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CALCULATION OF CONTINUOUS REINFORCED CONCRETE BRIDGES AND OVERPASSES IN SEISMICALLY HAZARDOUS AREAS

Shermukhamedov U.Z.[1,a)], Karimova A.B. [1,b)], Zakirov B.S. [1,c)]
[1]*Tashkent State Transport University, Tashkent, Uzbekistan*

[a)]*Corresponding author: e-mail: ulugbekjuve@mail.ru*
[b)] *e-mail: tillaboyeva_anora_karimova@mail.ru*
[c)] *e-mail: botirzakirov@list.ru*

Abstract. In recent years, in the Republic, the design and construction of continuous reinforced concrete bridges and overpasses were conducted at a colossal pace. Foreign advanced technologies, methods, and software systems were taken into account. Foreign experience in studying rubber-metal bearing parts of bridges and overpasses was analyzed. The article presents the calculation of a continuous reinforced concrete overpass for seismic impacts using the finite element method in the framework of the linear spectral theory. Numerical calculations have shown that the bearing part of the right end of the overpass does not allow the span to fall from the abutment because the maximum displacement of the rubber-metal bearing part is 0.2 m. As a result, the span structure and overpass supports have an overestimated margin of safety for an 8-point earthquake, according to MSK-64.

Keywords: bridges and overpasses, seismic isolation, support parts, span structure, pier, compression and tension, monolithic structures.

INTRODUCTION

Throughout the centuries-old history of human civilization, artificial structures (bridges, viaducts, aqueducts, and overpasses) served as an image of the beauty of cities, localities, and countries. As we know, these artificial structures are an integral part of the transport system; however, thanks to their beauty and elegance, they have become symbols of the best and most beautiful structures mankind has created, and they attract tourists worldwide [1].

Over the past 40-50 years, many interesting solutions were made in bridge engineering, which brought new types of bridges, such as cable truss bridges, split pre-stressed concrete bridges, long span bridges, etc. [2, 3].

In recent years, there has been an increased interest in the world in the modernization and expansion of the road network, including bridge structures, using modern technologies and designs of bridges and overpasses made of monolithic reinforced concrete. Even though monolithic construction began its development relatively recently, at present, this method of construction is considered the most promising one [4, 5]. Monolithic bridges are used in all developed countries worldwide. Monolithic engineering is a method of erecting buildings and structures in which the main material of the structures is monolithic reinforced concrete. The reinforced concrete structure is strong and durable and has high performance. The main feature of monolithic construction is that the construction site is the place to produce materials for monolithic bridges and other engineering structures. The use of monolithic reinforced concrete makes it possible to implement various architectural forms and reduce steel consumption by 7–20% and concrete by 10–12% [5, 6].

To improve the Republic of Uzbekistan's transport infrastructure, monolithic bridges and overpasses are widely used (Fig. 1). A clear example is the new overpass, which is being used built on the 1083rd km of the M-39 highway passing through the city of Samarkand.

Another example is the construction of a six-lane highway and three overpasses in Tashkent that connect the Sergeli district with the city's center. The overpass construction, which soon will become another excellent example of the creativity of architects, is carried out based on the latest technologies following international standards.

Fig. 1. Modern continuous (monolithic) reinforced concrete overpasses built in Samarkand.

It is known that the territory of Central Asia, especially Uzbekistan, is a seismically active zone. As a result, the design and construction of bridges, overpasses, and trestles must be highly demanding. In this regard, it is of interest to develop methods and software to conduct calculations of bridges and overpasses for the effect of seismic impacts.

The intensive development of information technology has given a big breakthrough to a radical improvement in the design and analysis of artificial structures, such as bridges and overpasses with continuous spans and modern seismic isolation devices (spherical sliders and rubber-metal supports), considering the loads acting during strong earthquakes.

