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The Influence of Ground Conditions on Intrusion Flows through Apertures in Distribution Pipes

Richard Collins ¹ and Joby Boxall ²

ABSTRACT

This paper presents a new, tractable analytical expression to describe the intrusion of fluids into buried pipes under steady-state conditions. The expression is validated with results from novel experiments. The derivation is based on the combination of the relevant existing models of flows through porous media and the losses through an orifice, with the resulting expression relating the intrusion flow rate to an applied driving pressure. The expression is shown to yield results directly equivalent to those generated from a full 3D CFD model of the intrusion process. Results from the experiments, quantifying volumetric intrusion from a realistic 3D porous media, presented here, compare favourably with calculated values, validating the expression. While the experimental and analytical results show a high level of agreement, it was found that the analytical expression tends to slightly under estimate the intrusion rate seen experimentally. The absolute difference in the values is low and is thought to be attributed to preferential flow path at the porous media and pipe interface that the analytical expression and CFD model do not include. It is shown mathematically and verified experimentally that the viscous and inertial resistance to flow in the porous media reduces the intrusion (or leakage) flow over that predicted by the standard orifice equation and places additional dependencies of the flow on the size of the intrusion orifice. The values obtained from the expression should be considered as a lower bound to intrusion (and leakage) rates, with upper bounds being provided by the standard orifice equation. Although developed to aid in the quantification of intrusion risk, such as associated with water distribution systems, the expression

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23 is also validated for leakage for the limited case that the external porous media is considered to be
24 fully compacted, consolidated and immobile.

25 **INTRODUCTION**

26 Pressurised pipes transport large volumes of some of the worlds most precious and/or vital
27 resources; whether that be oil and gas or drinking water. It is therefore vitally import to ensure that
28 these resources are not lost through leakage or contaminated by intrusion of unwanted physical
29 biological or chemical agents. Contaminant intrusion is particularly important in ageing Water
30 Distribution Systems (WDS) where there is concern that leakage points and cross connections
31 provide a potential pathway into the system. Once in the WDS the contaminants would then be
32 transported to customers and hence pose a risk to human health.

33 Lindley and Buchberger (2002) laid out three requirements for there to be a risk to human health
34 due to intrusion; there needs to be a pathway (leak, badly fitted joint, air valve, cross connection),
35 a driving force (pressure gradient) and the existence of a contaminant immediately external to the
36 pipe. The existence of leaks and hence pathways in WDS are well known. Due to the dynamic
37 nature of distribution systems, transient pressure waves and longer term de-pressurisation events
38 are known to occur (Walski and Lutes 1994; Kirmeyer et al. 2001; Gullick et al. 2004; Friedman
39 et al. 2004; Fleming et al. 2007; Besner et al. 2007) and could provide the required driving force.
40 These studies have reported low or negative pressure events occurring for varying durations, from
41 fractions of seconds to a number of minutes. There have also been a number of studies on the
42 existence of pathogens and chemicals in the environment surrounding water pipes (LeChevallier
43 et al. 2003; Karim et al. 2003; Besner et al. 2007). It therefore appears that the three theoretical
44 requirements for intrusion are fulfilled and there have also been a number of the cases where
45 intrusion has been the primary suspect in water quality failures (Kirmeyer et al. 2001; Friedman
46 et al. 2004), however the existence of contamination events in water distribution systems is yet to
47 be categorically confirmed.

48 To begin to be able to quantify the risk of intrusion to human health it is proposed that it is not
49 sufficient to simply acknowledge the existence of the three requirements determined by Lindley

50 and Buchberger. In particular it is important to understand how the low or negative pressures
51 interact with the pathway, the surrounding soil and the contaminant to produce the intrusion event,
52 and how they determine the magnitude of the possible intrusion event. In previous studies this
53 interaction has simply been modelled using the standard orifice equation (Kirmeyer et al. 2001;
54 Karim et al. 2003; Besner et al. 2007)

$$Q = C_d \frac{\pi d_o^2}{4} \sqrt{2g\Delta h} \quad (1)$$

55 where Q is the volumetric intrusion flow rate, C_d is a coefficient of discharge of the orifice, d_o the
56 orifice diameter and Δh the difference in the static head between the pipe and the head of ground
57 water external to the pipe. Based on this model intrusion will therefore occur the moment that the
58 static head inside the pipe drops below the external head and is always proportional to the square
59 root of that pressure difference. The orifice equation, although benefiting from simplicity, does
60 not take into account the effects of the surrounding soil conditions, the effect of pressure changes
61 on the orifice diameter, the transient nature of the flow through the orifice, the coupling of the
62 intrusion flow and the driving pressure and the re-intrusion of water that originated in the pipe.

63 To improve understanding of the intrusion process an analytical expression of the flow into
64 a pipe orifice buried in a homogeneous isotropic saturated porous media is presented here. The
65 model developed provides a more realistic account of intrusion than the orifice equation at no great
66 increase in complexity and using known or parameters that it is possible to estimate. Experimental
67 results validating the technical expression are presented.

68 **BACKGROUND**

69 A preliminary experimental study into transient driven hydraulic exchange required for intru-
70 sion into water distribution systems was undertaken by Boyd et al. (2004a, 2004b). Transients
71 were generated by either upstream valve closures or pump trips, with an intrusion element of a
72 column of water directly attached to the pipe. The paper confirmed intrusion occurred, however
73 was inconclusive in assessing severity or the relative significance of contributing factors.

74 Lopez-Jimenez et al. (2010) developed a 3D steady-state Computational Fluid Dynamics
75 (CFD) intrusion model for the case of a small scale pipe with a circular orifice surrounded by
76 water only, comparing it to experimental results with a good level of agreement. Collins *et al.*
77 (2010) also modelled steady state intrusion into a pipe system using 3D CFD but considering both
78 intrusion from water only and porous media surrounding the pipe. The porous media was modelled
79 as saturated with both viscous and inertial resistance. In the case of the porous media the steady-
80 state intrusion rates were reduced with respect to the water only case, but remained proportional to
81 the square root of the driving pressure. The porous media modified the coefficient of discharge and
82 added dependencies on the properties of the media and interestingly adds further dependencies on
83 the size of the orifice. The results showed a highly 3D external flow field with rapid dissipation of
84 pressure and flow rate with distance.

85 Walski *et al.* (2006) proposed a model of leakage from a pipe that accounts for the loss in a soil
86 by assuming the flow from an orifice is piped vertically to the surface of a saturated porous media.
87 The model couples the head loss due to the orifice and the head loss through the soil:

$$\Delta h = h_o + h_s \quad (2)$$

88 where h_o is the head loss through the orifice and h_s the head loss through the soil. The head loss
89 through the orifice is modelled using the orifice equation (1), and the loss through the soil using
90 the Darcy equation for seepage flows in porous media. The proposed model appears to match well
91 with experimental data. However it is known that the Darcy equation is only valid for Reynolds
92 numbers below 10, where the characteristic length of the Reynolds number is the mean particle
93 diameter. This would have been invalid in many of the experimental cases, indeed Walski (2006)
94 noted that in some cases the fluid velocity was at the point of fluidisation. Typically the orifice size
95 was an order of magnitude smaller in diameter than the column of porous media. There would have
96 been a significant decrease in pressure due to this expansion. Further issues with soil mechanics
97 where highlighted in a paper by Cassa and van Zyl (2011), in which they describe the mounding,

98 soil fracture and void formation that would have an effect on leakage and by extension intrusion
99 rates. Similar tests were presented in Collins *et al.* (2011) which describes the intrusion of water
100 due to transient low pressures through various types of orifice and porous media, when the porous
101 media is constrained in a vertical measuring cylinder. Results in the article show that the properties
102 of the porous media, as well as the size of the orifice have a significant impact on the total intruded
103 volume for a given transient.

104 **DERIVATION OF NEW ANALYTICAL EXPRESSION FOR INTRUSION FLOW RATES**

105 Equations for intrusion flow rates into a circular orifice in a pipe buried to a depth, D , under the
106 free surface of a saturated soil are developed. In order to facilitate a tractable solution the soil is
107 assumed to be homogeneous and isotropic with the flow to the orifice being radial, and spherically
108 symmetrical in all directions, while this is an idealisation the CFD work of Collins *et al.* (2010)
109 supports this approach. Using a similar conceptual approach to Walski *et al.* (2006), it follows that
110 the difference in the head in the pipe and the hydrostatic head due to the burial depth of the pipe
111 below the saturated free surface must be accounted for by the head loss in the soil and the head
112 loss through the orifice.

$$\Delta h = h_p - D = h_o + h_s \quad (3)$$

113 where h_p is the pressure head in the pipe, and D is the burial depth beneath the saturated surface.

