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# Horizontal Loading Effects of Fresh Concrete on Precast Arches

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## Abstract

This paper investigates the horizontal effect of fresh concrete on precast arches. A number of different models of horizontal pressure of fresh concrete are considered in this regard. The effects of fresh concrete on a precast arch are represented as a ratio of maximum normal stress from horizontal action of fresh concrete to the normal stress induced by the self weight of the precast concrete arch. A parameter study on a number of geometric and operational variables has been carried out. The implications of this horizontal loading from fresh concrete have been discussed within the context of the potential financial effects.

Keywords: Arch, Fresh Concrete, Construction, Stress, Design

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26 **INTRODUCTION**

27 Concrete behaves like a Bingham plastic (Wallevik 2006) when placed in its fresh  
28 form imparting horizontal pressure onto the support system in place, which may have  
29 significant implications for the supporting formwork (Peurifoy and Oberlender 1995).  
30 The supporting formwork must be of sufficient strength (Hurst 1983) to withstand this  
31 horizontal action that exists until the time when the concrete has hardened sufficiently to  
32 be self-supporting (Kovler and Roussel 2011). There exist numerous theories on the  
33 variation of horizontal pressure of concrete as a function of the depth of placement  
34 pertaining to vertical formwork. These theories all agree that this horizontal action and  
35 the resultant pressure is of significant magnitude (Santilli et al. 2010) and through the use  
36 of an appropriate pressure model, construction costs related to formwork may be  
37 minimized while ensuring safety.

38 A specific situation considered for the purposes of this paper is the horizontal  
39 loading on precast concrete arches by fresh concrete placed in to form hardened in-situ  
40 concrete. The situation arises for multi-span arch bridge structures with precast concrete  
41 arches with other in-situ elements. An example of such a bridge is presented in Figure 1.

42 Before the placing of fresh concrete, the precast arches remain simply supported.  
43 However, distributions of moments take place and the support conditions change  
44 significantly when the in-situ fresh concrete hardens. Consequently, stage-by-stage  
45 modeling is often required for design.

46           A special time window in this regard is when the fresh concrete is placed on the  
47 two sides of a precast arch. From a stability point of view, a check is required so that  
48 uplift does not take place due to the imbalance of loading in the form of fresh concrete on  
49 the two sides of the arch. This problem can be avoided by specifying the difference  
50 between the overall heights of each concrete placement on the two sides of the arch to a  
51 maximum stipulated value throughout the fresh concrete placement operation. However  
52 even under such circumstances, it is possible that significant normal stress is produced in  
53 the arch due to the lateral action of fresh concrete acting on the two sides of the arch.  
54 This significant normal stress may result in the possible violation of serviceability limit  
55 states, such as the control of crack width. Depending on the operation of placement, it is  
56 possible for concrete to remain in its fresh state until the completion of this operation. As  
57 such, during the design of fresh concrete placement, consideration must be given to the  
58 horizontal effects of fresh concrete acting on the structural element to satisfy all limit  
59 states, as outlined in Figure 2.

60           As observed in Figure 2, within the operation of concrete placement, there is a  
61 possibility of potential overloading and a compromise with the performance standards.  
62 Such a possibility is independent of codes of practices in different countries. Due to the  
63 presence of numerous theories for the modeling of horizontal pressure imposed by the  
64 fresh concrete and a lack of conclusive experimental data, there exists no consensus on  
65 the exact nature and magnitude of lateral loading acting on formwork (Puente et al. 2010).  
66 This paper evaluates the aforementioned effects on precast concrete arches employing a  
67 number of horizontal pressure theories of fresh concrete. The ratios of maximum normal  
68 stress due to horizontal action of the fresh concrete to the normal stress due to the self

69 weight of the arch are outlined and evaluated. The effects of different geometric and  
70 operational values are investigated and the eventual potential effects on costs are also  
71 discussed.