It should be noted that more than twenty monographs were published on the issues of seismic isolation and seismic attenuation of bridge structures. Classifications of seismic isolation devices are given in [7-12] and other studies. In [11, 12], the issues of seismic isolation and seismic attenuation of bridges were considered, taking into account the features of seismic vibrations of bridges and setting the design impact and the coefficients of combinations of seismic and moving loads.

Rubber bearings have proven effective in reducing seismic damage to bridges. The study in [13] is devoted to using combinations of rubber insulating bearings to improve the seismic performance of continuous girder bridges with T-beams; the bearings were studied using the method of dynamic analysis in time. It was determined that a bridge with continuous spans with insulating bearings such as Lead Rubber Bearings (LRB) and High Damping Rubber Bearings (HDRB) has approximately 20% - 30% less seismic response than NRB during earthquakes due to hysteresis energy.

The performance of an isolated LRB of the horizontally curved continuous bridge under various seismic loads was investigated in [14]. The effectiveness of the LRB in controlling the response of the bridge was determined by considering various aspects, such as changes in ground motion characteristics, multidirectional effects, the intensity of seismic motion, and the change in incidence angles. The effectiveness of bidirectional behavior was also studied, considering the interaction effect of the bearing part and the pier using the finite element method.

OBJECTS AND METHODS OF RESEARCH

The article deals with the spatial calculation of a continuous reinforced concrete overpass for seismic effects, taking into account the finite element method in the framework of the linear spectral theory in the conditions of the Republic of Uzbekistan.

The object of the study is supports, bearing parts, spans of reinforced concrete beam-continuous bridges, and overpasses on highways.

Bridge structures are usually modeled in the form of continuous-beam, continuous-beam, and cantilever-beam schemes when performing calculations for static and seismic impacts. Bridge structures are made up of many elements, the most important of which are piers and bearing parts. The piers and the bearing parts are the most vulnerable elements of the bridge structure; therefore, seismic isolating devices, particularly rubber-metal ones, are used for the bearing part [15, 16]. The bearing part is a seismic isolation device and allows the span to move in the longitudinal direction within the range from 0.1 m to 0.35 m, depending on the models used, due to low shear stiffness. The finite element method is the most appropriate calculation method. The finite element models an axial tension-compression, bending about perpendicular axes to the longitudinal axis of the bridge and torsion about the longitudinal axis. In this regard, the calculations are conducted by the finite element method for bridge structures; the Newmark method is used for the time variable. The impact is set in the form of a series of records of three component seismograms with amplitude correction for different intensities. The equation of motion of the structure after applying the discretization by the finite element method is reduced to the following form [17, 18]

$$[M]\{\ddot{u}\} + \eta[C]\{\dot{u}\} + [K]\{u\} = \{P\}, \tag{1}$$

with initial conditions from the static solution to the problem

$$\{u(t)\}_{t=0} = [u(0)], \quad \{\dot{u(t)}\}_{t=0} = \{\dot{u}(0)\}, \tag{2}$$

where $\{u(t)\}$ is the vector of absolute displacements of the nodal points of the finite element model of the structure; for nonlinear problems, matrices $[M]$, $[C]$, $[K]$ depend on the absolute displacement vector, $\{P(t)\}$ includes the set ground motion and acting forces [18].

STATEMENT OF THE PROBLEM AND INITIAL DATA FOR CALCULATION

The calculation of the overpass for seismic resistance at 1083 km of the M-39 highway in Samarkand is discussed in the article. The overpass is made in the form of two separate overpasses for each direction of motion. The span structure of each overpass is made of continuous monolithic reinforced concrete by design scheme 33m + 42m + 33m, as an individual project. The total length of the overpass is 110 m, and the width is 28.9 m. Each side of the overpass is divided into 3 lanes with a width of 3.5 m.

