Analysis of slab railway track system on stone column treated ground

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ABSTRACT

In this paper, the response of slab track system on stone column improved ground subjected to concentrated load moving with constant velocity has been obtained. Rail and slab have been represented by infinite Euler-Bernoulli beams with finite flexural rigidity. Rail pads, soft soil and the stone columns have been idealized as Winkler springs of different stiffnesses. The governing differential equations have been developed and the solution has been obtained employing iterative Gauss-Seidel method. The effect of inclusion of stone column on deflection of beams and critical velocity of the system has been studied. It has been observed that magnitude of applied load, stiffness and spacing to diameter ratio of stone columns significantly influence the response of slab track system. These results have been presented as ready to use charts which enable analysis and therefore the design of such slab track systems.

Keywords: slab track system; moving load; stone columns.

1 INTRODUCTION

Increase in speed of modern trains are accompanied by large axle load which emphasizes on the need to determine suitable type of track systems. Due to the reduced need for maintenance, low ground borne vibrations and enhanced service life, slab tracks and floating slab tracks (FST) have gained more popularity in the field of rail transportation systems. In view of this, various case studies have reported the results of vibration measurements for different track systems and discussed the effects of these vibrations on the subsoil (Wilson 1983; Nelson 1996; and Saurenman and Phillips 2006). Many attempts have been undertaken in order to apprehend the usefulness of such systems by using analytical models. Some of these include Cui and Chew (2000), Hussien and Hunt (2006), Li and Wu (2008), Galvin (2010) and Auersch (2012).

Random nature of substructure stiffness was considered by Mohammadzadeh et al. (2014) where they undertook stochastic approach to assess the dynamic behaviour of slab track system. Dimitrovová and Varandas (2009), Dimitrovová (2010) and Ang and Dai (2013) also investigated the abrupt transition in foundation stiffness in case of high speed rail system.

In all these studies, the rail track system was laid on natural ground. Presence of poor soil strata will cause excessive track deformation which may be beyond the permissible limit and hence cannot be permitted. In this regard, ground is strengthened or improved with the help of prefabricated vertical drains or stone columns or any other appropriate ground improvement technique (Zhuang and Wang, 2017).

Critical review of literature suggests that although the inhomogeneity of the foundation have been considered, no study was undertaken for the analysis of slab track system on improved ground. In view of this, an analysis has been proposed for slab track system on stone column reinforced ground subjected to moving load. The influence of magnitude of applied load, spacing to diameter ratio and stiffness of stone column on the response of slab track system has been analyzed with the help of detailed parametric study.

2 MODELLING AND ANALYSIS

Fig. 1 describes the slab track system as a double beam model subjected to a load Q moving with constant velocity v from left to right. Rail and slab have been represented as infinite beams with flexural rigidities E_1I_1, E_2I_2 and mass per unit length as ρ_1, ρ_2 respectively. Rail pads (k_1), foundation soil ($k_2 = k_s$) and stone columns ($k_2 = k_c$) have been idealized by Winkler springs. c_1 and c_2 are viscous damping coefficients for rail pads and the ground. The generalized differential equation of motion in order to obtain the flexural response of slab track system can be written as follows:

$$E_1I_1\frac{d^4y_1}{dx^4}+\rho_1\frac{d^2y_1}{dt^2}+c_1\frac{d(y_1-y_2)}{dt}+k_1(y_1-y_2)=Q(x,t)+\rho_1 g \quad (1)$$

$$E_2I_2\frac{d^4y_2}{dx^4}+\rho_2\frac{d^2y_2}{dt^2}+c_2\frac{dy_2}{dt}-c_1\frac{d(y_1-y_2)}{dt}+\left[k_2y_2-k_1(y_1-y_2)\right]=\rho_2 g \quad (2)$$

where, g is the acceleration due to gravity, y_1 and y_2, the deflections of top and bottom beam respectively.

