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# Influence of Contact Stress Model on the Stability of Bridge Abutment

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#### Abstract

This chapter deals with the behaviour of an abutment pier on subsoil subjected to flood changes. The floods increase the cross-section of the river bed and change the properties of the foundation soil under the foundation. First, the soil saturates with water. Then, fine-grained particles will wash away and finally parts of the basement rock will be washed off. Finite element method has been used for the calculation of the interaction between the foundation and the subsoil. The foundation has been modelled in a 2D environment using spatial components. For the subsoil, an element with effects of an elastic foundation has been used. The stiffness of the bedrock has been characterized by the *C* parameter. The chapter describes situations related to the collapse of the structure.

Keywords: bridge, abutment pier, basement rock, floods, soil-structure, interaction

# 1. Introduction

Unflagging growth of anthropogenic activities has been causing changes in the Earth's climate. These changes have led to the changes of weather in comparison to the past. Changes in weather frequently have brought increased values of loads (e.g. due to wind, snow and water) which can significantly influence reliability (see, e.g. Tikalsky et al., 2005; Pustka et al., Raizer, 2009; Briaud et al., 2014; Králik and Králik, 2014; Markova et al., 2014; Pustka, 2014; Janas et al., 2015; Pustka, 2015; Koteš et al., 2016) of (civil) engineering structures. To assure required level of reliability of these structures, it is necessary to deal with this issue. Climate's changes have brought, among others, heavier precipitations which have led to excessive water flows or even to floods. This unexpected flows of water can significantly damage bridge structures crossing these watercourses (see, e.g. Cajka and Manasek, 2005; Link et al., 2008; Pasiok and



Stilger-Szydlo, 2010; Burns et al., 2011; Wang et al., 2011; Yu et al., 2011; Khosronejad et al., 2012; Collins et al., 2013; Lin et al., 2014; Afzali, 2015; Ehteram and Meymand, 2015; Klinga and Alipour, 2015; Fael et al., 2016; Mohamed et al., 2016). In association with this growing risk, a study examining effects of scour to a bridge abutment was elaborated.

In the following model, an example of a bridge pier (Strasky et al., 2001; Navratil, 2004; CNI, 2005; Parke and Nigel, 2008; Navratil and Zich, 2013; Sucharda and Brozovsky, 2013) is considered. To analyse interaction between the basement rock and foundation (see, e.g. CNI, 1988; CNI, 2004; Cajka et al., 2011; Cajka, 2013a,b,c; Cajka et al., 2014; Unlu et al., 2013; Hrubesova et al., 2015; Lahuta et al., 2015; Hrubesova et al., 2016; Cajka et al., 2016a,b; Labudkova and Cajka, 2016) a parametric study has been created. In the study, the finite element method on elastic subsoil has been utilised. The floods increase the cross-section of the river bed and change the properties of the foundation soil under the foundation (see, e.g. Ettema et al., 2000). In the first stage, the soil saturates with water. In the second stage fine-grained particles will wash away. In the third stage, parts of the basement rock will be washed off.

# 2. Model example of an abutment pier

## 2.1. Assumptions of calculation

For the calculation of interaction between the foundation and basement finite element method has been used (FEM consulting, 2002). The foundation has been modelled in a 2D environment using spatial components. For the basement rock, an element with effects of an elastic foundation has been used. The *C* parameter represents properties of the basement rock.

### 2.2. Subsoil model

The most efficient way for solutions of interaction tasks is a 2D model of the basement rock. Such model represents correctly, through a surface model, deformation properties of the whole mass of the foundation soil. The physical properties are expressed by means of subsoil parameters. The set of the interaction parameters is marked briefly as *C*. The parameters are allocated directly to structure components that are in the contact with the basement rock. The parameters describe the properties that influence the stiffness matrix. To simplify the situation, the *C* parameter can be imagined as the supporting by means of a dense liquid  $\gamma = C_{1z}$  (MN m<sup>-3</sup>) or by means of a set of vertical springs with an infinite density. From the physical point of view, there is not any difference. In case of extreme simplification, the *C* parameter can be imagined as the support.

### 2.3. Modelling and description of the structure

As a material for the foundation concrete C16/20 has been considered. Dimensions of the abutment pier are evident from **Figure 1**. The pier has been loaded by the horizontal load-carrying structure

of the bridge (forces  $R_{gk}$  and  $R_{qk}$ ). The load developed by the soil and random load of the road that influences the back face of the pier structure, have been introduced by  $H_k$  force (see **Figure 1**).



