

# Full Scale Experiences with Flow Funnel

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## Abstract

This article describes some experiences with flow funnel in large concrete silos with a large discharge eccentricity. Some in-situ measurements were made (full-size experiments) and the results are described here. As a consequence of the experiments described here, the eccentric discharge funnel flow model of the Eurocode EN 1991-4 has been incorporated into the new DIN 1055 Part 6 standard for pressures on silo walls.

Finally some reference calculations are described which give some understanding of the variation of the main parameters in this funnel flow model and show the influence of these parameters on the bending moments developing in concrete silo walls.

**Keywords:** Silo, flow funnel, full-size experiments.

## 1. Introduction

### 1.1 Description of the concrete silos

This paper describes the structural responses in service of two circular reinforced concrete silos (non-prestressed) storing cement raw meal which are identical in construction. The silos are both 75.60 m high (level bottom plate to level roof parapet) and the filled volume of each silo is 12600 m<sup>3</sup>. The cylindrical section of each silo is 54.66 m high, has an inside diameter of 18.0 m and a wall thickness of 30 cm. The silo was constructed using concrete grade B55 in the upper section (+8.34 m until 23.00 m), with the rest of the silo using concrete grade B45.

Both silos have an inner upright cone, made using prefabricated concrete parts. The wall inclination of these inner cones is 60° to the horizontal and the height of each cone is 11.00 m (Figure 1).

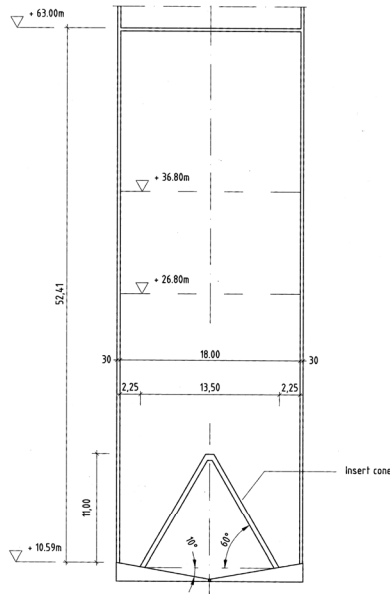


Figure 1: Main dimensions of the silo

Both silos are filled centrally at the top with a bucket elevator. At the bottom of the inner cone are 6 x 2 horizontal outlets. Aerated segments in the silo bottom in front of each outlet are operated in diametral pairs for about 10 minutes each and then the adjacent pair is activated, moving always in single steps in a clockwise direction (Figure 2). The aim of this method is to fluidise the bulk solid in the area of that section (this is termed a tangential aeration system).

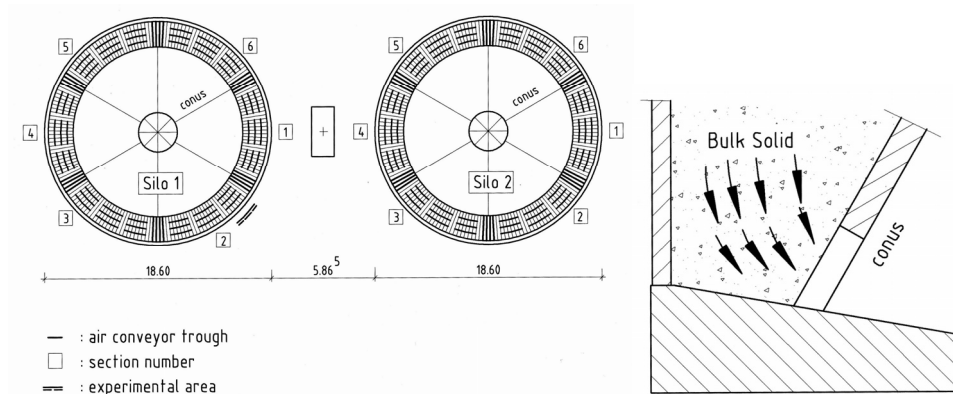


Figure 2: Top view of the inner cone, showing the sections of aeration and a typical outlet

