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Alzabeebee, Saif; Chapman, David; Faramarzi, Asaad

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1 **A comparative study of the response of buried pipes**
2 **under static and moving loads**

3 **Saif Alzabeebee (Corresponding author)**

4 Department of Civil Engineering, School of Engineering, University of Birmingham, Birmingham, B15
5 2TT, UK

6 E-mail: Saif.Alzabeebee@gmail.com

7 **David N Chapman**

8 Department of Civil Engineering, School of Engineering, University of Birmingham, Birmingham, B15
9 2TT, UK

10 E-mail: D.N.Chapman@bham.ac.uk

11 **Asaad Famarzi**

12 Department of Civil Engineering, School of Engineering, University of Birmingham, Birmingham, B15
13 2TT, UK

14 E-mail: A.Famarzi@bham.ac.uk

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23 **Abstract**

24 The buried pipes should be designed properly to withstand the loads imposed by the
25 backfill soil weight and traffic loads. However, a thorough literature review has shown
26 differing opinions on the effect of static and moving traffic loads on buried pipes.
27 Some studies have shown that moving loads produce higher displacement in buried
28 pipes compared to static loads, while other studies have shown contradicting results.
29 These differing opinions have created confusion among researchers who are
30 studying the response of buried pipes under traffic loads, where most of the studies
31 have been conducted using either static or moving loads without proper justification
32 to the selection of the loading type. To clarify this confusion, this paper presents a
33 rigorous study on the behaviour of buried pipes under static and moving traffic loads
34 using a robust finite element analysis. The static and dynamic finite element models
35 have been developed and validated using high-quality field data collected from the
36 literature. The developed models were then used to investigate the effect of the truck
37 speed, pipe stiffness and loading conditions on the maximum displacement of buried
38 pipes. The results showed that the displacement of buried pipes due to static loads is
39 always higher than the pipe displacement due to moving loads. In addition, it was
40 found that the ratio of the static to dynamic pipe displacement decreases as the pipe
41 stiffness increases and increases to a lesser extent as the truck speed increases.
42 Hence, future studies should consider the static loads in designs as these are the
43 most stringent loading condition. This is actually very helpful for designers if they are
44 using numerical methods in their designs, because static analyses are much more
45 straightforward to conduct and less computationally demanding compared to
46 dynamic analyses.

47 **Keywords:** moving traffic loads; static traffic loads; buried structures; soil-structure
48 interaction.

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50

51 **1. Introduction**

52 Nowadays, pipelines can be considered as one of the most vital infrastructures in
53 maintaining modern life as they provide a convenient way to transport products such
54 as gas, oil, drinking water, sewage and storm water (Zhou et al., 2017; Khemis et al.,
55 2016; Tee et al., 2013). Pipelines can also be used as economical and safe conduits
56 for electricity and telecommunication lines (Moser and Folkman, 2008). These
57 pipelines are usually buried in the ground to protect them from damage due to
58 natural hazards and/or vandalism. As a result of burying a pipe in the ground, during
59 their service life pipelines need to resist external forces from the soil overburden
60 pressure and traffic loads, if buried below transportation routes and buried at shallow
61 depths. Therefore, buried pipes need to be designed properly to withstand these
62 forces. However, a thorough literature review has shown differing opinions with
63 respect to the effect of static and moving traffic loads (Alzabeebee, 2017). The
64 results from research conducted on large elliptical and box culverts published by
65 Beben (2013) and Acharya et al. (2016) have shown that moving traffic loads
66 produced higher displacement in buried culverts compared to static traffic loads,
67 while other studies have shown contradictory results (Yeau et al., 2009; Sheldon et
68 al., 2015).

69 Yeau et al. (2009) investigated the performance of in-service corrugated steel
70 elliptical culverts under static and moving truck loads. A total number of 39 in-service
71 culverts were considered in the study. Two trucks were used in these tests. The first
72 truck had a total weight of 302 kN with a maximum axle load of 142 kN. The second
73 truck had a total load of 280 kN with a maximum axle load of 76 kN. Yeau et al.
74 (2009) found that the maximum culvert displacement due to the moving truck loads
75 was 10% to 30% lower than the maximum displacement due to the static truck loads.

76 Beben (2013) investigated the response of in-service corrugated steel plate elliptical
77 culverts subjected to static and moving truck loads. Four trucks were used in the test
78 with a total weight of 279 kN, 275 kN, 285 kN and 280 kN. The maximum culvert
79 displacement and strain were recorded in each test. The speed of the trucks ranged
80 from 10 km/hr to 70 km/hr. Bebn (2013) found that the maximum displacement and
81 strain induced by the moving truck loads were higher than the corresponding

82 displacement and strain due to static truck loads. The ratio of the dynamic to static
83 displacement ranged from 1.116 to 1.260, while the ratio of the dynamic to static
84 strain ranged from 1.105 to 1.293.

85 Sheldon et al. (2015) studied the displacement and the joint rotation of an in-service
86 buried metal pipe due to static and moving truck loads using field based studies. The
87 moving truck tests were conducted with four different truck speeds (8 km/hr, 16
88 km/hr, 32 km/hr and 48 km/hr). The test truck had a maximum axle load of 133 kN.
89 The results showed that the buried pipe experienced higher displacement due to the
90 static truck loads compared to the corresponding displacement due to the moving
91 truck loads.

92 Acharya et al. (2016) conducted field studies to investigate the behaviour of buried
93 rigid box culvert under both static and moving loads. The box culvert buried with a
94 backfill height of 0.65 m. The static and moving loads were applied using a low
95 loader truck loaded with a backhoe. The truck had a maximum axle load of 105 kN.
96 The speed of the truck ranged between 40 km/hr to 105 km/hr. Acharya et al. (2016)
97 found that the culvert displacement due to the moving load was higher than the static
98 culvert displacement. They also found an increase in the culvert displacement as the
99 truck speed increased.

100 On the other hand, most of the studies on the behaviour and the design of buried
101 pipes have been conducted using either static loads (Katona, 1990; Arockiasamy et
102 al. 2006; Petersen et al., 2010; Talesnick et al., 2011; Kang et al., 2014; Lay and
103 Brachman, 2014; Rakitin and Xu, 2014; Chaallal et al., 2015a, b; MacDougall et al.,
104 2016; Mohamedzein and Al-Aghbari 2016; Alzabeebee et al., 2017, 2018a) or
105 moving loads (McGrath et al., 2002; Li et al., 2017; Neya et al., 2017) without a
106 rigorous justification with regard to the selection of the loading type. Katona (1990),
107 Arockiasamy et al. (2006), Petersen et al. (2010), Talesnick et al. (2011), Kang et al.
108 (2014), Chaallal et al. (2015a, b), Mohamedzein and Al-Aghbari (2016) and
109 Alzabeebee et al. (2017) studied the behaviour of buried flexible pipes under static
110 surface loads. Lay and Brachman (2014), Rakitin and Xu (2014), MacDougall et al.
111 (2016) and Alzabeebee et al. (2017, 2018a) investigated the behaviour and the
112 design of buried concrete pipes under static surface loads. McGrath et al. (2002)
113 reported the results of a field study on the response of a buried flexible pipe

114 subjected to moving truck loads with a maximum axle load of 107 kN. Li et al. (2017)
115 investigated the response of a buried concrete pipe and a rectangular culvert under
116 the effect of a moving aircraft wheel load using a two-dimensional finite element
117 analysis. The wheel load was modelled as a strip load with a maximum stress of
118 1482 kPa. However, there was no justification with regard to the use of a strip load
119 and a two-dimensional finite element method for modelling such a complicated three-
120 dimensional problem. Finally, Neyya et al. (2017) conducted a three-dimensional finite
121 element study on the behaviour of a buried pressurized steel pipe under moving
122 vehicle loads.

