Research Article

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Integral bridge and culvert design, Designer's experience

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Abstract: This paper describes a small single-span integral bridge made of in-situ concrete. The bridge was designed by the author and built on the M9 motorway between the towns of Waterford and Kilcullen in Ireland. Selected parts of the bridge design are presented. First the principles of modelling and designing integral bridges and culverts are explained. Then the considered bridge's design is described. The advantages and disadvantages of such structures are discussed. The focus is on the design, construction, cost and in-service behaviour of small integral bridges and culverts. In Conclusions the author shares his knowledge and experience relating to the design of small integral bridges and culverts and puts forward recommendations as to further research on this type of structures in Poland.

1 Introduction

An integral bridge can be defined as a bridge whose span is monolithically connected with the supporting walls and whose structure interacts with the surrounding soil due to thermal effects and permanent and variable vehicle and pedestrian traffic loads. Such elements as bridge bearings, mechanical expansion joints and approach slabs are not required in this case, whereby the construction and maintenance of integral bridges is less expensive. Integral bridge structures have been widely used in the world since the 1930s. This paper is devoted to the design and construction of a small integral bridge with a monolithically made box structure. In the paper's part dealing with design, a comparative analysis of the bridge on a rigid subgrade versus on an elastic subgrade, interacting with the bridge structure, is presented. Other types of integrated bridges and viaducts, both single-span and multi-span ones, and

arch bridges are described in [1–4]. It is worth noting that the implementation of integrated bridges on this section of the motorway contributed to a significant reduction in the time and cost of construction of the motorway.

2 Example of integral road bridge

In this paper the integral bridge located in County Kilkenny in Ireland, on the M9 motorway connecting the towns of Kilcullen and Waterford (Figures 1-3), is described. The main function of the bridge is to carry agricultural traffic, agricultural machinery and livestock to the pastures separated by the motorway. There are several such bridges on the M9 motorway. According to the ten-

Figure 1: Longitudinal section of bridge

Figure 2: Cross section of bridge

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Table 1: Basic bridge parameters

Elements	
Effective design span length	$L_t = 6.45$ [m]
Overall span length	$L_p = 6.9$ [m]
Skew angle	$\alpha = 90^\circ$
Wall, floor slab and bottom slab thickness	$h = 0.45$ [m]
Minimal soil surcharge height over bridge structure	$H_n = 1.1$ [m]
Length of bridge without wing walls	$L_o = 30.6$ [m]
Overall length of wing walls	$L_s = 8.49$ [m]
Angle of rotation of wing walls relative to bridge length	$\beta = 45^\circ$
Span height to length ratio	1:15
Embankment height	6.0 [m]
Bottom slab and wing wall strip footing concrete grade	C32/40
Bridge wall, floor slab, wing wall and string course concrete grade	C40/50
Live load type	HA and HB45

Figure 3: Bird's eye view (Microsoft Bing Maps) [15]

der documentation, the bridge had to satisfy several major conditions. Firstly, it had to ensure grade-separated pasture-to-pasture crossing for vehicles and farm animals. Secondly, it had to be durable and inexpensive to build and operate. Taking this into consideration, a simple box bridge design similar to typical road box culverts was selected. The bridge was designed in accordance with the guidelines for bridges and road culverts. The traffic loads and the loading configuration conformed to the Irish Standard for bridges and culverts.

The bridge was designed as integrated with the surrounding soil. The bridge subgrade and backfill parameters were specified by a geotechnical engineer. The parameters are provided in the comparative analysis below. The grading of the 6N/6P aggregate used for backfilling is given in Table 2 [11]. There bridge carries a motorway with two one-way carriageways, each 7 m wide, separated by a 2.6 m wide median strip with a concrete Jersey barrier. At the outer edge of each of the two carriageways there is a 2.5 m wide shoulder limited by a steel safety barrier. A

4.0 m wide road with two 1.0 m wide sidewalks contiguous to it runs under the bridge. The embankment close to the bridge's wing walls are protected with wooden protective barriers with wire mesh. The basic parameters of the bridge are specified in Table 1.

The design documents were prepared in the Fehily Timoney & Company consulting office in Cork [10]. Working for Fehily Timoney & Company the author designed this bridge.

The following standards, among others, were used to design the bridge:

- The design of buried concrete box and portal frame structures [5].
- BD37/01 Loads for Highway Bridges [7],
- BS5400-04 Code of practice for design of concrete bridges [8].