For the purpose of simplicity, a variable ξ has been defined as the distance from point of action of load such that $\xi = x\text{-}vt$ and equations (1) and (2) have been expressed in nondimensional form using the following non-dimensional terms:

$$\xi^* = \frac{\xi}{L}\ ;\ Y_1 = \frac{y_1}{L}\ ;\ Y_2 = \frac{y_2}{L}\ ;\ \rho_1^* = \frac{\rho_1 v^2}{k_1 L^2}\ ;\ \rho_2^* = \frac{\rho_2 v^2}{k_2 L^2}\ ;\ I_1^* = \frac{E_1 I_1}{k_1 L^4}\ ;$$

$$I_2^* = \frac{E_2 I_2}{k_2 L^4}\ ;\ c_1^* = \frac{c_1 v}{k_1 L}\ ;\ c_2^* = \frac{c_2 v}{k_2 L}\ ;\ Q^* = \frac{Q}{k_1 L^2}\ ;\ w_1^* = \frac{\rho_1 g}{k_1 L}\ ;\ w_2^* = \frac{\rho_2 g}{k_2 L}\ ;$$

$$r = \frac{k_1}{k_2};\ R = \frac{E_1 I_1}{E_2 I_2}$$

where L is the half length of beam. Thus, the non-dimensional form of equations can be written as

$$\frac{d^4 Y_1}{d\xi^{*4}} + \frac{\rho_1^*}{I_1^*}\frac{d^2 Y_1}{d\xi^{*2}} - \frac{c_1^*}{I_1^*}\frac{d(Y_1 - Y_2)}{d\xi^*} + \frac{(Y_1 - Y_2)}{I_1^*} = \frac{Q^*(\xi^*)}{I_1^* d\xi^*} + \frac{w_1^*}{I_1^*} \tag{3}$$

$$\frac{d^4 Y_2}{d\xi^{*4}} + \frac{\rho_2^*}{I_2^*}\frac{d^2 Y_2}{d\xi^{*2}} - \frac{c_2^*}{I_2^*}\frac{dY_2}{d\xi^*} + \frac{Y_2}{I_2^*} + r\left[\frac{c_1}{I_2^*}\frac{d\left(Y_1 - Y_2\right)}{d\xi^*} - \frac{\left(Y_1 - Y_2\right)}{I_2^*}\right] = \frac{w_2^*}{I_2^*} \tag{4}$$

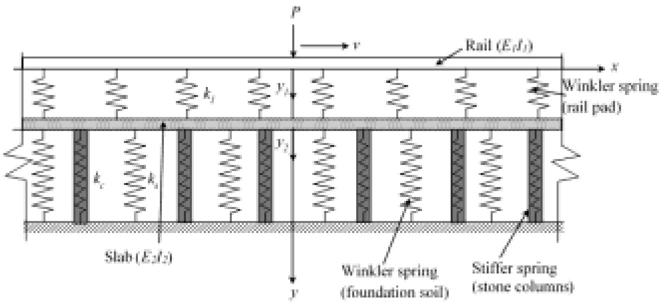

Fig. 1. Proposed model for slab track system

The above equations have been expressed in finite difference form for an internal node, i and solved employing the following boundary conditions in nondimensional form:

$$\frac{d^2 Y_1}{d\xi^{*2}} = 0;\ \ \frac{d^3 Y_1}{d\xi^{*3}} = 0;\ \frac{d^2 Y_2}{d\xi^{*2}} = 0;\ \frac{d^3 Y_2}{d\xi^{*3}} = 0$$

3 CRITERION FOR CONVERGENCE AND INPUT PARAMETRIC VALUES

A computer program based on the formulation presented above has been developed to obtain the required response for entire extent of the problem ($-L \le x \le L$). 5001 nodes have been considered for the analysis and a tolerance factor of 10^{-10} has been taken as an outcome of the convergence study.

The realistic values of all parameters have been considered from available literature and presented in Table 1. Viscous damping (c_1 and c_2) has been expressed in terms of damping ratios.

