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Dynamic modelling of bridge approach slabs under moving loads

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ABSTRACT

Differential settlement is a common problem in the bridge-roadway transition zone. Approach slabs are often constructed to mitigate the uneven settlement in this problematic zone. An appropriate simulation of the dynamic response of moving loads, approach slab and soil materials is necessary for realistic results. In the present study, the performance of the slab under traffic flow is investigated by a 3D dynamic analysis. For this purpose, the slab is modelled as a plate element while Mohr-Coulomb material model is adopted for base, subbase and subgrade soils. A number of parameters were considered to study the sensitivity of the proposed model to some soil, slab and moving load parameters that contribute to the behaviour of the approach slab. The main variables investigated in this study were the slab thickness, the restriction condition of the slab, the subgrade stiffness, weight of the passing vehicles and the analysis method adopted in such problems. Analysis results including predicted deformations and slab bending moments provide engineers with the necessary engineering knowledge to understand the response of approach slabs under different conditions.

1. Introduction

One of the main defects affecting the serviceability and durability of road-bridge system is the uneven settlement at bridge approaches. Bumps could be formed at the end of bridges cost a lot of money for maintenance. Investigators identified several reasons behind the differential settlement of bridge approaches. The main causes of this problem may include the rapid difference in material stiffness at road-bridge boundaries, poor compaction of the backfill and geotechnical properties of soil layers particularly primary and secondary consolidation (Short et al., 2018; Briaud et al., 1997; Miller et al., 2011; Luna et al., 2004). Also, issues associated to moving loads such as traffic level, vehicle speed, wheel loads and vibrations could highly affect the occurrence of approach settlement (Nassif et al., 2002). The negative impacts of this phenomenon are not limited to the high cost of maintenance but also include some serious problems, such as traffic accidents due to the unsafe driving conditions, traffic congestion at the bridge ends and, also, a reduction in the service life of vehicles.

Ha et al. (2002) carried out a literature survey aimed to investigate the settlement of bridge approaches, to determine the causes of this uneven settlement and to identify methods to mitigate the effects of this problem. In their review of this phenomenon, they found that 25% of USA bridges are influenced by this problem, resulting in a high maintenance cost reaches to 100 million dollars each year.

In situations where flexible pavement rested on unimproved fill material does not satisfy the settlement and requirements of bridge approaches, the performance can be improved by adopting the concept of approach slab. Numerically, this topic has been studied by several researchers. In this context, Cai et al. (2005) performed a finite element analysis to study the interaction between the soil and the approach slab and its role in forming the separation between them. Design aids were developed taking into account various slab dimensions. Rajek (2010) used the software Abaqus to investigate the performance of the structural and geotechnical elements at the transition area. A number of parameters including soil and concrete stiffness, abutment and approach dimensions and fixity conditions were studied. Zhang (2010) questioned the permitted differential settlement at the bridge-approach zone. Laplace transform with five degrees of freedom was adopted to model vehicles. Different scenarios were considered for the position of front and rear tires with respect to the approach pavement and slab. Chen and Fan (2017) used beam-

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on-elastic Winkler concept to develop a model of bridge approach slab system taking into account soil washout at the transition zone and the difference in deformations between the concrete slab and the pavement of the bridge approach. Results showed that the proposed model is an effective tool to predict the response of bridge approaches under dynamic loads. Hassona et al. (2017) developed a finite element model to investigate the differential settlement at the bridge ends. The proposed model was verified against some experimental and field measurements. Similarly, Abdelrahman et al. (2018) employed a 2D finite element software (Plaxis2D) to investigate the influence of some soil and structural properties on the behaviour of approach slabs. Bahumdain (2019) investigated the use of piles to control the settlement of different segments of approach slab. Design charts and empirical relationships were developed to calculate pile settlement under varying conditions.

The majority of the previous numerical studies treated the problem in a two dimensional manner. Also, moving loads were often considered as static loads for simplicity. The complexity involved in the nature of road-bridge system when exposed to moving loads needs further insight in how to model structural elements and how to simulate dynamic loads in finite element analysis. In the present study, a 3D dynamic model using Plaxis 3D was created to investigate the settlement of approach slab under vehicle moving loads. Furthermore, parametric studies were carried out to investigate the influence of some factors on output results.

2. Description of the dynamic model elements

As a standard case, a four wheel truck with axles spaced 4.0 m apart was used as a vehicle model. The centre-to-centre distance between each axle wheels was set to 1.95 m. Wheel-pavement contact area was calculated based on a wheel width of 0.25 m and a contact length of 0.3 m. The total weight of the vehicle was assumed to be distributed equally over the front and rear axles. Thus, a truck of 20 tons gross weight applies a distributed load of 654 kN/m^2 at each wheel-pavement contact area. The concept of distributed load was adopted instead of point loads to reduce the model error (Valaskova and Vlcek, 2017).