Moreover, the Irish Manual of Contract Documents for Road Works [11] and the project owner's (National Road Authority [9]) latest recommendations were used for the design.

Considering the interaction between the bridge and the surrounding soil, major structural components, such as the bridge structure and the backfill behind the bridge walls, are described in the following sections.

3 Bridge structure

The bridge bottom slab and the strip foundation of the wing walls were made of C32 /40 grade concrete. The bridge's side walls, the wing walls, the floor slab and the

string course were made of C40/50 concrete. All the members were made using the monolithic technology.

The following stages in the construction of the bridge can be distinguished:

- soil excavation,
- lean concrete placement,
- casting the bridge bottom slab and the strip foundation of the wing walls,
- casting the bridge side walls and the wing walls,
- casting the bridge floor slab,
- making expansion joints and installing interior insulation from the embankment side,
- installing longitudinal drainage behind the bridge walls and the wing walls,
- burying bridge walls and the floor slab with backfill 6N/6P,
- laying pavement and sidewalks on and under the bridge,
- erecting wooden fencing with wire mesh on the embankment at the string course and along the wing walls.

The vertical expansion joint between the bridge wall and the wing wall was made by inserting a flexible backer rod into the gap between the two members and gluing a 200 mm wide waterproof membrane to the inner surface from the embankment side, making sure that the membrane extended equally onto the two joined surfaces.

4 Backfill behind underpass side walls

The kind of material used to bury integral bridges and the way of laying it has a significant bearing on the distribution of internal forces in the bridge components. For this purpose, crushed-stone aggregate backfills of class 6N and 6P are used on the British Isles. Detailed information about the backfills is given in the Manual of Contract Documents For Road Works [11] (Table 2). During the construction of the considered bridge the internal friction angle of the backfill ranged from $\varphi = 35^\circ$ to 40° .

It is important that before bridge construction the geotechnical surveys are carried out in the places where the future supports will be located, the moduli of subgrade reaction are determined and the settlement of the supports is calculated. On the basis of this information the designer can create a computational model of the bridge structure which will most accurately describe the actual foundation conditions. The model represents a structure on elastic

Table 2: Grading of 6N and 6P backfills [11]

Square mesh sieve [mm]	Percent passing sieve [%]	
	6N	6P
125		100
100	100	
75	65 - 100	
37.5	45 - 100	
10	15 - 75	
5	10 - 60	
0.6	0 - 30	
0.063	0 - 15	

supports which behave flexibly under permanent and live loads. Moreover, if the stiffness of the structural members is low, the structure is flexible and better interacts with the surrounding soil, whereby the stresses in the structure are reduced. Owing to this the cross sections of the structural members of integral bridges can be smaller, whereby such bridges are less expensive to build than other types of bridges.

5 Loads and soil parameters

Only permanent loads were used in the comparative analysis of the influence of the flexible foundation and the rigid foundation on the values and distribution of bending moments in the bridge model. Considering the permanent character of the load, the shape of the bridge was assumed to be invariable along its length, and to simplify the calculations a two-dimensional structure with beam elements was adopted as the bridge structure model. In the calculations the structure was assumed to be founded on Winkler's unidirectional subgrade model. The elastic constraints connecting the bottom slab and the side walls with the soil are solely compression-loaded. This means that parts of the structure can detach from the surrounding soil. The superposition principle cannot be used in the calculations because of the nonlinear character of the bridge model support. For this reason, all the loads involved were scaled up by applying a partial load factor taken from the Design Manual For Roads And Bridges, appendix A [5] and incorporated into a single load case. For comparative purposes two models were built. The first model is founded on a flexible subgrade and the second one on a rigid subgrade. The first model has flexible constraints located under the bottom slab and behind the side walls of the bridge. In the second model only the bottom slab is supported. Owing to

Table 3: Elastic constraint stiffness values

Symbol	Range of influence [m]	Modulus of subgrade reaction [kN/m ²]	Stiffness of elastic constraints [kN/m]
k_1	0.3375	$k_v = 80000$	$0.3375 \cdot 80000 = 27000$
k_2	0.3625		$0.3625 \cdot 80000 = 29000$
k_3	0.5		$0.5 \cdot 80000 = 40000$
k_4	0.3375	$k_h = 37068$	$0.3375 \cdot 37068 = 12510$
k_5	0.3625		$0.3625 \cdot 37068 = 13437$
k_6	0.5		$0.5 \cdot 37068 = 18536$

the two models differing in only their support method one can estimate the effect of the surrounding soil on the distribution and values of the internal forces in the structure. The geotechnical parameters used in the calculations of the flexibility of the subgrade were obtained from geotechnical surveys. The surveys were carried out for the native soil on which the bridge is founded and for the backfill used to bury the structure. Abaqus FEA was used for the static load calculations [13]. The calculations of the modulus of the horizontal reaction of the subgrade behind the bridge walls were carried out according to Ménard's empirical formula given in [14].