72

### 73 **HORIZONTAL PRESSURE OF FRESH CONCRETE**

74 Significant amount of research has taken place concerning formwork pressure  
75 from fresh concrete (Santilli et al. 2011a). These investigations have researched the  
76 effects of horizontal pressure of fresh concrete on vertical formwork and the effects of  
77 varying parameters on the magnitude of the pressure. Some variability of pressure may be  
78 expected when the surface roughness or texture of the surface on which fresh concrete  
79 exerts pressure changes (Arslan et al. 2005). In the absence of conclusive experimental  
80 results or theories of the effects of horizontal action of fresh concrete on precast arches,  
81 envelopes of the existing theories are appropriate for the appreciation of the problem and  
82 the associated analyses. In this connection, some engineering pragmatism is required  
83 after considering the model-dependent variability of effects.

84 In this paper, the pure hydrostatic effects of concrete are thus not considered in  
85 great detail since a number of existing studies indicate that an approximate linear increase  
86 in pressure with depth carries on only to a certain depth. When concrete is left to set for a  
87 time, the pressure created deviates from the hydrostatic pressure line and reduces as it is  
88 beginning to form an internal structure (Arslan 2002). Also, a quicker curing may be  
89 expected to lead to a reduced lateral pressure. With the advance of admixtures, material  
90 improvements and need for improved concrete characteristics, there have been advances  
91 in concrete properties and performance. One such development is self-consolidating

92 concrete (SCC) which is able to flow and consolidate underneath its own weight by  
93 forming an internal structure. A downside of this is that the SCC, when placed, has a  
94 lower yield stress and with the plastic viscosity of the concrete there is an increase in the  
95 lateral pressure (Kim et al. 2012). Investigations into the effects on the lateral pressure of  
96 varying admixtures in SCC have also been conducted (Kim et al. 2010). The properties of  
97 SCC mean it can be exploited to produce concrete with a very high workability and/or  
98 concrete with a very high strength (Neville 1996). The effects of horizontal loading of  
99 fresh concrete acting on formwork can have significant implications for the overall cost  
100 of a concrete project (Hanna and Senouci 1997). Considering the absence of data under  
101 such circumstances, a number of different horizontal pressure models must be  
102 incorporated for such analysis, with varying parameters, to credibly assess the collective  
103 effects of horizontal pressure by producing an envelope of individual effects.

104

## 105 **MODELS OF HORIZONTAL PRESSURE**

106 Eight different models of horizontal pressure of fresh concrete are initially  
107 considered for the purposes of this paper, following existing studies (Santilli et al. 2011b).  
108 Of these eight models considered as shown in Table 1, six were chosen for detailed  
109 analyses. The hydrostatic pressure model (Equation 1) assumes that the fresh concrete  
110 acts hydrostatically with a density of liquid equal to that of concrete, where  $\rho$  ( $\text{kg/m}^3$ ) is  
111 the bulk unit mass of fresh concrete,  $g$  ( $\text{m/s}^2$ ) is the acceleration due to gravity and  $H$  (m)  
112 is the depth at which the horizontal pressure,  $P_{max}$  (kPa), is being considered with respect  
113 to the free horizontal surface of the fresh concrete. This model assumes a linear increase  
114 in the pressure as the depth of the concrete increases. This pressure model is highly

115 conservative as it does not allow for the concrete to reach a maximum pressure but  
116 instead considers the pressure to be constantly increasing until the bottom of the  
117 placement is reached. This model has thus not been included for detailed analysis.

118         The French Standard (NFP 93-350 1995) reports that the formwork must be  
119 designed to withstand forces due to the placing of concrete with a density of  $2,400 \text{ kg/m}^3$   
120 (Equation 2). The method considers the application of a hydrostatic distribution for  
121 formwork design up to 3 m high at which the pressure is at a maximum. The model may  
122 be unsuitable for many designs which are over the stipulated formwork height and does  
123 not consider effects of the construction process or environment. Consequently, it was  
124 decided to exclude this model for the purposes of this paper.