To simulate vehicle moving loads, the concrete plate was divided into segments with 0.3 m width each. This width was chosen to match the contact length of the wheel. Each segment has its own distributed load with time. This signal is known as dynamic multiplier in which each segment signal is multiplied by the distributed load to obtain the dynamic load at any time of vehicle movement. The time interval of the load impulse of each multiplier depends on the segment width and the vehicle speed. As segments having the same width and the truck speed is constant, this time step is repeatedly applied for each load multiplier. The distributed wheel load was assumed to increase linearly from zero at the beginning of time step to the maximum value at the mid-time, then decreased to zero at the end of time step. The interaction of load distributed over the adjacent segments during a time step was also considered by starting the calculations of load multiplier of the current segment from the mid-time of the previous one.

To determine the worst-case scenario (largest deflection of the approach slab) during movement, a single truck has been moved along the approach length. The truck was assumed to move from the bridge towards the approach. Therefore, at the beginning of analysis (t = 0 s), only front axle dynamic loads were considered. As the distance between the front and rear axles is 4.0 m and vehicle speed is 50 km/h, the rear axle loads were applied on the first segment at t = 0.288 s. This sequence was repeated for every segment taking into account the starting time of load multipliers. Following the vehicle speed of 50 km/h, the load distribution with time for both front and rear wheels used in the analysis is presented in Fig. 1. The distances of the front and rear wheels with respect to the bridge abutment were denoted as X1 and X2 respectively.

3. Geometry of the problem (standard case)

The approach slab used in the standard case having dimensions of 10 m in length and 6 m in width. A pinned-joint was adopted between the slab and the bridge abutment, while the other end of the slab was rested on the soil directly. A plate with two sets of properties was used to simulate the slab and pavement. Deformations of the bridge abutment are very small compared to the approach. Therefore, bridge abutment at the left side boundary was considered fixed (Fig. 2). Similarly, right and bottom boundaries which extended up to 20 and 10 m respectively were also fixed. The asphalt pavement on the top of approach slab was neglected. The concrete slab and pavement were modelled using properties shown in Table 1. Geotechnical properties needed in Mohr-Coulomb material model for base, subbase and subgrade soils are also presented in Table 1.

4. Results and discussion

4.1. Results of the standard case

Investigating the worst-case scenario showed that maximum deformations occur when front and rear axles placed at X2 = 8.85 m and X1 = 4.85 m, respectively. Fig. 3 portrays the 3D finite element model and the deformed shape of the concrete slab, where 10-nodded quadratic tetrahedral elements were used to generate the finite element mesh with a total of 29,034 elements. The maximum settlement due to the combination of slab self weight (DL) and truck moving load (ML) at the time of worst case was 5.3 mm. Fig. 4(a) shows the deflection envelope of the proposed model slab. It can be seen that at 5 m of the slab length onwards, deformations remain approximately constant. Following some criteria suggested for allowable settlement and slope, for example (Miller et al., 2011; Helwany et al., 2007), the bump formed in the approach slab is not problematic, nor even noticeable by the road users. However, this simple deformation could be developed to a complex problem throughout the life cycle of the slab. Bending moment diagram calculated along the slab shows maximum values at the position of axles (Fig. 4(b)). It is important

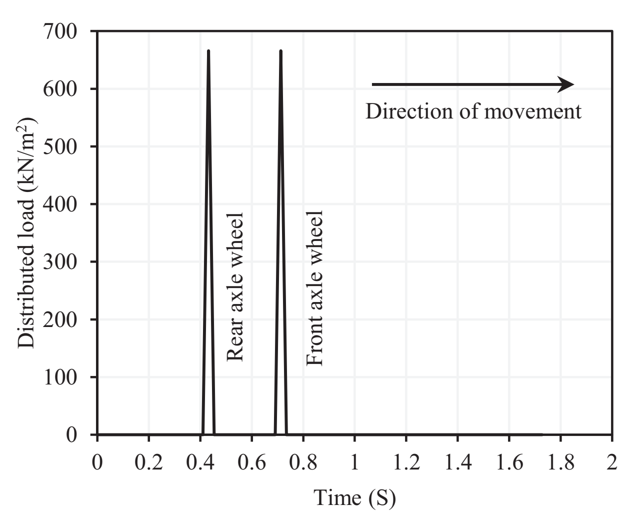

Fig. 1. Time history distribution of moving loads.

