

# A comparative study of the response of buried pipes under static and moving loads

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

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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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## 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,  $\rho$  is the density of the soil, *A* is the  
 178 cross-section area, *E* is the modulus of elasticity of the soil and  $\nu$  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 ( $\Delta t$ ) 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.

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

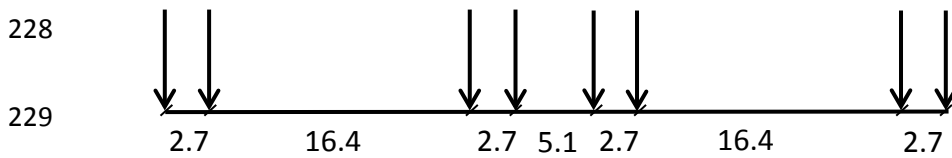
210 Where,  $C_n$  is the Courant number;  $L_{min}$  is the distance between two neighbouring  
211 nodes on the path of the moving load; and  $V$  is the speed of the moving load (i.e.  
212 speed of the train/truck).

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

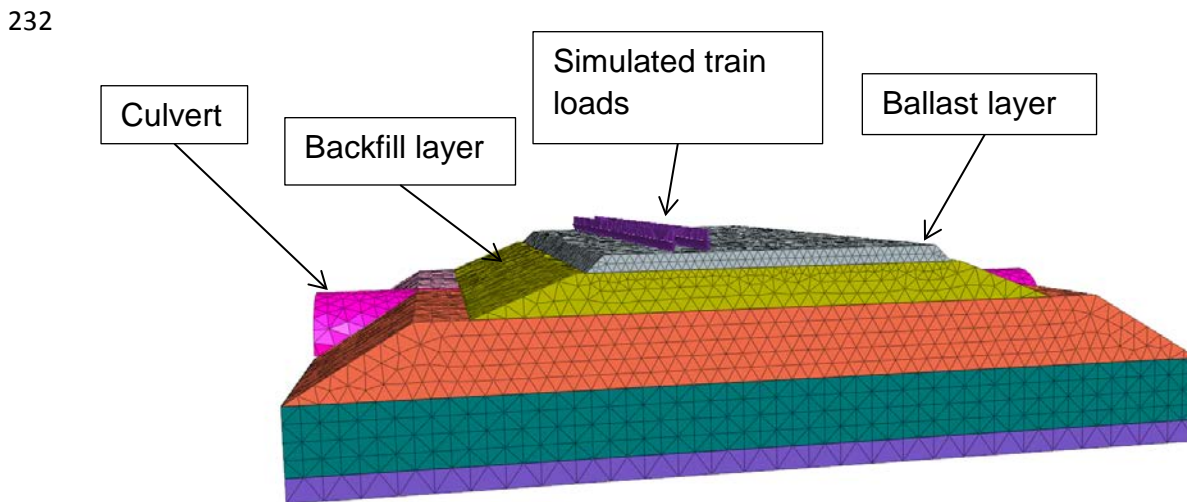
223 the trend of the displacement time relationship, as can be clearly seen in Figure 4.  
 224 Hence, these observations give confidence in the methodology adopted for  
 225 modelling this complex problem. Therefore, the developed model can be taken  
 226 forward to investigate other scenarios of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

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

Material	$E$ (kPa)	$\nu$	$\gamma$ (kN/m <sup>3</sup> )
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)



233  
 234 Figure 2: The finite element mesh used for validation problem 1  
 235  
 236

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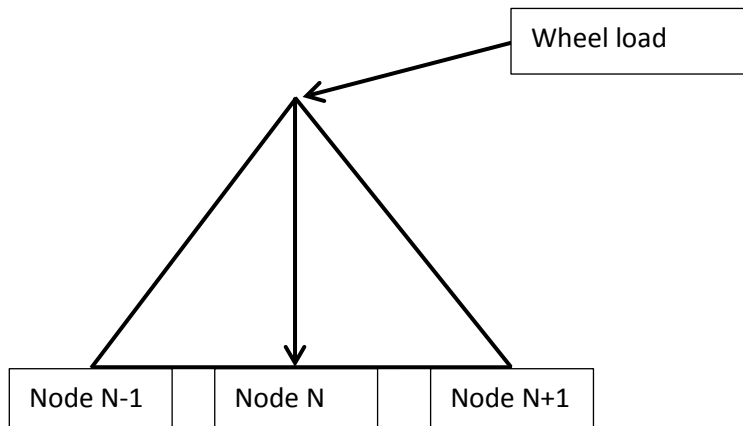
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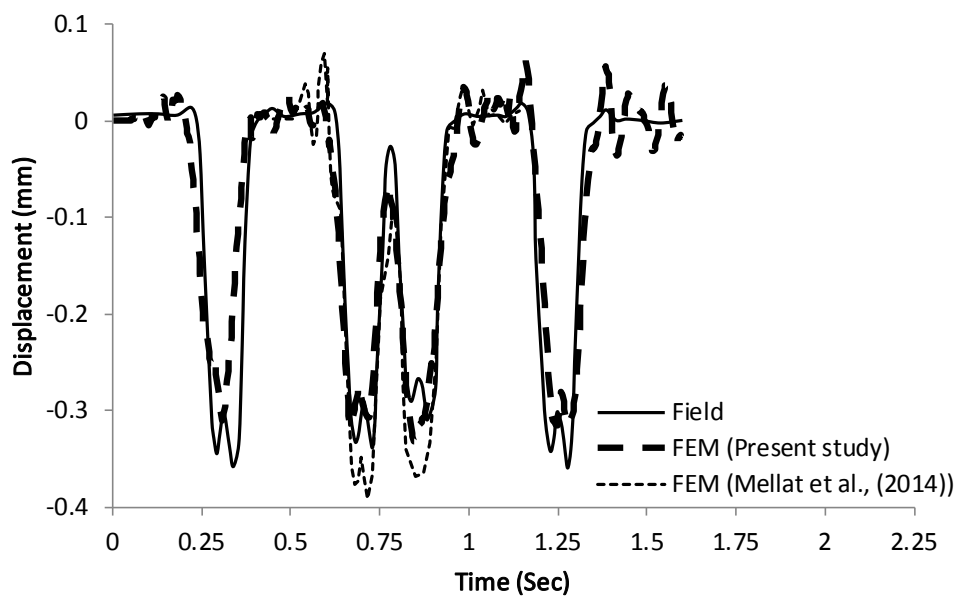
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Figure 3: The assumption of moving load distribution (Araújo, 2011; Sayeed and Shahin, 2016)