114 **Head Loss through Porous Media**

115 Flow through a fully saturated porous media has been extensively studied in a number of fields,
116 from hydrology, mining engineering to chemical and process engineering. The widely known
117 Darcy equation (Bear 1988) gives the pressure drop along streamlines in the media for slowly
118 flowing fluids:

$$\frac{dh_s(s)}{ds} = A \cdot q(s) \quad (4)$$

119 where s is the arclength along the streamline, $h(s)$ is the piezometric head, $q(s)$ the specific flow
120 rate through the porous media (it should be noted that this is the total volumetric flow rate divided
121 by the area of flow and not the actual velocity of a packet of fluid in the porous media), and

122 A the viscous resistance of the porous media. A is related to the more commonly referenced
 123 hydraulic conductivity, K , by $A = \frac{1}{K}$. The Darcy equation is known to be valid for Reynolds
 124 numbers below 10, where the characteristic length of the Reynolds number is the mean particle
 125 diameter, at higher Reynolds numbers a significant non-linearity is seen. This non-linearity will
 126 incur significantly increased pressure loss in the soil over that predicted by the Darcy relationship.
 127 In 1901 Forchheimer (1901) proposed an equation with an additional term, proportional to the
 128 direction preserving square of the specific flow rate, to account for this non-linearity:

$$\frac{dh_s(s)}{ds} = A \cdot q(s) + B \cdot |q(s)| q(s) \quad (5)$$

129 where B is the inertial resistance of the porous media. The direction preserving square term can be
 130 simplified to a simple square term if the sign of $q(s)$ remains constant and care is taken to define
 131 the direction of positive flow rate.

132 *Ergun Equation*

133 Relationships to determine the values of A and B in (4) and (5) for porous media composed
 134 of packed granular particles have been developed by Ergun (1952) based on the mean particle
 135 diameter, porosity and the viscosity of the penetrating fluid:

$$A = \frac{150 \mu}{\psi_p^2 d_p^2 \rho g} \frac{(1 - \epsilon)^2}{\epsilon^3}$$

$$B = \frac{1.75}{\psi_p d_p g} \frac{(1 - \epsilon)}{\epsilon^3} \quad (6)$$

136 with d_p the mean particle diameter, ψ_p the particle shape factor (equal to 1 for spherical particles),
 137 ϵ the porosity of the media, ρ and μ the fluid density and dynamic viscosity and g the acceleration
 138 due to gravity. Similar relationships have also been found by Barr (2001) based on the particle
 139 surface area.

140 Equation (5) provides a description of the motion of the fluid in the porous media; a conserva-
 141 tion equation is also required to calculate the intrusion flow rates. From Bear (1988) the volume

142 conservation equation for the steady state flow of an incompressible fluid through a homogeneous
143 and isotropic porous media is given as:

$$\nabla \cdot \mathbf{q} = 0 \quad (7)$$

144 thus the flow in porous media is seen to be a diffusion relationship.

145 *Geometry of the Intrusion into Orifices*

146 It was shown in Collins *et al.* (2010) using CFD modelling that intruding flow will enter an
147 orifice from all directions, see Figure 1a), with the flow paths being diverted as they flow past
148 the pipeline. If the diameter of the pipe is small compared to the size of the region of flow then
149 this flow field will increasingly appear to be a point sink in a three dimensional flow field Figure
150 1b). Hence in this work the external flow field is modelled as spherically symmetrical with the
151 intrusion orifice as a sink at the center. The external boundary of the flow field is at D the pipe
152 burial depth below the saturated surface. The sink of the flow field is at radius R , a radius that will
153 be determined to ensure that the flow velocities and head losses are accurately represented, being
154 similar to those exiting the orifice.

155 By assuming purely radial steady-state intrusion towards the center sink, Equation (7) becomes:

$$\frac{d}{dr}(r^2q(r)) = 0 \quad (8)$$

156 where the arclength of the flow lines is replaced by the radial distance from the center of the sphere.
157 It is then trivial to integrate (8) to give the specific flow rate as a function of the radial distance
158 from the center:

$$q(r) = \frac{C}{r^2} \quad (9)$$

159 with C as the constant of integration. The constant of integration can be found by considering the
160 total volumetric flow rate through the soil. The total volumetric flow, Q_s , is found by multiplying
161 the specific flow rate by the area of a sphere that the flow rate passes through, $Q_s = 4\pi r^2 \cdot q(r)$,

162 therefore:

$$\begin{aligned} q(r) &= \frac{C}{r^2} = \frac{Q_s}{4\pi r^2} \\ C &= \frac{Q_s}{4\pi} \end{aligned} \quad (10)$$

163 If the discharge is constrained to only expand into a fraction of the sphere due to the local
164 geometry, such as the pipe wall or other boundary, a geometry factor G needs to be included:

$$q(r) = G \frac{C}{r^2} \quad (11)$$

165 It is thought that the geometric term will be some combination of the pipe diameter and orifice
166 size. The constant of integration C is not affected by the inclusion of the geometric term as the
167 total flow rate from the soil is unaffected.

168 Equation (10) can be substituted into (11) for specific flow rates which can then be com-
169 bined with the momentum equation (5) to give the head loss per unit radius in the soil:

$$\frac{dh_s(r)}{dr} = \frac{1}{4} \frac{A G Q_s}{\pi r^2} + \frac{1}{16} \frac{B G^2 Q_s^2}{\pi^2 r^4} \quad (12)$$

170 The total head loss Equation (12) can be integrated over the soil domain to give the total head loss
171 through the soil:

$$h_s = \int_R^D \frac{dh(r)}{dr} dr = \left(\frac{1}{R} - \frac{1}{D} \right) \frac{A G Q_s}{4\pi} + \left(\frac{1}{R^3} - \frac{1}{D^3} \right) \frac{B G^2 Q_s^2}{48\pi^2} \quad (13)$$

172 If it is assumed that the burial depth of the pipe below the saturated surface of the soil is
173 significantly larger than the radius of the internal boundary, $D \gg R$, then:

$$\begin{aligned} \frac{1}{R} - \frac{1}{D} &\approx \frac{1}{R} \\ \frac{1}{R^3} - \frac{1}{D^3} &\approx \frac{1}{R^3} \end{aligned} \quad (14)$$

174 Applying these simplifications to (13) gives the expression for the total head loss in the soil:

$$h_s = \frac{1}{R} \frac{A G Q_s}{4\pi} + \frac{1}{R^3} \frac{B G^2 Q_s^2}{48\pi^2} \quad (15)$$

175 Orifice Losses

176 The standard orifice equation (1) is strictly only valid when the diameter of the orifice is at
177 least 2 times the wall thickness. In other cases the coefficient of discharge needs to be modified to
178 account for the extra frictional loss due to the length of the passage. If the flow through the orifice
179 is assumed to be turbulent this loss can be associated with the standard turbulent pipe loss (Bear
180 1988). The total loss through the orifice is then given by:

$$h_o = \frac{8Q_o^2}{\pi^2 g d_o^4} \left(k + f \frac{t}{d_o} \right) \quad (16)$$

181 where f is the Hazen-Williams friction factor of the orifice, and t is the pipe wall thickness. It
182 can be seen that as the ratio of the wall thickness to orifice diameter decreases the second term in
183 the brackets in equation (16) becomes negligible and the standard equation for head loss through
184 an orifice is recovered. It should be noted that it is assumed that k is independent of the orifice
185 diameter. In the following work $k' = k + f \frac{t}{d_o}$.