Table 1. Input parameter

Parameters	Notation	Value	Unit
Applied Load	Q	100-250	kN
Mass per unit length of top beam	ρ_1	60	kg/m
Mass per unit length of bottom beam	ρ_2	3500 (Mohammadzadeh et al., 2014)	kg/m
Relative stiffness of stone column with respect to surrounding soil	$\alpha = k_c/k_s$	10-100	-
Spacing to diameter ratio of the stone columns	s/d	2-4	-
Relative flexural rigidity of the beams	$R = E_1I_1/E_2I_2$	0.01-0.04 (Mohammadzadeh et al., 2014)	-
Damping ratio of the foundation soil	ζ_2	0-25 (Vucetic and Dobry, 1991)	%
Velocity of applied load	v	10-300	m/s

4 RESULTS AND DISCUSSION

4.1 Validation

In order to validate the developed methodology, the results from proposed model has been compared with those from Hussein and Hunt (2006). Following parameters have been adopted for the purpose of validation: E_1I_1=10×10^6 Nm^2, E_2I_2=1430×10^6 Nm^2, ρ_1= 100 kg/m, ρ_2= 3500 kg/m, k_1=40×10^6 N/m^2, k_2=50×10^6 N/m^2, $\zeta_1 = \zeta_2$= 5%. The results, as shown in Fig. 2, have been found to be in very good agreement and therefore, the validity of the developed model and methodology has been established.

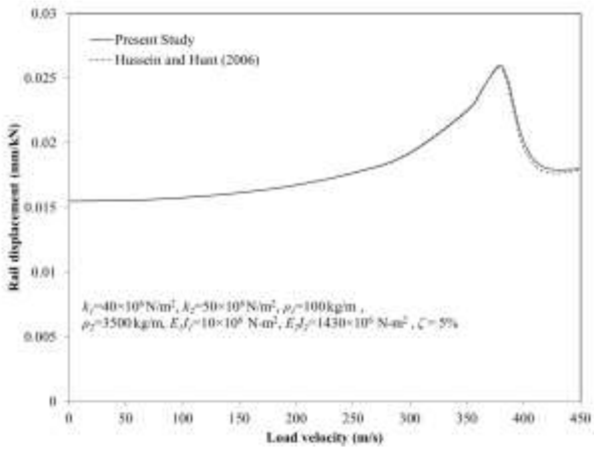

Fig. 2. Validation of proposed model.

4.2 Effect of inclusion of stone columns on critical velocity

The plot of maximum non-dimensional deflection of top beam for different velocity has been presented in Fig. 3 for soft rail pads (k_1=40×10^6 N/m^2) and stiff rail pads (k_1=300×10^6 N/m^2). The velocity corresponding to the peak value of the curves denotes the value at resonance and termed as critical velocity. It has been found to be independent of type of rail pad. However, inclusion of stone columns resulted in increase of critical velocity from 157 m/s to 292 m/s (about 86% increment) which is beyond the practically achieved value of velocity even for high speed trains.

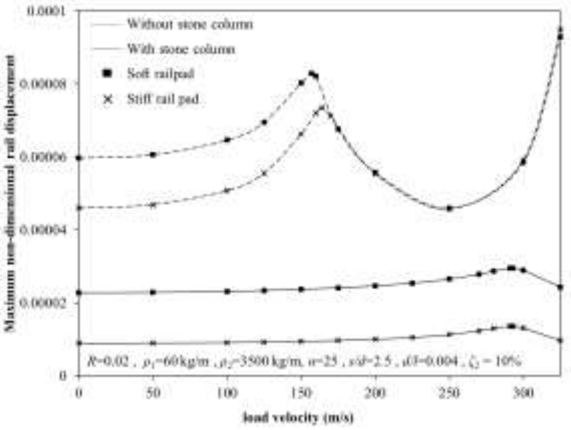

Fig. 3. Maximum non-dimensional rail deflection: Influence on critical velocity due to inclusion of stone columns

4.3 Effect of inclusion of stone columns on deflections

Fig. 4 shows the influence of inclusion of stone column on the deflection profile of top and the bottom beam for typical set of input parameters.

