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A BURIED ARCH BRIDGE – CONCLUSIONS ABOUT APPROACHES FOR FE MODELING

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Abstract: *Conclusions are made from comparison of different finite element analyses of a buried arch bridge. The modeling is carried out by the Plaxis 2D geotechnical software. Classical and advanced constitutive models for the materials are applied. Two types of finite elements are used for modeling of the bridge structure: beam and plate elements. The soil-structure interaction is approximated by interface elements. The road traffic loading is assumed according to the model LM1 of Eurocode. Pseudo static and dynamic "time history" seismic analyses are carried out. Analysis of the ground bearing capacity is performed using the shear strength reduction technique. Mechanical behavior of the bridge is studied by analyses of states in construction and service periods.*

Keywords: Arch bridge, Finite element, Constitutive model, Soil, Static and Seismic analysis

1. Introduction

The purpose of this paper is to comment the results from different approaches for FE numerical modeling and types of analysis of a buried arch bridge (Kazakov et al., 2019a;2019b;2020a; Kazakov et al., 2020b; Kazakov et al., 2021). The prototype of the structure is the bridge named Tri Voditsi in Bulgaria. It realizes a railway-road junction. The dimensions of the bridge are width of 15.29 m and height of 8.67 m. The bridge is built of prefabricated concrete elements of thickness in range 0.60-0.35 m. The connection between the retaining walls and the vault plate of the bridge is hinged (Fig.1). Two variants of foundation are considered - strip footing and piled-raft.

2. Finite element modeling

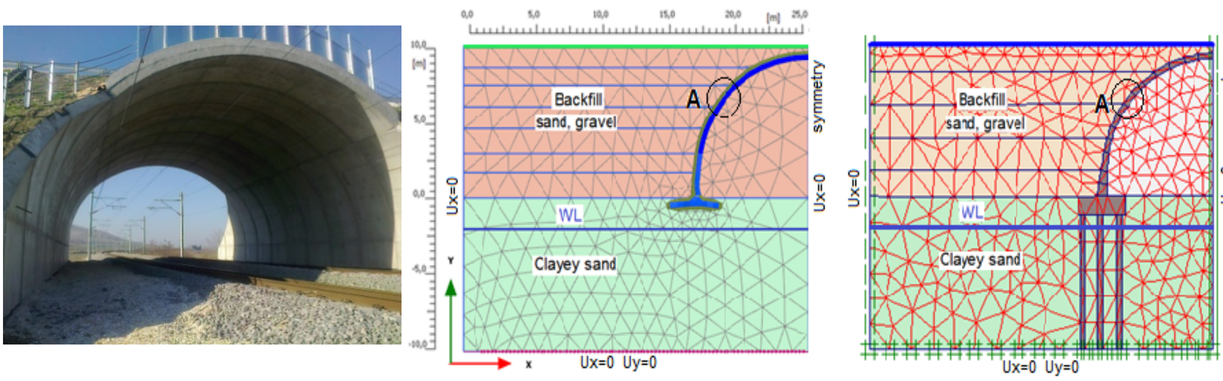

Fig. 1. The bridge Tri Voditsi:photo and FE models for static analysis

The FE plane strain discretization of the cross sections of the bridge structure and a rectangular soil body of width of 50 m and height of 20 m is shown in Fig. 2. The soil body is discretized using triangular 15-node finite elements with two node parameters: displacements U_x and U_y in *xy* plane. In relation to the dynamic analysis the criterion of Kuhlemeye and Lysmer (1973) is applied for determining of the mesh size. Two alternative types of finite elements are used for the bridge structure: 15-node triangular plate

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elements (Fig. 2a,b) and 5-node linear beam elements of width of 1 (Fig. 2c). The plate elements are formulated in normal and shear stresses. The beam elements are formulated in bending moments, axial and shear forces. A rotation stiffness of zero is defined in the beam joint of hinge (Fig. 2d). The hinge connection in plate elements here is simulated by a short beam element (Fig. 2e).

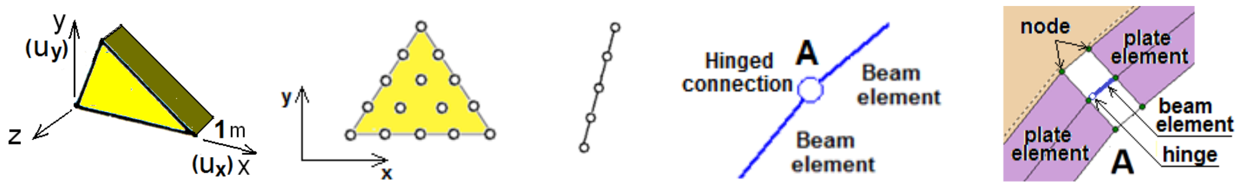

Fig. 2. Elements of FE models: (a,b) 15-node plane strain finite element; (c) and 5-node beam element; (d) hinged connection of beams; (e) hinged connection of plates

The soil-structure interaction is modeled by interface elements with thickness closed to zero. The interfaces reduce the shear strength in soil-structure contact compared to the shear strength in the soil.

