Advantages of Integral Abutments for Seismic Design of Bridges

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Abstract Seismic assessment is an essential part of bridge design. With the design of integral abutments, it is possible to improve the behaviour of bridges - both newly designed and existing ones - under seismic action.An analysis of the advantages of integral bridges compared to traditional ones in terms of seismic assessment is presented and an example is given to demonstrate that integral bridges should be applied on a large scale for certain bridge parameters.

1 Introduction

In traditional bridge design solutions, the superstructures of bridges are supported on the elements of the substructure (piers and abutments) by means of support devices - bearings. These support devices allow nearly free movement of the superstructure relative to the substructure. At the abutments, this requires the use of additional elements (expansion joints) to ensure the flat surface of the road (for road and pedestrian bridges) as well as the water tightness of the joint (for all bridges).

Solutions with joints at each support are preferable from a structural point of view and are more favourable for the elements of the substructure, since the displacements caused by temperature differences (and the stresses they produce) are smaller. A huge disadvantage, however, is the presence of many joints that need to be maintained, repaired, replaced, and eventually can lead to water leaking through them, which damages the elements of the substructure.

In the second half of the last century in the USA and Europe, and for several years in Bulgaria, the aim was to neutralize this main drawback of bridges with expansion joints. This was ensured with the application of the so-called integral bridges, where the connection between the elements of the superstructure and the substructure is not carried out with bearings but is a direct one. Thus, it becomes possible to remove the bearings and the joints. Unlike frame bridges, which also lack bearings and joints, integral structures take into account the interaction with the so-called ‘transition zone’ behind the abutments, which is involved in absorbing the horizontal actions. In order to transfer most of the horizontal reactions to the embankment, the abutment structure is designed with a low stiffness in the longitudinal direction. Some of the state transport organisations in the USA require that the foundation of the end supports of bridges be supported on steel H-piles oriented with their smaller stiffness in the direction of the axis of the bridge [1].

2 General description of the investigated facility

In order to illustrate the operation of integral bridges and compare them to traditional bridges, a comparative analysis of a three-span bridge structure - a road overpass over a motorway - was carried out (Figure 1).