This method of discharging the cement raw meal leads to a distinctive funnel flow pattern in the stored solid. It is clear that because the outlet in use keeps changing (10 minutes for each one, moving clockwise) more than one funnel flow channel will develop in the cement. It is also natural that the cross sectional area of the flow channel will change with height above the outlet. Examination of the top surface of the bulk solid while the silo was being discharged showed no sign of funnel flow: the surface sank down evenly, as would be expected in mass flow. This observation means that the cross section of the funnel flow channel must increase to fill the entire cross section of the silo above a certain level, with a form something like a trumpet (Figure 3). It is also natural to suppose that the outer shape of the funnel flow channel is probably not vertical throughout its height. It is more likely that the shape of the flow channel is somewhat helical in form due to the constant movement of the outlet position in a single direction.

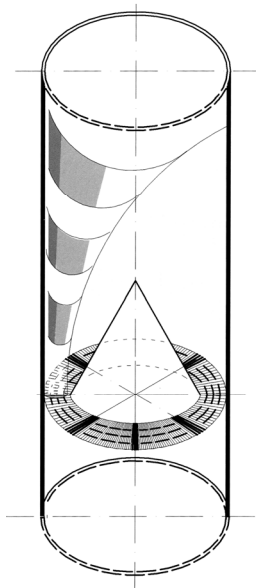


Figure 3: Assumed shape of the flow channel in this situation

### **3. Measurement and monitoring**

#### **3.1 Motive**

When the silos were in use, the service engineer found some alarming cracks on the outside of the concrete shell. At this time the silos contained about 13,000 tonnes of raw meal. Because nobody knew what the condition of the whole concrete shell might be (especially on the inside surface of the shell which could not be observed) and a static calculation of the stress state of the shell according to the existing DIN 1055 Part 6 standard did not investigate any condition of funnel flow, the first goal of the investigation was to reduce the main loads on the shell before further damage occurred.

Serious concern was felt to reduce the loads on the silo walls, and to remove the stored raw meal. To this end, it was decided to change the way that the aeration system operated in sections. To evaluate the result of this change, it was necessary to measure the consequences of the original aeration method and then to observe the changes caused by modifying the method of aeration.

### 3.2 Measurement equipment

To achieve this aim and to have an set of measurements with some redundancy, two different sensor types were chosen: strain gauges and crack sensors. The sensors were installed at the levels: 26.80 m and 36.80 m (the silo height was 54.66 m).

## 4. Measurement Results

### 4.1 Theoretical key points of the flow channel model

Rotter [1] published in 1986 an independent theoretical model to analyze the funnel flow problem (Figure 4). This model included several alternative assumptions which were open to further study, and over some time Rotter made several alternative proposals for these details [2, 3]. Finally a simple version of this model was adopted into the Eurocode 1 Part 4 [5] as a simple method of predicting the phenomena associated with discharge under large eccentricities ( $e/d \geq 0.25$ ). The new DIN 1055-6:2005-03 [5] is a relatively close translation of the Eurocode, though it is based on a draft of the Eurocode that preceded its publication by over a year, so there are some differences between the two. That means that the funnel flow model in the DIN is the same theoretical model as that of the Eurocode. Some minor modifications of the details of this model were made and published in [6].

