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MPM Investigation of the Fluidization Initiation and Post-Fluidization Mechanism Around a Pressurized Leaking Pipe

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12 Abstract

Pipe leakage can induce soil fluidization resulting in severe consequences to the urban 13 14 environment where underground buried pipes are extensively used. Soil fluidization is the process of transition of soil particles from solid-like to liquid-like behavior that can lead to the 15 failure of the supporting ground and buried utilities. This paper applies the advanced two-phase 16 17 double-point Material Point Method (MPM) technique to investigate the soil fluidization mechanism around a leaking pressurized water pipe embedded in fully saturated soil. In the 18 model, the inflow water velocity leading to the initiation and evolution of soil fluidization 19 around the leaking pipe is identified based on the changes in soil porosity and soil bed 20 expansion ratio. This study shows that the MPM results are consistent with published 21 experimental studies. Parametric analyses are presented to investigate the influence of different 22 parameters, including the orifice size, bed height, and soil porosity on soil fluidization. The 23 results show that the inflow velocity required for the onset and development of fluidization 24 decreases with the increase in orifice size and soil porosity. The bed height increases the 25 resistance of the soil bed against fluidization. The double-point MPM formulation is shown to 26 27 be an effective and promising way to study soil-water interaction resulting from a leaking pipe. The model developed in this study can be used as a prediction tool to estimate the significance 28 29 and progress of fluidization zone and to determine critical state that leads to ground failure. 30 Such tool would be of significant value to asset managers that are responsible for maintenance of buried pipes, their supporting ground and surface transportation infrastructure. 31

32 Introduction

Non-revenue water (NRW) refers to the water produced that is not delivered to the 33 intended consumers. These water losses can be physical losses induced by pipe leakage or 34 35 apparent losses resulting from inaccuracies in metering, theft, or unmetered usage. Whilst water utilities in developed countries have sophisticated systems for monitoring apparent losses, most 36 NRW loss occurs due to physical leaks and breaks. Water loss due to pipe leakage is a critical 37 problem in many urban areas. According to a survey conducted by the Organization for 38 Economic Co-operation and Development (OECD 2016), leakage rates range from 4% in 39 Amsterdam to 65% in Mexico City. Poor construction, corrosion, external loading, poor 40 41 maintenance, geological hazards, and seasonal changes can cause pipes to leak. According to the World Bank, the world pipe leakage amounts to over 8 billion US dollars in the annual 42 43 revenue loss (Kingdom et al. 2006). In addition to losing water and revenue, leaks may cause damage to underground and surface infrastructure by weakening the surrounding soils 44 45 (Waltham 1993). Often, this can cause significant financial damages or even fatal injuries (Rogers 2014). 46

47 Previous studies have shown that pipe leakage may result in soil fluidization if a sufficient leakage rate is present (Alsaydalani 2010; Li 2013). Soil fluidization is defined as 48 49 the process by which soil particles lose their interlocking forces and turn into a viscous fluid 50 or fluid-like state (Richards et al. 1990). This process initiates in the leak region as the effective 51 stresses reduce to zero due to an increase in pore water pressure. Soil fluidization due to water 52 leaking from underground water pipes can mobilize and displace the surrounding soil particles, generating an underground cavity in the region of the leakage (Guo et al. 2013). The formed 53 cavity can continuously develop induced by leaking fluid, and the bed can be ruptured to the 54 soil surface leading to a severe ground collapse (Tang et al. 2017). Considering the severity of 55 the pipe leakage problem, it is essential to understand the water-soil interaction around a leak 56 to maintain the safety of urban infrastructure. 57

Previous experimental studies have been conducted to predict the water loss induced by leakage (Germanopoulos et al. 1989; Lambert et al. 2001). These researches helped to develop different pressure-leakage models by proposing orifice flow equation. However, changes in the flow regime, pipe material behavior, and hydraulic fracturing increase the complexity of the interaction between the leaking pipe and the surrounding soil (van Zyl and Clayton 2007). A limited number of studies have focused on the pipe-leakage problem (Lennon et al. 1995; Awad and Karni 2000; Toshifumi et al. 2012). Experimental tests conducted by

Alsaydalani (2010) compared the ratio of total head loss through the orifice to that in the soil 65 bed. The total head loss due to flow through the orifice was obtained by estimating the 66 difference between the head upstream of the orifice and the head in the orifice. Alsaydalani 67 observed that most of the energy losses occurred through the orifice (98% of the total energy 68 losses) while a relatively small amount (2%) dissipated through the soil bed. This is consistent 69 70 with Walski et al.'s (2006) experimental verification that total head losses due to Darcy's flow 71 through the soil mass in the leakage problem are generally much smaller than that in the orifice 72 in the leakage problem. van Zyl et al. (2013) conducted a series of experimental studies on 73 fluidization induced by a vertical jet where they identified three zones in the vicinity of the leak: (a) a fluidized zone with mobilized soil particles caused by the water that extends from 74 the region of the leak to the soil surface, (b) a mobile soil zone in which the particles are tightly 75 packed, and (c) a static zone that might move but very slowly. Consistently, this study observed 76 that most energy losses in the jet occurred through the orifice. van Zyl et al. (2013) also 77 concluded that in some cases substantial pressure can be maintained within the leaking pipe 78 79 without the fluidized zone reaching the soil surface.