In the cross-section, each span is made of slabs with a rib width along the bottom of 8.5 m and a span of 2.3 m high above the pier. On the facade, the superstructure is made of a beam of variable height - 1.3 m in the span and 2.3 m above the pier. To reduce a dead load of reinforced concrete in the spans, it is planned to install void formers when concreting with low-pressure polyethylene pipes (LPPP) with a diameter of 400 mm; the length of the pipes in the side spans is 16.5 m, in the central span, it is 22 m. The overpass crosses the road at an angle of 9 degrees, which affects the design of spans (end sides are with a 9-degree oblique and rest on intermediate piers at an angle of 9 degrees to the axis of the overpass) [19]. The cross-section of the span structure is shown in Figure 2.

Calculation parameters:

- cross-sectional area of the span structure with a height of 1.3 m in the presence of channel formers is 11.450 m² (the first stage of concreting);
- cross-sectional area of the span structure with a height of 1.3 m in the absence of channel formers is 12.706 m² (the first stage of concreting);
- cross-sectional area of the span above the pier is 21.081 m² (first stage of concreting);
- the cross-sectional area of the span structure in the support zones at a length of 8.5 m varies in height from 1.3 m (12.706 m²) to 2.3 m (21.081 m²) along a concave arc with a radius of 36.75 m (the first stage of concreting);
- cross-sectional area of the span is 0.484 m² (second stage of concreting) - berms;
- span width, including traffic lanes and safety lanes, is 12.5 m (it includes a 115.5 mm thick pavement)
- the width of the span, including the service passage, the barrier fence located between the sidewalk and the carriageway, and the railing, is 1.35 m (pavement is not provided for in this section;
- the linear weight of the barrier fence and railing and the lighting pole is 0.2 t/m.

Permanent and live loads were assessed following SHNK 2.05.03-12 "Bridges and pipes" [22]. Based on the type of cross-section of the superstructure - a slab, the transverse location factor is equal to 1. Below are the values of the loads and coefficients taken in the calculation.

This span structure is designed for the following live loads:

- from vehicles in the form of AK lanes, load class K=14;
- from heavy single loads in the form of wheel load NK-100;
- pedestrian load on service passages following ShNK 2.05.03-12 "Bridges and pipes";

− other live loads and impacts: wind load, temperature effect, seismic loads.

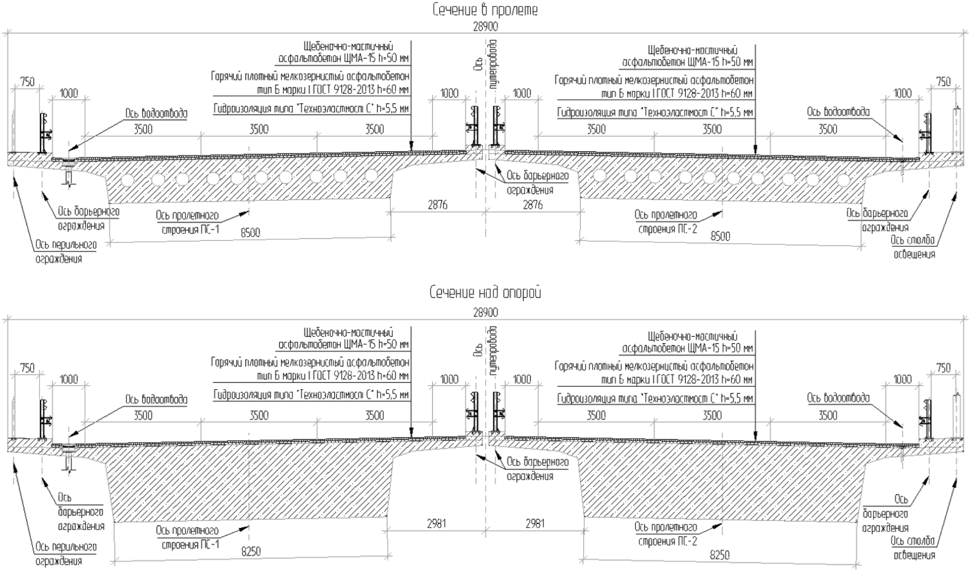

Fig. 2. Cross-section of the span structure of a continuous (monolithic) reinforced concrete overpass built in the city of Samarkand

RESULTS AND THEIR DISCUSSION

The calculation of the overpass for seismic impact was conducted using the *MiDAS Civil* software package (SP), which implements the finite element method (FEM) within the framework of the linear spectral theory.