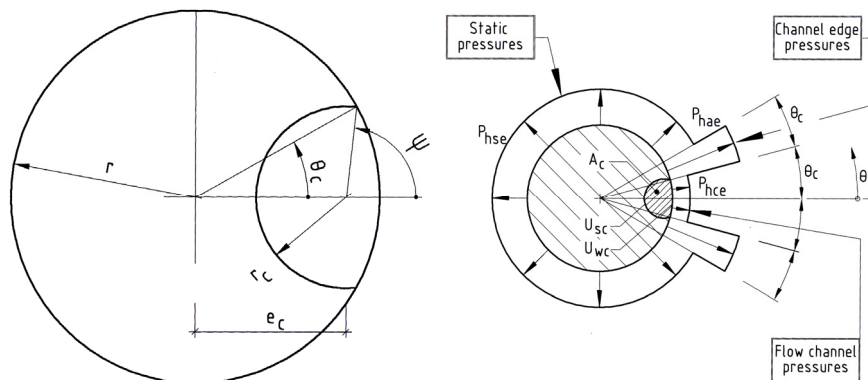


Figure 4: Cross section of the funnel flow model in En 1991-4

For simplicity, Rotter assumed that the funnel flow channel would have parallel vertical walls, since that was required to derive the resulting pressure pattern in closed form. The cross section is shown in Figure 4. Further he assumed that the wall friction is fully mobilised everywhere, and that a part of the flow channel is in contact with the wall. It should be noted that the boundary between the flowing and stationary solid is, however,

constantly subject to change, so this model is greatly simplified. To obtain a closed form solution, Rotter [1] used horizontal equilibrium of a slice in the same manner as Janssen [11].

#### 4.2 Measurement results and interpretation

The strain gauge and crack sensor measurements showed similar results. Because these results were very similar, only the results of the crack sensors are presented here.

Figure 2 shows the position and the numbering of the aerated sections and the position of the sensors from above. Figures 5 and 6 show the results of the measurements: Figure 5 shows those found under the original operating aeration scheme. By considering these observations for the complete measuring period at the height of 26.80 m, it is clear that the cracks opened and closed each time with the same frequency. At the start of the period presented in Figure 5, the cracks are open, but slightly less so than at the time of crack sensor installation, so they show a closure of about 0.04 mm. After a short period they closed by about 0.07 mm and then again by about another 0.07 mm. The cracks remained in this situation for about 850 s (which is closely related to the aeration time of the sections). After this period the cracks opened again to almost the initial position. Whilst the pattern is not precisely repeated each time, as might be expected with crack observations, the pattern remained essentially the same for each cycle. The sequence of closing and opening was repeated at approximately 1 hour intervals. The bars shown in these diagrams indicate the aeration period for each section. The crack sensors were located close to Section ?? 06 ?. The interval between successive aerations of this section has the same period (about 1 hour) as that of the cracks opening and closing on the silo wall.

