most important parameters on seismic response of isolated viaducts is discussed and illustrated on the example of the first isolated viaduct in Slovenia - viaduct Ločica. The viaduct is situated at the site, where the problematic ground characteristics are combined with relatively strong seismicity. Nevertheless, due to the seismic isolation it was possible to choose common dimensions of structural elements, which were not greater then those, based on non-seismic loads.

Key words: *engineering modelling, viaduct, seismic isolation, isolation device, seismic response.*

1. INTRODUCTION

The traditional seismic design relies on seismic energy dissipation due to the flexural damage of structural components. However, in such approach it may be difficult to control the extent of damage. Moreover, in some cases (e.g. in the case of very important bridges) the designer should prevent any damage at all. This may demand structural dimensions, which are uneconomic or even impossible to achieve. The solution is to reduce the seismic actions using the special isolation devices. It is possible to classify these devices as isolators or dampers. First group enlarge the flexibility of the structure and the second enhance the damping of the structure.

The basic principle of seismic isolation is simple, however its implementation in practice can be quite demanding. Behaviour of the isolated structures is time dependent and nonlinear. More precise data about the seismic load than in the structures without isolation are needed. Very precise data about the isolation devices are also needed. These characteristics are changing over the time. All these facts make the analysis of seismically isolated bridges quite challenging. Since the problem is complex, the authors believe that nonlinear time-history analysis is necessary for seismic design of isolated viaducts. Possible ways of engineering modelling of these structures, which include various types of isolation devices, are described in Section 3.

The most of the authors' practical experiences regarding the isolated viaducts have been obtained during the analysis of several potentially isolated viaducts on the new highways in Slovenia. One of them, viaduct Ločica (the first seismically isolated viaduct in Slovenia) has been already completed. The viaduct and the system used for its seismic isolation are briefly described in Section 4.

During the analysis of seismically isolated viaducts authors have realised that the response of the seismically isolated viaducts is influenced by several parameters, which usually do not affect the response of conventionally designed bridges. These parameters are described in Section 5. Their influence is illustrated using the results of the analysis of the viaduct Ločica.

2. BASIC PRINCIPLE OF SEISMIC ISOLATION

The basic idea of seismic isolation is to reduce the seismic actions and consequently to reduce or totally prevent the structural damage. When the seismic actions are reduced the dimensions of the structural elements can be typically decreased, too.

Two systems can be used for the reduction of seismic actions:

- Using special very flexible devices - isolators, the stiffness of the structure is reduced and consequently the period of the structure becomes longer. When the period is enlarged the seismic actions are typically reduced (see Figure 1). This technique corresponds to the basic definition of seismic isolation. Devices, which are frequently used to lengthen the natural period of viaducts, are elastomeric bearings. These devices are typically situated between the superstructure and columns.
- The seismic load could be also reduced if the energy dissipation capacity of the structure is enhanced (see Figure 1). This can be achieved using the special devices - dampers. Such devices are usually damaged and replaced after strong earthquakes. They are situated at the top of the columns or/and abutments.

In practice a combination of isolators and dampers are most frequently used for the seismic isolation of viaducts. This combination has been also used for the isolation of the viaduct Ločica (see Section 4).

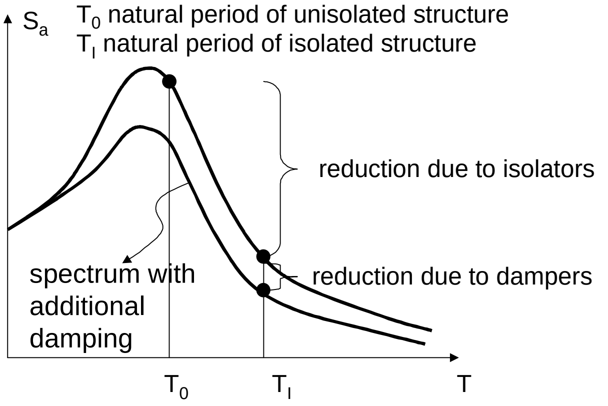

Fig. 1 Basic principle of the seismic isolation

3. ANALYSIS AND MODELLING OF THE ISOLATED VIADUCTS

When analysing the seismicaly isolated viaducts the following dynamic equation should be solved:

$$\boldsymbol{M}\ddot{u} + \boldsymbol{C}(t,\dot{u})\dot{u} + \boldsymbol{K}(t,u)u = \boldsymbol{F}(t)$$

In this equation the $\boldsymbol{M}$, $\boldsymbol{C}$ and $\boldsymbol{K}$ are mass, damping and stiffness matrix, respectively. Vectors $\ddot{u}$, $\dot{u}$, u and F are acceleration, velocity, displacement and load vectors, respectively. Time is denoted as t.