123 In summary, it cannot be conclusively established, based on the previous studies, if
124 the static or moving load should be used to study the behaviour of buried pipes and,
125 hence for the design of buried pipes. Therefore, this study aimed to find the critical
126 traffic loading condition on buried pipes by:

- 127 1- Developing and validating robust finite element models for simulating the
128 behaviour of buried pipes under static and moving traffic loads.
- 129 2- Investigating the effect of truck speed and pipe stiffness on the maximum pipe
130 displacement.
- 131 3- Investigating the effect of the truck speed and pipe stiffness on the ratio of
132 the pipe displacement due to static traffic loads to the pipe displacement due
133 to moving traffic loads.

134 The following section discusses the methodology of the finite element modelling.

135 **2. Finite element model development**

136 This section discusses the development and the validation of the methodology of the
137 dynamic and static finite element analyses. Six case studies have been used to
138 validate the models. These case studies were considered to develop a robust finite
139 element model able to accurately simulate the behaviour of buried culverts under
140 both static and moving loads with different loading configurations, and with different
141 speeds of moving loads.

142 **2.1. Modelling of buried pipes under moving loads**

143 This section presents the development of the finite element model for buried pipes
144 under moving loads using five case studies available in the literature (Mellat et al.,
145 2014; Sheldon et al., 2015).

146 **2.1.1. Validation problem 1**

147 Mellat et al. (2014) investigated the displacement of a buried, in-service, large
148 diameter, corrugated culvert under moving train loads using field and finite element
149 studies. An X52 commuter train with a speed of 180 km/h was used in the field test.
150 The culvert had an elliptical cross section. The horizontal dimension of the culvert
151 was 3.75 m, while the vertical dimension was 4.15 m. The total length of the train
152 was 54 m and consisted of two coaches. Each coach had four axles with a total axle
153 load of 185 kN. The distance between the axles is shown in Figure 1. The finite
154 element analysis involved modelling the field test using ABAQUS software, where
155 linear elastic modelling was considered in the finite element analysis.

156 This study was considered because all of the information required for conducting the
157 correct modelling (i.e. material properties of the culvert and the soil, culvert
158 dimensions and loading configurations) are available in Mellat et al. (2014). In
159 addition, the test was also modelled by Mellat et al. (2014) using ABAQUS software,
160 as mentioned in the previous paragraph; hence, this allowed a direct comparison
161 between the numerical modelling results of MIDAS GTS/NX (the finite element
162 software used in this study) and ABAQUS.

163 The problem was modelled using the dimensions for the field dimensions as
164 provided in Mellat et al. (2014). The corrugated culvert was simulated by using shell
165 elements with an equivalent thickness of 0.061 m as proposed by Mellat et al.
166 (2014). Four noded tetrahedron solid elements were used to model the ballast and
167 the backfill layers; while three noded triangular shell elements were used to model
168 the culvert. The base of the model was restrained against movement in all directions;
169 while the sides of the model were restrained against movement in the horizontal
170 direction. Ground surface spring elements (viscous dampers) were used in the sides
171 and the bottom of the model to model the infinite boundary conditions. This

172 technique is used to eliminate the effect of S and P wave reflection (Sayeed and
 173 Shahin, 2016; Sayeed and Shahin, 2017). The damper properties with respect to the
 174 P wave (*DPW*) and S wave (*DSW*) are calculated automatically in MIDAS GTS/NX
 175 using Equations 1 and 2, respectively (MIDAS IT. Co. Ltd., 2015).

$$DPW = \rho \times A \times \sqrt{\frac{\lambda + 2 \times G}{\rho}} \quad (1)$$

$$DSW = \rho \times A \times \sqrt{\frac{G}{\rho}} \quad (2)$$

$$\lambda = \frac{\nu \times E}{(1 + \nu) \times (1 - 2 \times \nu)} \quad (3)$$

$$G = \frac{E}{2 \times (1 + \nu)} \quad (4)$$

176 Where, *DPW* is the damper properties with respect to the P wave, *DSW* is the
 177 damper properties with respect to the S wave, ρ is the density of the soil, *A* is the
 178 cross-section area, *E* is the modulus of elasticity of the soil and ν is the Poisson's
 179 ratio of the soil (MIDAS IT. Co. Ltd., 2015).

180 The finite element model was developed with an average element size of 0.25 m, 0.5
 181 m and 0.5 m for the ballast layer, culvert, and the backfill and surrounding soil,
 182 respectively. A rough interaction (i.e. no interface element) between the soil and the
 183 culvert has been considered in the analysis. This is valid because the displacement
 184 induced in the culvert is very small and hence, the slippage between the soil and the
 185 culvert will have an insignificant effect on the accuracy of the developed model (Xu
 186 et al., 2017; Alzabeebee et al., 2018b). The mesh of the developed three-
 187 dimensional finite element model is shown in Figure 2.

188 The moving wheels were modelled as concentrated moving loads using a train
 189 dynamic load table available in MIDAS GTS/NX. This modelling technique allows the
 190 user to model moving loads by specifying the nodes of the loading path and
 191 arranging a table for the wheel loads, the offset distance between the wheels and the
 192 train speed. By using this technique, the program automatically changes the loads
 193 on the mesh as the time increases, depending on the speed of the train. The

194 program also assumes that for each point load, the load distributes in a triangular
195 fashion among three nodes as shown in Figure 3 (Araújo, 2011; Sayeed and Shahin,
196 2016). The program also calculates the location of the maximum load based on the
197 train speed. It should be noted that the moving wheels were modelled as
198 concentrated loads because the wheel load concentrates below the rail seat and
199 does not distribute equally on the whole sleeper area due to the issues associated
200 with the contact area between the sleeper and the ballast layer as noted by Shenton
201 (1978) and Abadi et al., (2015). Hence, using point loads to model the moving train
202 loads does not affect the accuracy of the finite element model predictions.

203 A time step (Δt) of 0.004 sec was considered in the analysis based on the finite
204 element mesh size and the speed of the train following the Courant-Friedrichs-Lewy
205 condition (Galavi and Brinkgreve, 2014) using Equation 5. The time step was
206 calculated based on the mesh size to avoid the model instability caused by the wave
207 progress in the dynamic finite element analysis (Vivek, 2011). The material
208 properties of the ballast, backfill and culvert were taken from Mellat et al. (2014) and
209 are shown in Table 1.

$$\Delta t = \frac{C_n \times L_{min}}{V} \quad (5)$$

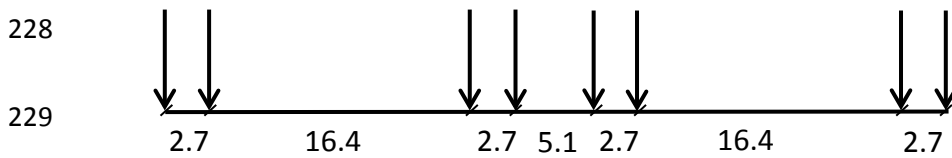
210 Where, C_n is the Courant number; L_{min} is the distance between two neighbouring
211 nodes on the path of the moving load; and V is the speed of the moving load (i.e.
212 speed of the train/truck).