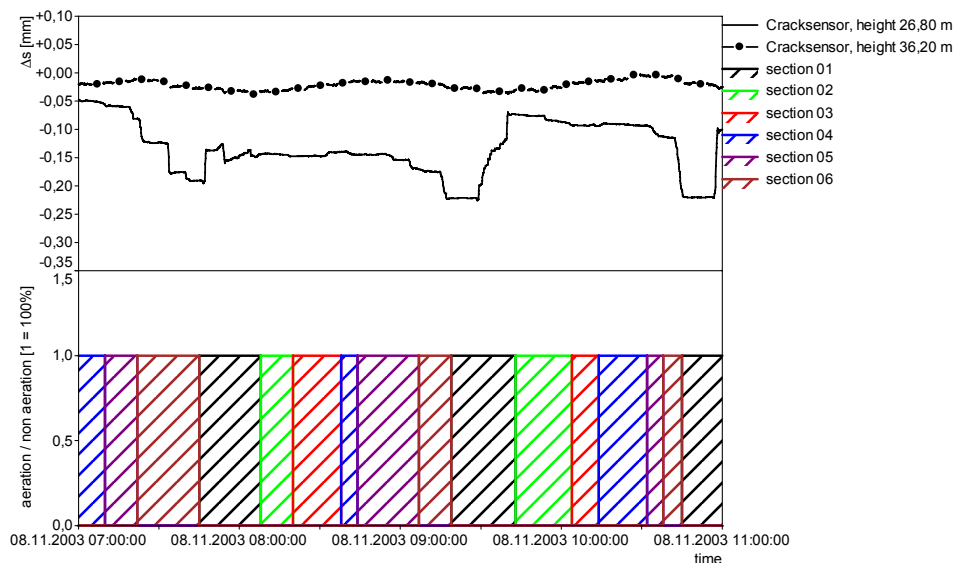


Figure 5: Results of the measurement by clockwise aeration

It is not possible to create an unambiguous correlation between the crack opening and closing and the aeration of the section. It is clear that flow channels were created by operating the outlets, but their shape is not necessarily well correlated with the simple model of Rotter [1, 2 and 3]. This model assumes that the flow channel above each outlet has vertical sides, but an attempt to correlate the opening and closing of the cracks with the operation of the outlets in this silo indicates that the flow channels must have had a shape that is more like a helix than a cylinder, since there is a delay between the crack movement and the outlet opening times. The cause of this problem is that Rotter's approach is based on a fixed location for an eccentric outlet.

Further, since the sensors were located at two different levels, it is possible to see that there is a significant difference between them. The measurements at the level 36.20 m show that there is only an insignificant effect caused by operation of an outlet, and consequently little influence from the flow channel. The only credible explanation for these differences is that the cross section of the flow channels grows steadily with height above the outlet, in a trumpet shape with its smallest dimension at the bottom. Above a certain level, all the flow channels arising from the operation of different outlets merge together, and this level is clearly below the 36.20 m observation level.

#### **4.3 Consequences of the measurement results**

One idea to reduce the loads on the wall was to change the aeration system of the sections. The volume of the air used to aerate the raw meal was decreased and the sequence of aeration of the sections was changed. In the initial aeration sequence, each section in turn clockwise was 100% aerated. To achieve a change, the Sections 01 and 05 were operated at the same time, but Section 01 only with 75% of the initial air volume. Then the Sections 02 and 06 were activated but Section 02 had similarly only 75%. Since these Sections were not diametrically opposed and not in well defined locations relative to each other, the sequence is here termed "random" operation. Figure 6 shows the results of these crack measurements. It can be seen immediately that changing the aeration procedure caused a drastic reduction in the crack opening behaviour, which can be inferred to have had a similar effect on the wall loads. This can be explained by a merging of the flow channels at a lower height, so that the effects seen previously at the higher level (36.20 m) were now obtained at the lower height (26.80 m).

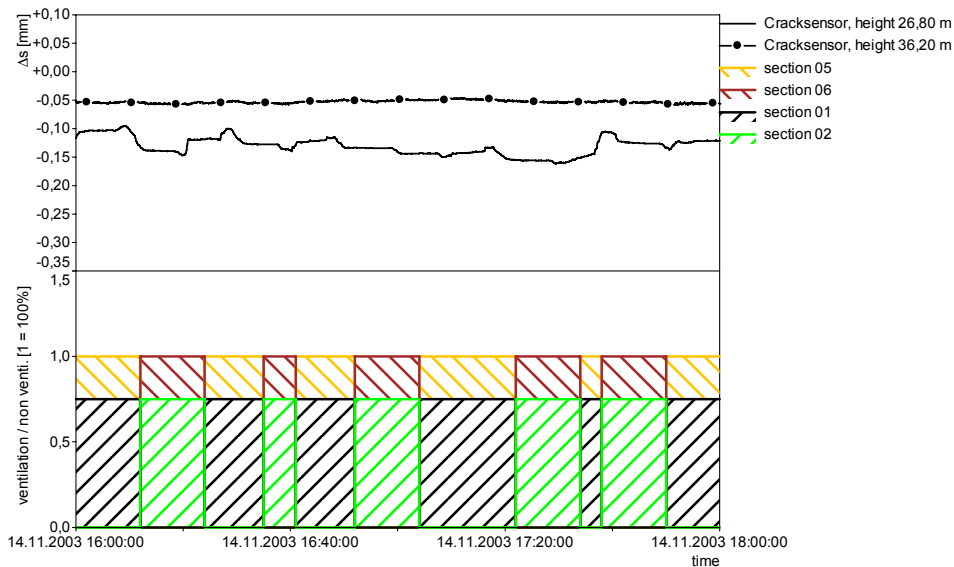


Figure 6: Results of the measurement by “random” aeration

## 5. Changes to the Flow Channel Model

The stress resultants in the silos were calculated according to DIN 1055-6 [5] or the Eurocode 1 Part 4 [4] using the funnel flow model and the Finite Element Method. According to this calculation, of these silos some areas to be discussed were detected by applying the funnel flow model in the form as it is presented in these standards.