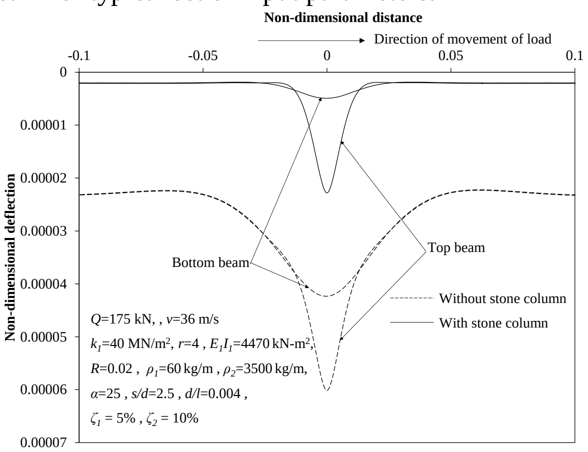

Fig. 4. Deflection profiles: effect of inclusion of stone column

The maximum non-dimensional deflection has been found to reduce by 62% and 88% for top and bottom beam respectively suggesting a significant amount of improvement in reducing the deflection due to inclusion of stone columns.

4.4 Effect of magnitude of applied load (*Q*)

Figs. 5 and 6 show the influence of applied load on the deflection profile of top and bottom beam respectively. The maximum normalized deflection has been found to reduce by 56% for top beam and 40% for bottom beam as the applied load reduces from 250 to 100 kN.

4.5 Effect of relative stiffness of stone column (α)

Fig. 7 depicts the effect of relative stiffness of stone columns with respect to surrounding soil on deflection profile of top beam. For the input parameters considered, a reduction of about 31% in the maximum normalized deflection has been observed corresponding to increase in ratio α from 10 to 100. The reduction in deflection has been observed due to the stiffer stone columns for higher values of α.

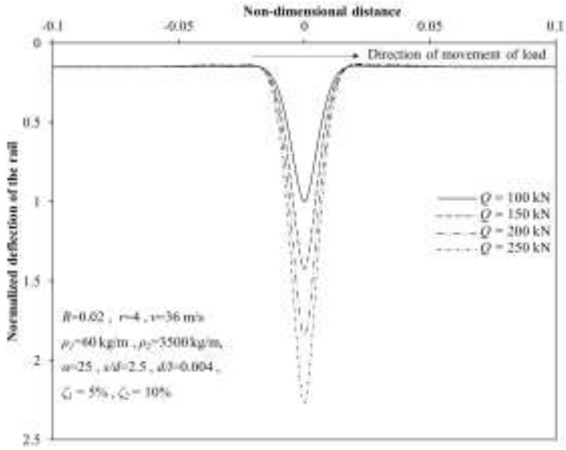

Fig. 5. Deflection profile of top beam: effect of applied load.

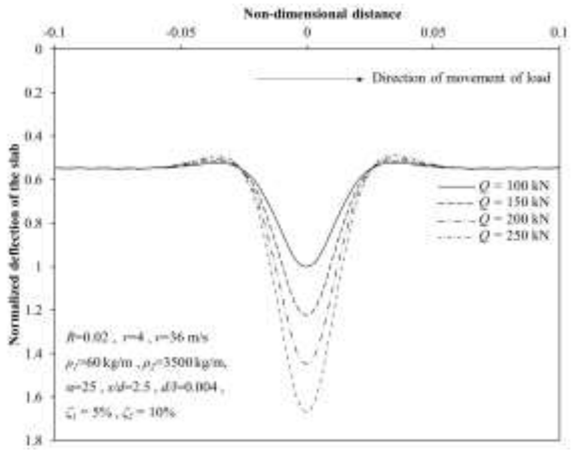

Fig. 6. Deflection profile of bottom beam: effect of applied load.