213 The measured (field) results, numerical results using ABAQUS (Mellat et al. 2014)
214 and the numerical results from the present analysis (using MIDAS GTS/NX) for the
215 culvert crown displacement induced due to a moving X52 train with a speed of 180
216 km/h are shown in Figure 4. It is worth mentioning that Mellat et al. (2014) did not
217 model all of the train loads in their finite element analysis; they considered only the
218 two middle bogie loads of the train to reduce the computational time. It can be seen
219 from Figure 4 that the developed model predicts the crown displacement with very
220 good accuracy compared to the field data and ABAQUS analysis results. The
221 maximum displacement is 0.33 mm compared to a recorded value of 0.35 mm
222 (percentage difference is 6%). Furthermore, the developed model is able to predict

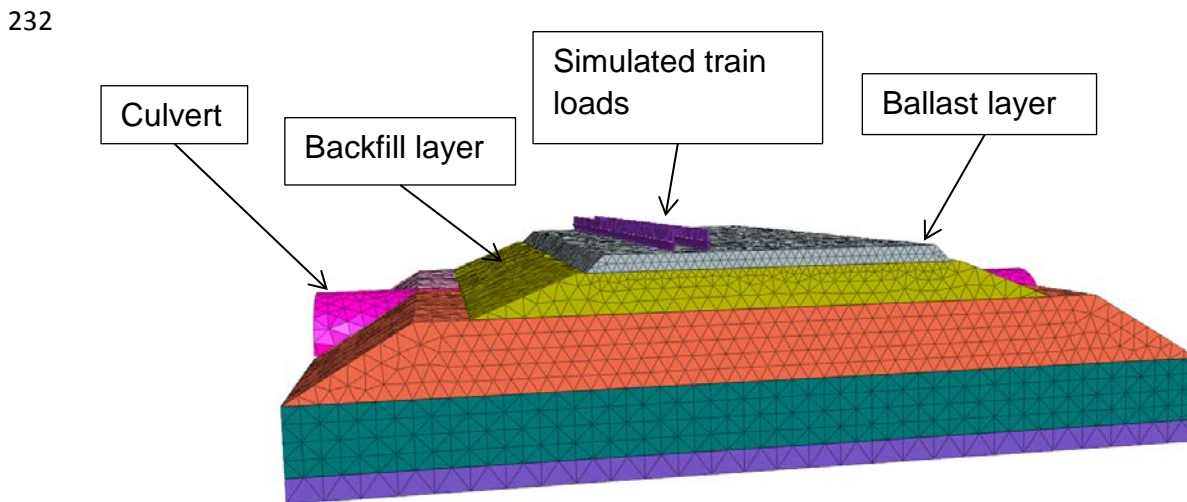
223 the trend of the displacement time relationship, as can be clearly seen in Figure 4.
 224 Hence, these observations give confidence in the methodology adopted for
 225 modelling this complex problem. Therefore, the developed model can be taken
 226 forward to investigate other scenarios of buried culverts under traffic loading.

227 Table 1: Material properties for the soil and the culvert (Mellat et al. 2014)

Material	E (kPa)	ν	γ (kN/m ³)
Ballast	200,000	0.3	17.65
Backfill and surrounding soil	100,000	0.3	15.7
Culvert	23,700,000	0.3	76.52



230 Figure 1: The distances between the axles of the X52 train (Mellat et al. 2014) (Note:
 231 all dimensions are in m)



234 Figure 2: The finite element mesh used for validation problem 1

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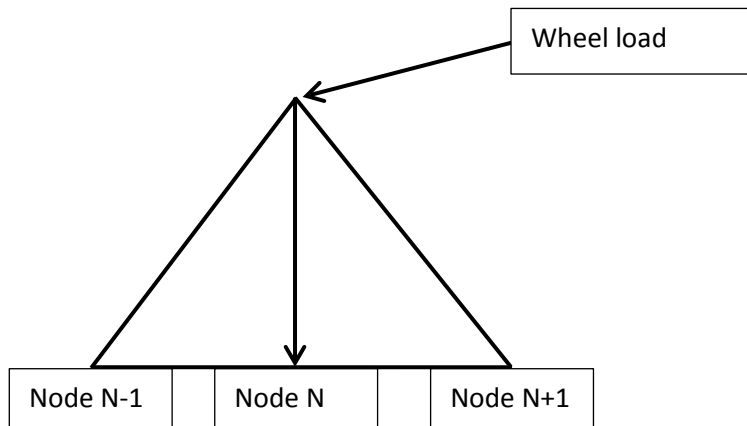
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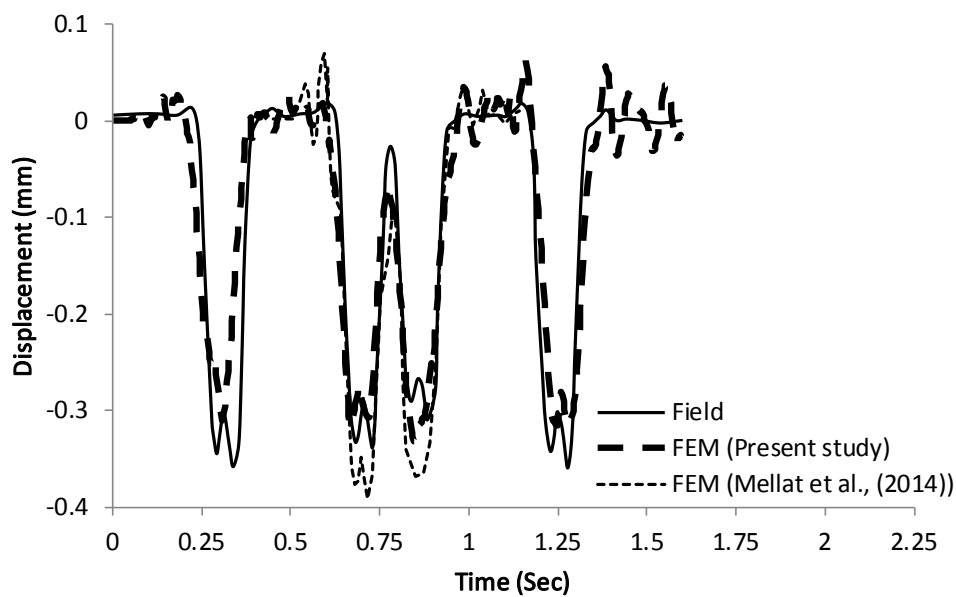
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Figure 3: The assumption of moving load distribution (Araújo, 2011; Sayeed and Shahin, 2016)

244



245

Figure 4: Crown displacement versus time response due to the effect of moving loads

2.1.2. Validation problem 2

Sheldon et al. (2015) reported the displacement response of a buried, in-service, corrugated metal pipe under the effect of static and moving truck loads. The moving truck tests were carried out at four different speeds (8 km/h, 16 km/h, 32 km/h and 48 km/h). The pipe had an inner diameter of 1.2 m and was buried with a backfill

253 height of 0.54 m. Linear displacement sensors were used to measure the crown
254 displacement. These sensors were installed in the upstream and downstream sides
255 of the pipe joint. The upstream sensor recorded the vertical displacement of the pipe
256 crown and the downstream sensor recorded the vertical displacement of the pipe
257 joint. The test truck had a steering axle load of 59 kN and rear axle load of 133 kN.
258 The axles were spaced at 4.3 m. The distance between the rear wheel pairs was
259 equal to 1.4 m.

260 These tests have been modelled using MIDAS GTS/NX to provide additional
261 confidence in the methodology of the dynamic finite element analysis. In addition, the
262 results have been compared to the results using static loads, as will be discussed in
263 section 2.2.