The problem is quite complex since the damping and stiffness matrices as well as the load vector are changing over the time. Changes of the load vector depend on the applied accelerogram. In isolated structures stiffness matrix is additionally changing due to the changes of the stiffness of isolation devices. These changes depend on the force level in the isolation devices. The damping of the isolation devices depends on the velocity. Since the velocity in isolation devices is changing over the time the damping matrix is also changing. Changes of the velocity of the system are influenced also by the applied load.

Since the behaviour of isolated bridges is nonlinear, it is recommended to use nonlinear methods for their analysis. Recently some simplified methods for nonlinear analysis have been developed (e.g. [2]). They proved to be successful in some cases. However, the authors believe they can be predominantly used in initial phases of the design for the preliminary optimisation of the isolation system. For final analysis the nonlinear time-history analysis is recommended, since the simplified methods may not address the whole complexity of the problem. Various programs can be used to perform this tape of analysis, e.g. Drain 3DX [3], OpenSees [4], etc. The first one was used for the analysis of the viaduct Ločica, too (see next sections). These programs enable the use of relatively simple models for various types of isolation devices (isolators and dampers). They are described in the next subsections.

Modelling of isolators

A model of seismic isolators is usually similar to that presented in Figure 2. The basic characteristics of this model are: initial stiffness K_{intl}, force under which the initial stiffness is changed F_y, stiffness K_0, maximum displacement u_{max} and maximum force in isolator F_{max}. The data about u_{max} and F_{max} is usually provided by the manufacturer of the device. The stiffness K_{intl}, K_0 and force F_y are usually based on the damping coefficient of the device ξ, which should also be declared in the manufacturer's specification of the device. The calculation procedure can be found in Refs. [5] and [6]. To obtain the behaviour presented in Figure 2 two contact elements (No. 4) in the program Drain 3DX can be used. One element has perfectly elastic and the second perfectly elastoplastic behaviour.

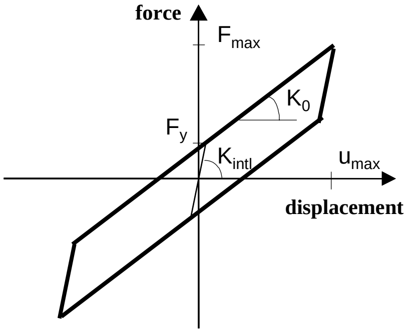

Fig. 2 Model of isolators

Modelling of dampers

The viscous dampers can be modelled as it is shown in Figure 3. The basic characteristics of the model are: initial stifness K_{intl}, yielding force F_y, and the strain hardening (the ratio between stiffness after device yielding and the initial stiffness). These data should be calculated based on the data about the damping and the velocities of the damper. All necessary data should be provided by the manufacturer of the device. These devices can shorten the period of the structure in the initial phase, due to the usually very large initial stiffness. However, the period usually becomes significantly longer when the yielding is reached, since the stiffness after yielding is practically zero.

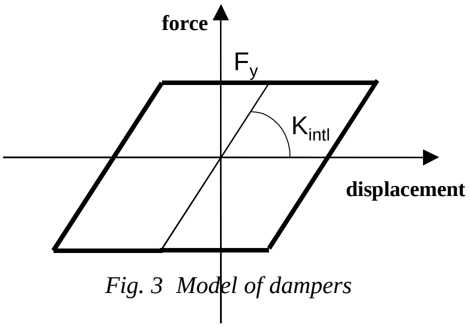

Fig. 3 Model of dampers

In the program Drain 3DX, the behaviour presented in Figure 3 can be modelled using a contact element (No. 4) with ideal elastoplastic behaviour.