The pre-publication draft of the Eurocode that was used as the basis for the new DIN presents the ratio of the radius  $r_c$  of the flow channel to the radius  $r$  of the silo with three values:  $r_c / r = 0.20/0.35/0.50$ . The use of these three ratios leads to rather smaller bending moments than those required to cause the crack movements observed in this silo. But when the ratio of the flow channel dimension to the silo radius was increased to  $r_c / r = 0.90$ , the bending moments were found to increase to a value that corresponded well with the crack movements.

It was also noted that, in this model, horizontal translational equilibrium is not satisfied by the pressures associated with a single flow channel on one side of the silo. Rotter [9] has explained this in terms of the need to maintain equilibrium of the correct mean pressure at any level, and there remains some uncertainty about whether the mean horizontal pressure or horizontal translational equilibrium should be satisfied. The net horizontal force leads to large global bending moments at the base of the silo, and these were found to be so great that an anchorage system would be necessary and that is not realistic. It is clear, however, that part of this problem lies in the chosen details discussed above and the simplicity of the final model adopted into EN 1991-4 [1].

Figure 7 shows the relationship between the  $r_c/r$  ratio and the angle  $\theta_c$  and the horizontal pressure. In the extreme situation, where  $r_c/r = 1.00$ , the complete cross section of the silo is the flow channel. That means, the Janssen-equation must be fulfilled. In the case of Janssen  $p_{hce} = p_{hae} = p_{hf}$ . In the diagram of figure 13 one can see, that this only in case of  $\eta = m / \tan \phi = 1.0$  ( $\mu$  is the wall friction coefficient and  $\phi$  is the angle of internal friction) works. Otherwise the value of the angle  $\theta_c$  do not really grows up, if  $\eta$  is nearby 1.

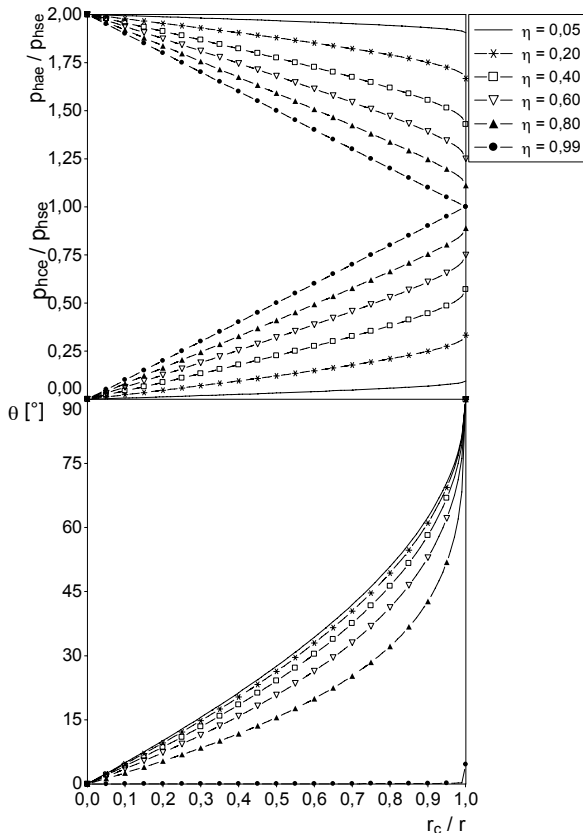


Figure 7: Relationship between  $r_c/r$ ,  $\theta_c$  and  $p_h$  s. also Rotter [1]

To fix these inadequacies in a first step, Ruckebrod and Kaldenhoff [12] developed a factor and limits, which were published in the correction of the DIN [6]. On this way, these changes are closed linked to the new DIN 1055-6 [5]. Details and background information to these correction can be found in Ruckebrod *et al.* [9].