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

248

### 2.1.2. Validation problem 2

249

250

251

252

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 ( $\Delta t$ ) 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

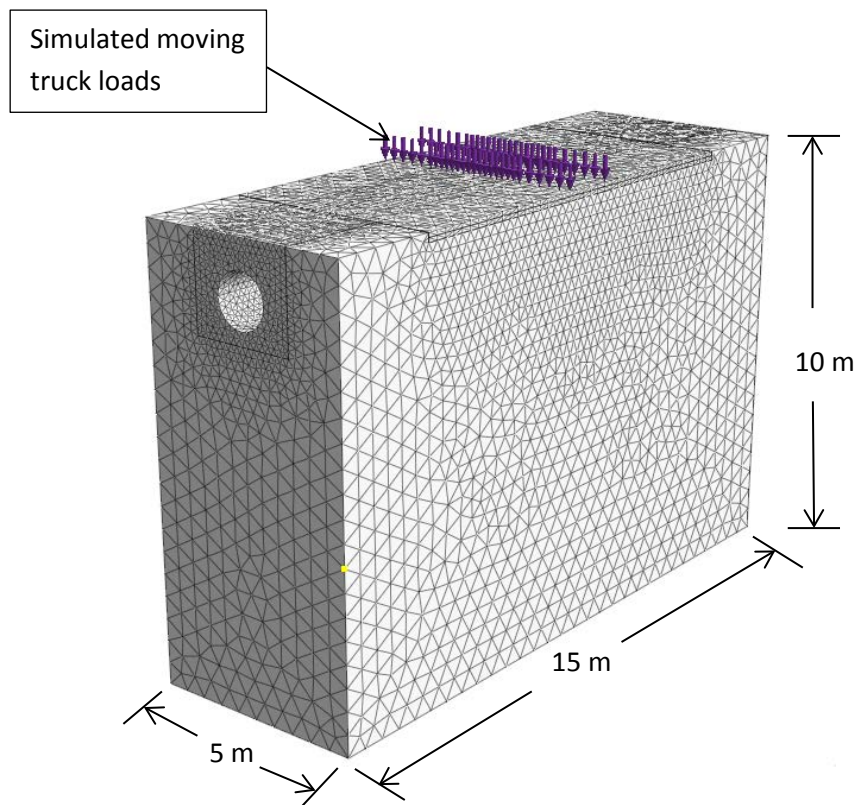
348 MC analysis was similar to that provided with the LE analysis. This observation is  
 349 consistent with that reported by Robert et al. (2016) and Katona et al. (2017).  
 350 Therefore, it can be concluded that the linear elastic model can be used to predict  
 351 the behaviour of buried pipes 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****
$\gamma$ (kN/m <sup>3</sup> )	21.00	21.00	23.23	78.00
$\nu$	0.3	0.3	0.3	0.2
$E$ (kPa)	49,685	30,813	4,500,000	200,000,000
$c'$ (kPa)	30	1	---	---
$\phi'$ (°)	36	48	---	---

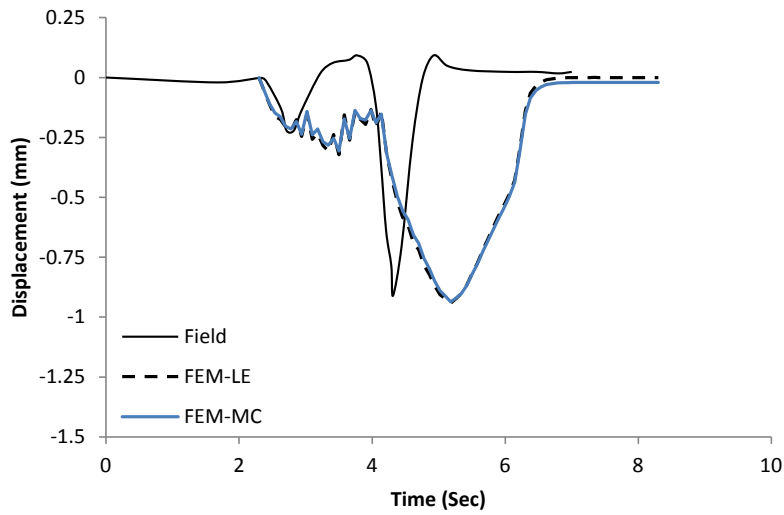
353 \* adopted from Alzabeebee et al. (2017); \*\* adopted from Boscardin et al. (1990) and  
 354 the modulus of elasticity calculated using Equation 6; \*\*\* adopted from Kang et al.  
 355 (2014); \*\*\*\* adopted from Sheldon et al. (2015).