264 Four noded tetrahedron solid elements were used to model the soil and the asphalt
265 layer; while three noded triangular shell elements were used to model the pipe. The
266 joint was not considered in the finite element model as the aim was to model the
267 behaviour of the buried pipe under static and moving loads to test the finite element
268 analysis methodology. The model had a width, length and height of 5 m, 15 m and
269 10 m, respectively. A trench with a width of 2.4 m, a height of 2.14 m and a length of
270 15 m was considered in the model to enable finer elements to be used around the
271 pipe to improve the prediction accuracy. The model was built with an average
272 element size of 0.15 m for the pipe, 0.15 m for the trench, 0.25 m for the road and
273 0.5 m for the natural soil. A rough interaction (i.e. no interface element) between the
274 soil and the pipe has been considered in the analysis. The pipe was modelled using
275 an effective thickness of 0.0165 mm; this value has been calculated by Sheldon
276 (2011). The three-dimensional finite element model is shown in Figure 5. The base
277 of the model was restrained against movement in all directions, while the sides of the
278 model were restrained against movement in the horizontal direction. Ground surface
279 spring elements were used in the sides and the bottom of the model to simulate
280 infinite boundaries.

281 A well graded sandy soil with a degree of compaction of 90% (SW90) was
282 considered in the model as a backfill soil, followed by an asphalt layer with a
283 thickness of 0.1 m. A linear elastic model was used to simulate the behaviour of the
284 pavement and pipe as the applied load was below the yield stress of both the asphalt

285 and the pipe material. However, the soil was modelled using the linear elastic model
 286 (LE) and the Mohr-Coulomb elastic perfectly plastic model (MC) to study the effect of
 287 including the soil plasticity on the accuracy of the predictions of the finite element
 288 model. The modulus of elasticity (E) of the SW90 soil was calculated using Equation
 289 6 (Janbu, 1963) utilising the hyperbolic soil model parameters ($K = 950$ and $n =$
 290 0.60) published by Boscardin et al. (1990). These hyperbolic parameters were
 291 determined from triaxial test results (further information can be found in Boscardin et
 292 al., 1990). A lateral stress (S_3) of 19.32 kPa was used in Equation 6 to calculate the
 293 modulus of elasticity. This lateral stress was calculated by taking the average height
 294 from the top surface of the model to the pipe invert using a coefficient of lateral earth
 295 pressure of 1.0 for the compacted backfill soil (Brown and Selig, 1991) (i.e. $(1.74 \times$
 296 $21 \times 1)/2$). The average height to the pipe invert has been considered in the
 297 analyses because the behaviour of the pipe is significantly affected by the support
 298 condition provided at the pipe springline and the pipe invert (Dhar et al., 2004). The
 299 natural soil was assumed to be stronger than the backfill soil ($K = 1500$ and $n =$
 300 0.65) (Alzabeebee et al., 2017). The material properties of the SW90 soil, the natural
 301 soil, the asphalt layer and the pipe are taken from the literature (Boscardin et al.
 302 1990; Kang et al., 2014; Sheldon et al., 2015; Alzabeebee et al., 2017) and are
 303 shown in Table 2. It should be noted that the pipe tested by Sheldon et al. (2015)
 304 was an in-service buried culvert. Hence, the backfill soil around the pipe was very
 305 compacted due to the repeated action of moving trucks and cars. Hence, the use of
 306 a very compacted soil (SW95) in the modelling of the backfill soil was deemed most
 307 appropriate. In addition, the parameters considered for the culvert are the real
 308 parameters of the pipe material based on Sheldon (2011). On the other hand, the
 309 parameters for the asphalt and the surrounding soil have been considered from other
 310 references due to the lack of information in the original references (i.e. Sheldon
 311 (2011) and Sheldon et al. (2015)).

$$E = K \times P_a \times \left(\frac{S_3}{P_a} \right)^n \quad (6)$$

312 Where, E is the modulus of elasticity of the soil; K and n are the hyperbolic
 313 parameters for the stiffness modulus; P_a is the atmospheric pressure (100 kPa); and
 314 S_3 is the lateral stress.

315 The moving truck loads were modelled, assuming concentrated moving loads, with
316 the aid of the dynamic train table available in the MIDAS GTS/NX software as
317 discussed in validation problem 1. The truck tyres were modelled as concentrated
318 moving loads because the load applied by the moving tyre concentrates and does not
319 distribute uniformly on the whole tyre contact area as noticed by De Beer et al.
320 (1997) and the tyre contact stress has not been measured during the tests.
321 Furthermore, Shakiba et al. (2017) noticed that using non-uniform complex loads in
322 modelling the effect of the moving loads affects the accuracy of the finite element
323 modelling only at shallow depths in comparison with the concentrated loads, where
324 the differences between non-uniform and concentrated loads diminish at the bottom
325 of the asphalt layer. Hence, the assumption of the concentrated load was considered
326 valid as the considered pipe is buried with a backfill height of 0.45 m. The space
327 between the concentrated loads was considered equal to 1.4 m, similar to that
328 reported in the field tests. The time step (Δt) was calculated based on the mesh size
329 and the velocity of the truck following the Courant-Friedrichs-Lewy condition (Galavi
330 and Brinkgreve, 2014) using Equation 5.

331 The measured and predicted crown displacement time response of the pipe under
332 moving trucks with speeds of 8 km/h, 16 km/h, 36 km/h and 48 km/h are shown in
333 Figures 6, 7, 8 and 9, respectively. It can be seen that the developed model is able
334 to predict the trend behaviour of the displacement time response for all of the
335 considered speeds. However, Figures 6 and 7 show a shift in the results of the finite
336 element simulation in comparison with the field tests. This might be due to issues
337 related to a change in the truck speed during the tests. Importantly, the developed
338 model predicted the maximum displacement with very good accuracy, where the
339 percentage difference of the field and numerical maximum crown displacements are
340 equal to 3%, 5%, 22% and 20% for truck speeds of 8 km/h, 16 km/h, 32 km/h and 48
341 km/h, respectively. Furthermore, the difference in the results can also be justified by
342 the potential variability in the test results, especially for such complicated field tests
343 and the uncertainties associated with such tests. Figures 6, 7, 8 and 9 also show that
344 the LE and the MC models give the same displacement, illustrating the insignificant
345 effect of including the soil plasticity on the results (i.e. pipe behaviour). This occurred
346 because the soil around the pipe did not reach the condition of failure due to the
347 applied surface pressure. Hence, the support condition provided to the pipe in the

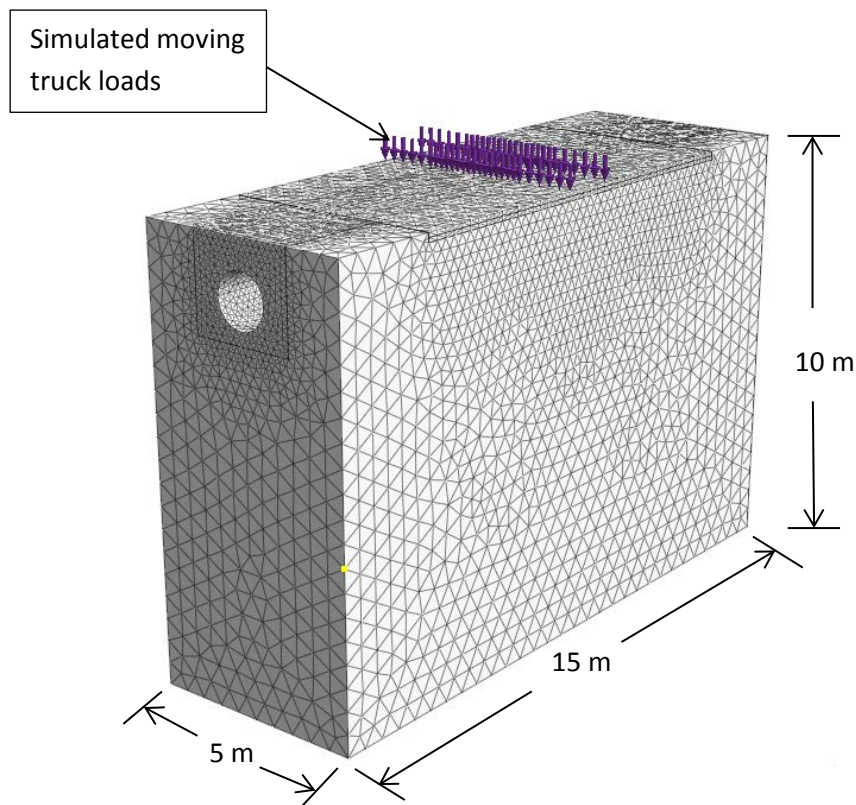
348 MC analysis was similar to that provided with the LE analysis. This observation is
 349 consistent with that reported by Robert et al. (2016) and Katona et al. (2017).
 350 Therefore, it can be concluded that the linear elastic model can be used to predict
 351 the behaviour of buried pipes under paved roads with a good accuracy.