$$k_h = \frac{3 E_p}{\left(1, 3 r_0 \left(2, 65 \frac{r}{r_0}\right)^\alpha + \alpha r\right)} \quad (1)$$

where:

k_h – modulus of horizontal subgrade (backfill) reaction

α, β – coefficients dependent on soil type and consistency, e.g. gravel $\alpha = 1/4, \beta = 1/2$

E_p – pressuremetric modulus of soil, $E_p \approx \beta \cdot q_c$

q_c – cone soil penetration resistance determined by cone penetration test (CPT)

r_0 – reference radius $r_0 = 0.3$ m

D – bridge side wall height $D = 5.9$ m

r – radius, at half of side wall height, $r = D/2 = 5.9/2 = 2.95$ m

Geotechnical surveys carried out using the CPT probe showed that the cone resistance for the backfill used on the construction site amounted to $q_c \approx 40000$ kN/m³. Hence the calculated pressuremetric modulus of the soil was

$$E_p \approx 40000 \cdot 0.5 = 20000 \text{ kN/m}^3 \quad (2)$$

Substituting the above data into the Ménard formula for modulus k_h the following was obtained:

$$k_h = \frac{3 \cdot 20000}{\left(1.3 \cdot 0.3 \left(2.65 \frac{2.95}{0.3}\right)^{0.25} + 0.25 \cdot 2.95\right)} \quad (3)$$

$$= 37068 \text{ kN/m}^3$$

The above is the modulus of the horizontal reaction of the subgrade behind the bridge wall. The modulus of the ver-

Figure 4: Location of elastic constraints

tical reaction of the subgrade on which the bridge was to be built amounted to:

$$k_v \approx 80000 \text{ kN/m}^3 \quad (4)$$

Many factors, such as the kind of soil, the type of load (short-term/long-term) and its size and the size of the foundation, have a bearing on the value of modulus k_v . After the two moduli had been determined their values were proportionally distributed on the bridge model's vertical walls (k_h) and its bottom slab (k_v). The calculated values of the particular elastic constraints and their application in the nodes of the bridge model are shown in Figures 4, 5 and in Table 3. All the calculated constraints (springs) are exclusively compression-loaded. The modulus of the horizontal subgrade reaction (k_h) was assumed to be constant along the height of the walls.

Permanent loads were applied to the bridge model according to one of the diagrams showing load cases given in standard [5]. The partial load factors for the permanent loads are given in Figure 6. The calculated values of the loads and their denotations are shown in Table 4 and Figure 7.

Figure 5: Location of nodes and beams and distribution of elastic constraints in cross section

Figure 6: Partial load factors consistent with diagram A/4a [5]

Figure 7: Load denotations and load action directions

Table 4: Permanent load

Load		Values [kN/m]
Road pavement	V_1	$2.3 \cdot 0.2 \cdot 9.81 \cdot 1.75 \cdot 1.1 = 8.7$
Surcharge over bridge	V_2	$2.0 \cdot 1.1 \cdot 9.81 \cdot 1.2 \cdot 1.1 = 28.5$
Earth pressure on bridge's left side	H_{L1}	$(2.3 \cdot 0.2 + 2.0 \cdot 1.1) \cdot 9.81 \cdot 0.33 \cdot 1.5 \cdot 1.1 = 14.2$
	H_{L2}	$(2.3 \cdot 0.2 + 2.0 \cdot (1.1 + 5.9)) \cdot 9.81 \cdot 0.33 \cdot 1.5 \cdot 1.1 = 77.2$
Earth pressure on bridge's right side	H_{P1}	$(2.3 \cdot 0.2 + 2.0 \cdot 1.1) \cdot 9.81 \cdot 0.6 \cdot 1.0 \cdot 1.0 = 15.7$
	H_{P2}	$(2.3 \cdot 0.2 + 2.0 \cdot (1.1 + 5.9)) \cdot 9.81 \cdot 0.6 \cdot 1.0 \cdot 1.0 = 85.1$
Self-weight of concrete	CW	$2.4 \cdot 1 \cdot 0.45 \cdot 9.81 \cdot 1.2 \cdot 1.1 = 13.99$

Table 5: Concrete elastic moduli and Poisson's ratios [11]

Member		
Bottom slab, concrete C32/40	E_{cm}, ν	33.34 [GPa] 0.2
Side walls, floor slab, concrete C40/50		35.22 [GPa] 0.2

6 Internal forces

The values of bending moments M_y were used only in the comparative analysis. Graphs of the forces for the individual components of the bridge modelled with subgrade flexibility taken into account and on a rigid subgrade are shown in Figures 8-10.