The following constitutive models are used: (1) the Hooke's model of linear elasticity (LE) for static and dynamic analyses of the concrete; (2) the Mohr-Coulomb's model (M-C) of elastic-perfectly plastic behavior for static analyses of the concrete and soil; (3) Hardening Soil (HS) model for static analyses; (4) Hardening Soil Small (HSS) model for dynamic (seismic "time history") analyses. The last two models are advanced constitutive conceptions using more than 15 soil parameters and describing the mechanical behavior of different types of soil with a high degree of accuracy (Plaxis, 2015) , (Schanz et al., 1999). But the HSS model takes into account "internal" soil damping during the dynamic loading to a degree less than actually observed. That is why an additional viscous damping is introduced following the model of the Rayleigh (Rayleigh and Lindsay, 1945).Two approaches are applied for determining the Mohr-Coulomb's material parameters (cohesion and friction angle) of the concrete (Kazakov et al., 2020a). The first is based on the theoretical uniaxial compressive strength and tensile strength of the material (Approach 1) and the second uses expressions in the Eurocode 2 (Approach 2).

The types of boundary conditions in FE models are: road traffic loading on the free terrain boundary; other three boundaries are fixed (displacements U_x= 0 and U_y= 0 in Fig. 1) for the static analysis and viscous for the dynamic analysis to absorb the seismic wave and simulate an infinite half-space of the earth base. The traffic loading is simulated by the pseudo static model LM1 according to the Eurocode 1. It consists of two load systems – a system UDL of uniformly distributed load q_1 and a system TS of point loads which are approximated as a distributed load q_2 applied at different locations (Fig. 3).

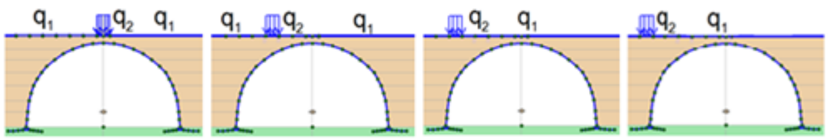

Fig. 3 Considered locations of the load q_2

3. Type of FE analyses

The following analyses are performed:

- In situ stress analysis – this analysis defines the initial stress state of the ground which involves values of normal vertical and horizontal stresses due to soil self-weight and ground water pressure.
- Simmulation of the construction process by a sequence of six static analyses which present the building of the bridge structure and the backfilling (Fig. 4).
- Seismic pseudo static analysis - approximation of the seismic action by static inertial forces in horizontal and vertical directions. The forces depend on the self-weight of the soil and coefficients of pseudo static seismic accelerations which are defined according to the Bulgarian map of seismic risk for a return period of 475 years.

Seismic "time history" analysis of loading presented by three accelerograms of significant earthquakes for the Balkan Peninsula - Vrancea (1976), Kalamata (1986) and Pernik (2012) (Tab. 1).

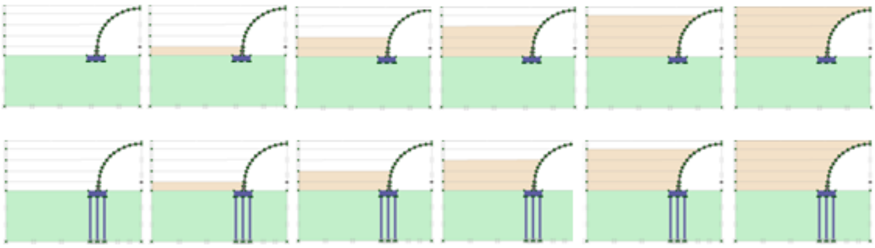

Fig. 4 States of construction period

Table 1

Earthquake	PGA (g)	Frequency (Hz)
Vrancea (1976)	0.19	0.8
Kalamata (1986)	0.21	3.0
Pernik (2012)	0.23	2.0

- Bearing capacity analysis of the ground - using the shear strength reduction technique (SSR) and considering the deformation and the strength properties of the soil the failure mechanism and safety factor of bearing capacity are developed.