356



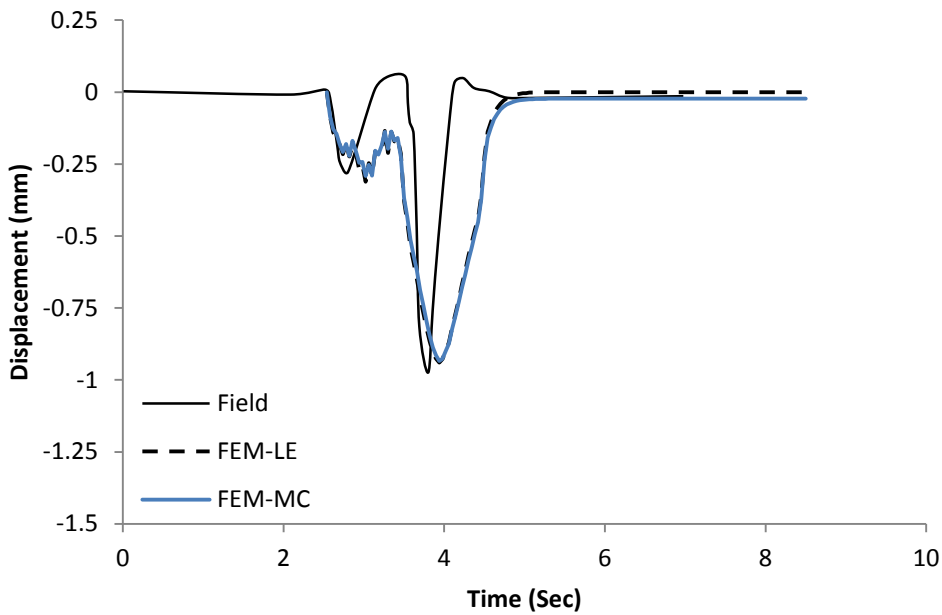
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358 Figure 5: The finite element mesh used for validation problem 2



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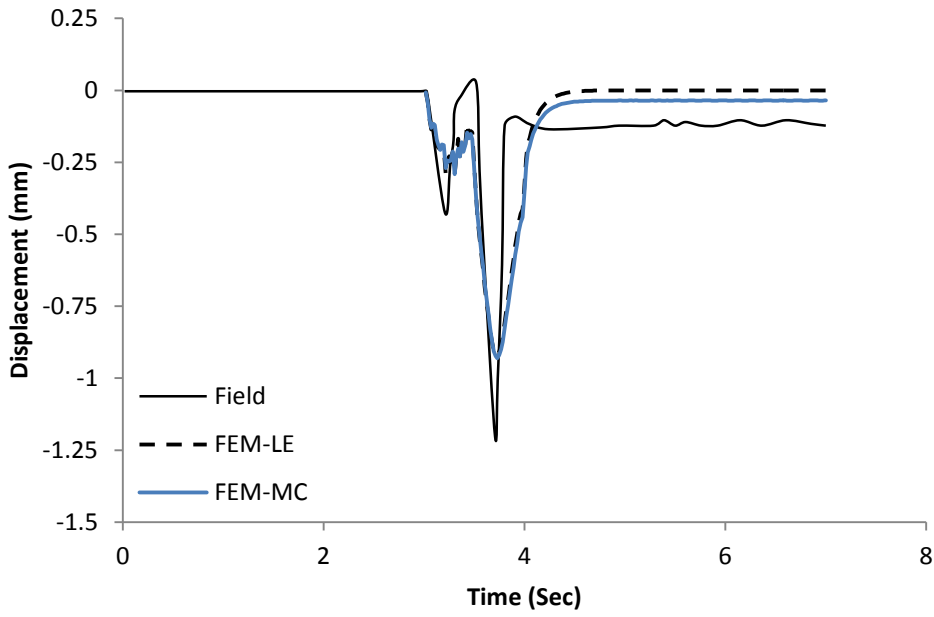
360 Figure 6: Crown displacement time response under a moving truck with a speed of 8  
 361 km/h