80 Alsaydalani and Clayton (2013) adopted an experimental approach using a small-scale model to investigate the soil fluidization mechanism around a vertical jet emanating from a 81 82 leak. In their tests, the leakage rate at the orifice into a granular soil layer was incrementally increased until the initiation of internal fluidization. It was observed that by increasing the flow 83 84 rate, the excess pressure in the soil bed increased up to a peak point. Immediately after the peak, an abrupt drop in excess pore water pressure was associated with the onset of fluidization 85 in the vicinity of the orifice. Alsaydalani and Clayton (2013) demonstrated that the onset of 86 soil fluidization is controlled by the size of the particles, the particle shape, and the bed height. 87 Using a set of experiment, He et al. (2017) showed the different soil fluidization stages 88 associated with the increase in leakage rate through an upward water jet into a granular soil 89 90 bed. These included (a) no cavity, (b) a stable cavity in the vicinity of the jet, (c) an unstable cavity, and (d) full fluidization. He et al. (2017) developed an analytical model to identify the 91 critical fluidization leakage rate based on the equilibrium of forces and Darcy's law. The 92 analytical model was used to predict the pore pressure distribution in experiments with different 93 sand-bed heights. 94

These studies testify to the considerable efforts exerted by researchers to understand the soil fluidization process. However, the limited flexibility in the data acquisition inhibited experimental models from defining crucial parameters for exploring the water-soil interaction, including the soil stresses and liquid pressure inducing soil fluidization. Further research is 99 required to gain a complete understanding of soil behavior and the post-fluidization100 mechanism.

Soil fluidization around a leaking pipe has also been studied using different numerical 101 approaches. Zhu et al. (2018) adopted two-dimensional Finite Element (FE) models to 102 investigate the effect of varying leakage pressure, crack size and location, and soil layering on 103 the flow regime. However, the initiation of the soil fluidization is associated with a localized 104 105 cavity formation in the vicinity of the orifice that is characterized by the localization of large strains and large soil displacements. The localized large deformations characteristic from this 106 107 problem inhibit FE method from simulating the whole fluidization process due to the mesh tangling (Wang et al. 2015). To overcome these drawbacks, Cui et al. (2012) used a coupled 108 Discrete Element Method-Lattice Boltzmann Method (DEM-LBM) to investigate the 109 inhomogeneities of granular particle behavior in the soil fluidization induced by a leaking pipe. 110 DEM is ideal for studying micro-mechanical particulate soil behavior, but it becomes 111 112 computationally too expensive for real-scale pipe leakage problems.

Considerable effort has been deployed to study the discharge coefficient, the flow 113 114 regime, the leakage pressure relationship, the pipe material, and the impact of the orifice type and shape on the leakage rate. However, limited studies focused on the effect of orifice size, 115 116 soil properties, and bed height on the pipe leakage problem. The fluidization mechanism induced by leakage makes them vulnerable parameters. In some cases, soil parameters and bed 117 geometry can be resistance to fluidization. Therefore, investigating the parameters involved in 118 soil fluidization phenomenon helps in identifying the critical state that causes the ground 119 120 subsidence.

In this study, the Material Point Method (MPM) (Sulsky et al. 1994) is proposed for 121 studying the soil fluidization around leaking pressurized pipes. MPM has proved to be a 122 powerful method in various geotechnical and hydraulic problems, such as the study of granular 123 flow (Więckowski 2003; Yerro et al. 2014; Phuong et al. 2014). MPM is capable of simulating 124 large deformations in multi-material and multi-phase problems (Bandara and Soga 2015). In 125 this method, the continuum is represented by a set of material points (MPs) that act as 126 integration points, which move attached to the media, carrying all the material properties, 127 including e.g., mass, stresses, strains, and displacements. The main governing equations, 128 generally related to dynamic momentum balance, are computed at the nodes of a computational 129 mesh that covers the whole computational domain. The solid-fluid (two-phase) interaction in 130 saturated porous media can be modeled using the two-phase double-point MPM approach (DP) 131

that consists of two sets of MPs (Bandara 2013; Abe et al. 2013; Martinelli 2016; Cao andNeilsen 2021).

This paper uses the DP approach to capture the initiation and evolution of soil 134 fluidization induced by a leaking pipe. Advanced in/outflow Boundary Conditions (BCs) are 135 employed to prescribe velocity-controlled inflow of material points (MPs) into the domain. An 136 137 advantage of the method adopted here is that it is capable of capturing the development of soil fluidization around a leaking pipe until it reaches the soil surface. However, to the best of the 138 authors' knowledge, there are no publications investigating the critical leakage velocity 139 140 inducing surface fluidization although there are some useful relationships to identify the onset of soil fluidization. The document is organized as follows. First, the basis of the two-phase DP 141 approach is reviewed, followed by a description of the in/outflow BCs for simulating the water 142 inflow to the domain. Then, the MPM pipe leakage model is presented and qualitatively 143 verified against experimental data. This model is then further parametrized to investigate the 144 145 effects of orifice size, soil-bed height, and soil porosity on the soil fluidization mechanism. All the analyses presented are performed with an in-house version of the open-source Anura3D 146 147 MPM software (Anura3D 2021).

148 **Two-Phase Double-Point MPM Approach**

149 Concept

The material point method (MPM) has been applied to solve large deformation 150 problems and multi-phase processes in saturated and unsaturated porous media (Abe et al. 151 152 2013; Yerro et al. 2015; Zhao and Liang 2016). The solid-fluid (two-phase) interaction in saturated porous media has been simulated using two distinct approaches (Ceccato et al. 2018), 153 154 two-phase single-point (SP) and two-phase double-point (DP). The SP formulation consists of one set of material points (MPs) (Zabala and Alonso 2011; Jassim et al. 2013). Each MP 155 156 represents a portion of the saturated media, and it moves together with the solid phase (i.e., Lagrangian description of the soil motion). The information from the liquid phase is also 157 carried by the MPs using an Eulerian approach. This framework usually assumes the validity 158 of Darcy's law; hence it is not valid when liquid flow is very rapid and non-laminar. The SP 159 160 formulation is also not appropriate when dealing with the interaction between free water and porous water since the first one has no representation in the domain. Contrarily, the DP 161 formulation (Bandara 2013; Abe et al. 2013; Martinelli 2016; Cao and Neilsen 2021) uses two 162 sets of MPs to represent the solid phase and the liquid phase separately; these are so-called 163

solid material points (SMPs) and liquid material points (LMPs). The DP approach takes full 164 advantage of the Lagrangian description for soil and liquid phases (Abe et al. 2013, Martinelli 165 and Rohe 2015). In the DP framework, the volume fractions theory (Truesdell and Toupin 166 1960) is used to simulate the solid-liquid interaction. This approach automatically assures the 167 mass conservation of both solid and liquid phases (Ceccato et al. 2018). The SMPs and LMPs 168 are used to compute the velocities of the solid skeleton and water independently, and they are 169 allowed to move separately and overlap. The LMPs can denote the free water as well as the 170 pore water. If the SMPs and LMPs coincide in the same element in the computational mesh, 171 the element is understood as saturated material; hence SMPs account for the pore water in the 172 soil skeleton. The mechanical behavior of the dry soil, saturated soil, free water, and pore water 173 can all be captured in the unified DP MPM framework. Both SP and DP formulations are 174 generally integrated explicitly and consider the weakly compressible liquid. 175