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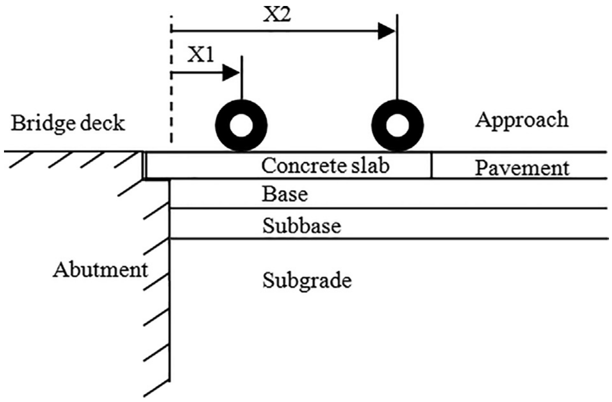

Fig. 2. Illustration of problem geometry.

to mention that moment distribution in both longitudinal and transverse directions of the slab varies with the movement of vehicle.

4.2. Parametric study

How the bridge approach reacts when subjected to moving loads is a function of different factors namely; the approach slab self weight, the restriction at the end of the slab, the method of analysis (static or dynamic), properties of subgrade soil and vehicle parameters. All parameters were numerically investigated under identical conditions to the standard case, unless stated otherwise.

4.2.1. Influence of the restriction of the slab end

The assessment of the influence of restriction of the approach slab at its pavement end on the behaviour of the slab was tested by considering two different cases. In addition to the standard case of free end support, a pinned-joint end was also examined. This connection can be obtained by using dowel bars in the slab-pavement contact zone (Chen and Fan, 2017). Moreover, this transition zone can be provided by a sleeper slab to control the slab settlement. As expected, investigating the worst-case scenario in the pinned-end case showed maximum slab response when the axle loads are identically positioned about the mid-length of the slab. According to the analysis results presented in Fig. 5 for the deflection behaviour of the approach slab, the maximum deflection was decreased by about 15% when pinned joint was adopted. On the other hand and owing to the additional restriction of the slab, maximum bending moment in the second case was higher than that calculated in the standard case by 25%. In both cases, the position of maximum moment is a function of wheel location during movement.

However, the construction of a pinned-end approach slab needs special attention. The sleeper slab should be designed carefully to resist the concentrated dead and moving loads. As the settlement of the soil beneath the supports is expected, mitigation techniques (such as geogrids) may be used to control the settlement and to increase the bearing capacity of the soil (Abu-Farsakh and Chen 2014).

4.2.2. Influence of the method of analysis

Static analysis is widely used to model the behaviour of pavement and other bridge and roadway elements (see for example, Cerri and Pullojani, 2018; Rajek, 2010; Nassif et al., 2002). To demonstrate the effect of method of analysis, a comparison in the response of approach slab in both static and dynamic analysis was conducted. Static wheel loads were placed at the location that induced worst scenario. The calculated maximum slab deflection when dynamic analysis is adopted was 23% higher than that induced in the static case (Fig. 6). Although the shapes of the predicted moment distribution are very identical, a slight increase in the dynamic maximum moment can be noticed. As the slab-wheel contact area was considered smooth and the bump is not formed yet in a previous phase of analysis, the difference in slab