362

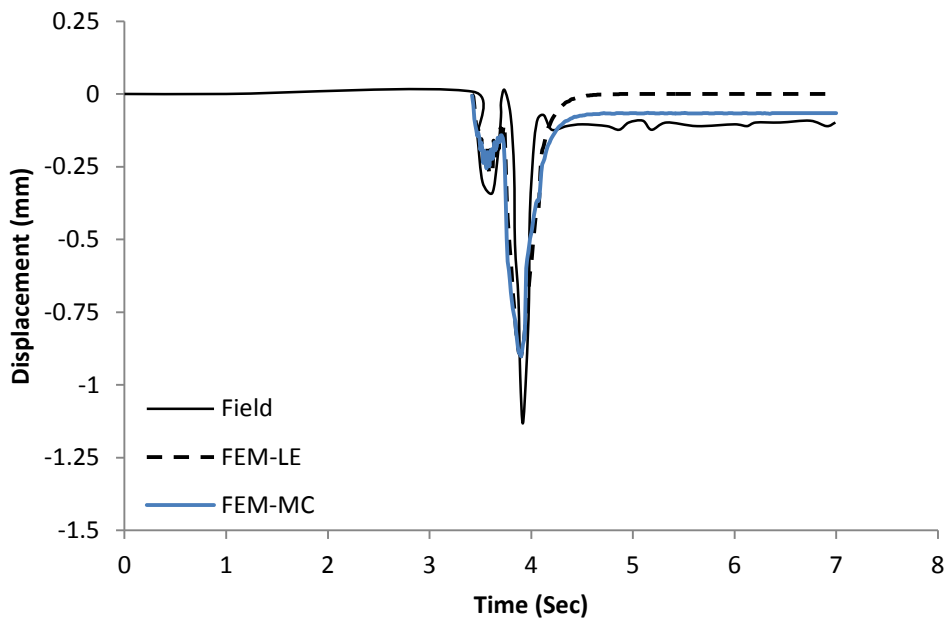
363 Figure 7: Crown displacement time response under a moving truck with a speed of  
 364 16 km/h





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

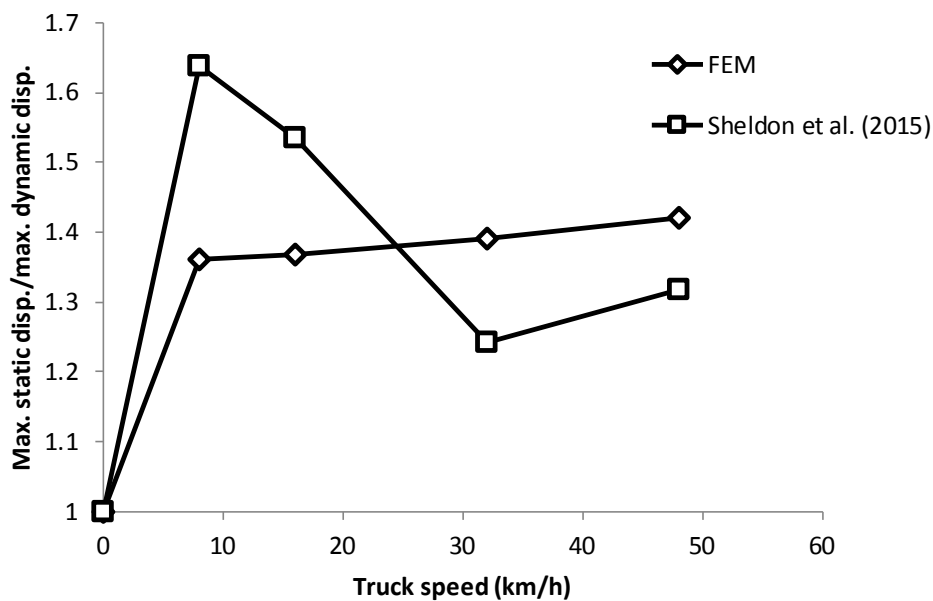
371           **2.2.       Modelling buried pipes under static loads**

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).

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

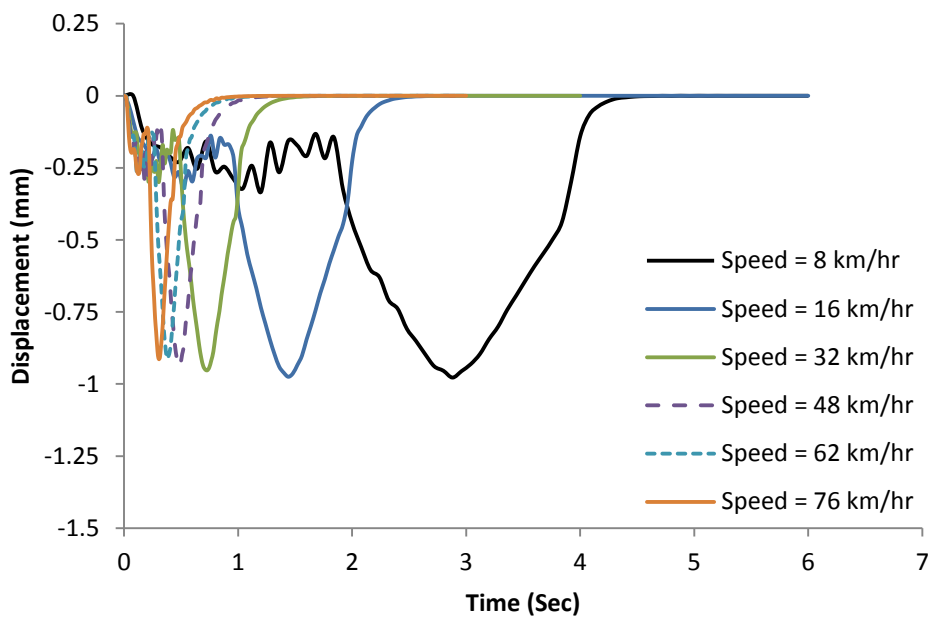
433 Where,  $E$  is the modulus of elasticity of the pipe;  $I$  is the moment of inertia of the  
434 pipe; and  $r$  is the mean radius of the pipe.