## 6. Numerical Studies to the Flow Channel Model

Motivated by the problems of the funnel flow especially in big concrete silos, some numerical (and also theoretical) studies were done. For this investigation one silo with similar geometry like he on e, described in chapter 1, was considered.

The DIN 1055-6 [5] including the correction [6] presents the ratio of the radius  $r$  of the silo to the radius  $r_c$  of the flow channel with three values:  $r_c/r = 0.35/0.05/0.65$ . In the investigation six more relationships of  $r_c/r$  were considered, figure 8. The geometry and the position of these theoretical flow channels were shown in figure 9.

LC	$r$ [m]	$r_c$ [m]	$e_c$ [m]	$\theta_c$ [rad]	$U_{wc}$ [m]	
LC 01	9,00	3,15	6,13	0,175	3,16	LC according to DIN
LC 02	9,00	4,50	4,87	0,272	4,89	
LC 03	9,00	5,85	3,58	0,392	7,06	
LC 12	9,00	1,50	7,83	0,112	2,02	
LC 21	9,00	3,00	6,28	0,168	3,03	
LC 22	9,00	3,00	6,54	0,224	4,04	
LC 23	9,00	3,00	6,98	0,281	5,05	
LC 24	9,00	3,00	8,09	0,337	6,06	
LC 34	9,00	4,50	6,74	0,51	9,09	

Figure 8: Considered relationships of  $r/r_c$

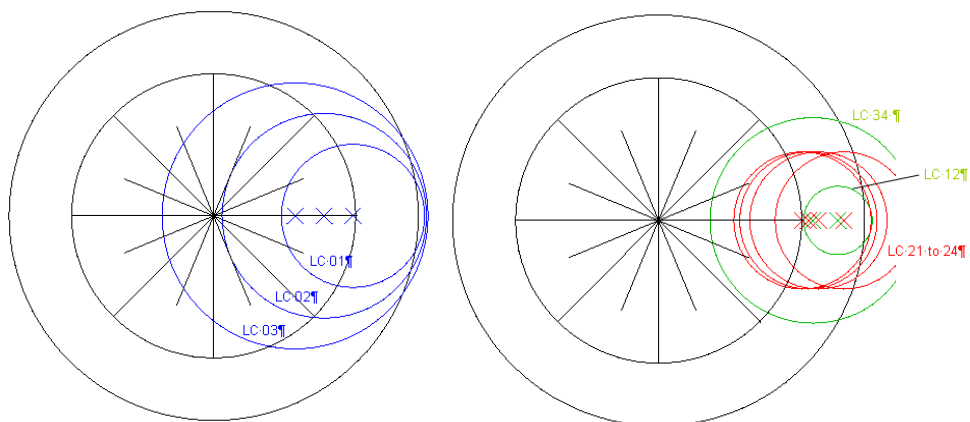


Figure 9: Position of the flow channel

Figure 10 shows the bending moments for LC 03 and LC 34.