MiDAS Civil is a software package for modeling and computational analysis of transport structures and building objects for various purposes, as well as designing and evaluating the bearing capacity of structural elements. *MiDAS Civil* is the engineering software tool that sets a new bridge and civil engineering design standard. It has a user-friendly interface and many features for designing from initial stages to nonlinear calculations. This highly advanced modeling and analysis tool allows engineers to overcome common problems in structural calculations using the FEM.

In the calculation models, the span structure is considered together with the piers, and the interaction with soil is considered. The models are made of rod elements of the *"Beam"* type (Fig. 3), the span is supported on the piers by setting the elastic links *"Elastic link"* (Fig. 4) of the required stiffness, the interaction with soil is realized by setting the links *"Point spring support"* (Fig. 5) of the required stiffness.

The material of all structures is concrete of class B35 in strength, with specific gravity γ = 2.5 tf/m^3, frost resistance grade F200 in salts, water resistance W8, elasticity modulus E = 35200 MPa, Poisson's ratio v = 0.2; reinforcement steel of class A-I from St3sp5 according to GOST 380-2005; reinforcement steel of class A-III from St25G2S according to GOST 380-2005; steel reinforcing ropes of class 1860, area 150mm². The bundle is formed from 19 ropes. The specified sections correspond to the presented general view drawing of the main overpass; for elements of a variable section, the dimensions were averaged over the boundaries of the element under consideration [19].

The seismicity of the territory of Samarkand, according to the seismic microzoning map plotted by the Institute of Seismology in 1980, is estimated at 9 and 8 points. The site of the projected construction is located in the 8-point zone.

Following Table 1.1 of KMK 2.01.03-96 [20] within the site in the upper 10-meter thick layer, counting from the base of the foundations, soils of the II category in terms of seismic properties occur - loams with a porosity coefficient of e<0.8, pebble soil). With this in mind, it is recommended to accept an 8 points seismicity of the projected construction site.