Modelling of sliding bearings

Sliding bearings (teflon) can be modelled in a similar way as dampers, using elastoplastic beam elements (see Figure 3). The yielding force *Fy* is usually based on the friction coefficient of the bearing. Even if the precise data exist, it is recommended to consider a range of values for friction during the analysis. This is necessary because bearing properties are constantly changing due to the weather conditions, temperature, different maintenance procedures etc. If there is no exact data, values between *0%* and *4%* can be used, considering the most unfavourable case.

Sliding guided rubber bearings (combined elastomeric and teflon bearings) can be modelled with two elements, one elastoplastic and one elastic beam element. Resulting hysteretic loop is presented in Figure 2.

4. SEISMIC ISOLATION OF THE VIADUCT LOČICA

Description of the viaduct

The superstructure of the Viaduct Ločica is eleven span continuous box girder, supported by abutments and ten single-column piers (see Figure 4). The total length of the viaduct is *849 m*. The height of the columns varies from *21.7 m* to *38.7 m* (see Figure 5). All columns are founded on foundation shafts.

The viaduct is situated at the site, where the low stability of the soil is combined with a relatively strong seimicity ($a_{gmax}=0.26\ g$). However, the earthquake load was not initially considered in the design of the foundations. Dimensions of columns' foundations were calculated to be as small as possible, in order to reduce the possibility of soil sliding. Therefore, without some additional mechanisms, the capacity of foundation would not be enough to carry relatively strong earthquake load [7].

Description of seismic isolation

To prevent the damage of foundations subjected to earthquake load, the viaduct was seismically isolated. The isolation devices were designed to reduce the earthquake load in such amount that the bending moments in foundations did not exceed the bending capacity of foundations needed to carry non-seismic load.

The scheme of the base isolation is presented in Figure 5. The elastomeric bearings combined with hydraulic dampers are used for isolation.

In the longitudinal direction "fixed" rubber bearings at piers P5 and P6 are used to isolate the structure. Due to the large flexibility of these bearings, the stiffness of the whole system and consequently seismic load in the longitudinal direction is reduced. At the top of all other columns elastomeric sliding (one or multidirectional) bearings are situated. These bearings resist friction forces only. Between the deck and the abutment hydraulic dampers, acting in the longitudinal direction are placed. The function of these devices is to reduce large displacement of the superstructure and to prevent impact of the superstructure and the abutments. They enable unconstrained displacements due to the regular "slow" load (temperature, creep, etc.), while they reduce the displacements caused by an earthquake. Since the response of the viaducts with a very long fundamental period (up to 7 s) is uncertain, dampers also provide the second line of defence to the structure.

In the transverse direction rubber bearings at piers P5 and P6 and elastomeric bearings at both abutments as well as at the top of the piers P3 - P7 and P10 are used to reduce the stiffness of the structure as well as seismic forces. Hydraulic dampers at piers P1 - P2 and P8 - P9 are installed to reduce the transverse displacements (enhance the damping) of the deck. Other bearings resist friction forces only.