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).

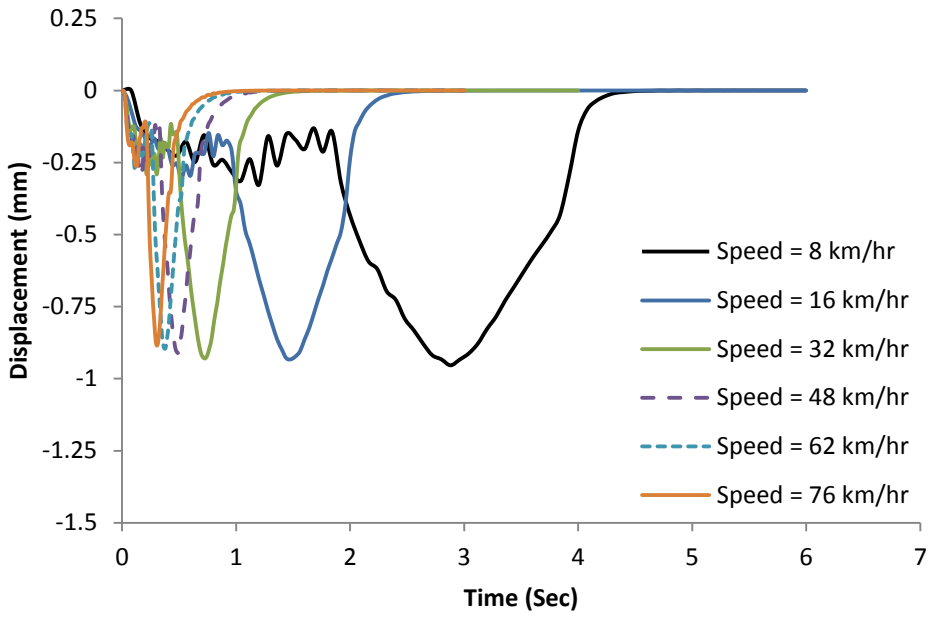
459 In summary, the results of the parametric study clearly illustrate that the static load  
460 represents the worst-case scenario in all the cases considered in this study.  
461 Therefore, the static load should be used in the analysis and the design of buried  
462 pipes.



463

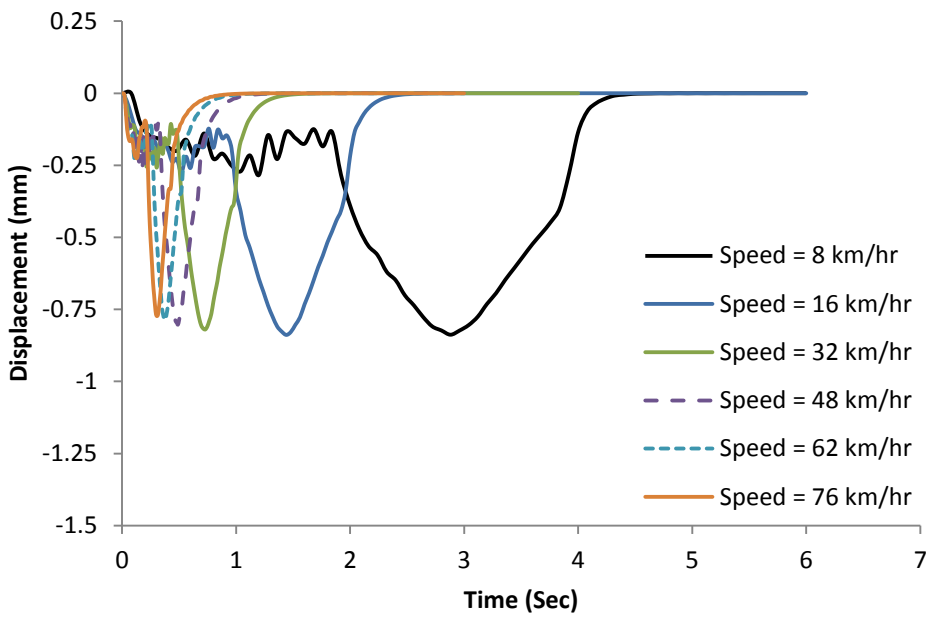
464 Figure 11: Crown displacement versus time response under a moving truck with  
465 different truck speeds for a very flexible pipe ( $PS = 0.5 \text{ kN/m}$ )