The comparative analysis shows that the value of bending moment M_y at the midspan is higher in the model which takes into account subgrade flexibility than in the

Figure 8: Distribution of bending moments in bridge's upper floor slab

model on a rigid subgrade. Whereas in the zone at the side walls the reverse is the case. If subgrade flexibility is not taken into account in the model, this can lead to excessive deflections and cracking of the floor slab at its midspan and to the over-reinforcement of the slab parts close to the side walls.

Figure 9: Distribution of bending moments in bridge left and right side walls

In the middle of the height of the bridge's side walls the value of bending moment M_y is lower in the model which takes subgrade elasticity into account than in the model on a rigid subgrade. The reverse is true for the lower wall zone at the bottom slab of the bridge, where the value of bending moment M_y is higher in the model taking into account subgrade elasticity. If subgrade elasticity is not taken into account in the bridge model, this can lead to the cracking of the side walls in the zone at the bottom slab from the embankment side and to the over-reinforcement of the middle zone of the side walls.

Figure 10: Distribution of bending moments in bridge bottom slab

Along the whole length of the bridge's bottom slab the value of bending moment M_y is higher in the model which takes subgrade elasticity into account than in the model on a rigid subgrade. If subgrade elasticity is not taken into account in the model, this can lead to the cracking of the top surface of the slab in the middle of its span and to the cracking of the bottom surface at the side walls. The bending moment values for which the bridge was designed are given in Table 6.

Table 6: Bending moment values used for bridge dimensioning

Member	Value [kNm]
Floor slab, midspan	362
Floor slab, at support	333
Bottom slab, midspan	196
Bottom slab, at support	287
Side wall at midspan	182

7 Conclusions

The bridge was put into service in the first half of 2010. In 2013 inspections of this bridge and other bridges designed by the author, situated on this section of the M9 motorway, were carried out. No cracks larger than the ones assumed in the design computations and no uneven settlement were revealed. Moreover, no water stains were visible on the bridge wall/wing wall connection where the vertical expansion joint was situated.

The comparative analysis shows that when the bridge is designed with subgrade elasticity taken into account, one gets a different distribution of bending moments than for the model on a rigid subgrade. Since the bridge was founded on a flexible subgrade it was proper to take this

into account in the calculations. If the elasticity of the subgrade had not been taken into account in the computational model, this could have led to excessive deflections and cracking in such bridge elements as the lower surface of the floor slab, the two surfaces of the bottom plate and the inner surface of the side walls from the embankment side.

It should be emphasized that prior to calculations which take subgrade elasticity into account the proper soil parameters for the both the bridge subgrade and the backfill must be determined. On the basis of such data the designer can develop a model of the structure founded on the specific subgrade. If one designs a bridge founded on a different subgrade than the target one (e.g. on a rigid subgrade), this can result in the over-reinforcement of some of the structural members and in the under-reinforcement of other members. After the inspection of the bridge and the other bridges on this road it was concluded that it had been proper to take into account the elasticity of the subgrade in the bridge calculations. It should be noted that the integral bridge presented here very well interacts with the surrounding soil, under permanent and live loads. Bridges of this type can have structural members with a smaller cross section in comparison with conventional design solutions in which the structure-soil interaction is not taken into account. Consequently, they are cheaper to build than conventionally built bridges owing to the reduced quantity of the materials used. In the author's opinion, integral bridges can and should be built in Poland since they are less expensive and take less time to build. One should take into account the fact that the air temperatures in Poland are different than on the British Isles and therefore it is necessary to investigate integral bridge structures in our climate conditions. Such research would give bridge engineers a deep insight into the behaviour of this type of bridges, whereby their span could be gradually increased. It is worth noting that increasingly more valuable publications on integral bridges and viaducts appear in Poland [12]. This indicates a growing interest in such structures on the part of bridge engineers in Poland.

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