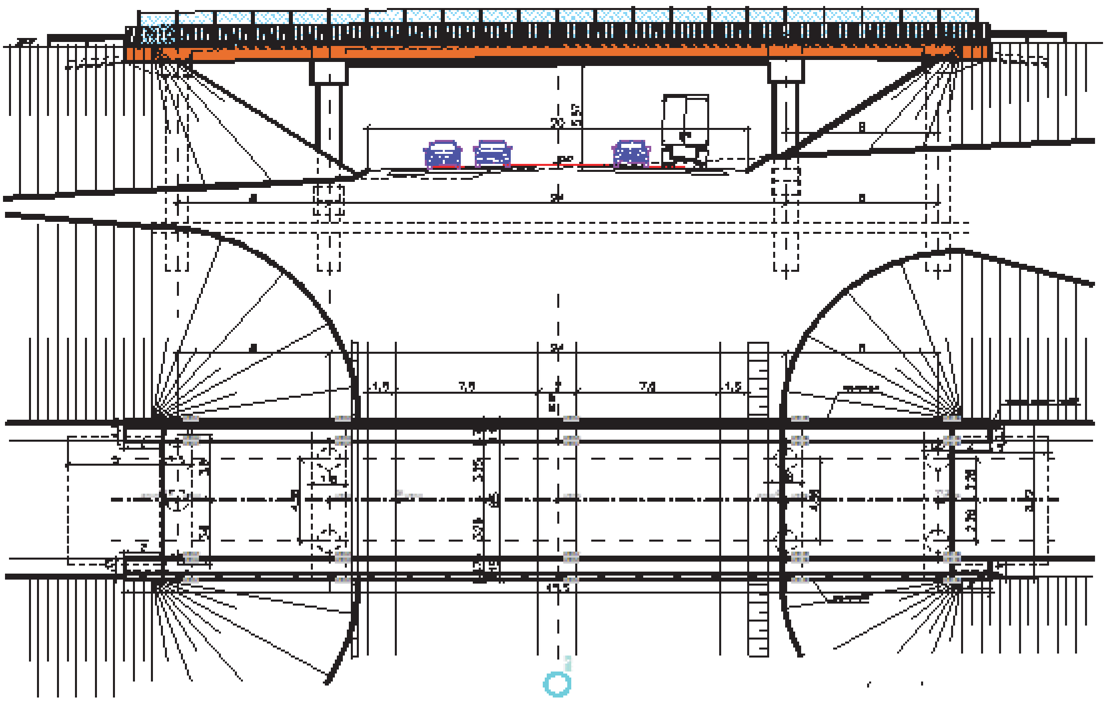

Figure 1: Longitudinal view and plan of the facility

Due to the lack of sufficient width of the median strip, and in order to increase the safe operation of the motorway, the middle span of the bridge passes over the entire motorway, without intermediate support, with a length of the static span of 24 metres.
Two beneficial effects are achieved with the end spans of the overpass:

- visibility is improved when driving on the motorway and the adverse psychological impact of the closed-end abutments on drivers is reduced;
- the construction of closed-end abutments for bridges of this type requires their height to be at least eight metres, which leads to a relatively heavy structure with large dimensions of the structural elements, i.e. walls and foundations.

The length of the end spans of the bridge is determined by the condition for designing the shape of the embankment cones, and the aim is to minimize the total length of the bridge. In addition to the construction costs, in the case of integral structures, this is particularly favourable from the point of view of reducing displacements due to temperature differences. Taking into account the height of the embankment and the assumed inclination of the embankment slopes, the length of the end spans of the bridge equals eight metres. Thus, the total length of the facility is 41.5 m. Adding both transition slabs that move with the bridge, the total length adds up to 51.5 m (Figure 2).

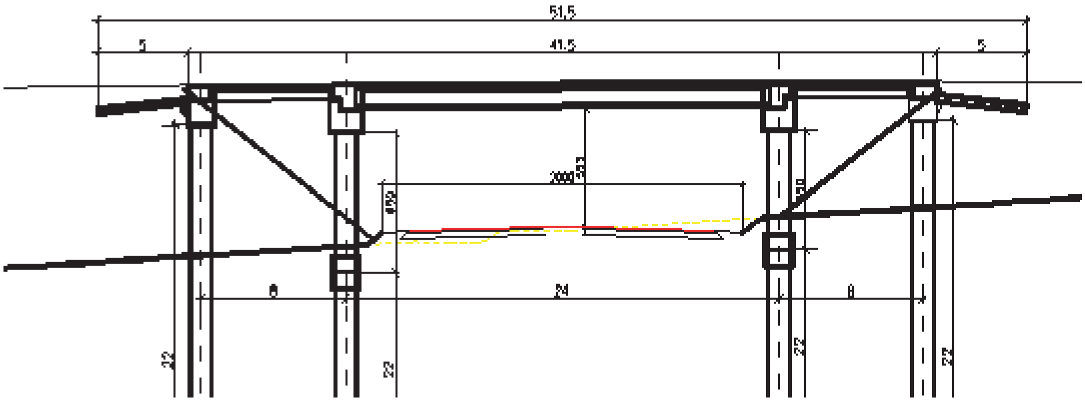

Figure 2: Longitudinal section

Considering the length of the spans, a girder with six pre-tensioned beams of the GT95 type joined with a monolithic slab of a thickness of 0.20 m was designed in the middle span (Figure 3), and the end spans were designed as a structures composed of prefabricated panels of a thickness of 0.45 m and a monolithic slab 0.20 m (Figure 4).