125         The Gardner model (1980), is based on laboratory studies on formwork (Equation  
126 3), where  $h_i$  (m) is the immersed depth of vibrator (minimum 1m),  $HP$  is the Horsepower  
127 of the vibrator,  $d$  (m) is the minimum formwork dimension in mm,  $R$  (m/hr) is the rate of  
128 placement,  $T$  ( $^{\circ}\text{C}$ ) is the temperature of the concrete and  $S$  (mm) is the slump after the  
129 application of superplasticizer. The model is limited by a maximum of a hydrostatic  
130 pressure and considers the bulk unit mass of fresh concrete as  $2400 \text{ kg/m}^3$ . For formwork  
131 design, the power of the vibrator was assumed as  $3/4$  HP per 305mm of smaller form  
132 section. The addition of super plasticizers and extra concrete additives (Gardner 1982,  
133 1984) seems to result in an increase in the mobility of concrete and a decrease in the rate  
134 of strength gain at early age, resulting in an increase in pressure.

135         Adam et al. (1965) proposes a model (Equation 4) based on laboratory test data  
136 which is reported to be appropriate for a formwork measuring 3 m in height, 2.5 m in  
137 length and varying widths. The model proposes that the loading on the formwork should

138 act as a hydrostatic pressure until it reaches its maximum pressure, after which pressure  
139 remains at a constant.

140 The approach (Equation 5) of E DIN 18218 (2008), a new draft of the German  
141 Standard, replaces the previous standard of DIN 18218 (1980), where  $K_D$  is a coefficient  
142 based on the setting time of the concrete. Included in the standard is a correction factor  
143 for concrete of bulk densities other than  $25 \text{ kN/m}^3$ , a recommendation to reduce  $P$  by 3 %  
144 for each degree below  $15^\circ\text{C}$  and increase  $P$  by 3% for each degree above  $15^\circ\text{C}$  to take  
145 into account the constant temperature in the equation.

146 The Construction Industry Research and Information Association (CIRIA) Report  
147 108 (1978) proposes a model based on a number of large scale field tests and  
148 investigations of pressures involved with the formwork (Equation 6). It includes  $C_1$ , a  
149 coefficient dependent on the size and shape of formwork,  $C_2$ , a coefficient dependent on  
150 constituent materials of the concrete and  $K$ , a temperature coefficient.

151 The Rodin model (1952) is another experimental model for internally vibrated  
152 concrete (Equation 7) where  $H_{max}$  (m) is the height at which the maximum pressure  
153 occurs. This equation has been found to be valid for a concrete mixture of 1:2:4  
154 (cement : sand : coarse aggregate mass fractions), a unit weight of  $2400 \text{ kg/m}^3$ , a slump of  
155 150mm and a temperature of  $21^\circ\text{C}$ . Correction factors may be applied for other situations.

156 The American Concrete Institute (ACI) Committee 347 (2004) considers  
157 trapezoidal pressure distribution (Equation 8), where  $C_w$  is the unit weight coefficient and  
158  $C_c$  is the chemistry coefficient. Although this model is dependent on rate of placement  
159 and concrete temperature, the equations may be limited by assumptions of normal

160 internal vibration with vibration immersion of less than 1.2 m, a slump less than 100 mm  
161 and the avoidance of admixtures among other things.

162         Theoretically, the horizontal pressure of fresh concrete has been related to shear  
163 strength properties based on soil mechanics principles (Olsen 1968; Alexandridis and  
164 Gardner 1981), where internal friction is considered as a basis for shear strength. The  
165 lateral pressure theory for soil is also observed in existing literature (Ritchie 1962;  
166 Graubner and Proske 2005). Computationally, these are no different in effect than the  
167 variation of theories already considered in this paper. Tresca yield criterion (Roussel and  
168 Ovarlez 2005), thixotropic considerations (Khayat and Assad 2005a,b), hysteresis loop  
169 (Douglas et al. 2005), shear stress necessary for breakdown of concrete (Shaughnessy and  
170 Clarke 1988) and many other particulars have often being discussed. The lateral pressure  
171 models considered in this section are however sufficient since the envelope of the curve  
172 and the understanding of the importance of consideration of horizontal effects of fresh  
173 concrete in design is not significantly extended by considering small variations of the  
174 fundamental existing models.