466



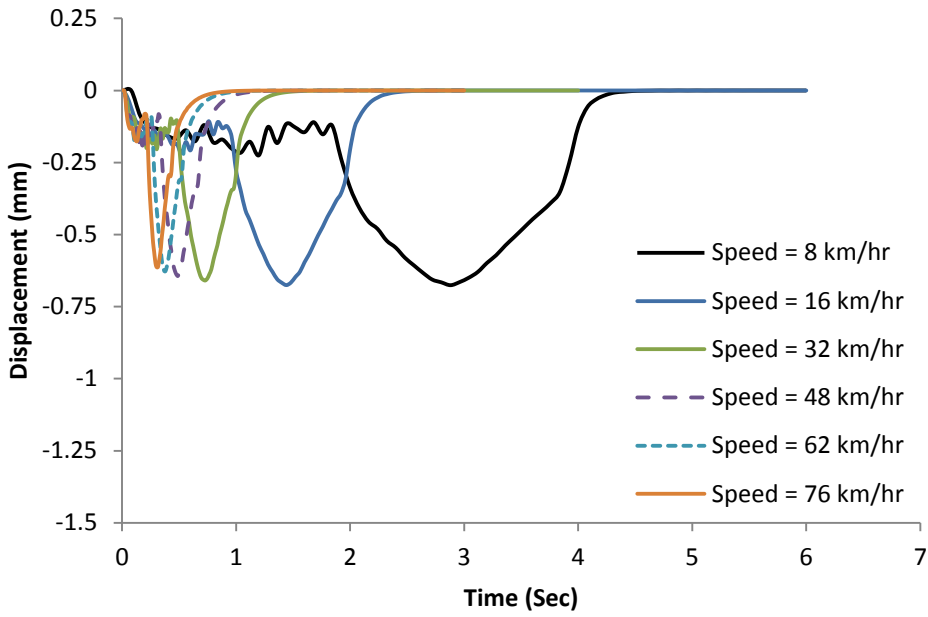
467

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



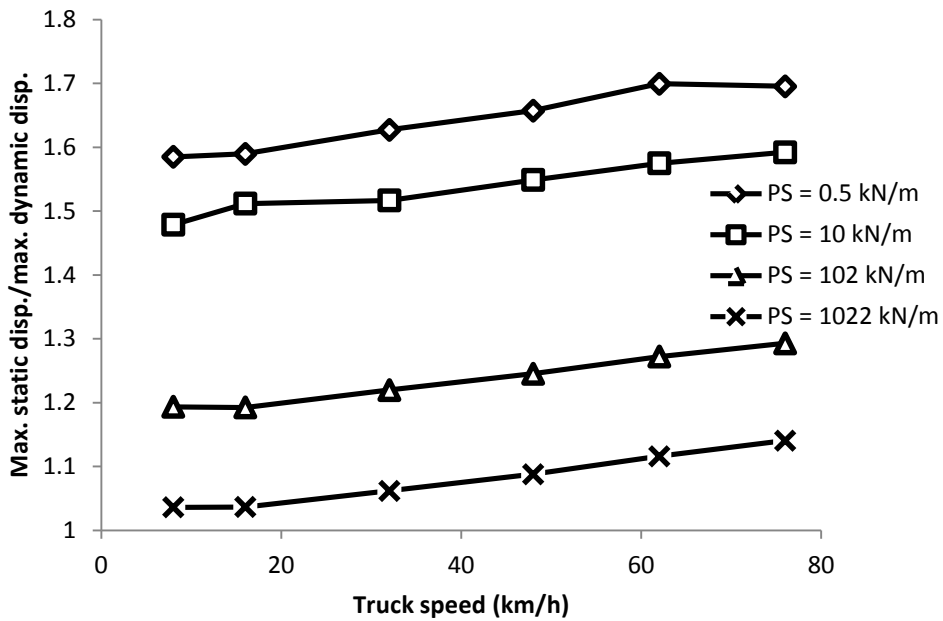
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471 Figure 13: Crown displacement versus time response under a moving truck with  
 472 different truck speeds for a semi-rigid pipe ( $PS = 102 \text{ kN/m}$ )



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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## 518 **References**

519 Abadi, T., Le Pen, L., Zervos, A. and Powrie, W., 2015. Measuring the area and  
520 number of ballast particle contacts at sleeper/ballast and ballast/subgrade interfaces.  
521 *International Journal of Railway Technology*, 4(2), 45-72.

522 Acharya, R., Han, J., Brennan, J.J., Parsons, R.L. and Khatri, D.K., 2016. Structural  
523 response of a low-fill box culvert under static and traffic loading. *Journal of*  
524 *Performance of Constructed Facilities*, 30(1), 04014184.

525 Alzabeebee, S., 2017. Enhanced design approaches for rigid and flexible buried  
526 pipes using advanced numerical modelling. PhD thesis, the University of  
527 Birmingham.

528 Alzabeebee, S., Chapman, D., Jefferson, I. and Faramarzi, A., 2017. The response  
529 of buried pipes to UK standard traffic loading. *Proceedings of the Institution of Civil*  
530 *Engineers - Geotechnical Engineering* 170(1), 38-50.

531 Alzabeebee, S., Chapman, D. and Faramarzi, A., 2018a. Economical design of  
532 buried concrete pipes subjected to UK standard traffic loading. *Proceedings of the*  
533 *Institution of Civil Engineers – Structures and Buildings*,  
534 <https://doi.org/10.1680/jstbu.17.00035>.

535 Alzabeebee, S., Chapman, D.N. and Faramarzi, A., 2018b. Development of a novel  
536 model to estimate bedding factors to ensure the economic and robust design of rigid  
537 pipes under soil loads. *Tunnelling and Underground Space Technology* 71, 567-578.