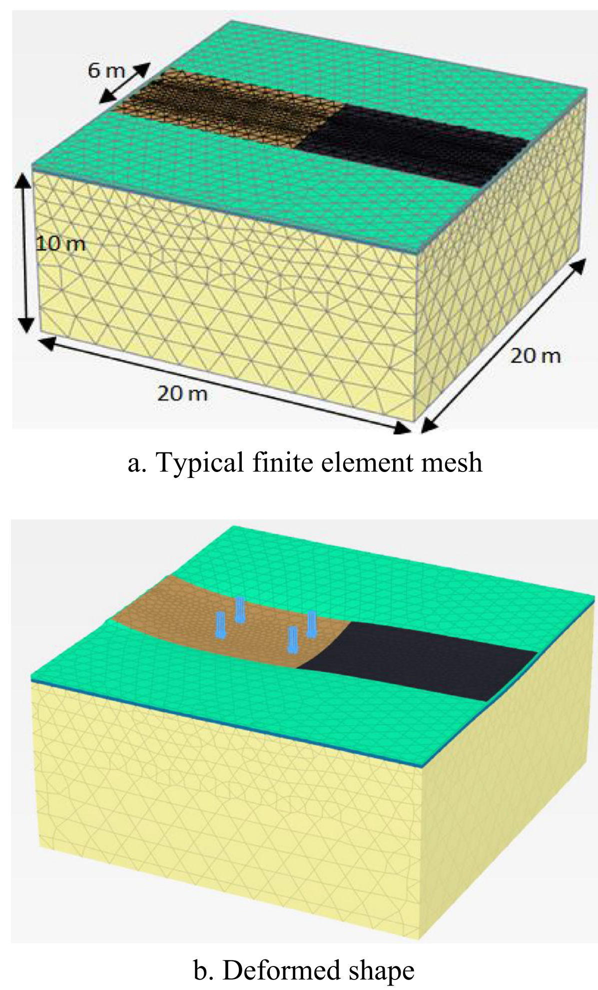

Fig. 3. Finite element model and the deformed shape of the slab.

Table 1
Properties of materials used in the analysis.

Layer	Thickness (mm)	Unit Weight (kN/m^3)	Elastic Modulus (MPa)	Poisson's ratio	Friction Angle (°)	Deltation Angle (°)	Cohesion (kPa)
Concrete slab	200	24	26,000	0.15	–	–	–
Pavement	100	24	1500	0.30	–	–	–
Base	200	20	70	0.30	42	12	5
Subbase	200	19	50	0.30	40	10	6
Subgrade	–	17	10	0.30	10	0	40

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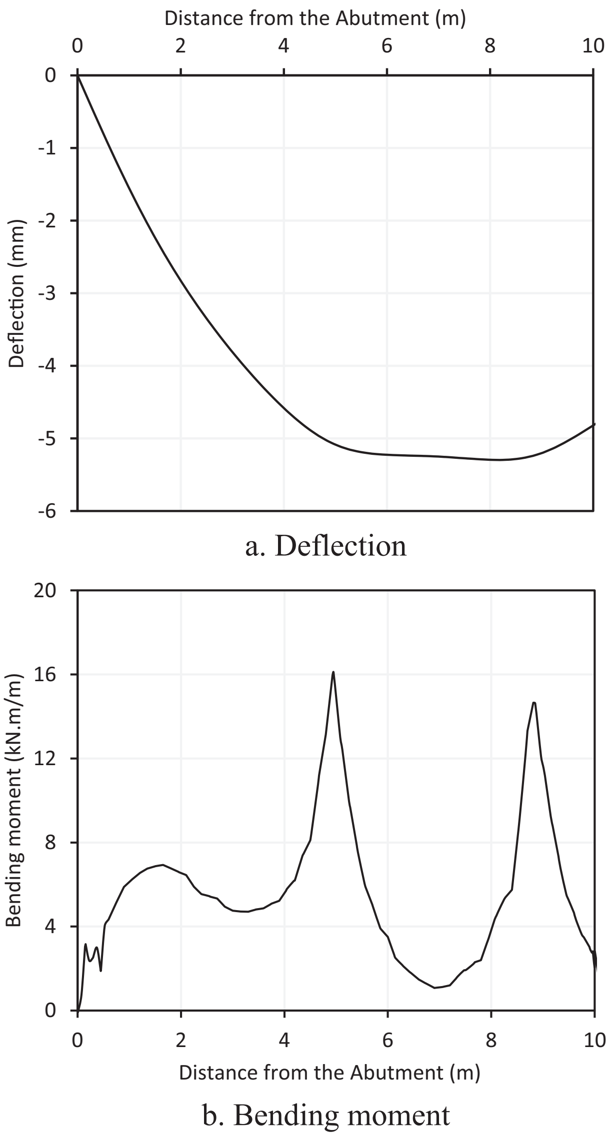

Fig. 4. Deflection and bending moment of the approach slab.