The SP formulation is only applicable to a laminar flow as the drag force considers the 176 177 validity of Darcy law. In contrast, the drag force implemented in the DP approach accounts for the gradient of the concentration ratio, laminar flow (in low velocity regime) and non-linear 178 179 flow (in high velocity regime). Therefore, the use of the DP formulation is vital when the flow velocity is high and the spatial variability of concentrations is significant (Ceccato et al. 2018). 180 181 In addition, an important feature of the DP formulation compared to the SP approach is the capability of capturing the interaction between the porous media and free water. This is an 182 essential aspect in various geotechnical problems, such as erosion, scouring and fluidization. 183 The number of MPs required to discretize the saturated media in the DP formulation is much 184 larger (at least double) compared to the SP approach. This will inevitably impact the 185 computational time. 186

In the two-phase DP MPM implementation proposed by Martinelli (2016), the 187 transition between the solid-like or liquid-like state of the solid-liquid mixture is distinguished 188 at the element level through a porosity threshold n_{max} . During the fluidization mechanism, 189 when the porosity of the mixture is lower than n_{max} , the reduction in the mean effective stress 190 leads to an increase in porosity. When the inter-granular contact between the soil grains 191 vanishes, the effective stress becomes zero. The mixture fluidizes when the mixture porosity is 192 greater than n_{max} , such that soil grains are substantially separated. It should be stated that, in 193 the case of sedimentation, the spaces between solid particles decrease, resulting in a reduction 194 in porosity. The effective stresses of the solid particles recur if the porosity of the mixture 195 becomes lower than n_{max} , indicating that the solid grains are in contact, causing the state of the 196

mixture to change from a fluidized state to a solid state. In a solid state, the rate of effective
stress in solid constituents is estimated using a conventional soil constitutive law. In the solidwater mixture, the liquid behaviour is described using Equation (2).

200
$$n_L \rho_L \vec{a}_L = \operatorname{div}\left(\bar{\sigma}_L\right) - \vec{f}_L^d + n_L \rho_L \vec{g}$$
(2)

where n_L is the volumetric concentration ratio of the liquid; ρ_L is the densities of the liquid; \vec{a}_L is the accelerations of the liquid; $\overline{\sigma}_L$ is the partial stresses for the liquid phase; \vec{f}_L^d is the drag force of liquid; \vec{g} is the gravitational acceleration.

However, in the liquid-like state, the deviatoric part of the stress tensor of the liquid $\sigma_{dev,L}$ is computed using the following Equation (3).

206
$$\sigma_{\rm dev,L} = 2\mu_{\rm L} \frac{D^L \varepsilon_{vol,L}}{Dt}$$
(3)

where μ_L is the liquid viscosity that considers the solid concentration ratio of the mixture; $\varepsilon_{vol,L}$ is the volumetric strain of the liquid. The deviatoric stress tensor of liquid is set to zero in the case of a solid-like response.

210 When the mixture porosity is lower than the porosity threshold, the defined granular constitutive model is used to describe the solid-like response of the material (SMPs), which is 211 controlled by the effective stresses. When the mixture porosity exceeds the maximum soil 212 porosity (i.e., critical porosity), the effective stresses in the SMPs become zero, and the liquid-213 like behavior of the mixture is described using the Navier-Stokes equation (Martinelli et al. 214 2017). In this process, the constitutive behavior of the material is a Newtonian fluid, which is 215 controlled by an equivalent viscosity that depends on the volumetric concentration ratio of the 216 solid material within the saturated mixture (Beenakker 1984). The equivalent viscosity μ_{eq} is 217 determined using the following Equation (4). 218

219
$$\mu_{eq}^{t} = 1 + \frac{5}{2}\tilde{n}_{S,el}^{L,t} + 5.2 \, (\tilde{n}_{S,el}^{L,t})^2 \tag{4}$$

220 where $\tilde{n}_{S,el}^{L}$ represents the interpolated element solid concentration ratio.

Very recently, the authors of this paper presented a preliminary analysis in which the soil fluidization mechanism due to a leak from a pressurized water pipe was investigated using MPM (Monzer et al. 2022). In this study, the capabilities of both SP and DP approaches are evaluated to simulate the onset and evolution of soil fluidization. It is concluded that the SP formulation is limited to identifying the initiation of the local fluidization due to (a) the inability of the constitutive model to represent the transition from solid-like to liquid-like behavior and
(b) the complexity of maintaining an inflow boundary condition when a cavity is formed in the
vicinity of the leak.

It is important to note that the use of a damage parameter to gradually transition from a 229 solid to a liquid response, rather than a sudden transition based on a porosity threshold, would 230 231 be more effective in modelling the behaviour of porous materials. However, the accurate implementation of a damage parameter is a complex task that requires a good understanding of 232 the material behaviour and constitutive models. It is important to calibrate the damage 233 234 parameter based on experimental data to ensure that it is accurately predicting the behaviour of the material. The accuracy of the sudden transition between solid to liquid by a porosity 235 threshold depends on the specific application and the assumptions made in the model. Although 236 the abrupt transition assumes that the material's properties change abruptly at this threshold, 237 the implemented formulation may provide a reasonable approximation for certain types of 238 porous materials, such as granular soils, which exhibit a sudden change in behaviour at a 239 specific porosity threshold. Additionally, the choice of porosity threshold is based on 240 241 experimental data, and it is difficult to find a good correlation between the porosity threshold and the damage parameter that can be affected by the material properties. In any case, the 242 243 implementation of advanced constitutive models in conjunction with the damage parameter is required to provide a robust and realistic representation of the material's behaviour during the 244 245 fluidization process.