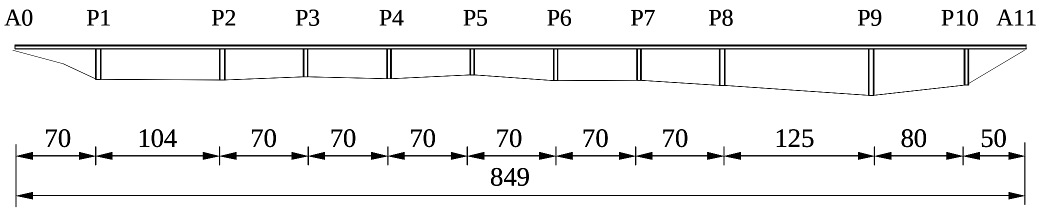

Fig. 4 Viaduct Ločica

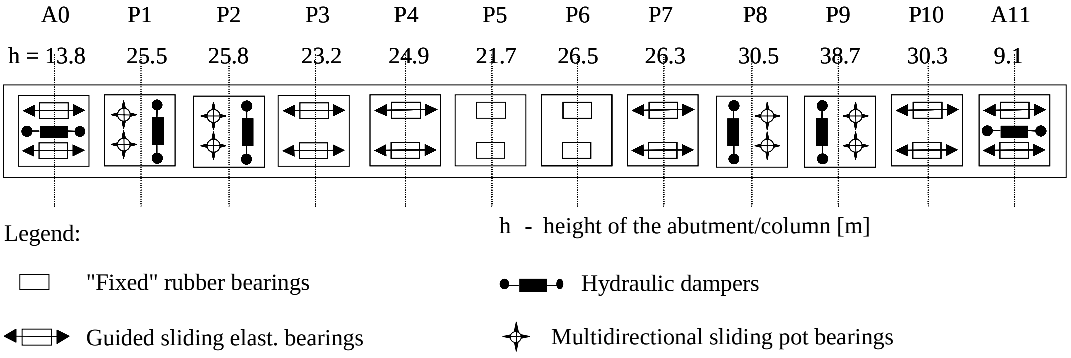

Fig. 5 Scheme of the isolation system of the viaduct Ločica

In both longitudinal and transverse direction the re-centring of the deck is provided through the restoring force of rubber bearings and small friction of elastomeric sliding bearings.

Seismic load

Seismically isolated viaducts are more sensitive to a type of applied earthquake than structures without seismic isolation. Therefore it is strongly recommended to generate an earthquake load specific for the site of the viaduct. This was also done for the viaduct Ločica (see Figure 6). The accelerogram was generated according to Eurocode 8/2 using elastic spectrum given in this standard.

5. IMPORTANT PARAMETERS INFLUENCING THE RESPONSE OF SEISMICALLY ISOLATED VIADUCTS

As mentioned in the previous section, one of the most important parameters, which influence the response of isolated viaducts is the applied accelerogram. In Figure 7 the displacement time history of an isolation device (in the viaduct Ločica) subjected to two different accelerograms is presented. These accelerograms resulted in very different displacements.

Next parameter, which influences the response of isolated viaducts, is friction in sliding bearings. Since these data are usually very uncertain (e.g. because of the weather, maintenance, etc.) and difficult to obtain, a range of values should be used to obtain the most unfavorable case. The influence of friction in sliding bearings on the response is illustrated in Figure 8. Envelopes of shear forces obtained for three different values of friction (*0.3%*, *1%* and *4%* of a tributary vertical load) are presented. Results are significantly different. In the majority of the columns (columns with sliding bearings) the largest forces were obtained for *4%* damping.

The analysis of viaduct Ločica confirmed the well-known fact that an isolated structure is very sensitive to modelling of the interaction between foundation and soil. An example is presented in Figure 9. Envelopes of the shear forces in columns for two different foundation models are compared. When the stiffer model of foundations (FGG2 - stronger fixity of the shafts into the soil) is employed, seismic load is greater and as the final result shear forces are considerably greater than in the second, more flexible model.

The properties of the isolating devices influence the response of the deck as well as the response of piers. When the connection between superstructure and columns is relatively weak (sliding bearings or isolating devices with highly non-linear behaviour), the seismic properties of isolated columns have considerable influence on the response. For example in the viaduct Ločica shear forces in some columns are increased for more than two times because of the accelerations of the column mass. Therefore, in some columns shear forces are considerably larger than those which are transmitted from the superstructure to the columns through isolating devices only. Contrary to the conventional bridges, where the half of the column mass is typically added to the superstructure mass, in seismically isolated structures mass of the column must be modelled precisely and separately form the mass of the superstructure.