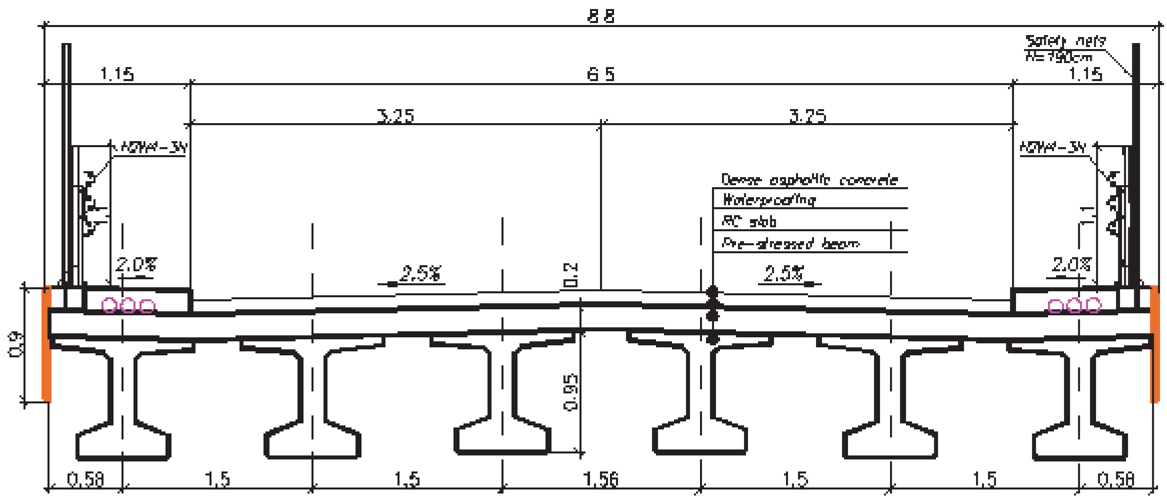

Figure 3: Cross section of the middle span

The piers consist of two round columns with a diameter of 1.20 m each, which continue into bored piles of the same diameter and of a length of 22 m.Two piles with a diameter of 1.20 m and a total length of 22 m each support the cap beams of the abutments.

Although from the point of view of mechanics, the ratio of the span lengths (1:3:1) does not provide optimal distribution of stresses, it is assumed that the facility will be continuous - without bearings and without joints. All elements of the substructure are fixed to the superstructure.

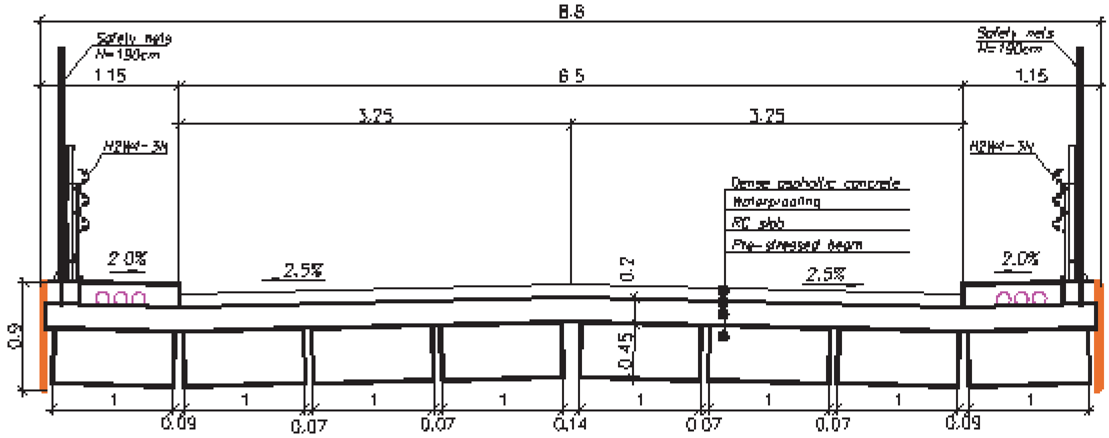

Figure 4: Cross section of the end spans

Thus, the bridge meets all geometrical requirements to be designed as an integral bridge:

- total length (with transition slabs) of 51.1m, which is less than the recommended limit value in [2] of 60 m;
- the bridge is straight - the abutments are perpendicular to the axis of the facility;
- small width of the overpass – 8.80 m;
- relatively "soft" abutments;
- a symmetrical structure.