246 In/Outflow Boundary Condition

For the numerical study of soil response under pressurized leaking pipes, it is necessary 247 to account for inflow and outflow BCs that can ensure consistent water flow through the orifice 248 and a constant water head at the ground surface, respectively. The in/outflow boundary 249 conditions (BCs) developed by Zhao et al. (2019) have been used here as a basis to model BCs. 250 In this analysis, the inflow and outflow zones are attached to the original model (Fig. 1a and 251 1b) to allow LMPs to enter and leave the computational domain. In the inflow region (Fig. 1a, 252 253 in green), a constant velocity is prescribed to the LMPs. A zero acceleration is prescribed at the inflow nodes that are shared with the regular elements of the computational region to 254 maintain the imposed velocity field at the boundary, applied to the computation of the 255 governing equation. When an inflow element becomes empty, new LMPs are introduced at the 256 Gauss point locations to refill the inflow elements. In the outflow element (Fig. 1b, in red), the 257 LMPs that enter the outflow elements are consistently removed and a zero pressure is defined 258

at the water surface. The nodes shared by the outflow elements with the computational region have a constant pressure (zero) boundary condition. In other MPM works, the water flow is modeled using a large water reservoir (e.g., Bolognin et al. 2017; Martinelli et al. 2017). However, the water level decreases as water flows throughout the model leading to a progressive drop of the total head at the inflow boundary. The implementation of the in/outflow BCs enables the modeling of constant velocity flows and optimizes the computational cost by simplifying the geometry and reducing the number of MPs.

266 Numerical Model

The purpose of this numerical analysis is to simulate the soil fluidization induced by a 267 leaking pipe using the two-phase DP MPM approach. The simulated problem is adapted from 268 the experiments conducted by Alsaydalani (2010). The two-dimensional model is shown in 269 Fig. 2, where a saturated homogeneous soil bed is connected to an inlet pipe through an orifice. 270 The soil bed is 300 mm in height and 1500 mm in length. The length of the modeled soil bed 271 272 is 2.5 times larger than the previous experimental study to avoid BC effects during the evolution of fluidization. A sensitivity analysis was conducted to examine the effect of the 273 length of the soil bed on solution accuracy. Therefore, a careful increase of the bed length was 274 necessary to minimize the numerical noise reflected from the BC. An orifice with a size of 10 275 mm is located in the middle of the soil base. As the focus of this study at this stage is to 276 investigate the soil behavior around the leaking pipe, only the orifice is modeled and not the 277 whole pipe. Note that the width of the smallest modeled orifice is 2.5 mm, which is 7 times 278 larger than previous experimental and numerical studies (Alsaydalani 2010; Cui 2013). The 279 smaller the orifice, the finer the mesh required to discretize the domain, and the computational 280 281 cost increases. For instance, the physical time for simulation for a model with an orifice (5 mm) is compared to that of the largest orifice (15 mm) using an Intel Core i7 at 2.50 GHz CPU with 282 283 8 GB RAM. The model with a 5 mm orifice consists of 5,153 linear triangular non-structured elements; where the minimum element size is 0.00125 m and increases towards the edges of 284 285 the model up to 0.033m. On the other hand, the model with a 15 mm orifice consists of 2,415 elements ranging from 0.00375 m to 0.033 m. The computational time decreases by 94% from 286 287 162 hour to 10 hour, when changing the orifice size from 5 mm to 15 mm. A parametric analysis is presented in the results section to study the effects of the orifice size. 288

The water flow is injected through the orifice by applying an upward constant fluid flow at the inflow BC. In the inflow elements (Fig. 2, in green), a prescribed velocity (v_i) is

assigned to the LMPs. An empty domain, which does not have any MPs, is attached to the 291 bottom of the inflow elements to avoid the effect of the boundary conditions on the inflow 292 elements. At the top of the model, the outflow region (Fig. 2, in pink) defines a constant free 293 water table consistent with the experiment from Alsaydalani (2010) by removing those LMPs 294 that enter the outflow elements. Free water zones (Fig. 2, in blue) include those elements 295 initially filled with only LMPs. The saturated soil domain (Fig. 2, in light brown) is initialized 296 by placing both SMPs and LMPs to represent the saturated medium. The model consists of 297 4,753 linear triangular non-structured elements. The mesh is refined around the orifice to better 298 299 capture the size of the crack and the inflow process. The minimum element size is 0.0025 m and increases towards the edges of the model up to 0.033 m. A parametric analysis to study the 300 influence of the element size at the orifice on the results is presented in the next section. Six 301 302 MPs per element (three LMPs and three SMPs) are initially assigned to the saturated soil domain, and six LMPs are assigned to the free water and inflow elements. Mechanical fixities 303 304 are applied at the boundaries as follows. At all boundaries except for the orifice region, the solid and liquid displacements are constrained in the normal direction and are free in the 305 306 longitudinal direction. At the orifice region, LMPs are allowed to move vertically. The nodes located at the corners between the base of the soil bed and the inlet pipe are fully fixed. Gradual 307 308 porosity change is considered at the interface of the saturated soil region and the free water. 309 This transition zone is linearly interpolated across the elements of pure liquid and liquid-solid, so it provides a smooth transition between the two regions. 310