538 Araújo, N.M.F., 2011. High-speed trains on ballasted railway track: dynamic stress  
539 field analysis, PhD thesis, University of Minho.

540 Arockiasamy, M., Chaallal, O. and Limpeteepakarn, T., 2006. Full-scale field tests  
541 on flexible pipes under live load application. *Journal of Performance of Constructed*  
542 *Facilities* 20(1), 21–27.

543 Beben, D., 2013. Dynamic amplification factors of corrugated steel plate  
544 culverts. *Engineering Structures*, 46, 193-204.

545 Boscardin, M.D., Selig, E.T., Lin, R.S. and Yang, G.R., 1990. Hyperbolic parameters  
546 for compacted soils. *Journal of Geotechnical Engineering ASCE*, 116(1): 88-104.

547 Brown, S.F. and Selig, E.T., 1991. “The design of pavement and rail track  
548 foundations.” In O’Reilly, M. P. and Brown, S. F. (eds.) *Cyclic loading of soils: from*  
549 *theory to practice*. Glasgow and London: Blackie and Son Ltd. pp. 249-305.

550 Bryden, P., El Nagggar, H. and Valsangkar, A., 2015. Soil-structure interaction of very  
551 flexible pipes: centrifuge and numerical investigations. *International Journal of*  
552 *Geomechanics*, 15(6): 04014091.

553 Chaallal, O., Arockiasamy, M. and Godat, A., 2015a. Field test performance of  
554 buried flexible pipes under live truck loads. *Journal of Performance of Constructed*  
555 *Facilities* 29(5), 04014124.

556 Chaallal, O., Arockiasamy, M. and Godat, A., 2015b. Numerical finite-element  
557 investigation of the parameters influencing the behavior of flexible pipes for pipes  
558 and storm sewers under truck load. *Journal of Pipeline Systems Engineering and*  
559 *Practice* 6(2), 04014015.

560 De Beer, M., Fisher, C. and Jooste, F.J., 1997. Determination of pneumatic  
561 tyre/pavement interface contact stresses under moving loads and some effects on  
562 pavements with thin asphalt surfacing layers. In *8th International Conference on*  
563 *Asphalt Pavements*. Seattle: pp.179-227. (Volume 1)

564 Dhar, A.S., Moore, I.D. and McGrath, T.J., 2004. Two-dimensional analyses of  
565 thermoplastic culvert displacements and strains. *Journal of Geotechnical and*  
566 *Geoenvironmental Engineering*, 130(2): 199-208.

567 Galavi, V. and Brinkgreve, R.B.J., 2014. Finite element modelling of geotechnical  
568 structures subjected to moving loads. In: Hicks et al., editors. VIII ECNUMGE –  
569 numerical methods in geotechnical engineering. Delft, Netherlands: Taylor & Francis  
570 – Balkema. pp. 235-40.

571 Janbu, N., 1963. "Soil compressibility as determined by odometer and triaxial tests."  
572 In the European Conference on Soil Mechanics and Foundation Engineering.  
573 Wiesbaden. Pp. 19-25 (Volume 1).

574 Kang, J., Parker, F. and Yoo, C.H., 2007. Soil-structure interaction and imperfect  
575 trench installations for deeply buried concrete pipes. *Journal of Geotechnical and*  
576 *Geoenvironmental Engineering*, 133(3): 277-285.

577 Kang, J., Stuart, S.J. and Davidson, J.S., 2014. Analytical study of minimum cover  
578 required for thermoplastic pipes used in highway construction. *Structure and*  
579 *Infrastructure Engineering*, 10(3): 316-327.

580 Katona M.G., 1990. Minimum cover heights for corrugated plastic pipe under vehicle  
581 loading. *Transportation Research Record: Journal of the Transportation Research*  
582 *Board*, 1288: 127-135.

583 Katona, M.G., 2017. Influence of soil models on structural performance of buried  
584 culverts. *International Journal of Geomechanics*, 17(1): 04016031.

585 Khemis, A., Chaouche, A.H., Athmani, A. and Tee, K.F., 2016. Uncertainty effects of  
586 soil and structural properties on the buckling of flexible pipes shallowly buried in  
587 Winkler foundation. *Structural Engineering and Mechanics*, 59 (4), 739-759.

588 Lay, G.R. and Brachman, R.W.I., 2014. Full-scale physical testing of a buried  
589 reinforced concrete pipe under axle load. *Canadian Geotechnical Journal* 51(4), 394-  
590 408.

591 Li, Y., Song, G. and Cai, J., 2017. Mechanical response analysis of airport flexible  
592 pavement above underground infrastructure under moving wheel load. *Geotechnical  
593 and Geological Engineering*, 35(5), 2269-2275.

594 MacDougall, K., Houtt, N. A. and Moore, I.D., 2016. Measured load capacity of  
595 buried reinforced concrete pipes. *ACI Structural Journal*, 113(1), 63-73.

596 McGrath, T.J., DelloRusso, S.J. and Boynton, J., 2002. Performance of  
597 thermoplastic culvert pipe under highway vehicle loading. *Pipelines2002: Beneath  
598 Our Feet: Challenges and Solutions*. ASCE, Cleveland, Ohio, USA, pp. 1-14.