186 Orifice and Soil Coupling

187 The two equations that describe the flow through the soil and the orifice need to be combined
188 to generate an overall expression for intrusion flow rate. Substituting (15) and (16) into (3) gives:

$$\Delta h = + \frac{8k'}{\pi^2 d_o^4 g} Q_o^2 + \frac{1}{R} \frac{A G}{4\pi} Q_s + \frac{1}{R^3} \frac{B G^2}{48\pi^2} Q_s^2 \quad (17)$$

189 Obviously the total volumetric flow rate through the soil must equal that which enters the orifice,
190 $Q_s = Q_o = Q$. Similarly the area of the internal boundary of the soil domain should equal that of
191 the orifice.

$$\frac{\pi d_o^2}{4} = \frac{4\pi R}{G} \quad (18)$$

192 Rearranging for R gives:

$$R = \sqrt{G} \frac{d_o}{4} \quad (19)$$

193 Thus R is proportional to the size of the orifice, typically of the order of millimetres and given
 194 that pipe burial depths, D , are typically greater than 1 metre the assumptions made in Section 3 are
 195 valid.

196 The expression relating the intrusion flow rate and the head loss in the pipes is therefore given
 197 as:

$$\begin{aligned} \Delta h &= \frac{8k'}{\pi^2 d_o^4 g} Q^2 + \frac{\sqrt{G} A}{d_o \pi} Q + \frac{4}{3} \frac{\sqrt{G} B}{d_o^3 \pi^2} Q^2 \\ 0 &= \frac{8}{\pi^2 d_o^4 g} \left(k' + \frac{d_o g \sqrt{G} B}{6} \right) Q^2 + \frac{\sqrt{G} A}{d_o \pi} Q - \Delta h \end{aligned} \quad (20)$$

198 As equation (20) is a quadratic in Q an analytical solution for the steady-state intrusion flow-
 199 rate can be found:

$$Q = \frac{\pi d_o^2}{4} \left\{ \frac{-d_o g \sqrt{G} A + g \sqrt{d_o^2 G A^2 + 32/g \left(k' + d_o g \sqrt{G} B/6 \right) \Delta h}}{4 \left(k' + d_o g \sqrt{G} B/6 \right)} \right\} \quad (21)$$

200 It is worth investigating this equation further as a number of simplifications can be made under
 201 certain realistic conditions. Using the standard notation for quadratics where

$$a \cdot Q^2 + b \cdot Q + c = 0 \quad (22)$$

202

$$\begin{aligned} a &= \frac{8}{\pi^2 d_o^4 g} \left(k' + \frac{d_o g \sqrt{G} B}{6} \right) \\ b &= \frac{\sqrt{G} A}{d_o \pi} \\ c &= -\Delta h \end{aligned} \quad (23)$$

203 If the ratio $\frac{b^2}{-4ac}$ is greater than about 5 the square term in (22) is not significant and the flow-rate

204 can be found by simply $Q = -\frac{c}{a}$:

$$Q = \frac{d_o \pi}{\sqrt{GA}} \Delta h \quad (24)$$

205 There are two possible cases where this situation will occur, the most likely is if c the driving
206 pressure difference is small. In this case regardless of the properties of the porous media the flow
207 velocities will be small, and as described in Section 3 the head loss in the soil will then follow
208 Darcy's linear law. The second case is when the viscous resistance of the soil (A) significantly
209 exceeds the Inertial resistance (B). If the porous properties for a granular media are calculated from
210 the Ergun (6) then high Viscous resistances are seen for low porosity (highly packed) materials
211 composed of particles with small mean grain diameters, typically very fine sands and silts.

212 If the ratio $\frac{b^2}{-4ac}$ is small, typically less than 10^{-3} then the linear terms of Q in (22) can be ne-
213 glected and the flow-rate is found via $Q = \sqrt{-\frac{c}{b}}$. By substitution of (23) and some rearrangement
214 the following formula is generated:

$$Q = \frac{1}{\sqrt{k' + \frac{d_o g \sqrt{GB}}{6}}} \frac{\pi d_o^2}{4} \sqrt{2g \Delta h} \quad (25)$$

215 It clear that this equation has a similar form to the standard orifice equation (1). The simple
216 coefficient of discharge is however replaced by a function of the orifice diameter, the inertial re-
217 sistance of the porous media, the frictional losses in the orifice and the geometric shape factor
218 G . Further it can be seen that the expression simplifies exactly to the orifice equation by setting
219 $B = 0$, the situation where there is no resistance from an external porous media.

220 Analytical Results

221 Figure 2 shows typical results generated from the newly derived intrusion expression, Equation
222 (21). In Figure 2 the solid line shows the steady-state intrusion rate predicted for water only
223 external to the pipe, the simple orifice equation. The other lines show decreasing flow rates due to
224 increasing resistance of the external porous media. It can also be seen in Figure 2 that for a high
225 value of the viscous resistance, A , the linear terms predominate over squared terms resulting in a
226 flatter shape to the pressure / flow response. For the relatively large orifice size shown in Figure

227 2, the effects of the porous media are very apparent. For smaller diameter orifices the presence of
228 the porous media has decreasing effect on the overall intrusion rate, this is due to the orifice losses
229 predominating over the losses in the soil.

230 VERIFICATION AND VALIDATION OF THE INTRUSION MODEL

231 Two methods were used to provide verification of the intrusion volumes predicted by the model
232 derived in this article. Firstly the model is compared to the results of the CFD model of a pipe,
233 orifice and surrounding porous media described in Collins *et al.* (Collins et al. 2010). Secondly
234 experimental results were obtained of the leakage and intrusion flow rates into a consolidated and
235 constrained porous media, using an experimental facility at the University of Sheffield.

236 Verification Using CFD Modelling

237 A number of CFD models of the intrusion process for different orifice diameters were created
238 using commercially available Fluent modelling software (ANSYS 2006), and used to assess the
239 intrusion rates for different external porous resistances.

240 Figure 3 is a schematic of the modelled geometry. The meshed 3D model consists of the
241 pipe volume, the surrounding porous media and the through wall thickness circular leak. Model
242 geometries with a 10 mm diameter circular orifice located at the top of the pipe were assessed. The
243 flow rate is calculated through a plane that runs through the leak orifice at the mid wall thickness.

244 The porous media surrounding the pipe is modelled as a fully saturated homogeneous isotropic
245 porous continuum, implemented as a momentum source/sink term in the standard Navier-Stokes
246 equations. The source term contains both a viscous and inertial resistance as in (5). In Collins
247 *et al.* (2010) the coefficients of the viscous and inertial resistance were determined by the Ergun
248 relationship as in (6). The input particle diameter, porosity and the output values of A and B are
249 given in Table 1. Different values of the geometric shape factor were investigated, with the best fit
250 being found when $G = \frac{1}{\sqrt{4d_o}}$, this value was then used through out.

251 Figure 4 shows steady-state results from the CFD model compared to the results obtained from
252 the new analytical expression, Equation (21). In the figures the dashed lines are CFD results, the
253 solid lines are the results from (21). It is clear that there is very good agreement between the two
254 models. Figure 2 used a representative range of parameter values for the porous media, while
255 Figure 4 uses values that are predicted by the Ergun equation. Comparison of the Figures shows
256 the impact of a range of porous properties.

257 **Experimental Validation**

258 *Experimental Set-up*

259 To measure intrusion volumes through various porous media and orifice combinations an ex-
260 perimental intrusion element was built. This was composed of a large diameter outer pipe, capped
261 at both ends, through which a small diameter pipe runs. Figure 5 shows a schematic of the intru-
262 sion element. The volume between the two pipes was filled with porous media, see Figure 6. The
263 inner pipe was 50 mm internal diameter Medium Density Polyethylene (MDPE) pipe with 6 mm
264 wall thickness, this pipe was capped at both ends, one cap being fitted with an inverse U-bend. The
265 external pipe consists of a 380 mm diameter, 8 mm wall thickness Acrylonitrile Butadiene Styrene
266 (ABS) pipe. CFD simulations after Collins *et al.* (Collins et al. 2010) were undertaken to deter-
267 mine that the external pipe was of sufficient size such that the flow field through the porous media
268 was not significantly affected by the boundary of the external pipe, for the ranges of pressures and
269 flows used in these tests. The external pipe is 400 mm in length and has 12 1/4" British Standard
270 Pipe (BSP) tappings equally spaced (in three groups of four around the circumference) to allow for
271 the water egress, see Figure 5. A final tapping point on the top of the pipe at the mid-length point
272 was added to allow for air removal and as a pressure measurement point, using a Gems Sensors
273 2200.