The soil bed is set to be a fully saturated homogenous layer. A linear elastic-perfectly 311 plastic Mohr-Coulomb constitutive model (MC) is used to model the soil constitutive behavior. 312 Mohr-Coulomb is a simple failure criterion that predicts the shearing behavior of soil and thus 313 the overall soil deformation. The free water is modeled with a Newtonian fluid model, while 314 the porous water is assumed linear elastic. The water bulk modulus considered in the simulation 315 is 50000 kPa which is 40 times lower than the real one to increase the critical time step and 316 optimize the computational time with the explicit MPM integration scheme. This does not have 317 a significant influence on the results as it is still considerably larger than the effective bulk 318 modulus of the solid matrix. In order to analyse the effect of water bulk modulus, the original 319 model is compared with another one with a higher bulk modulus of 100000 kPa (reduced by 320 20 times). The computational time required to analyse the problem with lower water bulk 321 modulus is 10 hour whereas the one with higher water bulk modulus is 97 hour using the same 322 323 machine, which is almost 10 times faster simulation. This is due to the fact that the critical time

step depends on the bulk modulus of the material; the higher the bulk modulus, the larger the 324 critical time step (Liang, 2010). However, the observed fluidization mechanism in both cases 325 is consistent in terms of the porosity distribution and ground movement. This approach of 326 reducing the water bulk modulus to speed up the simulation has been used previously by Liang 327 (2010) and Martinelli et al. (2017). According to Liang (2010), the increased compressibility 328 of water has marginal impacts on the results as the speed of sound is over ten times greater than 329 the maximum flow speed. In addition, a lower bulk modulus of the water is considered to 330 incorporate the possible inclusion of air, and therefore higher compressibility of the water 331 (Ceccato, 2015). Thus, it is concluded that using a reduced water bulk modulus by a factor of 332 40 is an acceptable approximation. The detailed soil and water parameters used in the analysis 333 are listed in Table 1, which are based on the experimental study conducted by Alsaydalani 334 335 (2010).

It is worth mentioning that the DP MPM formulation considered here is consistent with 336 337 the one proposed by Martinelli (2016), in which the Darcy's law is generalized with a nonlinear term (Ergun 1952) to account for laminar and steady flow in high-velocity regime. The 338 339 soil intrinsic permeability (k) is updated using the Kozeny-Carman formula (Bear 1972) that depends on the solid grain diameter (D_n) and the soil porosity (n). Finally, the maximum soil 340 porosity (n_{max}) that differentiates the solid and liquid states of the mixture is determined based 341 342 on the provided maximum void ratio from Alsaydalani's (2010). A strain-smoothing algorithm 343 is also applied to reduce the kinematic locking (Al-Kafaji 2013).

The effective stresses are initialized via an earth pressure coefficient at rest (K_0) procedure, and pore pressures are initially hydrostatic. In each simulation, a constant inflow velocity (v_i) is prescribed at the orifice throughout the calculation.

347 Element size in the orifice

The mechanical boundary conditions or fixities in MPM are generally imposed at the 348 mesh nodes. For the problem analyzed here, special attention needs to be paid to the corners of 349 the orifice (Fig. 3). Due to the boundary conditions of the two nodes located at the corners 350 between the base of the soil bed and the inlet (Fig. 3, red nodes), the mobility of the MPs 351 located in the neighboring elements is restricted by this boundary condition (zone of influence 352 of corner nodes). In particular, if an LMP moving vertically from the inflow zone with a 353 prescribed inflow velocity (v_i) enters an element containing one of the corner nodes; it will 354 artificially slow down. This means that v_i is not fully transmitted to the soil. The comparison 355

of the two figures (Fig. 3a and 3b) illustrates that the smaller the elements in the orifice, the smaller the zone of influence restricted by the corner nodes (Fig. 3b).

In order to further understand the effect of the zone of influence of the corner 358 boundaries in the inflow liquid velocity (v_i) , a parametric analysis is performed, varying the 359 number of elements at the orifice between one to ten elements. In this analysis, the LMPs are 360 prescribed with three different inflow velocities (v_i) of 0.02, 0.04, and 0.10 m/s through a 10 361 mm orifice. The mesh dependency for the ratio of the transmitted water velocity at the orifice 362 363 (v_{o}) with respect to the inflow velocity (v_{i}) at the inflow BC is shown in Fig. 4. In the simulated problem, the energy losses through the orifice are not considered. Thus, the flow velocity at 364 the orifice (v_o) is expected to be equal to the applied inflow velocity (v_i) . The water velocity 365 at the orifice (v_o) is measured by averaging the velocity of the material points passing the 366 orifice region. The ratio of the transmitted water velocity is only 0.4 if one element is 367 considered at the orifice. The ratio increases rapidly from 0.4 to 0.9 when the number of 368 elements increases up to four. Beyond these values, an approximately steady state of the ratio 369 of the transmitted water velocity is observed. Consistent results are obtained for the different 370 prescribed inflow velocities. Therefore, the mesh dependency minimizes as the mesh is refined 371 with the better transmission of the water velocity. Increasing the number of elements beyond 372 four does not significantly improve the results, but it does increase the computational cost. To 373 optimize the computational time while having reasonable results, all models presented herein 374 consider four elements at the orifice. 375

Results and Discussion

The results obtained with the two-phase DP MPM approach are presented below. First, the soil fluidization mechanism for a reference scenario is discussed. Then, the effects of orifice size, soil-bed height, and soil porosity on the soil fluidization process are investigated through parametric analyses.

381 Soil Fluidization Mechanism

Soil fluidization initiates when the drag forces exerted by an upward fluid balances the gravitational forces of the bed. This process loosens the soil packing and thus increases the porosity of the material. In this paper, by using the double-point (DP) MPM approach, the transition between solid-like and the liquid-like response of the soil is based on the porosity threshold value n_{max} ; $n < n_{max}$ soil has a solid-like behavior while $n \ge n_{max}$ soil is fluidized. Therefore, tracking the evolution of porosity in the soil mass (SMPs) is a straightforward way to represent the soil state in the model.