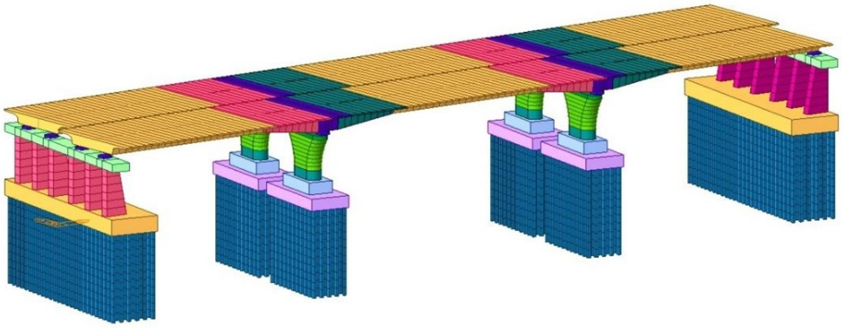

Fig. 3. Calculation model of the overpass designed using *SP MiDAS Civil*

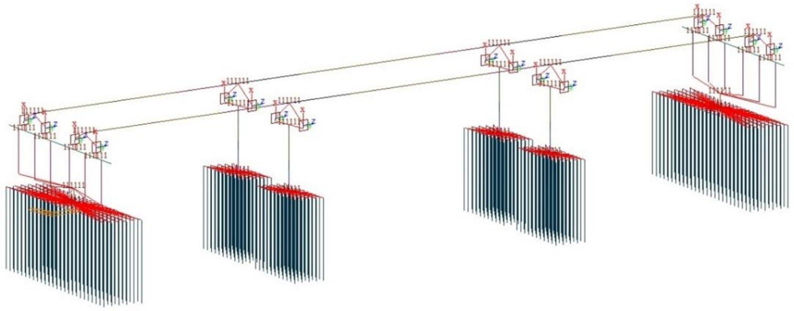

Fig. 4. Span anchoring with elastic bracing using *SP MiDAS Civil*

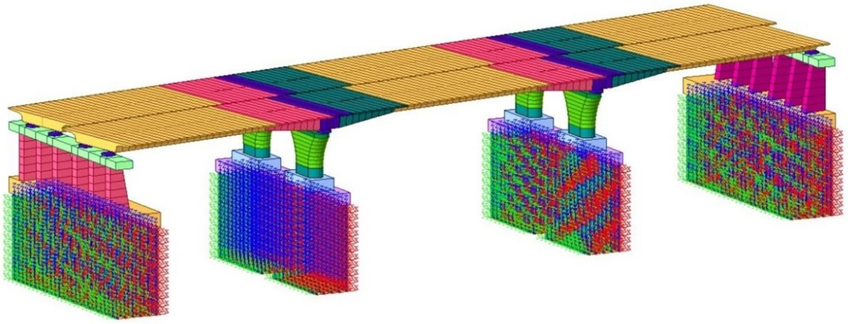

Fig. 5. Securing the piles with soil using *SP MiDAS Civil*

Seismic isolation of the structure occurs due to the displacement of the oscillation of fundamental periods to the zone of high values. Earthquake energy is also dissipated due to the lead core deformation for *LRB* insulators.

Rubber-metal insulators with a lead core of the *LRB* series (Fig. 6) are rubber-metal bearings consisting of steel plates alternating with layers of rubber, made by hot vulcanization, with a cylindrical lead core. The energy dissipation the lead core provides during its plastic deformation makes it possible to achieve values of the equivalent viscous damping factor of about 30% [21].

Due to the high energy dissipation capacity, it becomes possible to reduce horizontal displacements compared to an insulation system having the same equivalent stiffness but lower energy dissipation capacity. As a rule, insulators are round in shape, but on request, they can be made square or rectangular in the plan; in addition, they can be equipped with more than one lead core.

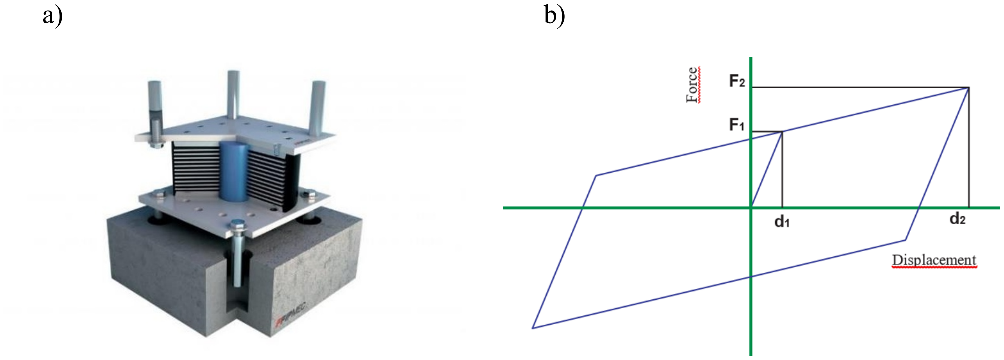

Fig. 6. Design of the seismic isolation of the overpass:
a is rubber-metal insulator with a lead core of the LRB series;
b is typical hysteresis loops of the insulator obtained during dynamic tests with an increase in the amplitude of the shear deformation.