Figure 1. Scheme of the abutment pier with considered loads.

As far as the structure of the abutment pier is concerned, the foundation structure has been used only for the calculation. The loading of the whole upper construction has been re-calculated and simplified. Only the vertical loading and bending moment in the centre of gravity of the stem have been taken into consideration. The basement rock has been modelled using the  $C_z$  parameter. For purposes of the calculation, the following reference value has been used:  $C_z = 25$  MN m<sup>-3</sup>. This rough value is given by characteristic of gravel with fine-grain particles and by the loading and deformation for a specific type of the basement rock. The interaction has been solved for several cases: the value of  $C_z$  has changed because of the lower stiffness of the basement rock that was caused by the washing off of the fine-grain particles. In another case, the washing off of the basement rock has been investigated. **Figure 2** shows the foundation with considered distributions of the basement rock stiffness  $C_z$ .



**Figure 2.** The foundation with considered distributions of the basement rock stiffness  $C_{z}$ .

#### 2.3.1. Partial loss of contact between the foundation and basement rock

The flow of water washes away the basement rock. This reduces the contact surface resulting in increase of the stress in the foundation joint. Because of the non-homogeneous distribution of the tension in the foundation joint, the settlements in points 1 and 2 (see **Figure 2**) are

(1)

different. Consequently, the foundation joint rotates. **Table 1** shows the settlements of the pier in the points 1 and 2 and the total rotation. Assumed deformation of the foundation is shown in **Figure 3**. Rotation is calculated according to Eq. (1):

 $\varphi = arctg \frac{\Delta w}{1}$ 

						× ,
x [m]	Origin (1.9 – <i>x</i> ) [m]	w <sub>1</sub> [mm]	w <sub>2</sub> [mm]	$\Delta w = w_2 - w_1  [\mathbf{mm}]$	Rotation of foundation [deg]	Max. stress on foundation surface [MPa]
0.0	1.9	6.92	11.98	5.06	0.152	0.299
0.1	1.8	5.50	14.95	9.46	0.285	0.361
0.2	1.7	3.68	19.07	15.39	0.464	0.435
0.3	1.6	1.35	24.81	23.46	0.707	0.526
0.4	1.5	-1.66	32.88	34.54	1.042	0.638
0.5	1.4	-5.57	44.37	49.94	1.506	0.778
0.6	1.3	-10.71	60.99	71.70	2.163	0.955
0.7	1.2	-17.56	85.45	103.01	3.109	1.182
0.8	1.1	-26.83	122.29	149.12	4.506	1.479
0.9	1.0	-39.65	179.31	218.96	6.632	1.877
1.0	0.9	-57.82	270.62	328.44	10.004	2.426

Table 1. Deformation of the foundation for the case 'a'.



Figure 3. Assumed deformation of the foundation.

**Figure 2** shows the *x*-coordinates related to considered distribution of the basement rock stiffness  $C_z$ . When the contact surface is reduced to a certain level, tensile forces are generated. Elements, where tensile stress appeared, have been excluded from the calculation. **Figure 4** 

shows the chart for the calculation where the tension in the contact surface is taken into account (case (a\*)). For case (a), an iteration method has been used.



#### 2.3.2. Gradual decrease in the stiffness of the basement rock

In case (b) (see **Figure 2**), the interaction parameter  $C_z$  decreases gradually. The development of the  $C_z$  values is constant up to the place that is, in all likelihood, affected by water penetration. From that point onwards, the stiffness is linear up to the point 1 where the stiffness of the basement rock is assumed to be zero. Resulting values are listed in **Table 2**. The development of the values is shown in **Figure 4**.

#### 2.3.3. Gradual washing-away of soil and washing-off of fine-grain particles

Combination of both the previous situations represents the case 'c'. Here, the  $C_z$  is considered to be constant below the point 1 (see **Figure 2**). The soil is washed off gradually, thus decreasing  $C_z$ . Resulting values are listed in **Table 3**. From the chart in **Figure 4**, it is evident

x [m]	Origin (1.9 – <i>x</i> ) [m]	$w_1$ [mm]	w <sub>2</sub> [mm]	$\Delta w = w_2 - w_1$ [mm]	Rotation of foundation [deg]	Max. stress on foundation surface [MPa]
0.0	1.9	6.92	11.98	5.06	0.152	0.299
0.1	1.8	6.29	13.30	7.02	0.212	0.321
0.2	1.7	5.60	14.81	9.21	0.278	0.344
0.3	1.6	4.88	16.52	11.64	0.351	0.364
0.4	1.5	4.12	18.42	14.31	0.431	0.381
0.5	1.4	3.33	20.54	17.21	0.519	0.396
0.6	1.3	2.53	22.85	20.32	0.613	0.405
0.7	1.2	1.74	25.36	23.63	0.712	0.410
0.8	1.1	0.96	28.05	27.09	0.817	0.409
0.9	1.0	0.22	30.90	30.69	0.925	0.401
1.0	0.9	-0.35	33.78	34.13	1.029	0.392