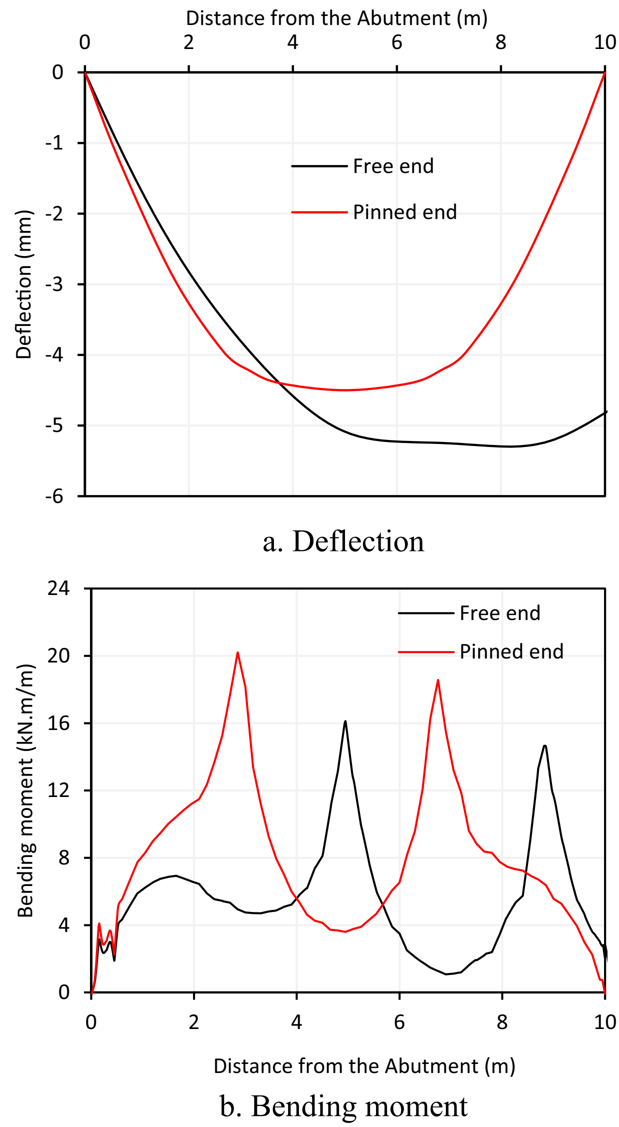

Fig. 5. Effect of restriction of the slab end.

response was small. Taking these factors into account with varying vehicle speed would notably increase the slab response (Briaud et al., 1997; Cai et al. 2005; Yin et al., 2019).

In order to find an appropriate value to the dynamic load factor, trial runs were conducted by changing the magnitude of static wheel loads. The outputs were, then, compared to the maximum deflection obtained by the dynamic analysis (5.3 mm). Results showed that a value of 900 kPa of applied static wheel load gives a maximum deflection of 5.3 mm. By comparing this value of the static load by the value of dynamic load used in the standard case (654 kPa), a dynamic load factor can be obtained as (900–654)/654 = 1.37. This value is only a little higher than that recommended by the AASHTO Bridge Design Manual of 1.33.

4.2.3. Influence of the slab self weight (or slab thickness)

Fig. 7 shows the effect of slab self weight (DL) on the deflection of the slab. It can be noticed that the contribution of the dead load in the overall deflection of the slab was about 55%. In order to obtain deformations due to moving loads (ML) only, deformations resulting from slab weight should be subtracted from the total deformations (Cai et al. 2005).

To examine the influence of the slab thickness (i.e. slab self weight), deflection profiles were evaluated at three values of slab thickness (d): 200, 500 and 700 mm. Two cases were considered for the supports, namely free-end and pinned-end. As shown in Fig. 8, slab deflections calculated in the two cases showed opposite trends with the increase of slab thickness. The free-end slab recorded an increase in deflection values with the increase of slab thickness, while pinned-end slab showed a reduction in its deflection values. In the case of pinned-end slab, the majority of the additional weight induced by increasing slab thickness is carried by the two supports (bridge abutment and sleeper slab) rather than applied directly on the soil. This finding has been observed, also, by Abu-Farsakh and Chen (2014). However, when free-end slab is adopted, the additional weight will be distributed over the slab length causing more distributed loads on the soil beneath. As a result, slab deflection increases in the second case in spite of increasing flexural rigidity of the slab.

4.2.4. Influence of subgrade elastic modulus

Prior to the design of approach slab, an accurate value of the subgrade elastic modulus (E) should be obtained. As a result of some natural phenomena such as earthquakes and rain erosion,