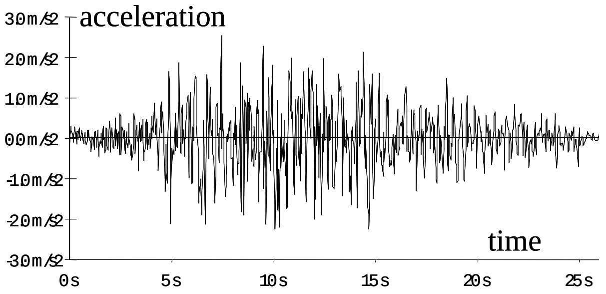

Fig. 6 Accelerogram, specific for the site of the viaduct Ločica

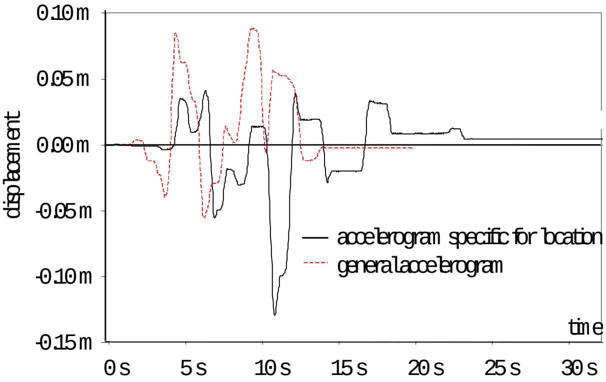

Fig. 7 Displacement time history of isolation devices subjected to different accelerograms

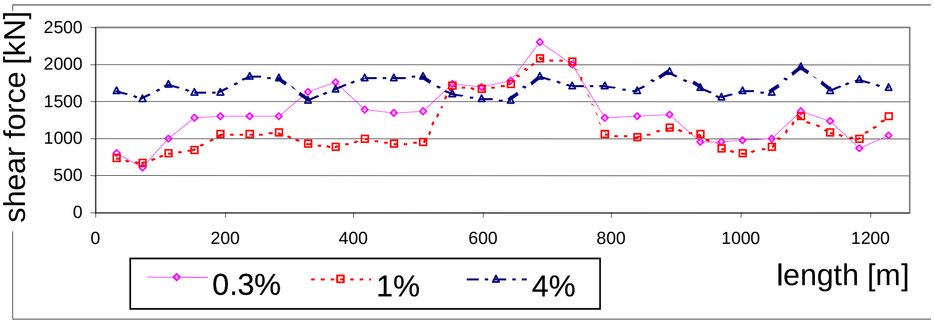

Fig. 8 Shear forces in columns when various amounts of friction in sliding bearings are considered (Viaduct Blagovica)

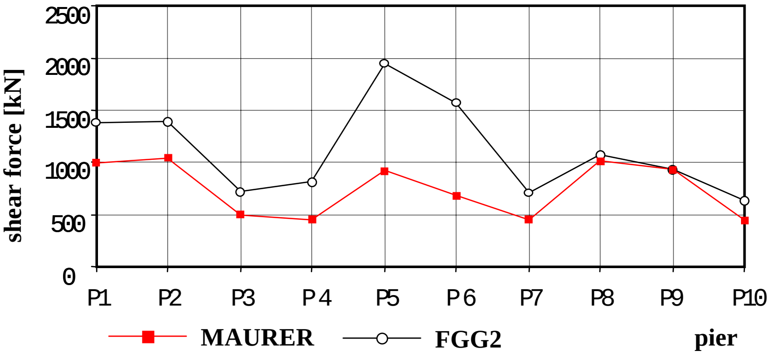

Fig. 9 Influence of different foundation models to the response (viaduct Ločica)

Important parameter, which has to be considered when choosing an isolation system is the ability of the re-centring. Since the displacements of isolated structures are usually relatively large, deformations of the isolating devices are large, too. If these deformations are plastic, the whole structure can be permanently displaced. Once the structure is permanently displaced, it is difficult to return it to initial state. In the viaduct Ločica the system of isolation itself is able to re-centre the structure. This is illustrated on Figure 7, where displacements of one of the isolating devices are presented. The permanent plastic deformations of the device are negligible.

Based on the study of the viaduct Ločica and some other viaducts and parametric studies [7, 8] it is concluded that for the efficient isolation different types of the devices should be combined: elastomeric bearings, which behave predominantly elastic and e.g. hydraulic dampers with elastoplastic behaviour.

6. CONCLUSIONS

Response of the seismically isolated viaducts is in many cases more complicated than the response of conventionally designed structures. Therefore more precise methods of analysis and models of a structure are necessary. The nonlinear time-history analysis is strongly recommended. However, the model of a structure should be as simple as possible to enable the control of quite complicated response. The engineering models including combination of beam and contact elements (elements with zero thickness) can be successfully used for the analysis of isolated bridges.