274 The steady state intrusion process was driven by an external pressure applied to the tapping
275 points of the outer pipe. An internal pipe pressure of 70 mm was maintained by the inverse U-
276 bend, ensuring the internal pipe was kept full at all times. Intrusion flow rates were measured at
277 the outlet of the U-bend, using a time/volumetric method. Due to the low flow rates in the porous
278 media the static pressure at the leak was assumed to be the height difference between the sensor
279 and the leak position. A range of orifice sizes and porous media combinations were then tested by
280 varying the external pressure and measuring the corresponding flow rate.

281 In preliminary tests it was found that there was a large amount of variability in results due to
282 inconsistencies in packing the porous media into the intrusion element. In addition there was evi-
283 dence of movement of the particles during the tests. To overcome this a bladder was installed in one

284 end of intrusion element which when filled with water and pressurised, prevented the movement
285 of the particles and ensured a consistently compacted and consolidated porous media.

286 *Experimental Method*

287 To run an intrusion test an inner pipe with the required leak orifice was installed. The selected
288 porous media was then carefully packed around the pipe and compacted, whilst the intrusion el-
289 ement was in the vertical position. When the required level of fill was achieved the bladder was
290 placed on top of the gravel and the end cap firmly attached and sealed. The bladder was then in-
291 flated and the whole intrusion element was rotated to the horizontal position (see Figure 6) with the
292 leak orifice on the top of the pipe. Once in this position the intrusion element was filled with water
293 to saturate the porous media, carefully bleeding air through the tapping at the highest point on the
294 external pipe. A test run comprised of pressurising the external head measuring the intrusion flow
295 rate three times and then sequentially raising the external head across the required range. Once the
296 highest required pressure had been reached the pressure was returned to the lowest value and the
297 flow measured again to ensure the tests had not altered the porous media properties during the test.
298 The range of driving pressures used was 0 - 9 m in 1 m increments. In reality the driving force
299 would generated by low pressures in the pipeline limited to the cavitation pressure at around -10
300 m. For each orifice and media combinations tested three repeat tests were conducted. Between
301 tests the porous media was disturbed and re-packed following the same procedure.

302 *Orifice Size and Porous Media*

303 It was decided to test only round orifices to negate any variability due to pressure dependent
304 area changes associated with cracks. Orifices were drilled with diameters of 1, 2 and 10 mm.
305 It was noted that due to visco-elastic effects the actual orifice size achieved was different to that
306 drilled. The actual size of each orifice was measured 4 times with digital callipers, the average
307 value is given in Table 2. To determine the coefficients of discharge of the orifices, tests were
308 carried out with no porous media present. The coefficients were then found by fitting the results to
309 the standard orifice equation, Table 2.

310 Three different porous media, in addition to water only, were investigated in this study: 6 mm

311 smooth spherical plastic balls (BB's); 6.25 - 9.5 mm Pea Gravel (Gravel 1); 3.25 - 5.5 mm Pea
312 Gravel (Gravel 2). Spherical beads were included to provide a consistent homogeneous porous
313 media without the inherent variability of graded gravel. The two gravels were chosen to represent
314 the British standard for pipe burial of 5 - 10 mm pea gravel (BS-CP312-1 1973).

315 The resistance to flow generated by the porous media is one of two primary input variables for
316 the new model, the other being the orifice loss coefficient. Literature reports a range of viscous
317 and inertial resistance coefficients dependent on the porous media in question, and that these can
318 be significantly different to those generated from the Ergun equation. Therefore experiments were
319 conducted to accurately measure the resistances effects of the different porous media used. An 800
320 mm long section of the inner test pipe was packed with media, capped with mesh screens at each
321 end, and then pressurised at one end to a range of values with the resulting flow rate and pressure
322 drop being measured. Tests were repeated 3 times for each porous media with the pipe section
323 repacked between each. In order to account for the effects of the mesh screens results from water
324 only tests were then subtracted and a parabolic regression fit undertaken to determine the porous
325 resistance properties of each media. The results and parametric values including the regression
326 coefficients are given in Figure 7 and Table 3. The smooth regular BBs gave consistent results,
327 with low resistance compared to the gravel.

328 The resulting parametric values, particularly those of the gravels, are found to be significantly
329 different, with a higher A and lower B coefficient, to those predicted by the Ergun equation that
330 had previously been used for the CFD modelling.

331 **Validation Results**

332 Figures 8 to 10 show the steady-state results from experiments with the three different orifice
333 sizes and three different porous media, and water only, for the range of driving pressures. Results
334 from the analytical expression are included as lines, calculated using the properties of the orifice
335 and porous media given in Tables 2 and 3. Computation CFD results are not included as they have
336 previously been shown to be virtually indistinguishable from the analytical outputs. Unfortunately
337 the control of the driving head during the tests was poor, oscillated around the required value,

338 accounting for some of the scatter in the data that is visible in Figures 8 to 10.

339 Figure 8 shows the result for the 1 mm drilled orifice. It can easily be seen that the results
340 for experimental tests with porous media present are indistinguishable from those with water only.
341 Hence for orifices with small diameters, particularly in relation to the wall thickness, it appears
342 that the orifice losses dominate those of the porous media. Therefore the experimental relationship
343 between intrusion flow and pressure collapses to the standard orifice equation, (1). The analytical
344 results from the new expression correctly predict that the media effects are insignificant, showing
345 negligible difference between the cases when a porous media is present or not.

346 Figure 9 shows the results for the 2 mm drilled orifice. Due to the scatter in the data, and small
347 differences due to the porous media effects it is hard to draw clear conclusions on the impacts of
348 the porous media from the experimental results by eye. However if curves are fitted to the data
349 (not shown) it is possible to discern that gravel 1 and 2 are not equal to the water only case, with
350 Gravel 2 having a greater effect than gravel 1. There is little or no distinction between the BBs and
351 water only results. The analytical expression developed in this article predicts small effects due to
352 the porous media, generally predicting slightly greater impacts than the measured data. The trend
353 for greater impact from gravel 2 than 1 is correctly predicted. Overall it is apparent that, as with
354 the 1 mm drilled case, the effects of the 2 mm drilled orifice still dominate over those of the porous
355 media, for both the experimental data and analytical outputs.

356 Figure 10 shows the results for the 10 mm drilled orifice. In this case the resistance of the
357 porous media has an appreciable effect on the resultant intrusion flow rates. The experimental data
358 shows clear distinction between the different porous media. The BBs with the smallest resistances
359 have the smallest effect as expected, with Gravel 2 the largest. In absolute terms the impact of
360 porous media can be seen to be increasing with negative driving head. The outputs of the analytical
361 expression generally show reasonable agreement with the experimental data, tending to provide a
362 lower bound (as was the case for Figure 9) and with improving quality of fit with increasing driving
363 head.

364 DISCUSSION

365 The new results presented in this paper, from the derived analytical expression and the vali-
366 dating experimental results, show that the existence of a porous media external to a pipe orifice
367 will affect the intrusion flow rates for a given steady-state pressure. Both the experimental and
368 the analytical results show that the effect of the porous media is more pronounced for larger ori-
369 fice sizes and that both the resistance and inertia properties of the media are important. For very
370 small orifices, the orifice losses appear to be the dominating effect, collapsing back to the response
371 predicted by the standard orifice equation, with appropriate fitted C_d value). From Table 2 it can
372 be seen that the fitted (to the water only experimental data) coefficient of discharge for the 1 mm
373 orifice is significantly smaller than for the other size orifices. This can be accounted for by signif-
374 icant piping losses being present in addition to the inlet and outlet losses, see Section 3. Therefore
375 for small diameter holes and cracks of narrow diameter, relative to the pipe wall thickness, where
376 piping losses will be a significant factor, one should use lower C_d values. This is consistent with
377 the theory of the the flow through cracks and orifices expounded in, for instance, Massey (1998).