3 FEM model

For the purposes of the present study, the described construction was considered as the main option (Option 1). A simplified FEM computational model was developed, shown in Figure 5. No detailed modelling of the superstructure was sought, as the main research objective was the dynamic behaviour and seismic response of the facility.

The following parameters were used during the seismic analysis: reference seismic acceleration - 0.23*g; the importance factor - 1.4; behaviour factor– 1.5; soil Type C.

4 Results

From the research for Option 1a, without taking into account the passive earth pressure behind the supports, the following results were obtained:

- The first period of natural oscillations in the longitudinal direction – T1L0 = 0.436s:
- Horizontal displacement – d0 = 31.1mm*1.5 = 46.6 mm;

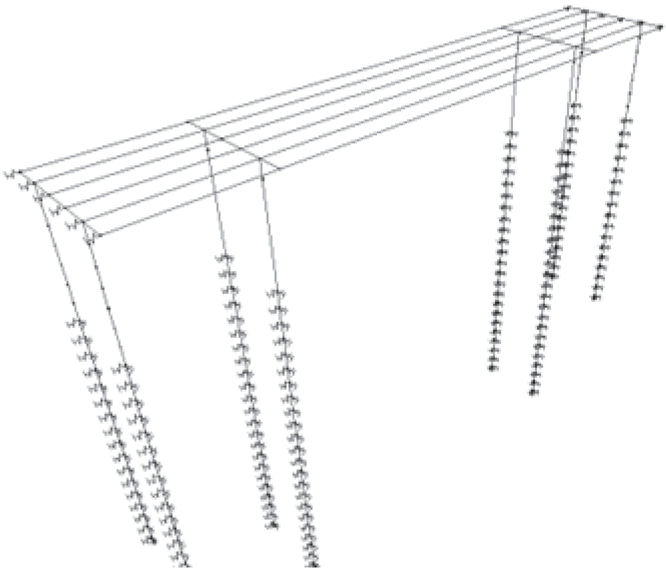

Figure 5: Finite element model of the facility

- Bending moment in the column-cap beam joint – MU0 = 3215 kNm;
- Bending moment in the pile of the pier– MP0 = 1798kNm.

It can be deduced that without considering the contribution of the embankment, the horizontal displacement is greater than the limit value, which for this importance class is 40 mm [3].
In Option 1b, the stiffness of the interaction between the abutment and the embankment behind it is assumed to be 11,500 kPa/m. The interaction is modelled with discrete elastic springs having a total stiffness of 11,500*15.66 = 180,000 kN/m. This stiffness is distributed equally to both supports, according to the recommendations of [4]. The obtained results are the following:

- The first period of natural oscillations in the longitudinal direction – T1L1 = 0.320s:
- Horizontal displacement – d1 = 16.8 mm*1.5 = 25.2 mm = 0.54*d0;
- Bending moment in column-cap beam joint – MU1 = 1738 kNm = 0.54*MU0;
- Bending moment in the pile of the pier – MP1 = 870kNm = 0.48*MP0.
- Horizontal stresses in the embankment – R1 = 289 kPa.

Option 2 was also studied, in which there are bearings and joints at both ends of the bridge, which allows mutual displacements between the superstructure and the abutments. With fully movable bearings, the obtained results were:

- The first period of natural oscillations in the longitudinal direction – T1L2 = 0.629 s:
- Horizontal displacement – d2 =51.1mm*1.5=76.7mm = 1.54*d0
- Bending moment in column-cap beam joint – MU2 = 4941 kNm = 1.54*MU0
- Bending moment in the pile of the pier – MP2 = 2886 kNm = 1.61*MP0

The results of the study of the three options are presented in Table 1.