175         Based on the discussions and the scope of the pressure models as presented in this  
176 section, the CIRIA model, ACI model, Gardner model, Rodin model, Adam et al. model  
177 and E DIN 18218 model of horizontal pressure from fresh concrete are chosen for a more  
178 detailed study with respect to their effects on precast concrete arches. Since many  
179 parameters are involved with the models and the arch, a baseline case has been  
180 established for the purposes of illustration. The baseline case considers the span, the  
181 height and the width of a parabolic precast concrete arch to be 15, 3 and 15 m  
182 respectively, where the thickness of the arch is 400 mm. The rate of placement of

183 concrete is assumed to be 3 m/h, at a temperature of 20 °C. The difference between the  
184 heights of each placement is kept at a constant of 400 mm, with each placement being  
185 alternated between the two sides of the arch and a maximum placement of 800 mm being  
186 considered. The slump of concrete is assumed to be 100 mm and the vibrator is assigned  
187 a value of 0.75 HP under operation. To determine the effect of the horizontal loading of  
188 the fresh concrete acting on the arch, ratio of the maximum normal stress due to the  
189 horizontal loading acting on the arch to the normal stress due to the self weight of the  
190 arch was determined. Sections were taken along the height of the arch and the normal  
191 stress for the self weight and the maximum normal stress from the horizontal loading  
192 were found, with the normal stress taken to be acting perpendicular to the section  
193 surfaces. Figure 3 displays the arch with baseline conditions following the second  
194 placement of the fresh concrete and a section through the arch with the direction of the  
195 normal stress is shown.

196 Figure 4 presents the pressure envelope of the six chosen models with baseline  
197 values as described above acting over the height of the arch at a maximum placement of 3  
198 m. All six models presented act as a hydrostatic pressure model until the pressure reaches  
199 a maximum. In the cases of CIRIA, ACI, Gardner, Adam et al. and E DIN 18218 the  
200 maximum pressure as determined by the respective model, once reached, remains at a  
201 constant until the base of the arch. In the case of the Rodin model there is a reduction in  
202 the pressure once the maximum pressure is reached. This is explained through  
203 experimental data for internal vibration based on which a conclusion was drawn that once  
204 the maximum pressure is reached there is a reduction in the pressure experienced by the  
205 supporting formwork below the point of maximum pressure. In fact, the CIRIA model

206 does acknowledge this pressure decrease but considers the modeling of the same to be  
207 difficult and uncertain, consequently recommending a conservative non-decreasing  
208 estimate of pressure after the pressure maximum has been reached following a  
209 hydrostatic approach. The model which produces the lowest value of horizontal pressure  
210 is the Adam et al. model, while the Gardner model has the maximum value of horizontal  
211 pressure for the baseline case considered.

212         Figure 5 presents the pressure envelope of the six chosen models with varying  
213 operational parameters. The values of all other parameters in the models are identical to  
214 the baseline case. The rates of placement and temperature's represent minimum and a  
215 maximum values chosen around the baseline value. The minimum value of the rate of  
216 placement was chosen as 2 m/hr and the maximum as 4 m/hr, while the minimum  
217 temperature chosen was 5 °C, with a maximum of 40 °C. The Rodin model has been  
218 excluded from the temperature dependent pressure envelopes as it does not include  
219 temperature as a varying parameter, and as such will remain the same as the baseline  
220 model. For all four varying parameters, the Adam et al. model registers the smallest  
221 maximum pressure. The increase of the rate of placement parameter increases the  
222 pressure acting on the arch significantly. This indicates the importance of the rate of  
223 placement as a parameter for all pressure models when examining the effects of  
224 horizontal pressure experienced by the arch due to the placement of fresh concrete. The  
225 increase of initial temperatures of the fresh concrete also produces significant differences  
226 in the pressure acting on the arch during placement. For an initial temperature of 5 °C,  
227 only the Adam et al. model reaches its maximum pressure. The CIRIA, ACI, Gardner and  
228 E DIN 18218 models do not reach their respective maximum pressure and as a result are

229 hydrostatic in nature. For a temperature of 40 °C all models reach their respective  
230 maximum pressures.