378 The derivation of the analytical expression in Section 3 makes a number of simplifications and
379 assumptions that it is important to re-consider. Firstly, it is assumed that the pipe is buried a sig-
380 nificantly depth in a saturated porous media. This allow the external boundary of the integration
381 domain to be large, allowing the assumption that the flow rate at the boundary is negligible, and
382 is therefore in effect a free surface. The saturated condition also allows any movement of the free
383 surface to be ignored, realistic if the saturated region is sufficiently large. A further extension to
384 this work could consider the effects of intrusion from unsaturated porous media. It is debatable
385 whether the resultant differences would be significant. A pre-requisite for intrusion is a leakage
386 point, and it is likely that the water leaking out of this orifice, under normally high operating pres-
387 sures, would create a large region around the pipe that is close to being saturated. These saturated
388 conditions were certainly valid for the experimental set up used. Secondly it is assumed that the
389 flow into the orifice is driven by a steady pressure and is completely radial, that the deflection of
390 the flow paths around the pipe are negligible. Results from CFD simulations for flows into an

391 orifice presented in Collins *et al.* (2010) show that flows can enter from all directions around the
392 pipe, and that the zone of influence of pressure effects around the pipe is approximately spherical
393 but that there is a local distortion due to the pipe. The close agreement of the analytical and CFD
394 outputs suggest that this assumption is valid. Thirdly, the porous media has been assumed to be
395 a perfectly homogeneous and isotropic continuum. By making this assumption we are applying
396 average effects of the resistance to the flow that a large number of particles would have and apply-
397 ing that to the entire integration regime. Given that it is impossible to know the exact orientation
398 of particles in the porous media, and even if it was possible, the calculations required to generate
399 resistances would be prohibitive, this seems reasonable. Very close to the orifice, where the flow
400 may pass only 1 or 2 particles of porous media the continuum assumptions may break down. An
401 additional area where the continuum assumptions may break down is the wall effects of the pipe.
402 Due to the presence of the solid surface of the pipe, the packing of the porous media is not as dense
403 as in the rest of the continuum (Taylor et al. 2000), potentially providing a preferential pathway for
404 flow along, and/or around, the pipe. This condition is not considered in the analytical expression
405 due to the simplification described above that the flow is perfectly radial. Nor is this condition
406 described by the CFD calculations where the continuum model is allowed to extend perfectly to
407 the wall of the pipe. This preferential flow path could explain the slightly greater intrusion flow
408 rates measured in the experiments, compared to the lower bound solution provided by both the
409 analytical and CFD results.

410 The experimental results were obtained from a specially designed intrusion element. CFD
411 models were generated for the design of the element so that the sphere of influence in the porous
412 media was well within the boundary of the outer pipe section. The 12 tapping points used to
413 apply the driving head were also modelled to ensure that they did not have a significant effect on
414 the resultant flow field in the porous media. Hence there is good confidence in the experimental
415 configuration used. However the driving head was applied from the mains supply in the laboratory
416 and was found to be significantly variable between the tests. This resulted in a scatter in the
417 experimental data. If the tests were to be repeated, care should be taken that the pressure source is

418 carefully isolated and well controlled.

419 In addition to orifice size and coefficient of discharge required by the orifice equation, the new
420 analytical expressions requires inputs for the properties of the porous media. In real networks,
421 when trying to assess the risk of intrusion, the size, shape and location of orifices will always be
422 uncertain. The additional requirements to describe the porous media properties of the surrounding
423 ground conditions add to this uncertainty. However, it can be seen from the comparison of the
424 experimental and analytical results that the new expression tends to predict a lower bound of the
425 measured flow rates, while an absolute upper bound to measured intrusion flow rate is provided
426 by the water only standard orifice equation. By selecting realistic, if not perfectly precise, porous
427 properties the new expression and the standard orifice equation can be effectively used to provide
428 upper and lower bounds on the potential intrusion respectively. While this does not perfect rep-
429 resents the actual situation, it provides a significant increase to understanding the potential risk
430 associated with intrusion events.

431 **Leakage**

432 Although developed to try and describe intrusion processes, the analytical expression derived
433 is theoretically reversible and thus able to estimate leakage flow rates. In order to validate the
434 applicability of the expression for leakage calculations a further set of experiments were conducted.
435 For these tests the intrusion element described above was installed in a pipe test facility at the
436 University of Sheffield, with the inner pipe becoming part of a 150 m long pipe loop of the same
437 material. A wide variety of flows (up to 2 m/s or 0.004 m³/s) and pressures (up to 45 m) can be
438 generated in the pipeline, although in for these tests the flow loop was statically pressurised up to 30
439 m. For this exploratory test the same 10 mm orifice, which showed greatest variation for intrusion,
440 was used now as a leakage point. The 12 tapping points on the outer pipe were connected together
441 using increasing diameter pipe lengths and through an inverted U-bend, to ensure that the media
442 remained fully saturated at all times. Leakage flow rates were measured at the outlet of the U-bend,
443 using a time/volumetric method.

444 In a paper by Clayton and van Zyl (2007) it was hypothesised that the dynamics of media (soil

445 movement, fracture and fluidisation) surrounding a leakage aperture may have a significant effect
446 on the leakage flow rate. These effects are currently not well understood with respect to leaks.
447 To provide an idealised validation situation for the analytical expression, which does not model
448 dynamic porous media effects, the porous media was again fully consolidated and constrained
449 to prevent fluidisation and to provide homogeneous and isotropic steady conditions. This was
450 maintained during tests by the application of the steady pressure to the compression bladder in
451 excess of the leakage pressure, as in the intrusion experiments.

452 Figure 11 shows comparison of the experimental leakage rates for 10 mm drilled orifice in the
453 same range of media considered for intrusion case. It can be seen that similarly to the intrusion
454 case, the analytical expression exhibits the same shape curve as the leakage experiments. Similar
455 to the intrusion case the analytical expression slightly under predicts the leakage rate. Again it
456 is hypothesised that this is due to the preferential paths around the leak, and potential movement
457 in the soil despite the compacting pressure. In the leakage case a higher range of pressures were
458 available, and the relationship with the analytical expression appears to be maintained up to the
459 high pressures. A better level of control of was achieved in the driving pressures, as a results a
460 decreased level of scatter can be seen in the data. From the results, it appears that the analytical
461 expression provides a good fit to the data when the assumptions of static and homogeneous external
462 media can be made.

463 **CONCLUSIONS**

464 A new analytical expression to describe flow into pipes, with an aperture, buried in porous
465 media (intrusion) is presented and validated in this paper. The expression improves on the orifice
466 equation by considering viscous and inertial effects of the surrounding media and accounts for
467 external 3D effects by making the assumption of an idealised point sink for the aperture. The
468 analytical expression has been verified against a full 3D CFD model of the intrusion process, and
469 good agreement found. To fully validate the analytical expression, a series of experiments that
470 allow true 3D flow in an external porous media were carried out. These experiments provide
471 quantification of intrusion flow rates for a range of driving pressures and different porous media.

472 The analytical expression was found to give a close match to the experimental results, generally
473 giving a lower bound to the intrusion flows. The analytical expression is conceptually reversible
474 for application to leakage, and experiments were conducted to validate this. Good agreement was
475 again found when assumptions of static hydraulic conditions and fully compacted and consolidated
476 porous media could be made. As with the intrusion case, the analytical expression tended to
477 slightly under estimate the amount of leakage. The lower bound nature of the new expression, in
478 comparison to physical results, may be due to preferential flow paths at the pipe media interface.
479 There is potential for further work to investigate dynamic effects on the intrusion and leakage
480 process, whether that be due to the changing external media properties or due to dynamic changes
481 of pressure as a driving force.

482 The experimental, analytical and CFD results presented here have shown that the coupled
483 porous media and orifice effects cannot be ignored when considering either intrusion or leakage
484 associated with buried pipelines. Future realistic modelling, such as to assess the potential health
485 risk due to intrusion events, should therefore include these. The new expression can be used, in
486 combination with the standard orifice equation, to provide previously unavailable upper and lower
487 bound limits for intrusion and leakage flow rates.

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551		the values of the regression fit.	29

TABLE 1. Table of porous media properties from Collins *et al.* (2011)

Case	Condition	D_p (m)	ϵ (-)	A (s m ⁻¹)	B (s ² m ⁻²)
1	Free Fluid	-	-	-	-
2	Loose Gravel	0.01	0.4	0.8633	167.24
3	Compact Gravel	0.01	0.25	5.5255	856.27
4	Loose Sand	0.001	0.4	86.337	1672.40
5	Compact Sand	0.001	0.25	552.554	8562.69

TABLE 2. Table of the measured orifice and best fit coefficient of discharge

Orifice	Average Measured Diameter	C_d
1 mm	0.4 mm	0.45
2 mm	1.55 mm	0.59
10 mm	9.6 mm	0.57

TABLE 3. Table of average porous properties of the 3 different media used in the study and the values of the regression fit.