A set of numerical models subjected to different inlet velocities through a 10 mm orifice 389 are simulated to investigate the onset and development of soil fluidization mechanism. The 390 porosity distribution at different inlet velocities after 2s of simulation through the centerline of 391 the soil bed is plotted in Fig. 5a. It is observed that the soil porosity increases with the increase 392 in the inflow velocity (v_i) and increases faster in those points located closer to the orifice (i.e., 393 394 0.05 m above the orifice). The maximum soil porosity $(n_{max} = 0.50)$ corresponds to the critical porosity; hence, $n < n_{max}$ indicates solid-like behavior and $n \ge n_{max}$ indicates 395 396 fluidized material. When v_i increases from 0.002 m/s to 0.020 m/s, the soil porosity immediately above the orifice exceeds (for the first time) the maximum porosity, indicating 397 that fluidization initiates at the orifice. The porosity across the bed height remains essentially 398 constant and equal to the initial value of 0.45. As v_i increases, the fluidized zone expands and 399 develops upward through the soil bed. When v_i reaches to 0.040 m/s, the first point situated 400 above the orifice (0.05 m) reaches the critical porosity, which is considered the onset of soil 401 fluidization in the vicinity of the orifice (i.e., onset or initiation of soil fluidization of the soil 402 bed). 403

At the initiation of soil fluidization, the particles above the orifice are mobilized and 404 moved with the leaking water. This was identified by Alsaydalani (2010) as an 'internally 405 fluidised zone' where the soil within this region was uplifted while those outside the region 406 407 remained steady (Fig. 6a). The development of the internally fluidized zone is presented in Fig. 408 6c and 6e. Similarly, Fig. 6b shows the distribution of the porosity after 2s of the MPM simulation across the whole domain for $v_i = 0.04 m/s$; the fluidized zone localized around the 409 orifice is clearly distinguished in red. The fluidized zone developed with the increase in the 410 inflow velocity (Fig. 6d and 6f). Finally, when the v_i increases up to 0.10 m/s, the fluidized 411 zone reaches the ground level (i.e., surface fluidization). Fig. 6g shows how the fluidized region 412 extends from the orifice to the ground surface. The LMPs flow along the ground surface and 413 are consequently dragged away from the fluidized zone. 414

The inflow velocity required for the initiation of soil fluidization is identified by monitoring the soil bed expansion ratio, which is the ratio between the final soil-bed height Hand the initial bed height H_0 (Taghipour et al. 2005). The soil fluidization initiates when the expansion ratio exceeds a value of one resulting in a significant heave of the bed (Chen et al. 2011). The heaving of the soil bed occurs when the upward drag force applied by the water 420 overcomes the bulk weight of the soil. In the numerical model, the soil bed expansion starts 421 when $v_i = 0.040 \text{ m/s}$, as noticed in Fig. 7, which is in good agreement with the porosity results. 422 The soil bed heaves significantly (10%) by the time the fluidization reaches the surface at an 423 inflow velocity of 0.10 m/s.

The soil fluidization mechanism is associated with the uplift of the granular materials 424 above the orifice as was recognized by Alsaydalani (2010) in Figure 8a. The vertical soil 425 displacement for $v_i = 0.040 m/s$ based on the MPM simulation is presented in Fig. 8b; 426 displacements are relatively small (maximum of 1.0 m) in the vicinity of the orifice at the onset 427 of fluidization. The MPM prediction is consistent with the experimental result by Alsaydalani 428 429 (2010). It is worth mentioning that Alsaydalani (2010) assessed the effect of orifice size on the onset of the soil fluidization mechanism. It was concluded that the fluidization zone is not 430 influenced by orifice size for the tested conditions. The inclination angle of the mobilized zone 431 measured from the MPM result is in the order of 63° (Fig. 8b), which is consistent with 432 Alsaydalani's experiment (2010) that used the same soil properties (Fig. 8a). Furthermore, the 433 obtained angle is expected theoretically based on the angle of shear failure that depends on the 434 angle of friction of the soil (34°), i.e. $[45^\circ + \frac{34}{2}] = 62^\circ$. The soil displacements increase as 435 the fluidization reaches the soil surface to 10 m at an inlet velocity of 0.10 m/s (Fig. 8c). The 436 uplift mechanism in the soil bed occurs where the soil is lifted in an upward direction above 437 438 the orifice leading to the formation of the fluidized zone. Previous researchers (Zoueshtiagh and Merlen 2007; Montellà et al. 2016) have described the significant uplift as a chimney, 439 440 which is a narrow zone of upward movement of water and soil. The upward progression of the fluidized region results in the entire erosion and instability of the soil in the chimney. Overall, 441 these results qualitatively validate the observations from previous experimental results. 442

The fluidization mechanism is also attributed to an abrupt drop in the effective stress 443 where the contact forces between the grains vanish. The effective stress at different inflow 444 445 velocities through the centerline of the soil bed is plotted in Fig. 9 after 2s of simulation. It is found that the effective stress decreases with the increase in the inflow velocity (v_i) and drops 446 faster at the vicinity of the orifice. When v_i increases from 0.002 m/s to 0.040 m/s, the 447 effective stress at 0.05 m above the orifice decreases to zero, indicating the onset of the soil 448 fluidization at which the leakage force exerted by the upward flow balances the bulk weight of 449 the soil. When the v_i increases, up to 0.10 m/s, the effective stress across the bed height 450 becomes null where the fluidization reaches the ground surface. It is worth noting that this 451 study focuses on the initiation and progression of the fluidization mechanism up to the ground 452

453 surface. Once the fluidized zone reaches the bed surface, the simulation becomes unstable, and 454 the post-fluidization mechanism (i.e., behavior after the fluidization reaches the ground 455 surface) cannot be analyzed. One explanation for the numerical instabilities is that the two-456 phase DP MPM approach used here considers the liquid as weakly compressible, which can 457 generate pressure oscillations when simulating nearly incompressible pressurized flows 458 (Kularathna and Soga 2017; Yamaguchi et al. 2020; Zhao and Choo 2020; Kularathna et al. 459 2021; Sołowski et al. 2021).