The hysteresis behavior of an LRB series insulator can also be plotted as a single line graph, with the effective stiffness K_e and the equivalent viscous damping factor ξ_e, depending on the maximum displacement d_2 and the corresponding force F_2 to which they refer [21]

$$K_e = \frac{F_2}{d_2}\ ; \tag{3}$$

$$\xi_e = \frac{2}{\pi} * \left[\frac{F_1}{F_2} - \frac{d_1}{d_2}\right]. \tag{4}$$

where K_e is the effective horizontal stiffness (at displacement d_2);
ξ_e is the coefficient of equivalent viscous damping (at displacement d_2);
F_2 is the maximum horizontal force (at a displacement for the value of d_2);
F_1 is the resistance limit (yield point);
d_1 is the displacement to the yield point.

To design a continuous monolithic overpass, taking into account seismic isolation, the selection of parameters – K_e, ξ_e, K_v, F_1, d_2, and F_2 was made; these parameters, characterizing the bilinear curve, are given in Table 1 for the LRB-SN series insulator with different allowable displacements [21].

Table 1

Initial parameters of rubber-metal insulators of the LRB-SN series with different allowable displacements

Allowable displacements, mm	Insulator type	K_e	ε_e	F_2	F_1	K_v	D_g
		кН/mm	%	kN	kN	kN/mm	mm
200	LRB-SN 900/144-160	at d_2 =167mm			241	3509	900
		3.83	20	639			
250	LRB-SN 900/171-185	at d_2 =208mm			312	2892	
		3.49	23	728			
300	LRB-SN 900/162-150	at d_2 =250mm			312	2892	
		2.27	21	817			

The value of seismic load *F* was taken following the regulatory documents:
– KMK 2.01.03-96 "Construction in seismic regions" [20];
- ShNK 2.01.20-16. Construction of transport facilities in seismic regions [23];

– Eurocode 8 EN 1998-2-2011 "Design of structures for earthquake resistance - Part 2" [24];

– SP 268.1325800.2016. "Transport facilities in seismic regions. Design rules" [25].

The calculated seismic forces are assumed equal to the following expressions, taking into account the spectral theory:

– for horizontal impact in the directions of the *X* and *Y*-axes

$$S_{i,k}^{X,Y} = Q_k \cdot A \cdot K_\delta \cdot \beta_i \tag{5}$$

– for vertical impact in the direction of the *Z*-axis,

$$S_{i,k}^{Z} = 0.5 \cdot Q_k \cdot A \cdot \frac{1}{q} \cdot \beta_i \tag{6}$$

where 0.5 is the multiplying factor following paragraph 4.16 of ShNK 2.01.20-16;

Q_k is the weight of the structure (or its element), referred to point *K*, determined taking into account the design loads;

A is the acceleration taken in accordance with paragraph 8.3.34 of SP268.1325800.2016, A=0.2*g m/s^2 for an 8-points seismicity;

K_δ is the dissipation coefficient following paragraph 2.16 of KMK 2.01.03-96 $K_\delta = e^{\left(0.548-\sqrt{\delta}\right)\left(0.1+\frac{0.7}{\sqrt{T_1}}\right)}$, applied to horizontal components of seismic impact *FX, FY;*

q is the work factor according to Eurocode 8 EN 1998-2-2011.

According to paragraph 2.3.2.2 of Eurocode 8 EN 1998-2-2011, the formation of plastic hinges in pre-stressed structures is not allowed; taking into account the use of seismic isolation devices on supports, and paragraph 2.3.2.3 of Eurocode 8 EN 1998-2-2011, the work factor q=1.5 is introduced into the calculation to the vertical component of seismic impact *FZ,*

β_i is the dynamic amplification factor, depending on period *T*.

In the calculation, the spectral curve β_i(T) was taken according to ShNK 2.01.20-16 but without considering the requirement for β_i>0.8 (Fig. 7).