that the tensile stress in the contact surface appears as early as in the first phase. The procedure has been similar to that used in case (a). An iteration method has been used for case (c). The case (c\*) describes the situation where the basement rock is subjected to the tension.

Table 2. Deformation of the foundation for the case 'b'.

x [m]	Origin (1.9 – <i>x</i> ) [m]	w <sub>1</sub> [mm]	w <sub>2</sub> [mm]	$\Delta w = w_2 - w_1$ [mm]	Rotation of foundation [deg]	Max. stress on foundation surface [MPa]
0.0	1.9	-3.57	59.18	62.75	1.893	0.38
0.1	1.8	-9.10	74.74	83.84	2.530	0.427
0.2	1.7	-18.68	98.10	116.78	3.526	0.49
0.3	1.6	-36.13	135.23	171.35	5.181	0.574
0.4	1.5	-70.31	199.51	269.82	8.192	0.691
0.5	1.4	-141.30	319.79	461.09	14.184	0.861
0.6	1.3	-323.69	602.49	926.18	30.374	1.182
0.7	1.2	-669.93	1253.43	1923.36	91.693	2.009

Table 3. Deformation of the foundation for the case 'c'.

#### 2.3.4. Step decrease in the parameters of the basement rock

Because the soil is saturated with water and fine-grain particles have been washed off, the stiffness will decrease (see **Figure 2**). In contrast to the calculation with the linear distribution (case 'b'), a step division of  $C_z$  has been chosen. When modelling by means of two parameters, the entering of values is simpler and faster. When modelling the linear development, the entering of values is more complex and  $C_z$  is different for each element. **Table 4** and **Figure 4** give the values for case 'd.

x <b>[m]</b>	Origin (1.9 – <i>x</i> ) [m]	w <sub>1</sub> [mm]	$w_{2}$ [mm]	$\Delta w = w_2 - w_1$ [mm]	Rotation of foundation [deg]	Max. stress on foundation surface [MPa]
0.0	1.9	6.92	11.98	5.06	0.152	0.299
0.1	1.8	6.29	13.30	7.02	0.212	0.321
0.2	1.7	5.65	14.75	9.09	0.274	0.342
0.3	1.6	5.06	16.27	11.21	0.338	0.369
0.4	1.5	4.52	17.84	13.31	0.401	0.372
0.5	1.4	4.09	19.39	15.30	0.461	0.38
0.6	1.3	3.77	20.87	17.10	0.516	0.382
0.7	1.2	3.59	22.24	18.65	0.562	0.379
0.8	1.1	3.56	23.45	19.88	0.600	0.372
0.9	1.0	3.69	24.17	20.48	0.618	0.36
1.0	0.9	3.96	25.29	21.33	0.643	0.346

Table 4. Deformation of the foundation for the case 'd'.

## 3. Conclusion

Figure 4 summarises the results of the conditions described above. Also, the chart shows the rotation of the foundation surface. Table 1-4 can be used to determine the values for a specific case and to determine the maximum stress that appears in the contact surface. The structure collapses if the basement rock plasticizes and the load-carrying capacity is lost. According to the limiting rotation requirements by CNI (1988), the ratio  $\Delta w/b = 0.003$ applies to the concrete foundation structure. The rotation angle is  $\phi$  = 0.17°. It follows from the calculation that the structure does not meet this requirement when the x-parameter (case 'b') decreases below the foundation surface 0.1 m. This is the beginning of the condition when the fine-grained particles start washing away. Most adverse results occur in the case 'c' when the lower stiffness of the basement rock is combined with the loss of contact with the basement rock. Because of the lost contact between the foundation and basement rock, the stress re-distributes and tensile stress appear in the contact surface. It is clear from the chart that there is a difference in the calculations (case 'a' and case 'c') where the tensile stress is, or is not, considered for the contact surface. The situation where the tensile stress exists is marked with an asterisk. The results are absolutely different. Therefore, the tensile stress in the foundation surface should not be taken into account.

## **Conflict of interest**

The authors declare that there is not conflict of interest.

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