Media	A	B	R ²
BB's	9.88	102	0.999
Gravel 1	13.7	188	0.994
Gravel 2	19.4	252	0.991

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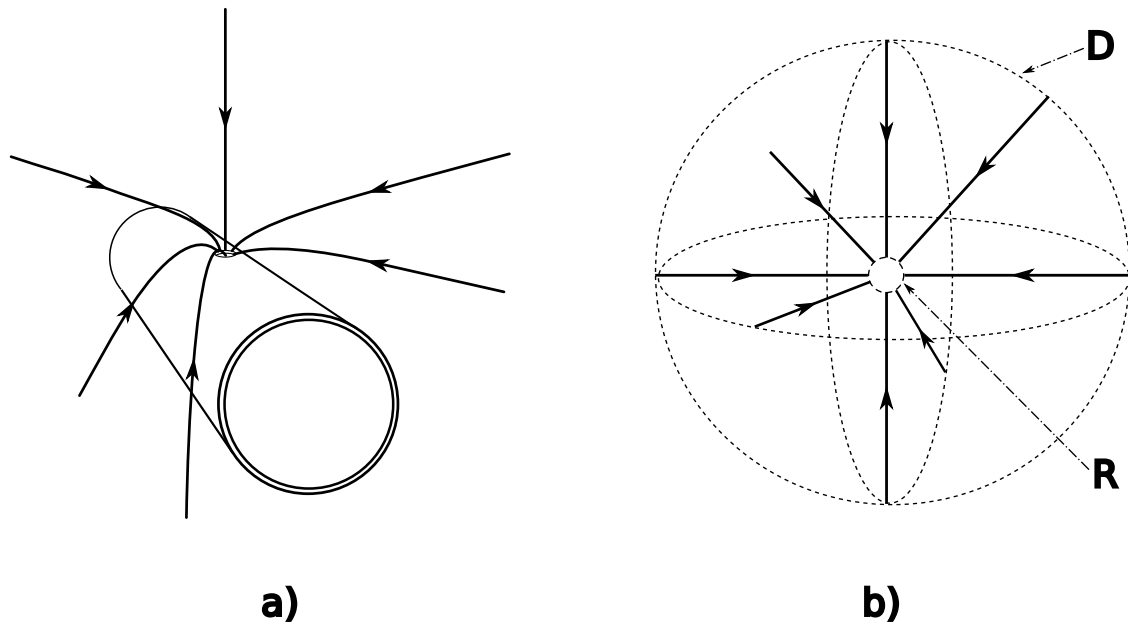


FIG. 1. Flow into a submerged orifice, a) actual case, b) conceptual model, showing D the external boundary of the model, and R the internal boundary

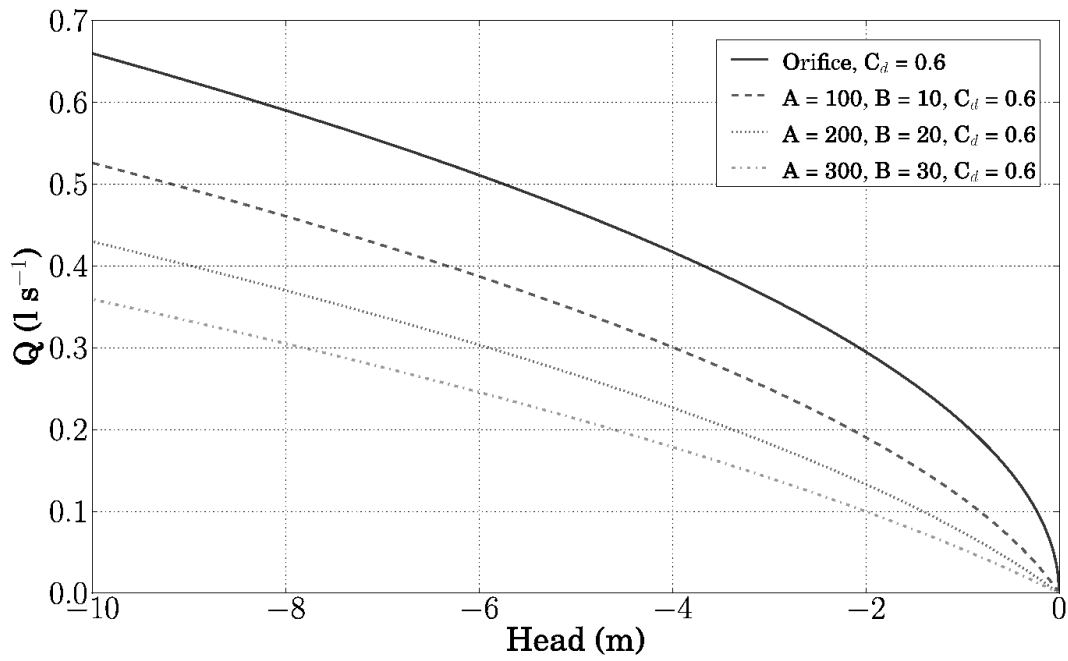


FIG. 2. Typical output of the new steady state analytical intrusion model showing the effect of different porosities and orifice losses for a 10 mm circular orifice

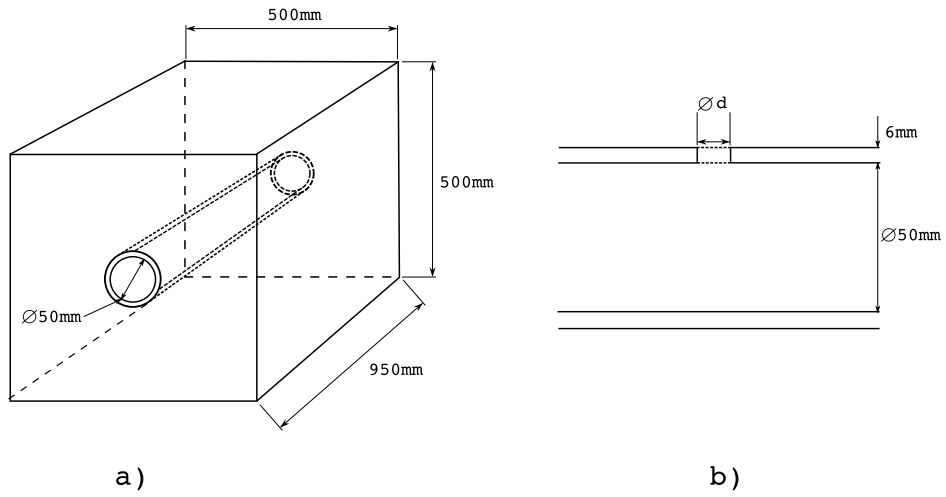


FIG. 3. Schematic of the modelled geometry, a) shows the pipe and the boundary of the porous media, b) is a cross section of the pipe showing the location of the leak orifice. Data from Collins *et al.* (2010)