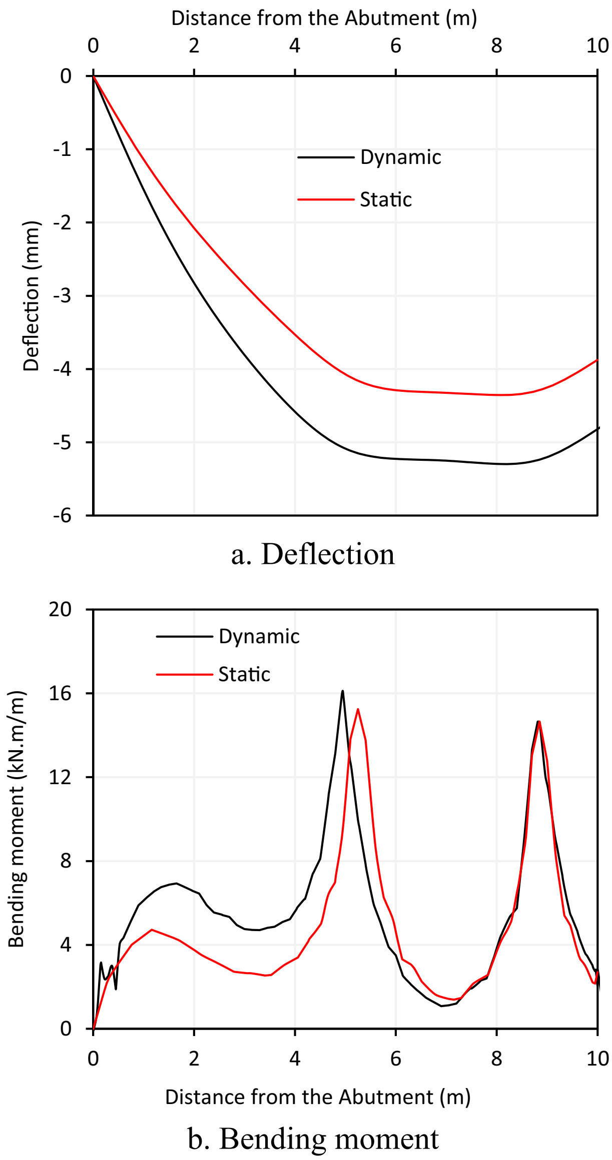

Fig. 6. Effect of the method of analysis.

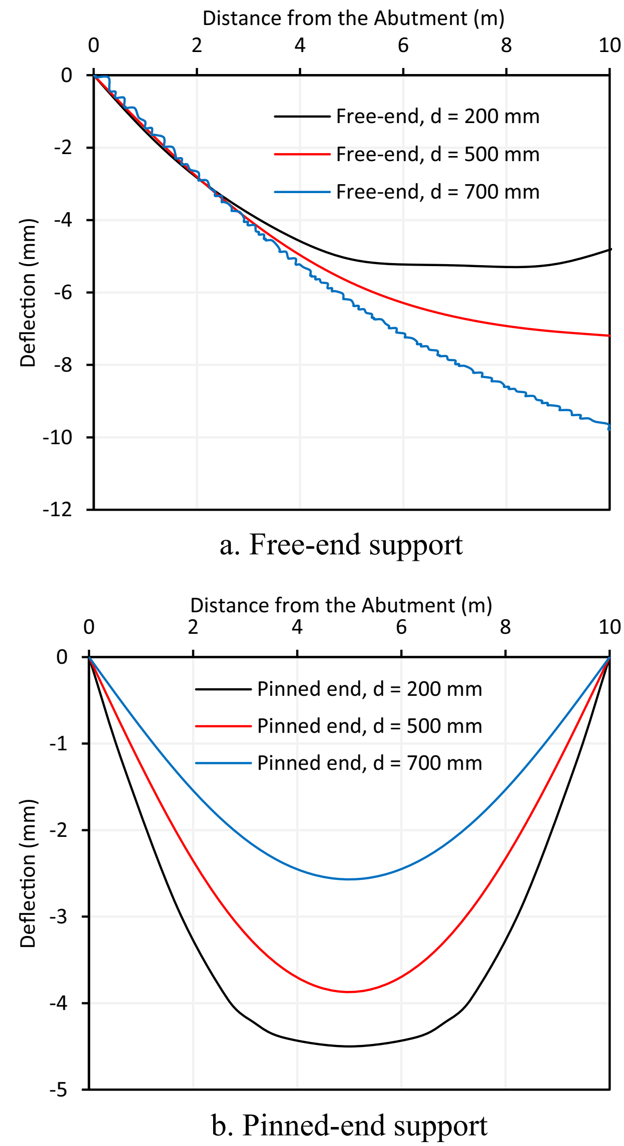

Fig. 8. Effect of slab thickness on the deflection.

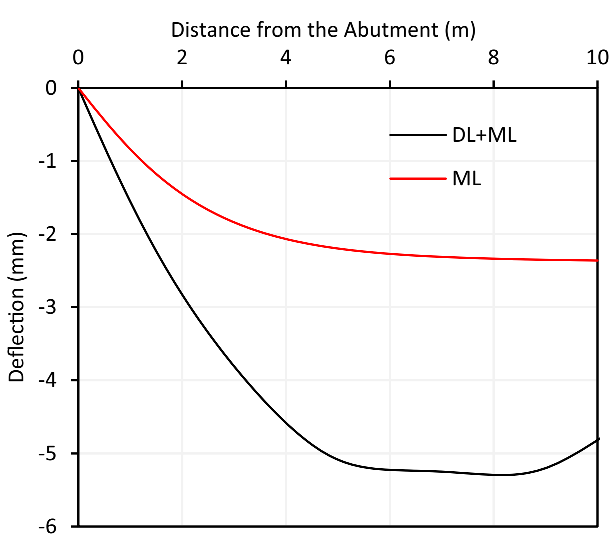

Fig. 7. Effect of slab dead load on the deflection.