352 Table 2: Material properties used in the finite element analysis

Property	Natural soil*	Backfill soil**	Asphalt***	Pipe****
γ (kN/m ³)	21.00	21.00	23.23	78.00
ν	0.3	0.3	0.3	0.2
E (kPa)	49,685	30,813	4,500,000	200,000,000
c' (kPa)	30	1	---	---
ϕ' (°)	36	48	---	---

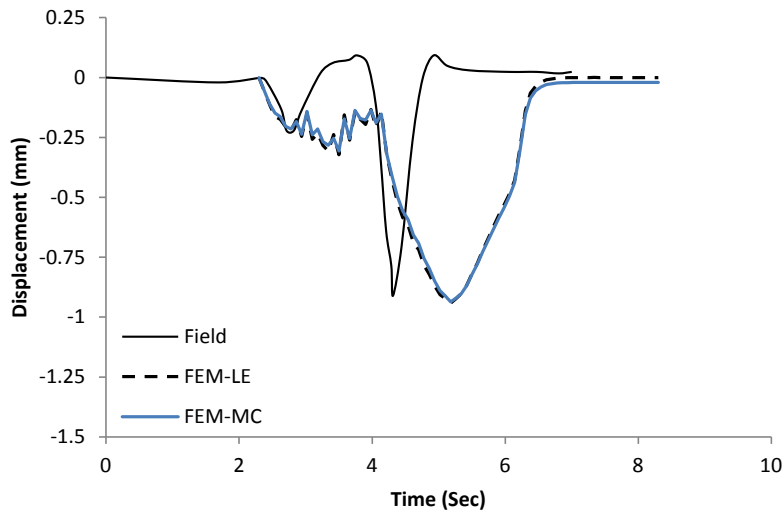
353 * adopted from Alzabeebee et al. (2017); ** adopted from Boscardin et al. (1990) and
 354 the modulus of elasticity calculated using Equation 6; *** adopted from Kang et al.
 355 (2014); **** adopted from Sheldon et al. (2015).

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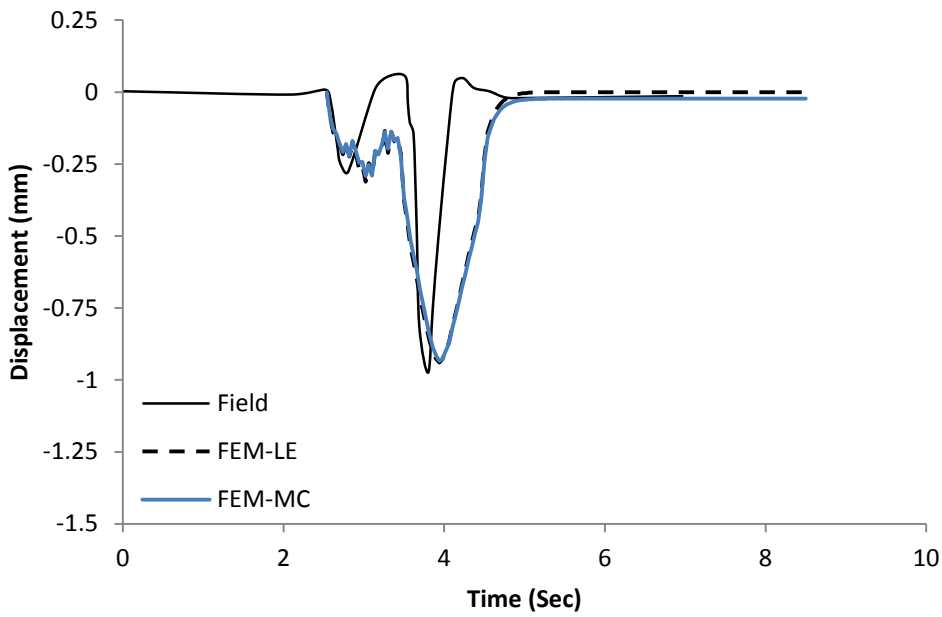
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358 Figure 5: The finite element mesh used for validation problem 2



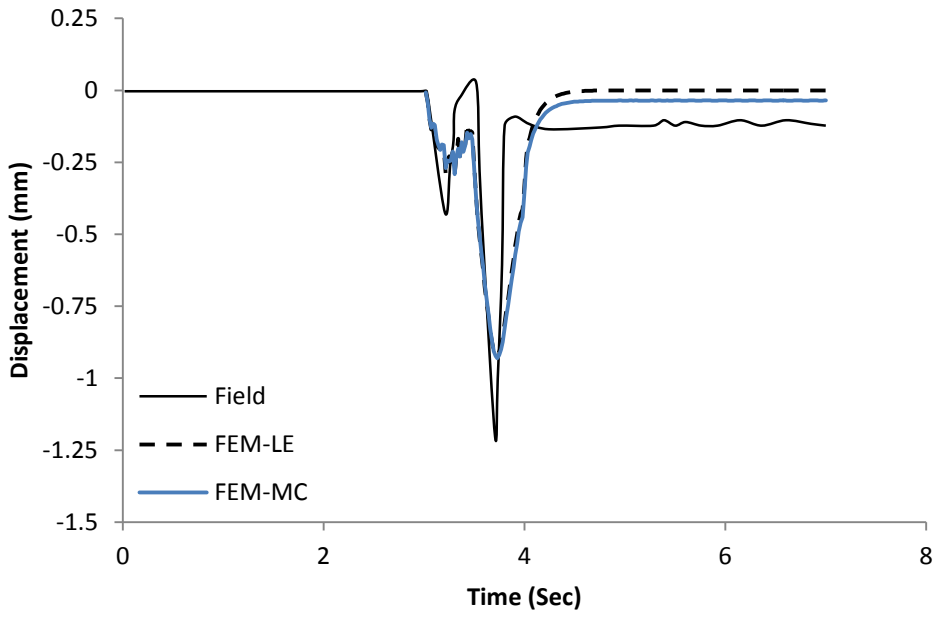
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360 Figure 6: Crown displacement time response under a moving truck with a speed of 8
 361 km/h