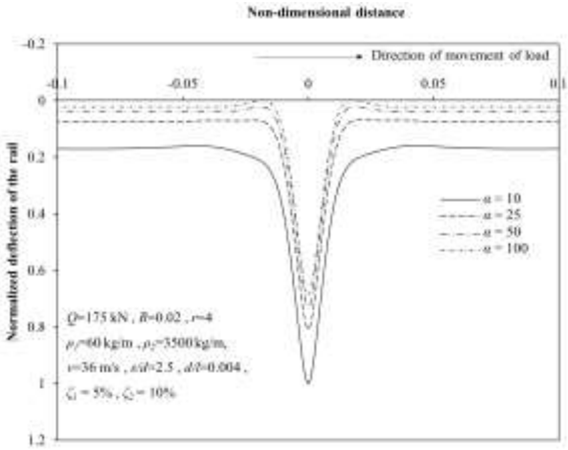

Fig. 7. Deflection profile of top beam: effect of relative stiffness of stone columns.

4.6. Effect of spacing to diameter ratio (*s/d*)

For a particular value of diameter of stone column, spacing has been varied from 2 to 3.5 times the diameter and the corresponding responses of top and bottom beams have been presented in Figs. 8 and 9 respectively. It has been observed that the normalized maximum deflection of top beam increases by 10% whereas in case of bottom beam, it increases by 73% which suggests that deflection of bottom beam is more sensitive towards this variation. Larger value of *s/d*, signifies the presence of lesser number of stone columns below the beams and therefore results in larger deflections.

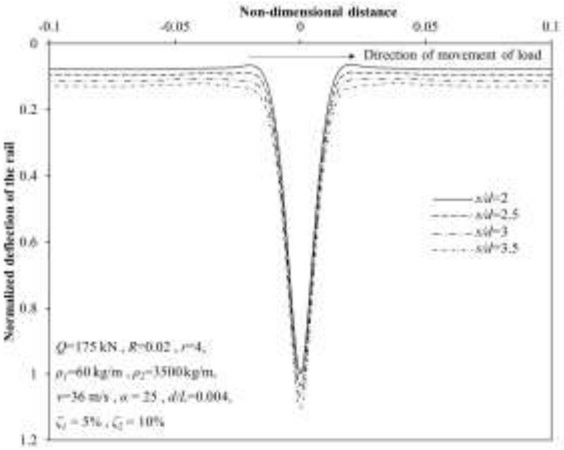

Fig. 8. Deflection profile of top beam: effect of *s/d* ratio.

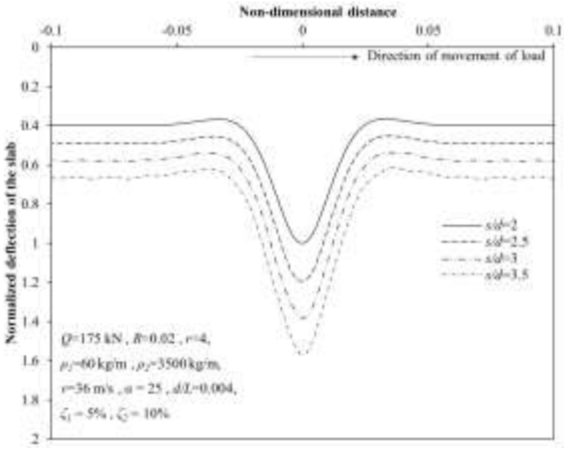

Fig. 9. Deflection profile of bottom beam: effect of *s/d* ratio.

5 CONCLUSION

Based on the analysis and detailed parametric study, the following conclusions can be drawn:

i) As a result of improvement by stone columns, 86% increment in critical velocity of the system has been observed. Further, maximum non-dimensional deflection for top and bottom beams have been found to reduce by 62% and 88% respectively.

ii) Moving load has been found to have significant effect on maximum normalized deflection of both top and bottom beam with reduction of 56% and 40% respectively for the range of values considered.

iii) Upon variation of relative stiffness of stone column from 10 to 100, a reduction of 31% and 85% have been observed in maximum normalized deflection of top and bottom beam respectively.

iv) For soft rail pads, deflection of top beam has been found to be less sensitive towards change in spacing to diameter ratio of stone columns as compared to bottom beam.

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