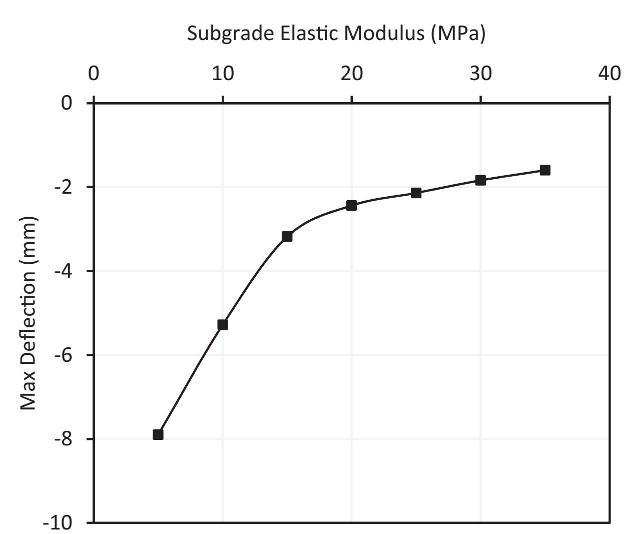

Fig. 9. Effect of subgrade elastic modulus.

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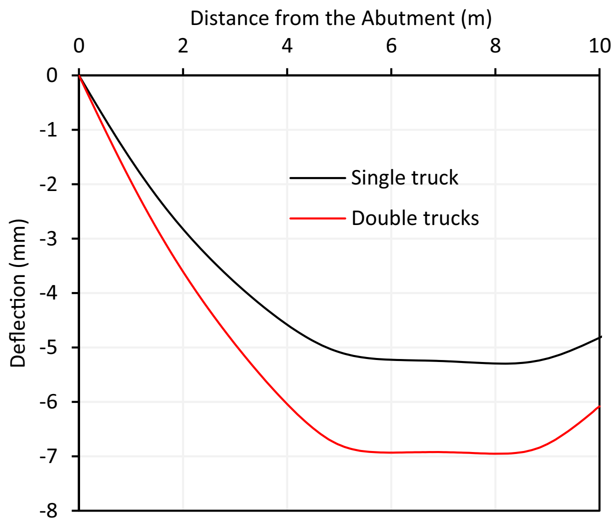

Fig. 10. Deflection profiles at single and double trucks.

the strength of the subgrade soil may be affected. To investigate the influence of natural soil stiffness on the response of approach slab, maximum deflections were evaluated at various values of subgrade elastic modulus ranging from 5 to 35 MPa. Comparison reveals that slab deflection increases with the decrease of natural ground stiffness. Based on Fig. 9, two distinct zones can be noted. At low values of E (E = 5 – 15 MPa), slab deflection decreased sharply with the increase of soil stiffness. Beyond E = 15 onward, maximum deflections tend to decrease at decreasing rate with increasing E values. The significant difference in maximum deflections reflects the importance of the input value of elastic modulus.

4.2.5. Influence of vehicle parameters

The 6 m approach slab width has been divided into two lanes of 3 m each. Two trucks have been moved simultaneously along the slab lanes until the worst-case position achieved. For two trucks modelling, Fig. 10 reveals an increase in the maximum settlement of about 33% compared to that calculated in the standard case. Fig. 11 illustrates the differences in bending moment distribution calculated in the slab in the two cases. It is obvious that double truck movement induces higher moments peaked at positions of the eight wheels compared to those recorded in the case of single truck.

The deflection of the slab under different wheel loads (q) is shown in Fig. 12. The obtained results agree well with the engineering expectation as the deformations increase with the increase of applied moving load values.