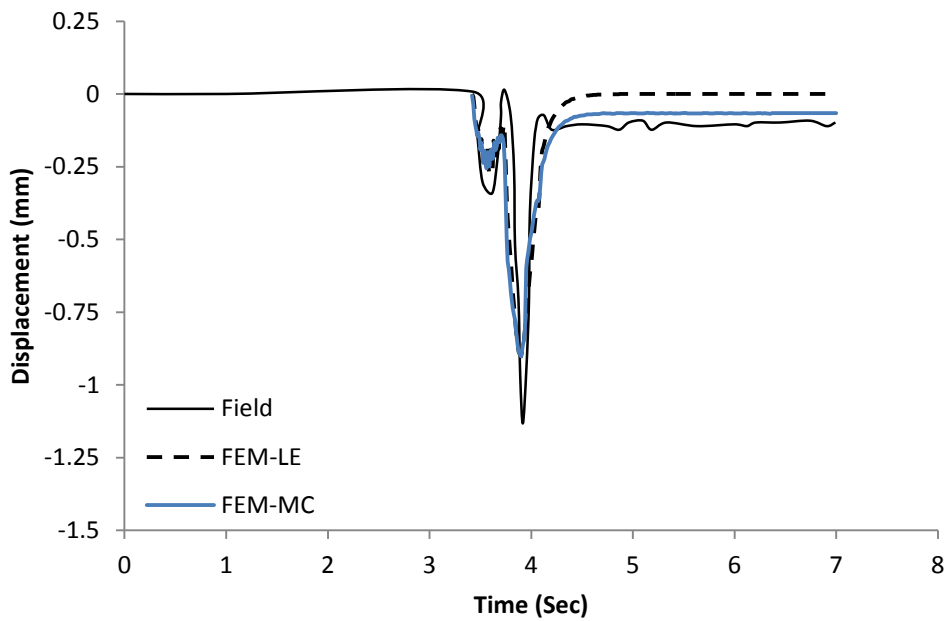
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363 Figure 7: Crown displacement time response under a moving truck with a speed of
 364 16 km/h



365

366 Figure 8: Crown displacement time response under a moving truck with a speed of
 367 32 km/h



368

369 Figure 9: Crown displacement time response under a moving truck with a speed of
 370 48 km/h

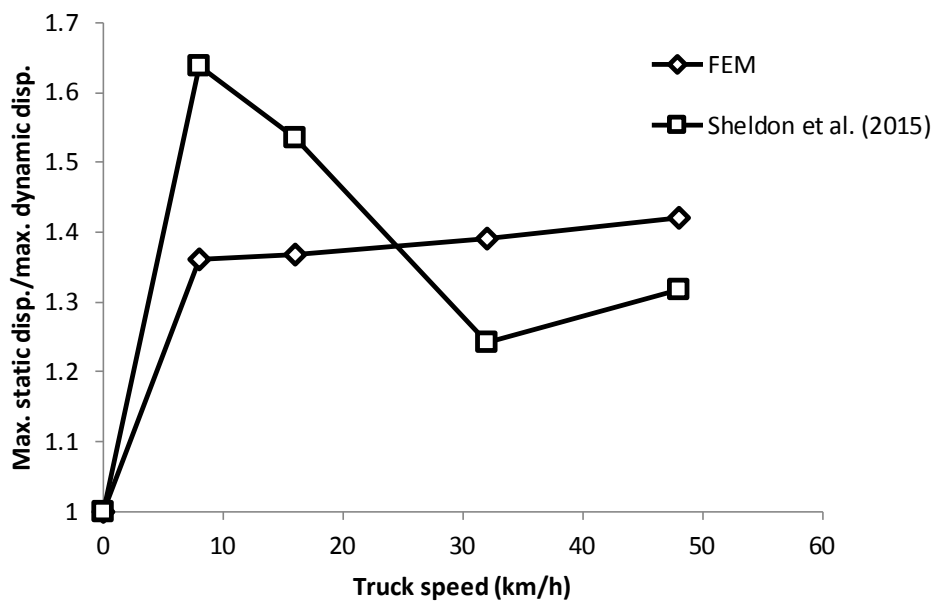
371 **2.2. Modelling buried pipes under static loads**

372 Another finite element model for buried pipes under static loads has been developed
373 and validated in this section to study the behaviour of the metal pipe (modelled in
374 validation problem 2) under static loads and to compare the behaviour under static
375 and dynamic moving loads. The case of the rear axle being directly on the top of the
376 pipe was considered as Sheldon et al. (2015) found that this loading condition
377 created the worst-case scenario. The static loads were applied in one increment
378 because the linear elastic static analysis does not require the load to be applied in
379 steps. The tyre load was modelled as a surface pressure over a tyre foot print area
380 of approximately 0.25 m x 0.50 m (Sheldon, 2011); as this technique was found to
381 provide a good prediction to the response of the buried pipes under static loads
382 (Yeau et al., 2014; Alzabeebee et al., 2017, 2018a, b). The obtained maximum static
383 displacement of the crown of the buried pipe was equal to 1.28 mm, compared to an
384 experimental value of 1.49 mm, indicating a good predictive ability for the developed
385 model.

386 Figure 10 shows the ratio of the maximum predicted static crown displacement (1.28
387 mm) to the maximum predicted dynamic crown displacement (pipe displacement due
388 to the moving traffic loads predicted from the finite element model) for different truck
389 speeds (obtained from Figures 6, 7, 8 and 9). It can be clearly seen from the Figure
390 10 that the static displacement is higher than the dynamic displacement for all of the
391 truck speeds, where the ratio ranges from 1.36 to 1.42 depending on the truck
392 speed. This is similar to the observations reported by Yeau et al. (2009). In addition,
393 Figure 10 also shows the same ratio (i.e. the maximum static crown displacement to
394 the maximum dynamic crown displacement) calculated based on the results from
395 Sheldon et al. (2015). It can be seen that the ratio based on the results from Sheldon
396 et al. (2015) show some differences from those predicted based on the finite element
397 modelling. The ratio increases with the increase of the truck speed up to 8 km/hr,
398 then decreases as the speed increases from 8 km/hr to 32 km/hr. Finally, the ratio
399 increases again as the speed changes from 32 km/hr to 48 km/hr. These differences
400 may be due to the potential variability in the test results, especially for such
401 complicated field tests and the uncertainties associated with such tests as discussed
402 in Section 2.1.2. In addition, the relative magnitudes of the static and dynamic

403 displacement are very small (less than 1.25 mm), and hence a small
404 difference/inaccuracy could produce a large variation in the ratio.

405 It can also be seen in Figure 10 that there is a drop in the ratio as the truck changes
406 from moving to static (i.e. speed = 0 km/hr). This is due to the significant difference
407 of the stress distribution caused by the moving load action as demonstrated by De
408 Beer et al. (1997). On the other hand, the load distributes uniformly for the static load
409 case. The drop in the ratio has also been noted by Yea et al. (2009) and Sheldon et
410 al. (2015).



411

412 Figure 10: Ratio of the maximum static displacement to the maximum dynamic
413 displacement for different truck speeds for a buried metal pipe

414 3. Parametric study

415 A parametric study has been carried out to study the effect of the truck speed and
416 pipe stiffness (*PS*) on the maximum pipe displacement and the ratio of the static to
417 dynamic maximum pipe displacement. This was considered because the behaviour
418 of the buried pipe is significantly affected by the pipe stiffness based on the arching
419 mechanism (Moore, 2001; Kang et al., 2007). In addition, increasing the pipe
420 stiffness decreases the response of the buried pipe to the applied loads. Therefore, it
421 was important to conduct this investigation before recommending the use of the

422 static load in future pipe studies. A truck speed ranging from 8 km/hr to 76 km/hr was
423 considered in the analyses. The pipe stiffness was calculated using Equation 7
424 (Petersen et al., 2010). Four values of pipe stiffness were considered in the analysis
425 (0.5 kN/m, 10 kN/m, 102 kN/m and 1022 kN/m). These values cover the range of
426 very flexible, flexible, semi-rigid and rigid pipes (Bryden et al., 2015). The diameter
427 for all of these pipes was kept constant (1.2 m), i.e. similar to the diameter of the
428 metal pipe used in the validation problem, while the thickness was assumed to be
429 equal to 0.08 m. However, the modulus of elasticity was changed to alter the pipe
430 stiffness based on Equation 7. The truck used in the analyses had a loading
431 configuration to the same as that used in the study of Sheldon et al. (2015) (i.e. the
432 truck used in Validation problem 2).