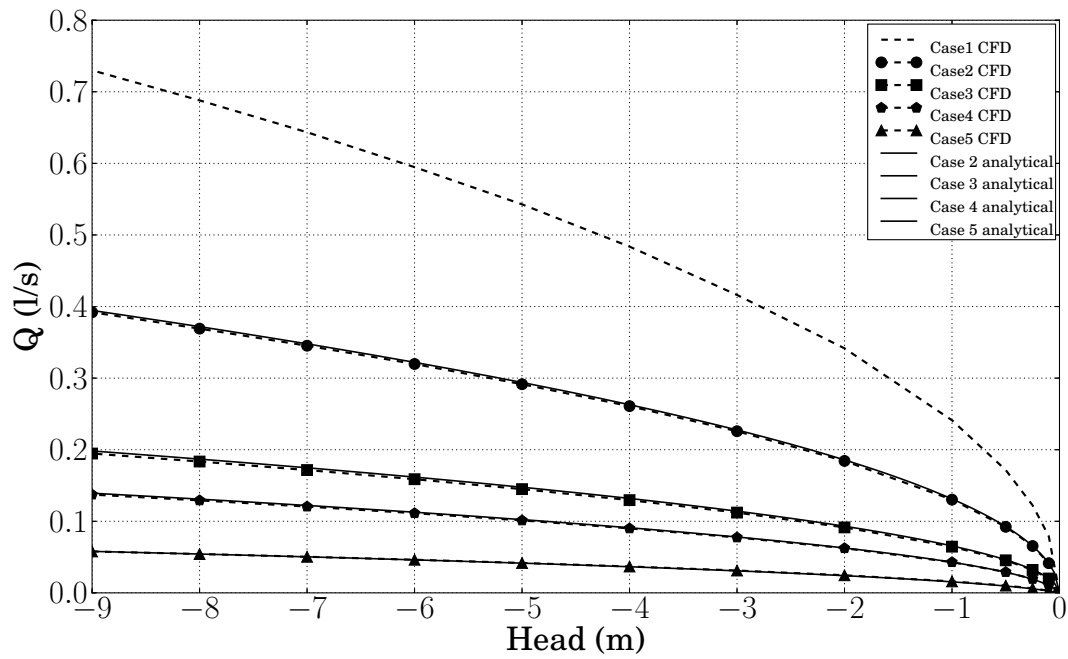


FIG. 4. Comparison of the results for intrusion volumetric flow rates predicted by the CFD simulation and the newly derived analytical expression for different media cases, see Table 1, for a 10 mm circular orifice. Dashed lines are CFD results, solid lines the newly derived analytical expression

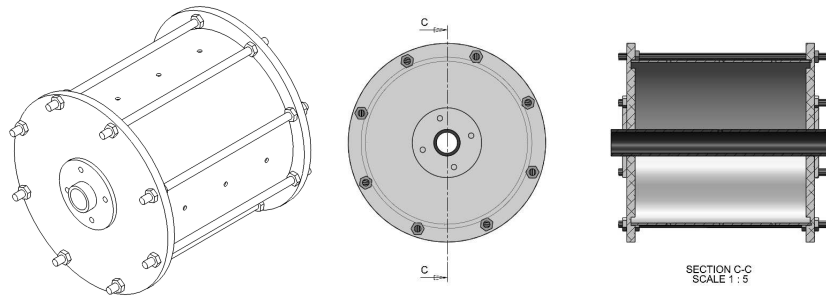


FIG. 5. Schematic of the experimental intrusion element

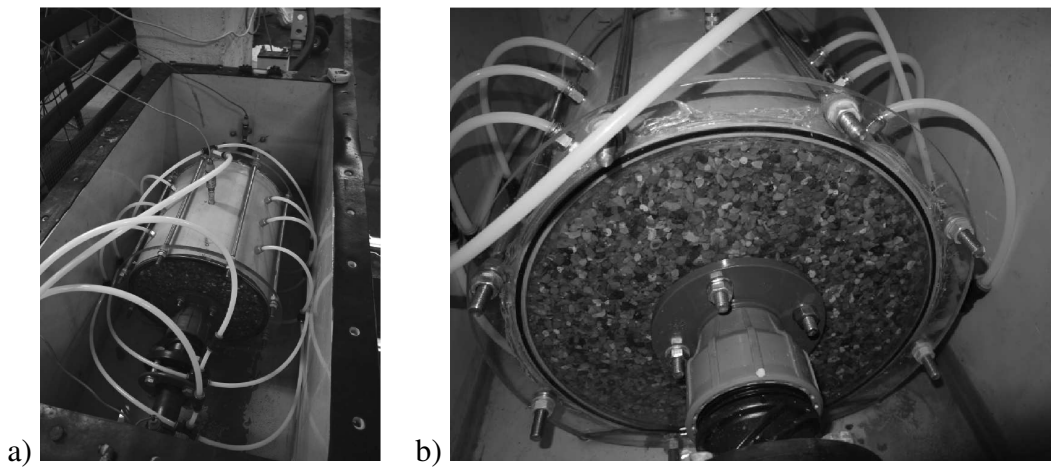


FIG. 6. Experimental intrusion element a) showing the external pipe and the 12 pipes used to feed water into the porous media. b) Close up of the porous media compacted in the intrusion element

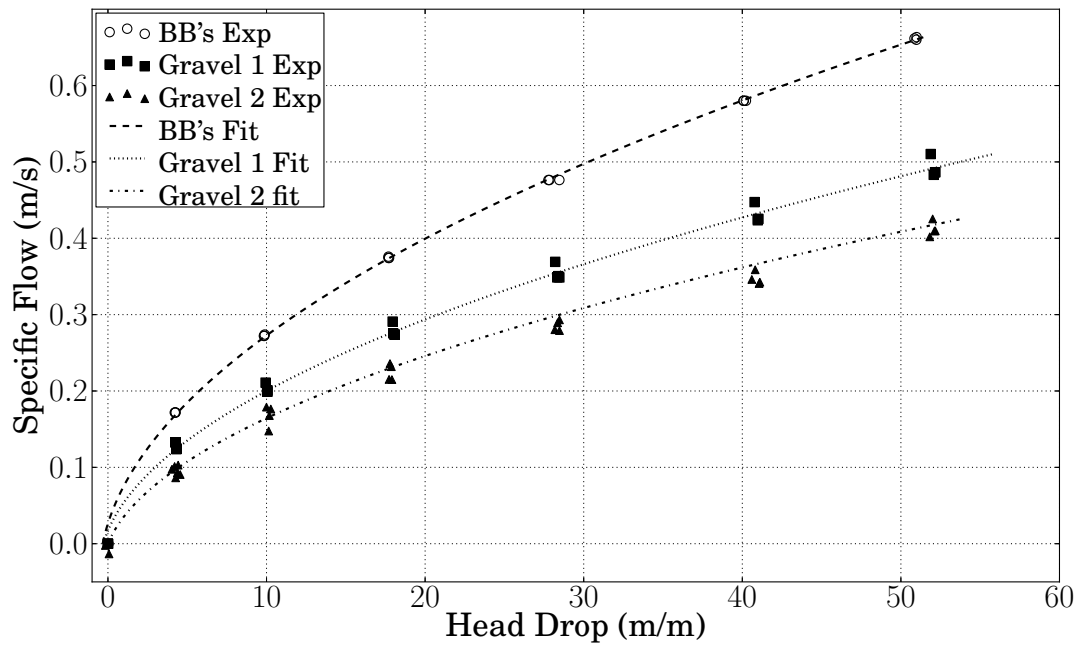


FIG. 7. Determination of the porous properties of the BB's and the two Gravel Media used in the test. Experimental results are given by the points, the solid lines are fitted 2nd order polynomials.

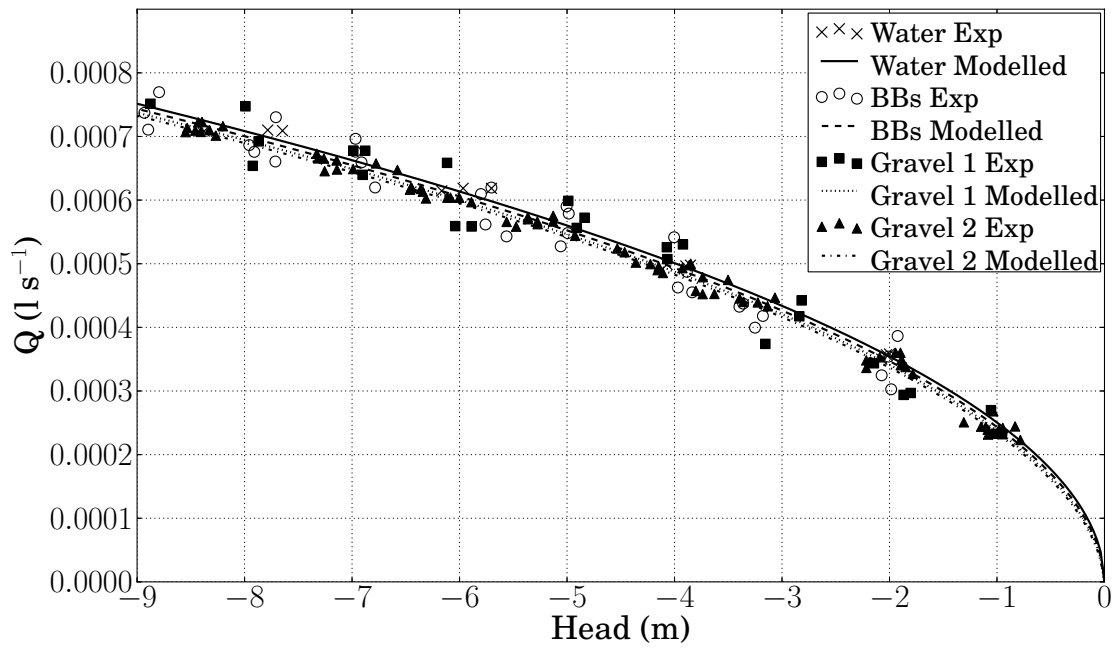


FIG. 8. Comparison of the experimental results and the outputs of the analytical expression for intrusion into a 1 mm orifice. Experimental results are given by the points, the analytical expression with the lines