When modelling the seismically isolated viaducts several parameters, which are usually neglected in the analysis of the traditionally designed structures, should be taken into account:

1) The interaction of the isolated viaduct with the foundation soil should be modelled quite precisely since it significantly influence the overall response.

2) Response of the seismically isolated viaducts is very sensitive to the type of the applied seismic load, too. Therefore the seismic load should be modelled more precisely than for the conventional structures. The best solution is to generate the seismic load, which is specific for the location of the viaduct.

3) When modelling seismically isolated bridges the friction in sliding bearings (which is usually neglected in the analysis of traditional bridges) should be taken into account.

4) Masses of columns should be also modelled more precisely, especially in the cases where the connections between superstructure and columns are weak.

7. AKNOWLEDGEMENTS

The authors would like to express their gratitude to Renzo Medeot, who made initial proposal for isolation system of the viaduct Ločica. Some results presented in the paper are part of the graduating thesis of Marko Žibert.

8. REFRENCES

[1] Eurocode 8/2 - Design provisions for earthquake resistance of structures - Part 2: Bridges, European Prestandard ENV 1998-2, CEN, Brussels, 1994.

[2] M.J.N. Priestley, F. Seible and G.M. Calvi, *Seismic Design of Bridges*, John Wiley & Sons, New York, Chapter 6 - Design of bridges using isolation and dissipation devices, pp. 457-533, 1996.

[3] V. Parkash, G.H. Powell and F.C. Filippou, DRAIN-3DX: Base program user guide, Department of Civil Engineering, University of California, Berkeley, USA, 1993.

[4] F. McKenna and G.L. Fenves, The OpenSees Command Language Manual - Version 1.2, PEER Center, University of California, Berkeley, 2001.

[5] P. Fajfar, *Dinamycs of Engineering Structures*, Faculty of Civil and Geodetic Engineering, University of Ljubljana, Ljubljana, 1984. (in Slovenian)

[6] R.I. Skinner, W.H. Robinson and G.H. McVerry, *An Introduction to Seismic Isolation*, John Wiley & Sons, Chicester, England, 1993.

[7] M. Žibert, Seismic isolation of viaducts, Diploma Thesis, Faculty of Civil and Geodetic Engineering, University of Ljubljana, Ljubljana, 2000. (in Slovenian)

[8] M. Kolenc, Parametrical study of the seismic isolation of the viaduct Blagovica, Diploma Thesis, Faculty of Civil and Geodetic Engineering, University of Ljubljana, Ljubljana, 2000. (in Slovenian)

INŽENJERSKO MODELIRANJE POTRESNO IZOLIRANIH VIJADUKATA

SAŽETAK

Osnovno načelo potresne izolacije je jednostavno: smanjiti potresna djelovanja na konstrukciji pomoću specijalnih naprava za izolaciju. S obzirom da je to relativno nova tehnologija, u članku je najprije opisan njezin osnovni princip. Potom su dane upute za modeliranje naprava za potresnu izolaciju.

Na potresni odgovor izoliranih mostova utječu mnogi parametri, koji na odgovor klasičnih konstrukcija najčešće imaju zanemarljiv utjecaj. Zato analiza i modeli izoliranih konstrukcija moraju biti precizniji nego što je to slučaj kod klasičnih konstrukcija. Pri modeliranju potresno izoliranih vijadukata iznimno je važno precizno modelirati interakciju stupova i tla, potresno opetrećenje u području dugih perioda, trenje u kliznim ležajevima i mase stupova.

Utjecaj najvažnijih parametara koji utječu na odgovor potresno izoliranih vijadukata u članku je prikazan na primjeru prvoga potresno izoliranog vijadukta u Sloveniji - Vijadukta Ločica. Konstrukcija se nalazi na vrlo problematičnom tlu u području relativno jake seizmičnosti. Uprkos nepovoljnim parametrima, zahvaljujući primjeni potresne izolacije izgradjen je vijadukt uobičajenih dimenzija.

Ključne riječi: *inženjersko modeliranje, vijadukt, potresna izolacija, izolacijska naprava, potresni odgovor.*