$$PS = \frac{EI}{0.149 r^3} \quad (7)$$

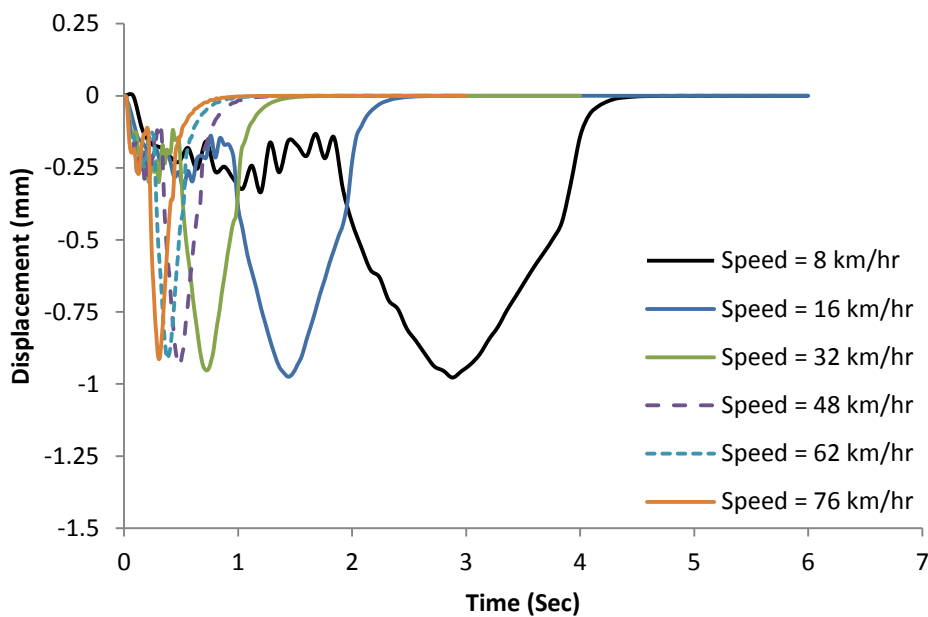
433 Where, E is the modulus of elasticity of the pipe; I is the moment of inertia of the
434 pipe; and r is the mean radius of the pipe.

435 Figures 11, 12, 13 and 14 show the crown displacement against time response due
436 to the effect of moving traffic loads for very flexible, flexible, semi-rigid and rigid
437 pipes, respectively. The figures show that the trend of the crown displacement with
438 time is similar for all the pipes. In addition, the figures also show that increasing truck
439 speed slightly decreases the induced maximum pipe crown displacement. Increasing
440 the truck speed from 8 km/hr to 76 km/hr decreases the maximum pipe crown
441 displacement by 6%, 7%, 8% and 9% for very flexible, flexible, semi-rigid and rigid
442 pipes, respectively. In addition, the results show that increasing the pipe stiffness
443 decreases the crown displacement. This behaviour is due to the decrease in the
444 response of the buried pipe to the applied load as the pipe stiffness increases
445 (Alzabeebee et al., 2017).

446 Figure 15 shows the relationship between the ratio of the static to dynamic maximum
447 pipe displacement and truck speed for different values of pipe stiffness. It can be
448 seen from the figure that the static pipe displacement is always higher than the
449 dynamic pipe displacement (i.e. the ratio is higher than 1) for all of the considered
450 values of pipe stiffness. In addition, the figure shows that the ratio of the static to

451 dynamic pipe displacement slightly increases as the truck speed increases. This
452 behaviour is due to the slight decrease in the maximum dynamic pipe displacement
453 as the truck speed increases. Furthermore, the figure shows that increasing the pipe
454 stiffness significantly decreases the ratio of the static to dynamic pipe displacement.
455 For example, for a truck speed of 8 km/hr and 76 km/hr, the ratio of the static to
456 dynamic pipe displacement decreases by 34% and 33%, respectively, as the
457 stiffness of the pipe changes from 0.5 kN/m to 1022 kN/m (i.e. the pipe changes from
458 very flexible to rigid).

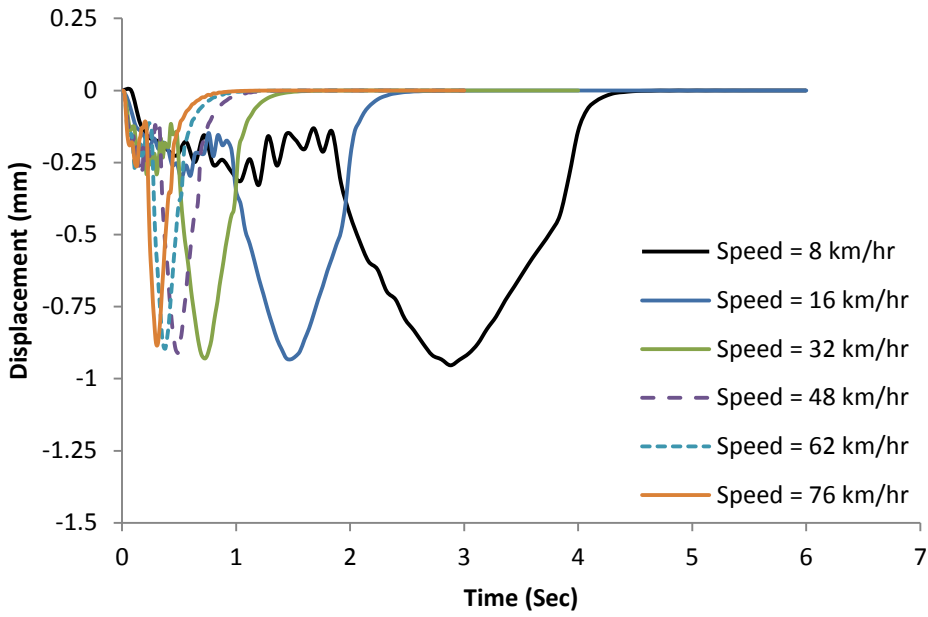
459 In summary, the results of the parametric study clearly illustrate that the static load
460 represents the worst-case scenario in all the cases considered in this study.
461 Therefore, the static load should be used in the analysis and the design of buried
462 pipes.



463

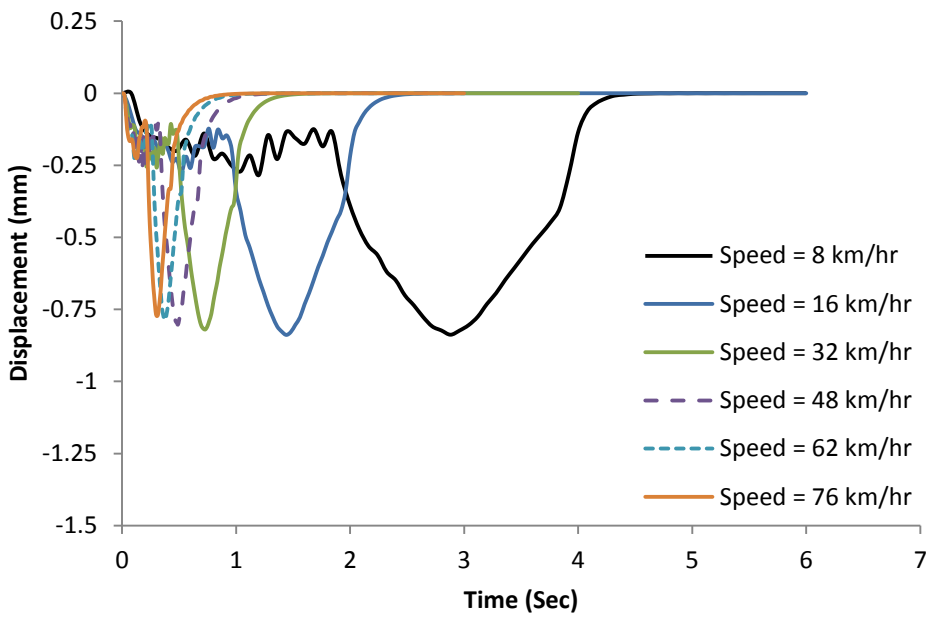
464 Figure 11: Crown displacement versus time response under a moving truck with
465 different truck speeds for a very flexible pipe ($PS = 0.5 \text{ kN/m}$)