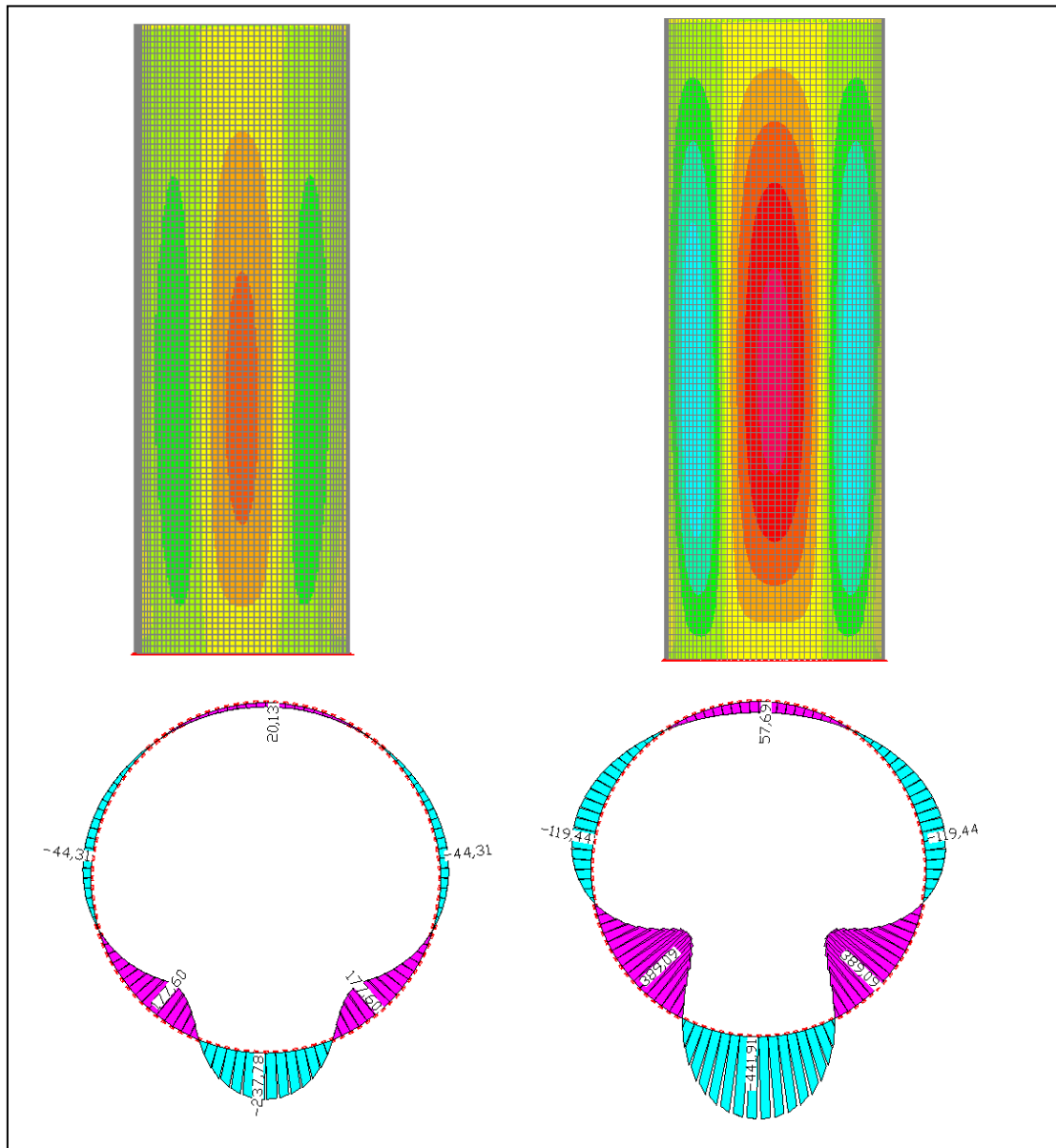


Figure 10: Bending moments [kNm/m] for LC 03 and LC 34, cross section in 20m height  
 The results of the study shows, that in the case of  $r_c = \text{constant}$ , the bending moments increase with rising eccentricity  $e_c$  or, if the eccentricity is constant, the bending moment increase with rising radius  $r_c$  of the flow channel. This means at the end, that always the

two parameter  $r_c$  and  $e_c$  have to be considering to optimize the loading to wall (i. e. with some kind of feeders). Figure 11 shows the results of this study: The plot of the bending moment against the two parameter  $r_c$  and  $e_c$ .