231 Figure 6 presents the pressure envelope of the six chosen models with varying  
232 heights of the arch. The values of the parameters for the models were the same as those  
233 chosen for the baseline case, with the exception of the height of the arch. For an arch of  
234 height 2 m, the Adam et al. model alone reaches its maximum pressure, after which the  
235 pressure is constant. The CIRIA, ACI, Gardner, Rodin and E DIN 18218 models do not  
236 reach their respective maximum pressures and thus act as a hydrostatic pressure loading.  
237 For the arch of height 4m, the Rodin model experiences a significant reduction in  
238 pressure once the maximum pressure is reached. The maximum pressure of the CIRIA  
239 model records an increase on the baseline value due to its inclusion of the overall height  
240 of the formwork as a parameter. The ACI, Gardner, Adam et al. and E DIN 18218 models  
241 have a maximum pressure which is identical to the Baseline model. With the increase in  
242 height, the pressure exerted on the arch by the fresh concrete for all models is  
243 significantly increased and will cause a significant increase in the normal stress ratio  
244 experienced by the arch.

245

## 246 **EFFECTS OF HORIZONTAL LOADING ON PRECAST CONCRETE ARCH**

247 A number of parameters are chosen in this paper for numerical studies based on  
248 finite-element models to illustrate the effects of the horizontal pressure of fresh concrete  
249 on a precast arch. This section attempts to investigate the location of maximum stress  
250 ratios and to establish an approximate idea regarding the order of magnitude of the stress  
251 ratios due to the horizontal action of fresh concrete. The temperature of concrete ( $T$ ), the

252 rate of placement ( $R$ ), the height of the arch ( $H$ ) and the ratio of the dimensions of the  
253 precast arch between the span of the arch and the width of the arch ( $S / W$ ) were chosen  
254 for investigation in this paper, with the values of the parameters for each study listed in  
255 Table 2. These parameters were assigned to each of the six models considered for the  
256 purposes of a comprehensive investigation into the influence of the parameters on the  
257 models, and thus on the normal stress ratio experienced by the arches.

258 A finite element model of the arch was created using Strand7 finite element  
259 software (Strand7, 2005). Eight node hexahedral (Hexa8) brick elements were chosen for  
260 modeling purposes. A comparison with sixteen node (Hexa16) and twenty node (Hexa20)  
261 brick elements was carried out to ensure the sufficiency of the use of eight node brick  
262 elements. The Hexa8 brick model agreed with the Hexa16 and Hexa20 brick models to  
263 within 99.2%, with significantly less computing time and thus chosen for arch models.  
264 The order of the number of nodes per model was over one hundred and sixty thousand.  
265 The loading was applied for different load cases, where each load case represents a  
266 different placement of concrete, and range from the arch being empty to the completion  
267 of the placement of concrete. The models were then solved using a linear static solver and  
268 the solved models analyzed.

269 The ratio of absolute maximum normal stress due to the horizontal action of fresh  
270 concrete to the normal stress for self-weight alone is considered for illustration (Figure 7).  
271 The most onerous effects are observed occurring at quarter span.

272 Figure 7 indicates a similar stress ratio pattern for all models considered in this  
273 study along the height of the arch. For all six models, it was the penultimate placement of  
274 concrete which produced the highest normal stress ratio, with one side of the arch having

275 the fresh concrete placement completed, to a depth of 3 m, and the opposite side having a  
276 fresh concrete depth of 2.8 m. The Adam et al. model produced the lowest stress ratio.  
277 This is consistent with the fact that the model produced the smallest maximum pressure  
278 as compared to other models considered, as observed in Figure 4. The Gardner model  
279 produced the largest stress ratio, with the CIRIA, ACI, Rodin and E DIN 18218 models  
280 producing slightly lower stress ratios. The presence of absolute maximum values of the  
281 normal stress ratios near quarter spans indicates that this location now becomes an  
282 important section for serviceability checks for fresh concrete placements. The maximum  
283 stress ratio, as defined in this paper, at the quarter span of the arch is in the region of 4.5.