4. Conclusions

The comparative analysis of the results confirms the following conclusions:

- The finite element solutions which use plate elements or beam elements for the bridge structure modeling obtain approximately same values of bending moments.
- The solutions which use models with beam elements for the bridge structure gives from 1.2 to 1.4 times larger values of the axial forces than those obtained with the solutions which use models with plate elements for the bridge structure.
- The FE model using beam elements for the bridge structure gives from 1.1 to 1,3 times larger values of the vertical displacement of the bridge than those using plate elements.
- The HS model gives from 2 to 10 times lower values of the bending moments in comparison with the M-C model.
- The HS constitutive model gives from 1.1 to 1.4 times larger values of axial forces in bridge structure in comparison with M-C constitutive model.
- HS and M-C constitutive models give similar results for the vertical displacements of the bridge structure.
- The values of vertical displacements of the bridge when it is founded by strip foundations are too big and the serviceable limit state requirements are not satisfied. Because of this reason a piled-raft foundation is designed, too.
- The FE analysis using the Hooke's constitutive model for the concrete bridge structure gives the most conservative results for the stresses in the structure.
- The FE analysis using the M-C constitutive model for the concrete shows that the values of the strength parameters – cohesion and angle of internal friction – have significant influence on the results of the stresses in the bridge. Therefore, the constitutive modeling of concrete structures according to the Mohr-Coulomb's law requires precise analysis of the strength parameters.
- The pseudo static and time history seismic analyses give similar results for displacements of the bridge.
- The seismic bearing capacity analysis shows an asymmetric failure mode of the soil deposit and its safety factor is less about 10 per cents than the safety factor at the basic load action.
- For the earthquake Pernik PGA = 0.23g and the acceleration on the top of the bridge is equal to 0.07g.
- The time history analysis gives larger values of the bending moments and axial forces, respectively 1.5 times and 1.2 times, in comparison with the pseudo static seismic analysis.
- The safety factor of bearing capacity is $F_s > 1$ for all load combinations in construction and service period of the bridge structure which means that there is not a risk of failure of the bridge.

• The seismic bearing capacity analysis shows an asymmetric failure mode of the soil deposit and its safety factor is less about 10 per cents than the safety factor at the basic load action.

• The analyses which use elastic LE and elastic-perfectly plastic M-C constitutive models of the concrete give similar distribution of areas with extreme values of stresses;

• The solution using the LE constitutive model for the bridge structure gives the most conservative results for the stresses;

• The values of the Mohr-Coulomb's strength parameters – cohesion and angle of internal friction – have significant influence on the results of the stresses in the bridge structure. The Approach 1 uses strength parameters about 7 times larger than the strength parameters in the Approach 2. And the Approach 1 gives larger values of max stresses in the bridge in comparison with the Approach 2: 3 times in the vertical normal stress; 2.6 times in the horizontal normal stress; 1.3 times in the shear stress;

• The rather high values of the strength parameters in the elastic-plastic Approach 1are the reason for results of this model closed to the results of the elastic model LE: the differences are about 15% and 4% in the normal and the shear stresses, respectively.

• The Vrancea earthquake has a value of the predominant frequency of 0.8 Hz, close to the value of the natural frequency of the ground which is equal to 1 Hz. Therefore, although the PGA value of the Vrancea earthquake is lowest, the displacements and forces of the structure have highest values and the differences are more pronounced in displacements. The value of maximum horizontal displacement $U_{x,max}$ in the Vrancea earthquake is 3.6 and 7.5 times larger than the values in the Kalamata earthquake and the Pernik earthquake, respectively. The value of maximum vertical displacement $U_{y,max}$ in the Vrancea earthquake is 1.5 and about 2 times larger than the value in the Kalamata earthquake and the Pernik earthquake, respectively. The value of maximum bending moment M_{max} in the Vrancea earthquake is 7% and 25% higher than the value in the Kalamata earthquake and the Pernik earthquake, respectively. And the value of maximum normal force N_{max} is 2% and 10% higher than the value of the Kalamata earthquake and the Pernik earthquake, respectively.

• The lowest values of the reaction of the structure are obtained in the earthquake Pernik, although it has the highest value of PGA. The reason is the locally expressed value of PGA against the background of significantly lower amplitudes of the earthquake acceleration.

• The pseudostatic analysis performed in gives significantly lower values of the structure response compared to the "time history" analysis. For example, the Vrancea pseudostatic analysis gives 8.5 times less value of the maximum horizontal displacement and 2.8 times of the maximum vertical displacement. In terms of the maximum values of internal forces, the differences are as follows: 3 times less bending moment and 1.3 times less normal strength.

• The advanced soil constitutive models describe precisely mechanical behavior of the soil because they use a lot of parameters. But the correct application of the advanced models requires performing accurate experimental procedures and sensitivity analyses for identification of the model parameters.

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