5. Conclusions

In the current study, a description of a three dimensional numerical model for a dynamic analysis of an approach slab under moving loads is presented. The performance of the slab under vary-

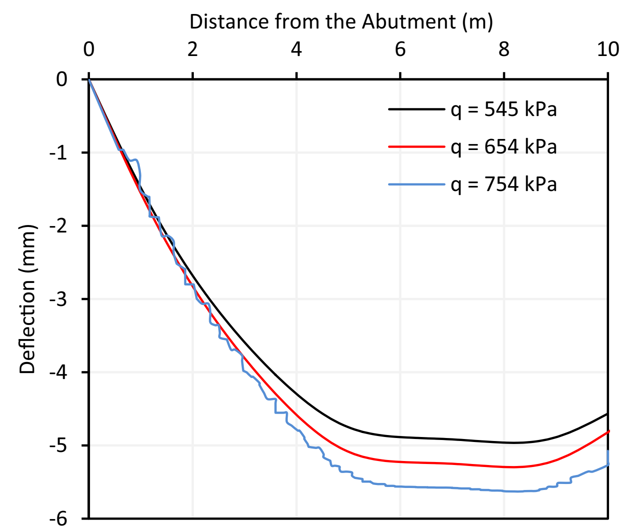

Fig. 12. Effect of wheel loads.

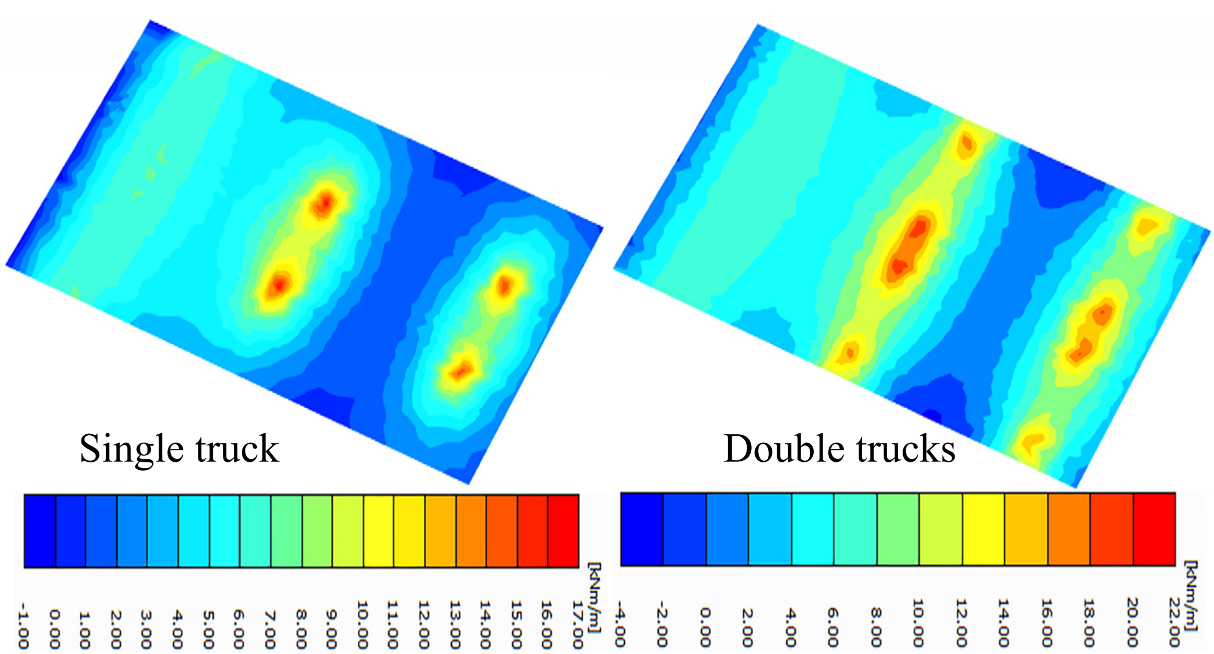

Fig. 11. Bending moment distribution at single and double trucks.

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ing parameters was investigated. Based on analysis results, the following conclusions were obtained:

1. Comparing the dynamic and static responses of the approach slab showed considerable differences especially in maximum deflections. The difference was less pronounced for the calculated bending moments. Static analysis can be performed only when a proper load factor is provided. Results showed that conducting a static analysis with loads multiplied by 1.37 would induce deflections similar to those obtained in the dynamic analysis.

2. Providing pinned joints at both ends of the approach slab could reduce settlement of the slab. On the other hand, the additional restriction might produce a redistribution of the induced bending moments and an increase in their values.

3. Reliable analysis can not be ensured without considering the slab self weight as it contributes to a substantial amount of the overall time-dependent response. The weight of the slab can be changed by changing the slab depth, with other dimensions constant. The predicted deflection suggests that increasing slab thickness will not mitigate the effect of the bump and minimise the severity of the problem unless pinned end or simply supported slab is adopted.

4. Slab deflection increases with the decrease of natural ground stiffness. However, the order of increasing rate is not the same over the adopted range of subgrade elastic modulus.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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