284

## 285 **PARAMETER STUDY**

286 The effects of the change of various parameters affecting the horizontal pressure  
287 of fresh concrete and on the normal stress ratios in the arch are considered in this section.

288 The rate of placement of the concrete is a parameter which can be controlled  
289 using a pumping rig onsite. The difference between the different rates of rise values is  
290 investigated (Figure 8) ranging from 2 to 4 m/hr, with the baseline having a rate of rise of  
291 3 m/hr (Figure 7). The rate of rise appears to vary the normal stress ratio the least of all  
292 the changing parameters analyzed in this paper. It appears that relatively large variations  
293 in the rate of rise do not have a significant impact on the stress ratios, ranging from in the  
294 region of 4.0 to 4.5. All models exhibit similar patterns of stress ratio. As an easily  
295 controlled parameter during construction, the rate of placement of the fresh concrete may  
296 be controlled so as to limit the normal stress ratio experienced by the arch.

297           The influence of temperature is included in the ACI, CIRIA, Adam et al., Gardner  
298 and E DIN 18218 models, but is considered constant for the Rodin model. Consequently,  
299 the Rodin model was excluded from varying temperature analysis. Three initial  
300 temperatures of concrete (5 °C, 20 °C and 40 °C) were considered for this purpose. All  
301 models registered a reduction in the normal stress ratio for increasing temperature. The  
302 change in the normal stress ratio with variable temperature is more prominent for a  
303 change of temperature from 20 °C to 40 °C than for a change of temperature from 5 °C to  
304 20 °C. Keeping the temperature of concrete below 20 °C was observed to change the  
305 stress ratios very little. The variability of stress ratios within different models is also  
306 greater for higher temperatures. The CIRIA, ACI, Gardner, and E DIN 18218 all have  
307 equal stress ratios for  $T = 5\text{ °C}$ , as all the models do not achieve their respective  
308 maximum pressures and are fully hydrostatic in nature. The Adam model creates the  
309 lowest value of stress ratios as the model achieves its maximum pressure and is thus less  
310 conservative than the other models considered.

311           Changes in geometric properties produce the largest changes in terms of the  
312 normal stress ratio. To investigate the impact of changes in geometry on the normal stress  
313 ratio, heights were chosen below and above the baseline arch height. Figure 10 illustrates  
314 the ratio of normal stress acting along the height of the arch for arches of 2 m and 4 m in  
315 height. The lowest height chosen was a 2m high arch, which produced the lowest normal  
316 stress ratio for all parameters considered when sections taken through the arch along the  
317 height of the arch were analyzed. The CIRIA, ACI, Rodin, Gardner and E DIN 18218  
318 models all showed identical values as their maximum pressures were not reached and all  
319 five models were fully hydrostatic in nature under these circumstances. The Adam et al.

320 model alone reached a maximum pressure in this case but did not produce any notable  
321 difference in the normal stress ratio when compared to the other models. For an arch of  
322 4m height, there is a substantial increase and variability in the normal stress ratios.  
323 Additionally, for an increased height the variability of stress ratios among different  
324 pressure models are more significant than those observed from changing rates of  
325 placement or the initial temperature of the fresh concrete. All models show similar stress  
326 ratio patterns, with the Gardner model producing the largest normal stress ratio. The  
327 Adam et al. model is significantly lower than the other five models, as it proposes that the  
328 horizontal action from fresh concrete is more limited than suggested by other models.

329         The final parameter chosen for analysis was the ratio of the arch plan dimensions.  
330 A ratio of the span of the arch to the width of 2 : 1, the baseline ratio of 1 : 1 and a ratio  
331 of 1 : 2 were considered in this regard. The varying of the arch geometry produced the  
332 second largest normal stress ratios of all variable parameters considered for the purposes  
333 of this paper. The difference in normal stress ratios between the span to width ratio of 2 :  
334 1 and the baseline ratio of 1 : 1 was found to be small. This proved significantly different  
335 for the plan dimension ratio of 1 : 2, which produced a very high value for the normal  
336 stress ratio (Figure 11). This indicates that it is the span of the arch which has a more  
337 significant influence on the normal stress ratio experienced by the arch than the width of  
338 the arch. For the arch of ratio 2 : 1, the CIRIA, ACI, Rodin, Gardner and E DIN 18218  
339 again produce similar values, with all models indicating a slight reduction in the normal  
340 stress ratio from the baseline. For the arch of ratio 1 : 2, all models show a significant  
341 increase in the normal stress ratio, with the CIRIA, ACI, Rodin, Gardner and E DIN

342 18218 models indicating similar results and the Adam et al. model producing the lowest  
343 stress ratio. The largest ratio was obtained from the Gardner model.