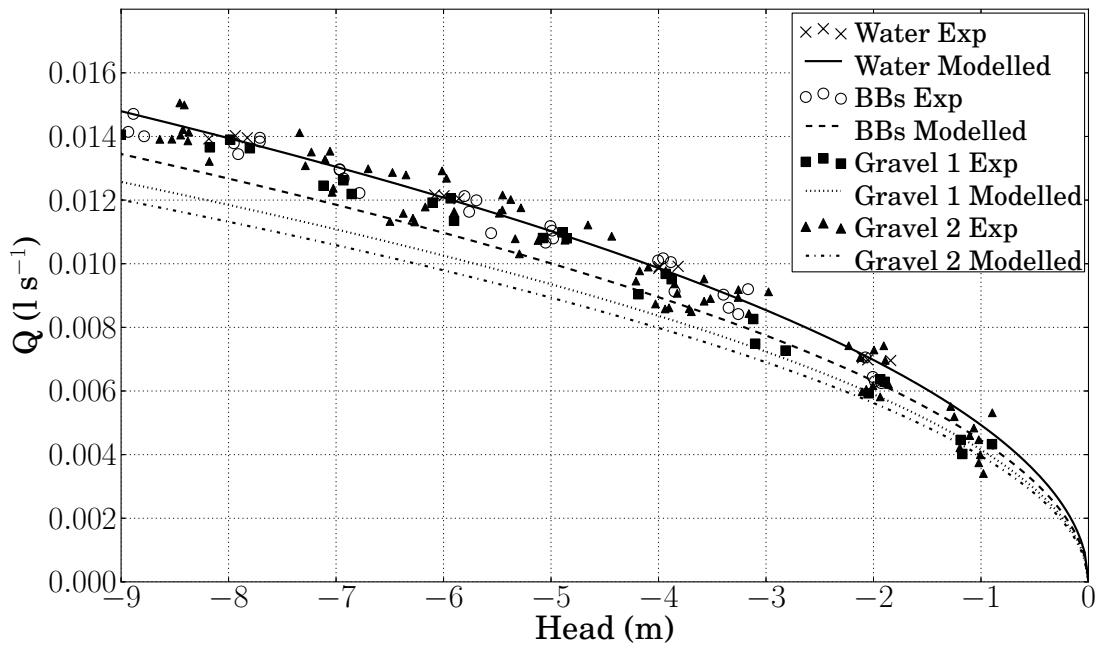


FIG. 9. Comparison of the experimental results and the outputs of the analytical expression for intrusion into a 2 mm orifice. Experimental results are given by the points, the analytical expression with the lines

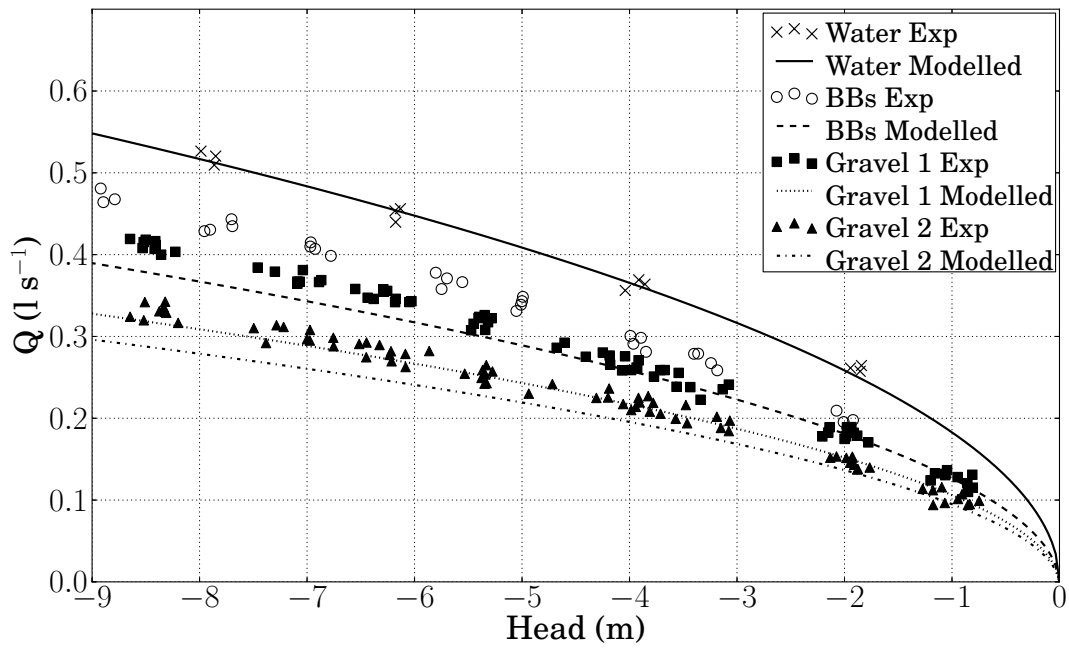


FIG. 10. Comparison of the experimental results and the outputs of the analytical expression for intrusion into a 10 mm orifice. Experimental results are given by the points, the analytical expression with the lines

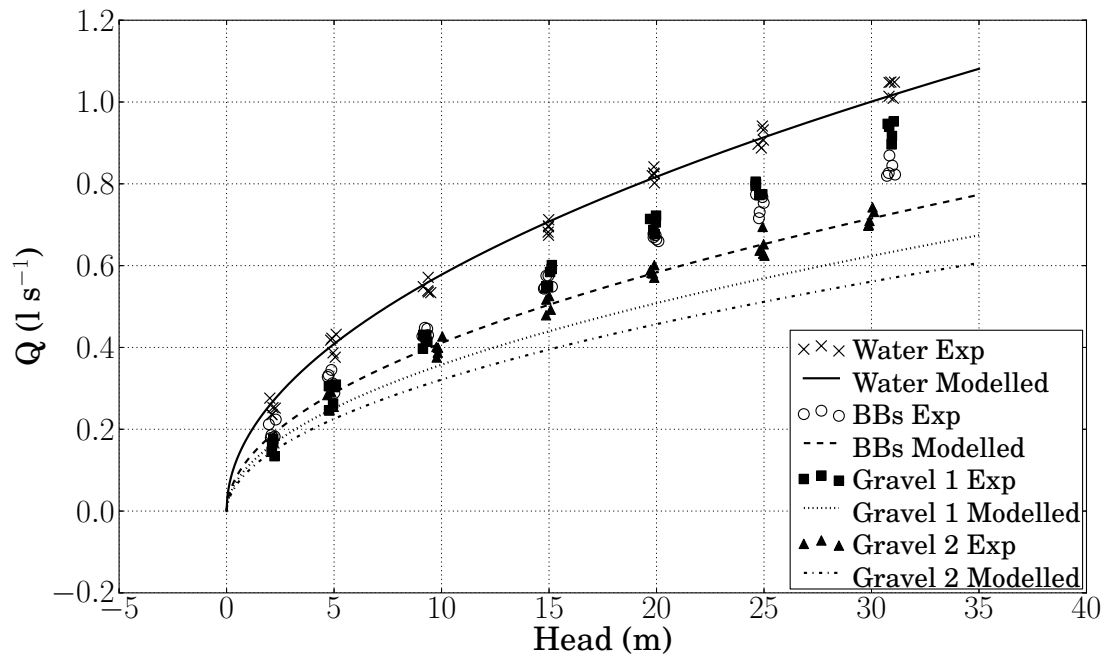


FIG. 11. Comparison of the experimental results and the output of the analytical expression for leakages out of a 10 mm orifice. Experimental results are given by the points, the analytical expression with the lines