599 Mellat, P., Andersson, A., Pettersson, L. and Karoumi, R., 2014. Dynamic behaviour  
600 of a short span soil–steel composite bridge for high-speed railways–Field  
601 measurements and FE-analysis. *Engineering Structures*, 69(15): 49-61.

602 MIDAS IT. Co. Ltd. Manual of GTS-NX 2015 v2.1: new experience of geotechnical  
603 analysis system. South Korea: MIDAS Company Limited; 2015.

604 Mohamedzein, Y. and Al-Aghbari, M.Y., 2016. Experimental study of the  
605 performance of plastic pipes buried in dune sand. *International Journal of  
606 Geotechnical Engineering*, 10(3): 236-245.

607 Moore, I. D., 2001. Buried pipes and pipes. In Rowe, R. K. (ed.) *Geotechnical and  
608 Geoenvironmental Engineering Handbook*. Norwell: Kluwer Academic Publishing.  
609 pp. 539-566.

610 Moser, A.P. and Folkman, S., 2008. *Buried pipe design*. 3rd ed. New York: The  
611 McGraw-Hill.

612 Neya, B.N., Ardeshir, M.A., Delavar, A.A. and Bakhsh, M.Z.R., 2017. Three-  
613 Dimensional Analysis of Buried Steel Pipes under Moving Loads. *Open Journal of  
614 Geology*, 7: 1-11.

615 Petersen, D.L., Nelson, C.R., Li, G., McGrath, T.J. and Kitane, Y., 2010. NCHTP  
616 Report 647: Recommended Design Specifications for Live Load Distribution to  
617 Buried Structures. Transportation Research Board, Washington.

618 Rakitin, B. and Xu, M., 2014. Centrifuge modeling of large-diameter underground  
619 pipes subjected to heavy traffic loads. *Canadian Geotechnical Journal*, 51(4), 353-  
620 368.

621 Robert, D.J., Rajeev, P., Kodikara, J. and Rajani, B., 2016. Equation to predict  
622 maximum pipe stress incorporating internal and external loadings on buried pipes.  
623 *Canadian Geotechnical Journal*, 53(8): 1315-1331.

624 Sayeed, M.A. and Shahin, M.A., 2016. Three-dimensional numerical modelling of  
625 ballasted railway track foundations for high-speed trains with special reference to  
626 critical speed. *Transportation Geotechnics*, 6: 55-65.

627 Sayeed, M.A. and Shahin, M.A., 2017. Design of ballasted railway track foundations  
628 using numerical modelling Part I: Development. *Canadian Geotechnical Journal*,  
629 <https://doi.org/10.1139/cgj-2016-0633>.

630 Shakiba, M., Gamez, A., Al-Qadi, I.L. and Little, D.N., 2017. Introducing realistic tire–  
631 pavement contact stresses into Pavement Analysis using Nonlinear Damage  
632 Approach (PANDA). *International Journal of Pavement Engineering*, 18(11): 1027-  
633 1038.

634 Sheldon, T., Sezen, H. and Moore, I.D., 2015. Joint response of existing pipe  
635 culverts under surface live loads. *Journal of Performance of Constructed*  
636 *Facilities*, 29(1): 04014037.

637 Sheldon, T.A., 2011. Beam-on-springs modeling of jointed culvert systems. MSc  
638 thesis, The Ohio State University.

639 Shenton, M. J., 1978. Deformation of railway ballast under repeated loading  
640 condition”, in “Proceeding of Railroad Track Mechanics and Technology, Kerr, A.D,  
641 (Editor), Princeton University, 1978.

642 Talesnick, M.L., Xia, H.W. and Moore, I.D., 2011. Earth pressure measurements on  
643 buried HDPE pipe. *Géotechnique*, 61(9): 721-732.

- 644 Tee, K.F., Khan, L.R. and Chen, H.P., 2013. Probabilistic failure analysis of  
645 underground flexible pipes. *Structural Engineering and Mechanics*, 47(2): 167-183.
- 646 Vivek, P., 2011. Static and dynamic interference of strip footings in layered soil.  
647 M.Tech thesis. Indian Institute of Technology, Kanpur.
- 648 Xu, M., Shen, D. and Rakitin, B., 2017. The longitudinal response of buried large-  
649 diameter reinforced concrete pipeline with gasketed bell-and-spigot joints subjected  
650 to traffic loading. *Tunnelling and Underground Space Technology*, 64: 117-132.
- 651 Yeau, K.Y., Sezen, H. and Fox, P.J., 2009. Load performance of in situ corrugated  
652 steel highway culverts. *Journal of Performance of Constructed Facilities*, 23(1): 32-  
653 39.
- 654 Yeau, K.Y., Sezen, H. and Fox, P.J., 2014. Simulation of behavior of in-service metal  
655 culverts. *Journal of Pipeline Systems Engineering and Practice*, 5(2): 04013016.
- 656 Zhou, M., Du, Y.J., Wang, F., Arulrajah, A. and Horpibulsuk, S., 2017. Earth  
657 pressures on the trenched HDPE pipes in fine-grained soils during construction  
658 phase: Full-scale field trial and finite element modeling. *Transportation*  
659 *Geotechnics*, 12: 56-69.