344

345

## 346 **DISCUSSION ON COST IMPLICATIONS**

347         The horizontal pressure of fresh concrete has direct implications on overall  
348 construction costs. While the length of the span and the width of the arch for a particular  
349 project is usually predetermined by geometric and site conditions, the thickness of the  
350 arch is dependent on the lateral pressure of fresh concrete poured onto the arch during  
351 construction. The thickness of arch can be influenced by horizontal pressure of fresh  
352 concrete even in the presence of significant reinforcement. Under-designing the arch by  
353 underestimating the effects of the lateral pressures associated with fresh concrete may  
354 result in failure in the serviceability limit state. This may result in replacing the precast  
355 arch after manufacture, adding significant costs to the project. If the problem is noticed  
356 after the hardening of concrete, the structure then represents a compromised limit state  
357 situation. Conversely, overestimation of the effects of lateral pressures will result in an  
358 unnecessarily oversized arch, which will also increase costs of construction.

359         Through the use of a model arch with baseline dimensions and characteristics as  
360 previously described in this paper, the costs of precast arches with varying thicknesses in  
361 relation to the overall construction costs was established. The values were obtained for  
362 the currently existing rates quoted in the Republic of Ireland. If overdesign occurs by the  
363 overestimation of the effects of the horizontal pressure of fresh concrete, costs will be  
364 increased unnecessarily through the use of excessively large arch. It was found that by

365 increasing the thickness of the arch from 200 mm to 400 mm can increase construction  
366 costs of the bridge by 14%. Conversely, if the stress caused by the horizontal action of  
367 the fresh concrete is not designed for and the arch is undersized, a larger replacement  
368 arch would be required leading to large and unnecessary increase in costs of up to 40%.

## 369 **CONCLUSIONS**

370 This paper demonstrates that the horizontal pressure of fresh concrete can have  
371 a significant effect on the design and construction of precast arch bridges. The effects  
372 were quantified in this paper through the ratios of absolute maximum normal stress due to  
373 horizontal action of fresh concrete and that due to self-weight. A number of horizontal  
374 pressure theories were considered for fresh concrete and the stress ratios were computed  
375 to demonstrate the significant effects of such horizontal action. The quarter span of the  
376 simply supported arches were found to be the location of maximum stress ratio values  
377 independent of the geometry, material and operational factors. This location is  
378 recommended to be checked for serviceability criteria considering horizontal action of  
379 fresh concrete.

380 When conclusive field tests are lacking, a stress envelope generated from  
381 different horizontal pressure models for fresh concrete is recommended for use.  
382 Although, certain geometric and operational conditions may produce stress ratio  
383 envelopes of relative insignificance, this variation can be quite significant for many other  
384 conditions. All models considered produced stress effects of the same order under similar  
385 input parameters.

386 Parameter studies revealed that the variation in stress ratios is chiefly guided by  
387 the geometric proportions of the arch. When the geometric proportions are under control,

388 the higher temperatures of concrete seem to have a significant effects on the stress ratios.  
389 The effect of temperature on stress ratios were observed to be of less significance below  
390 20°C. Rate of placement of concrete does not appear to have a significant effect on stress  
391 ratios.

392 Horizontal effects of fresh concrete have direct cost implications. By ignoring  
393 this action, serviceability limits may be violated and the replacement of a structure  
394 through redesign would incur additional costs. An overdesign will result in ignoring the  
395 pressure model envelope and carrying out approximate calculations using a hydrostatic  
396 model will also lead to incurring additional costs.

397

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