460 **Parametric Study**

461 *Effect of Orifice Size*

Five simulations with different orifice sizes (2.5, 5.0, 7.5, 10.0, 12.5, and 15.0 mm) are 462 463 conducted to investigate the effect of orifice size on the soil fluidization process induced by a leaking pressurized water pipe. The numerical results of the porosity at different inflow 464 velocities through the centerline of the soil bed for different orifice sizes (*o*) are plotted in Fig. 465 10. Consistently with the results presented in the previous section, the onset of soil fluidization 466 is determined when the SMPs at 0.05 m above the orifice fluidizes ($n \ge n_{max}$), while surface 467 fluidization is determined when all SMPs through the centerline of the soil bed are fluidized 468 $(n \ge n_{max})$. The inflow required for the onset (v_{io}) and surface fluidization (v_{is}) in models 469 with different orifice sizes are presented in Fig. 11. The vertical lines represent the accuracy of 470 the inflow velocity that are calculated based on ranges of values of soil porosity (Fig. 10). It is 471 472 observed that the inflow velocity inducing the onset of the soil fluidization (v_{io}) decreases with an increase in the orifice size. As the orifice size increases from 5 mm to 15 mm, v_{io} decreases 473 from 0.08 m/s to 0.02 m/s. It is of interest to note that the inflow flow rate is a function of 474 orifice area multiplied by the inflow velocities. The critical flow rate to initiate soil fluidization 475 decreases considerably from 1440 l/h to 1080 l/h, corresponding to an orifice size of 5 mm 476 and 15 mm, respectively. The inflow velocity inducing the surface fluidization (v_{is}) decreases 477 from 0.16 m/s to 0.08 m/s as the orifice size increases from 5 mm to 15 mm. Therefore, the 478 larger the orifice size, the smaller are the inflow velocities required to trigger the onset and 479 surface fluidization. These results are consistent with the analytical predictions developed by 480 Tang et al. (2017) in their study for the sand erosion caused by an upward water jet. If the 481 orifice is large enough, the soil fluidization progresses rapidly and reaches the surface at 482 minimal leakage velocity. In contrast, smaller orifices provide less water flow to fluidize the 483 soil bed. 484

The range of orifice sizes considered in this study is at least 7 times larger than the experimental study used for reference (Alsaydalani 2010), which used o = 0.336 mm. This is selected to reduce the computational cost of the models and avoid numerical instabilities as smaller orifice requires finer mesh to discretize the domain. From the numerical results, a second-order polynomial trendline for the inflow required for the onset of soil fluidization (v_{io}) is plotted in Fig. 11. This trendline is represented using the following Equation (5).

491
$$v_{io} = 0.0003o^2 - 0.0126o + 0.1345$$
 (5)

where v_{io} is in m/s, and o is the orifice size in mm. Note that Equation (4) is specific for the 492 material properties and soil bed heigh considered in the MPM model, which are consistent with 493 Alsaydalani (2010), and it is not a generic expression. The experimental results from 494 495 Alsaydalani (2010) indicate that $v_{io} = 0.12 m/s$ was required to initiate soil fluidization through a 0.336 mm orifice. This value is derived after deducting the velocity loss measured 496 through the orifice. Based on Equation (1), the predicted inflow velocity causing the initiation 497 of soil fluidization (v_{io}) for an orifice size of 0.336 mm is 0.13 m/s (Fig. 11), which is very 498 499 similar to the experimental results. This exercise further validates the consistency of the model 500 with the available data.

The change in expansion ratio H/H_0 with the inflow velocity for different orifice sizes 501 is presented in Fig. 12. The larger orifice size results in more heaving of the soil bed at the 502 same inflow velocity. This agrees well with the experiment conducted by Weisman and Lennon 503 (1994) in the development of fluidizer systems. As the orifice size increased, the soil 504 fluidization occurred rapidly at minimal leakage velocity. An increase in the orifice opening 505 leads to a lower expansion ratio at the onset of fluidization. The final expansion ratio as the 506 fluidization reaches the ground level is not significantly affected by the orifice size. Therefore, 507 508 the orifice size mainly affects the initiation of the soil fluidization process.

509 Effect of Soil-Bed Height

Five numerical models with different soil-bed heights are simulated to explore the effect of bed height on the soil fluidization mechanism. To eliminate the effect of boundary conditions on the fluidization zone, the ratio Length/Height of the soil bed is kept constant for the different simulations. Thus, four simulations with different bed heights of 300, 400, 500, 600, and 700 mm are conducted with a soil-bed length of 1500, 2000, 2500, 3000, and 3500 mm, respectively. Fig. 13 shows the change in the inflow velocity needed for the onset (v_{io}) and surface (v_{is}) fluidization at a 10 mm orifice with the change of the bed height. In the presented example, the inflow velocity leading to the initiation of the soil fluidization (v_{io}) increases with an increase in the soil bed height. As the bed height increases from 300 mm to 700 mm, v_{io} increases from 0.04 m/s to 0.10 m/s. Similarly, the water velocity at the orifice required to observe surface fluidization (v_{is}) increases considerably from 0.10 m/s to 0.40 m/s, corresponding to a bed height of 300 mm and 700 mm, respectively. Thus, the velocity required to induce surface fluidization significantly increases with the bed height.