Table 1: Results for the different options

	T_{1L} [s]	d [mm]	M_U [kNm]	A_{sU} [cm^2]	M_P [kNm]	A_{sP} [cm^2]
Option 1a	0.436	46.6	3215	129	1798	44
Option 1b	0.320	25.2	1738	41	870	0
Option 2	0.629	76.7	4941	242	2886	109

In Table 1 the following symbols are used:

- T_{1L} – the period of the first mode of natural oscillations in the longitudinal direction;
- d – the superimposed displacement at the superstructure level due to seismic impacts;
- M_U – the bending moment in the column-cap beam joint in the piers from the longitudinal component of the seismic action;
- $A_{s,U}$ – the required longitudinal reinforcement of the column of the pier, at the column-cap beam joint;
- M_P – the maximum bending moment in the pile of the pier;
- $A_{s,P}$ – the required longitudinal reinforcement in the pile of the pier.

To calculate the required reinforcement, the following additional data were used:

- normal compressive force: 2000kN
- concrete grade C35/45;
- reinforcing steel B500;
- cross-section diameter: 120 cm;
- concrete cover of the stirrups: 5.5 cm;
- adopted number of longitudinal reinforcing bars: 18, with an axial distance between the bars of 18 cm
- minimum amount of longitudinal reinforcement: 1% of the concrete section or 113 cm2. Accepted minimum longitudinal reinforcement – 18 N28 with a total area of 111 cm^2.

5 Conclusion

In addition to the general advantages of integral bridges compared to traditional ones (with joints at the abutments), the following conclusions can be drawn for the studied options of the considered facility:

- even without taking into account the stiffness of the embankments behind the abutments, the stresses in the substructure are significantly reduced, resulting in a smaller amount of longitudinal and transverse reinforcement (Figure 6). Apart from a reduction in construction costs, which can be considered a secondary benefit, the smaller number and diameter of the reinforcing bars and/or the larger distance between them are a prerequisite for better compaction of the concrete mixture and hence - better quality of the executed structure;

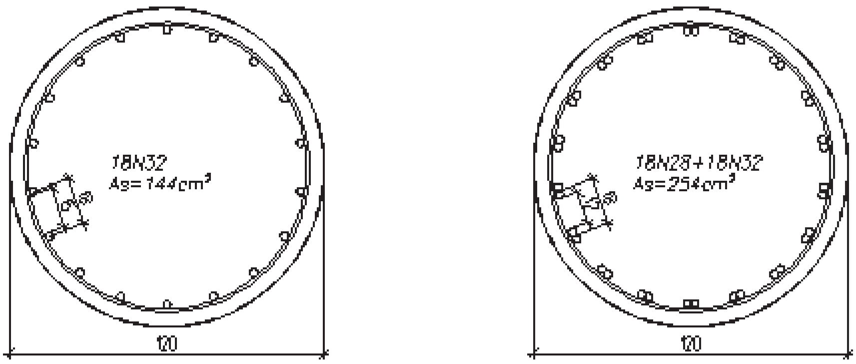

Figure 6: Cross-section of pier's column with different amount of longitudinal reinforcement

- when considering the contribution of the embankments behind the abutments, even at low stiffness values, the reduction of stresses in the elements of the substructure and the described benefits of this reduction become even greater – no reinforcement is required in eigher the column or the pile.

The stiffness of the embankments has to be applied very carefully. In the case of facilities of the considered type - with open-end abutments and relatively high embankments, the influence of two additional factors must be taken into account - the quality of execution related to ensuring the set parameters of the embankment during the construction of the bridge and, to a greater extent, maintaining these parameters throughout the operational period. In view of the level of maintenance of the road network in Bulgaria, a conservative approach should be taken to the full use of the reduction of stresses in the elements of the substructure. A number of examples can be given (Figure 7) of the poor condition of the embankment cones of bridges.

6 Acknowledgments

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Figure 7: An example of damage to the embankments at an open-end abutment

of the Council of Ministers No 577/17.08.2018 and supported by the Ministry of Education and Science (MES) of Bulgaria (Agreement No Д01-363/17.12.2020).

7 References

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