466



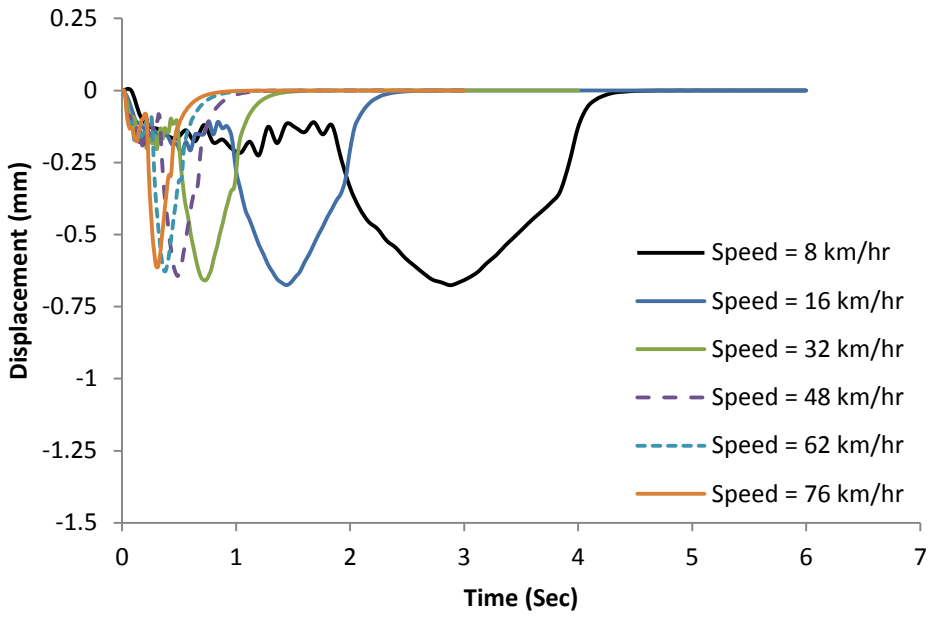
467

468 Figure 12: Crown displacement versus time response under a moving truck with
 469 different truck speeds for a flexible pipe ($PS = 10 \text{ kN/m}$)



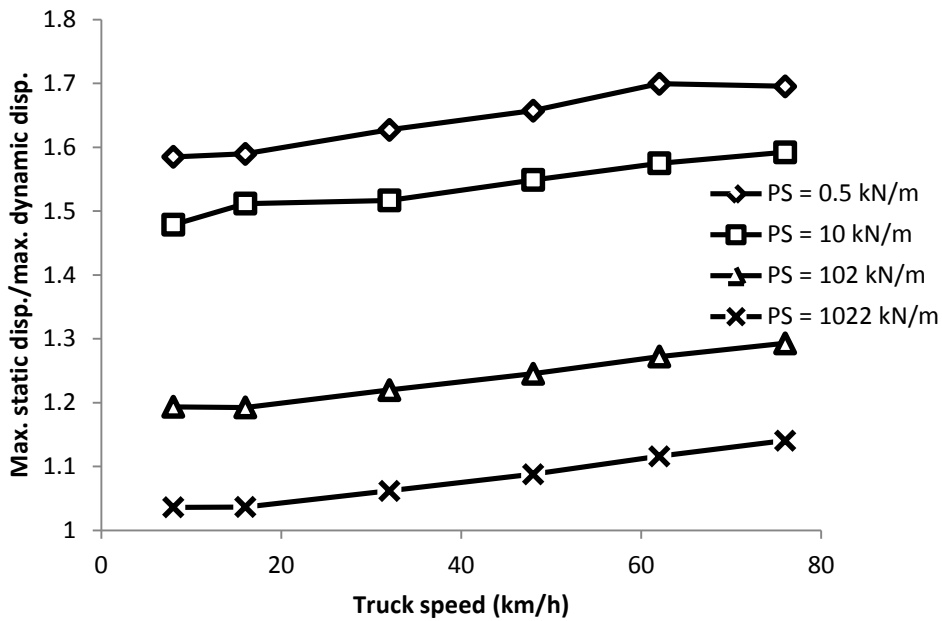
470

471 Figure 13: Crown displacement versus time response under a moving truck with
 472 different truck speeds for a semi-rigid pipe ($PS = 102 \text{ kN/m}$)



473

474 Figure 14: Crown displacement versus time response under a moving truck with
 475 different truck speeds for a rigid pipe ($PS = 1022 \text{ kN/m}$)



476

477 Figure 15: Effect of the pipe stiffness on the static to dynamic pipe displacement for
 478 different truck speeds

479

4. Summary and conclusions

480 This paper has compared the behaviour of buried pipes under both static and
481 moving traffic loads to find the critical loading condition which should be used in the
482 analysis and the design of buried pipes. The study was conducted using rigorous
483 finite element analyses. The methodology of the dynamic and static finite element
484 analysis was validated using six case studies available in the literature. A parametric
485 study was then conducted to study the effect of the truck speed and pipe stiffness on
486 the induced maximum pipe crown displacement. In addition, the ratio of the static to
487 dynamic pipe crown displacement was also investigated. The following conclusions
488 can be drawn based on the findings from this study:

489 1- Including the soil plasticity does not affect the accuracy of the finite element
490 analysis of buried pipes under paved roads. Hence, linear elastic analyses
491 can be used to simulate the behaviour of buried pipes under a paved road
492 with a backfill height equal to or more than 0.45 m and subjected to static and
493 moving traffic loads with a maximum axle load of 133 kN. The percentage
494 difference of the finite element analyses and the field tests results ranged
495 from 3% to 20%, indicating a good prediction from the finite element models,
496 given the assumptions made in the numerical analyses and the uncertainties
497 associated with complicated field tests.

498 2- Simulating the moving traffic loads using concentrated loads produced very
499 good agreement with the field results. This finding confirms the observation of
500 De Beer et al. (1997), who noted that the forces transmitted from the moving
501 wheel to the pavement tend to concentrate and do not distribute uniformly
502 over all of the wheel contact area.

503 3- Increasing the truck speed caused a small decrease in the induced maximum
504 pipe crown displacement. The percentage decrease was 6%, 7%, 8% and 9%
505 for very flexible, flexible, semi-rigid and rigid pipes, respectively, as the truck
506 speed changed from 8 km/hr to 76 km/hr.

507 4- The static traffic loads produced a deformation higher than the moving traffic
508 loads for all of the pipes considered in this study. The ratio of the static to
509 dynamic maximum pipe displacement ranged between 1.04 to 1.70
510 depending on the pipe stiffness and the truck speed. Hence, future studies

511 should consider the static loading condition to simulate the worst-case
512 scenario.

513 5- The ratio of the static to the dynamic pipe crown displacement decreases with
514 an increase in pipe stiffness.

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