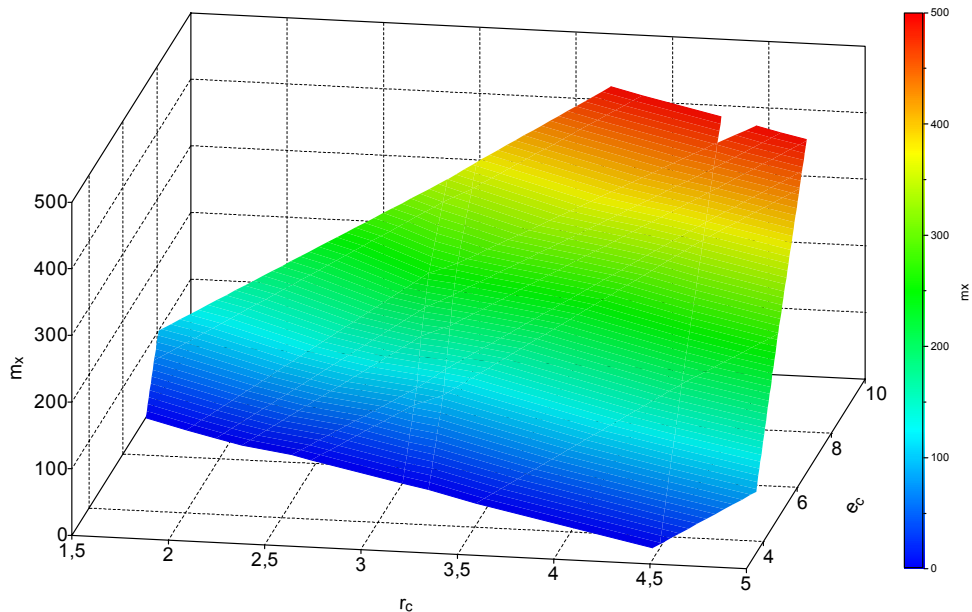


Figure 11: Bending moment depends on  $e_c$  and  $r_c$

If the bending moments are plotting against the arc length of the contact between the flow channel and the wall  $U_{WC}$  (figure 12), it can be shown, that increasing  $U_{WC}$  leads to increasing the bending moment.

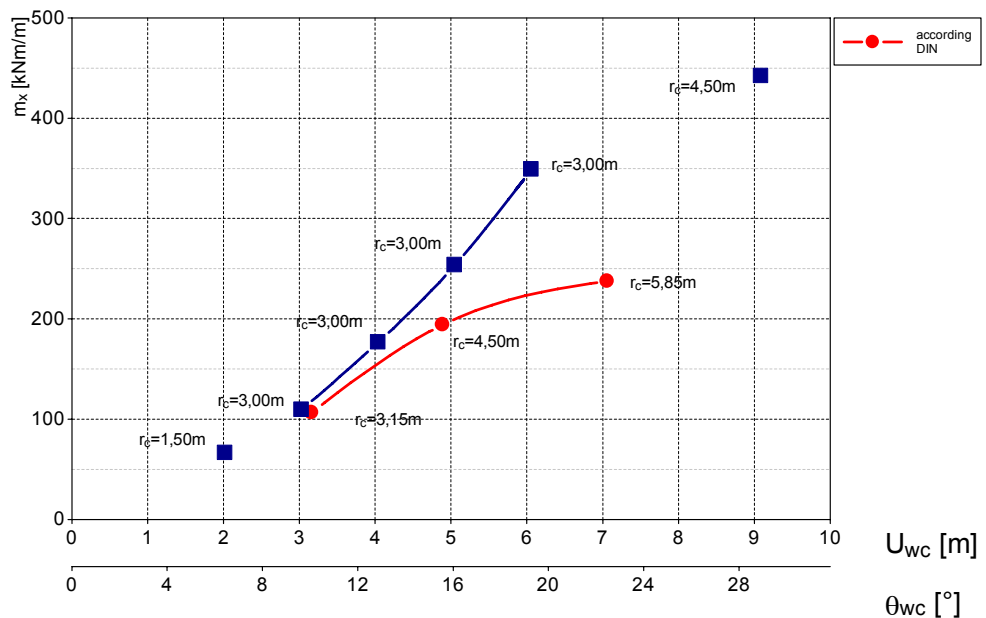


Figure 12: Bending moments versus  $U_{wc}$

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