The variation in the expansion ratio H/H_0 with the inflow velocity is plotted for different 523 bed heights in Fig. 14. The thicker the soil-bed, the lower the expansion ratio H/H_0 at the same 524 inflow velocity. As the height of the soil bed increases, higher leakage velocity is required to 525 526 initiate soil fluidization. The effect of the soil-bed height is not significant in terms of the expansion ratio at the onset of fluidization. However, the thicker the soil-bed height results in 527 a lower expansion ratio when the fluidization reaches the surface. This agrees with the previous 528 study conducted by Tang et al. (2017) that concluded the thicker soil bed is characterized by 529 more resistance of the mobilized soil region. Therefore, a larger inflow velocity is required to 530 fluidize the above soil bed. 531

532 Effect of Soil Porosity

To explore the effects of the soil porosity on soil fluidization induced by a leaking pipe, 533 models with four different initial soil porosity (0.30, 0.35, 0.40, and 0.45) have been conducted. 534 In the simulated problem, the intrinsic soil permeability (k) depends on the solid grain diameter 535 (D_p) and the soil porosity (n) (Bear 1972). Alsaydalani and Clayton (2013) stated that 536 permeability, and therefore soil porosity, can be expected to have a large effect on the water 537 538 flowing into the soil bed. Water seepage in the soil bed with higher porosity will be easily dissipated, which can quickly induce soil bed fluidization at the lower inflow velocity. For 539 example, an inflow velocity (v_{io}) of 0.10 m/s at a 10 mm orifice in a soil bed with 0.30 initial 540 541 porosity is sufficient to initiate the soil fluidization (Fig. 15a). For higher soil porosity (0.45), the soil fluidization is initiated at a lower inflow velocity (v_{io}) of 0.04 m/s. Soil fluidization 542 initiates under a lower inflow velocity in a higher porosity soil bed. Similarly, the inflow 543 velocity (v_{is}) required to develop fluidization reaching the bed surface decreases with an 544 increase in the soil porosity. The inflow velocity inducing the surface fluidization (v_{is}) 545 decreases from 0.16 m/s to 0.10 m/s as the soil porosity increases from 0.30 (Fig. 15b) to 546 0.45 (Fig. 15e). Thus, the inflow velocity required for the onset (v_{io}) and surface (v_{is}) 547 fluidization decreases linearly with the increase of the soil porosity. Hence, soil porosity is an 548

essential parameter in soil fluidization, and lowering the soil porosity can effectively improvethe stability of the soil bed.

The effect of porosity on the surface heaving at the onset of fluidization is also studied. 551 552 Fig. 16a shows the change in soil-height expansion ratio as the inflow velocity increases in the soil bed with different initial soil porosity. The inflow velocity that induces soil fluidization 553 554 (v_{i0}) is determined when the soil bed expansion ratio H/H_0 exceeds one. Water can easily flow through the soil when the soil porosity is large, and soil-bed fluidization is initiated at a lower 555 556 inflow velocity, as shown in Fig. 16a. This higher water velocity results in an increase in the expansion ratio. On the other hand, flow is more difficult through the lower porosity soil 557 558 because of the lower permeability. The higher the porosity of the soil-bed, the lower the expansion ratio at the same leakage velocity. The expansion ratio is lower as the soil 559 fluidization reaches the surface in highly porous soil. Fig. 16b and Fig. 16c show the vertical 560 soil displacement as the fluidization reaches the soil surface in soil bed with an initial soil 561 porosity of 0.30 and 0.35, respectively. The soil vertical displacements in lower porous soil are 562 relatively high (maximum of 0.06 m) compared to the vertical displacements that occurred in 563 highly porous soil (maximum of 0.05 m). Chen et al. (2011) stated that the driving force 564 565 exerted by the water to the solid skeleton decreases as the soil porosity increases, and this decrease in driving force makes the soil bed more difficult to heave. 566

567 Summary and Conclusions

In this study, the onset and development of soil fluidization induced by a leaking 568 pressurized water pipe embedded in fully saturated soil are simulated using the two-phase 569 570 double-point MPM approach, together with the use of in/outflow boundary conditions. This formulation captures the transition from solid to liquid behavior resulting from the fluidization 571 572 mechanism considering a threshold porosity; beyond that value, the material is considered a Newtonian fluid. The MPM results capture the initiation and evolution of soil fluidization and 573 soil bed expansion changes during the infiltration process. As the leakage velocity increases, 574 the soil porosity close to the orifice increases until it exceeds the maximum porosity at the 575 onset of fluidization. Soil fluidization results in a significant soil bed expansion that increases 576 with the propagation of the fluidized zone. Based on this analysis, an equation is proposed to 577 578 predict the inflow velocity at which fluidization starts to verify the numerical model against previous experimental works. The MPM model is used to investigate the impacts of the orifice 579

size, soil bed height, and soil porosity on the soil fluidization mechanism around a leaking pipe.
Based on the numerical simulations, the following conclusions can be made:

- An increase in orifice size can considerably decrease the inflow velocity resulting in
 soil fluidization. The surface fluidization mechanism is not significantly affected by the
 orifice size.
- The inflow leakage velocity required for the onset and evolution of soil fluidization significantly increases with an increase in the soil-bed height. The effect of the soil-bed height is more than the effect of orifice size, which means that it will be more effective to increase the pipe burial depth to reduce fluidization risk; and
- The soil porosity is an essential factor in soil fluidization, and the decrease in soil porosity can effectively strengthen the stability of the soil bed. Thus, soil with lower porosity should be used around underground pipes.

592 These results contribute to the understanding of the consequences of pipe leakage in 593 pressurized water pipes and help identifying the most important parameters contributing to the 594 initiation and propagation of soil fluidization. It is worth mentioning that further work is needed 595 to address the soil-fluid transition in a more accurate way by means of using advanced 596 constitutive models.

597 Data Availability Statement

598 Some or all data, models, or code that support the findings of this study are available 599 from the corresponding author upon reasonable request.

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Material Parameter	Symbol	Unit	Value
Initial porosity	n_0	_	0.45
Intrinsic permeability	k	m ²	4.0×10^{-11}
Density soil	$ ho_s$	kg/m ³	2660
Water density	$ ho_l$	kg/m ³	1000
Water bulk modulus	K _l	kPa	50000
Water viscosity	μ_d	kPa.s	10 ⁻⁶
K ₀ -value	K ₀	_	0.44
Effective Poisson ratio	v'	_	0.3
Effective Young's modulus	E'	kPa	69000
Effective Cohesion	с′	kPa	1.0
Effective friction angle	ϕ'	degree	34
Soil grain diameter	D _p	mm	0.9
Maximum soil porosity	n _{max}	—	0.50

Table 1. Material properties of the silica sand and water used in the model (Alsaydalani 2010).























