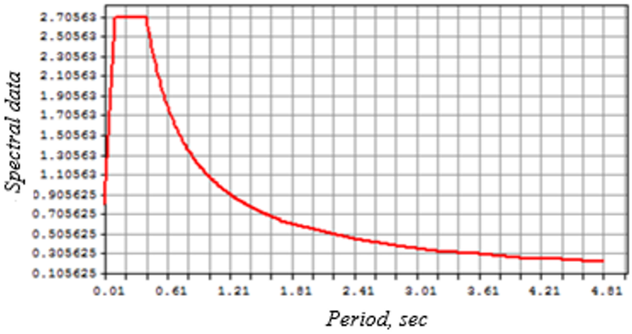

Fig. 7. Graph of the spectral curve

Seismic forces. For further calculation, a design model of the overpass was planned in the *MiDAS Civil* software package. The results of calculations of a monolithic overpass under dynamic loads are presented, *FX, FY, FZ* are applied in three orthogonal directions, and the resulting forces and displacements should be considered with both signs. Below are the displacements of the span under longitudinal and transverse seismic impacts (Figures 8-11).

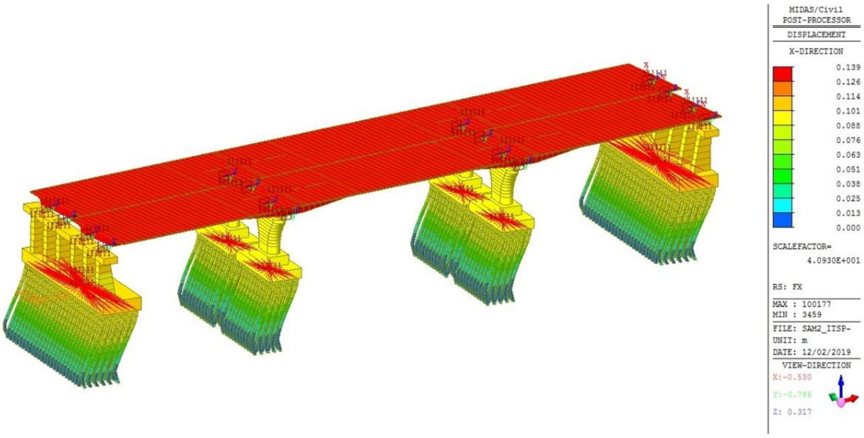

Fig. 8. Longitudinal displacements under seismic impacts

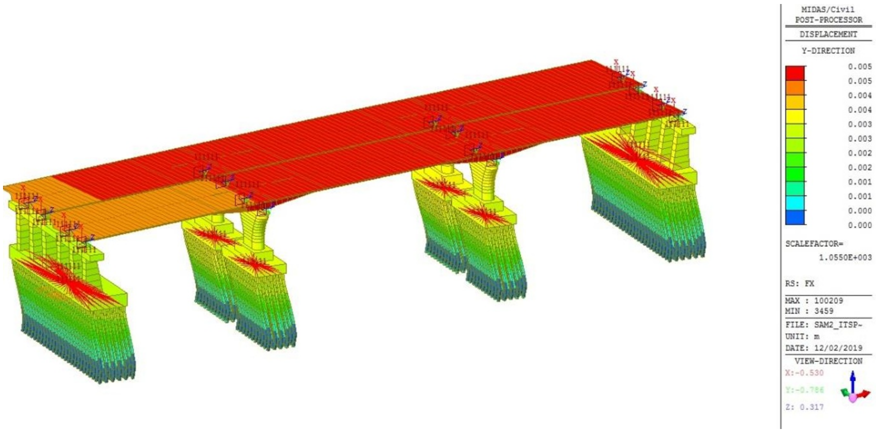

Fig. 9. Transverse displacements under seismic impacts

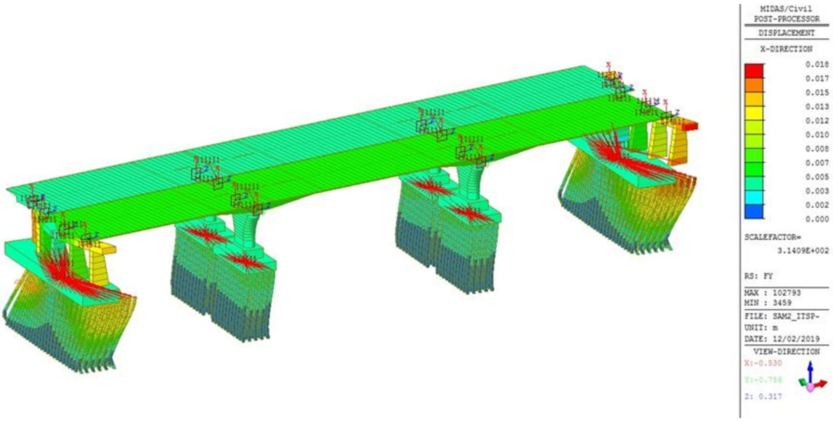

Fig. 10. Longitudinal displacements under seismic effects

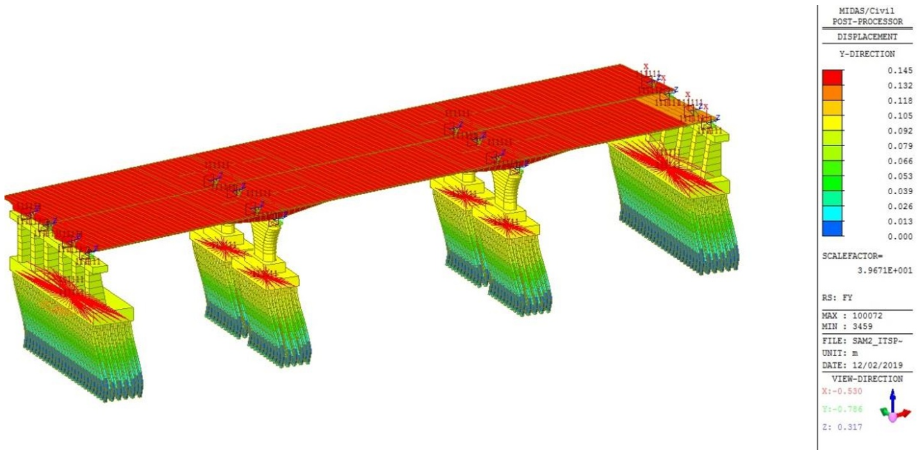

Fig. 11. Transverse displacements under seismic effects

An analysis of the calculations of the overpass under seismic impacts (Figs. 8-11) shows that longitudinal displacements are the most dangerous. The graphs (Figs. 8 and 11) show that the longitudinal displacement under longitudinal seismic impacts is 0.139 m, and the transverse displacement under transverse seismic impacts is 0.145 m.

CONCLUSION

1. In recent years, many engineering structures have been built in Uzbekistan, particularly bridges and overpasses. Analyzing the work performed during this period, we can say that in our Republic, there is a certain experience in the design and construction of typical bridges without architectural attractiveness and individuality. To avoid this shortcoming, the design and construction skills found in developed countries are implemented in the construction of monolithic bridges and overpasses
2. The calculation of the overpass for seismic impacts was conducted using the MiDAS Civil software package, implemented by the finite element method within the framework of the linear-spectral theory, which ensures their reliability and durability. The use of the MiDAS Civil software package for calculating intermediate piers of bridges and overpasses significantly speeds up the calculation and design process and ensures the calculation's quality.
3. As is known, in earthquake-resistant construction, the main cause of destruction (damage) of bridge supports is the occurrence of longitudinal (horizontal) seismic effects in the direction along the axis of the bridge.
4. Numerical calculations have shown that the bearing part of the right end of the overpass does not allow the span to fall from the abutment because the maximum displacement of the rubber-metal bearing part is 0.2 m. The performed calculations show that the span structure and the piers of the overpass have an overestimated margin of safety for an 8-point magnitude earthquake, according to MSK-64.

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